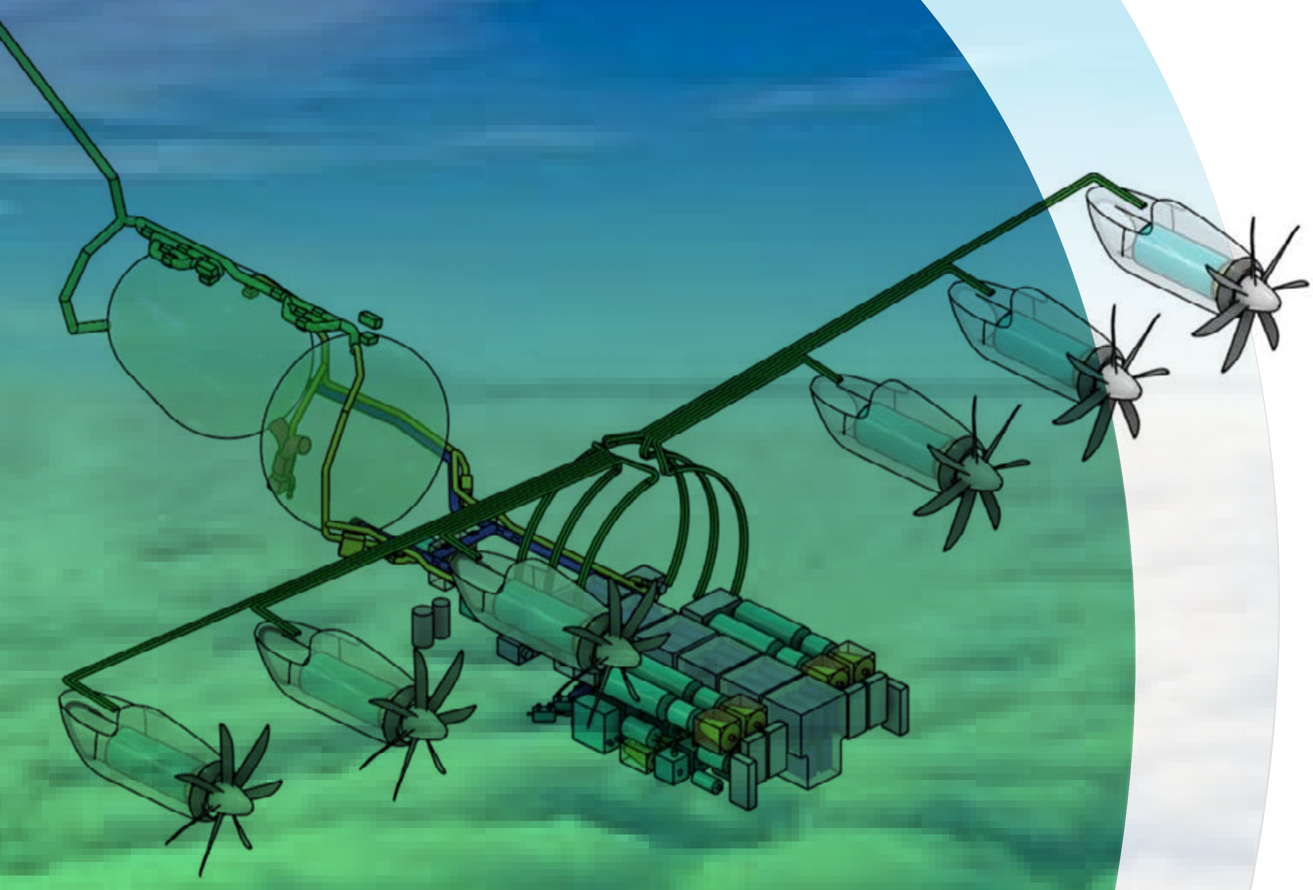
# AIRCRAFT SYSTEMS



FLY ZERO

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# ABOUT FLYZERO

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

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

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

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

# ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY

**The aviation industry has reached a pivotal moment in its history. Classical tube and wing aircraft have improved enormously over the past decades, but further incremental improvements will not satisfy global initiatives to limit climate change and will not lead to zero-carbon emission commercial flight.**

To investigate if this is indeed possible, FlyZero was established in early 2021 as an intensive research project to determine what changes needed to be made to realise this goal. A key finding from this work [1] has been that the goal is achievable, and that cryogenic liquid hydrogen is the best future aviation fuel.

Given such a revolutionary change in fuel type, the knock-on changes to the design of aircraft will give rise to significant challenges. Conversely, these will also generate significant opportunities which UK industry, and in particular the systems supply chain, is well placed to exploit.

This paper reviews the challenges and opportunities for civil aircraft systems brought about by the unique characteristics of liquid hydrogen as an aviation fuel and the opportunities for UK industry. Of all the systems on an aircraft two, namely electrical power and fuel, would need to be most radically changed. In order to examine these in sufficient detail they are covered in dedicated FlyZero reports - see [2] and [3] respectively and hence are not covered in this paper. It should also be apparent that significant changes will be needed to airport infrastructures and the fuel supply chain. Again these are not discussed here but are covered in other FlyZero documents - see [4] for example.

The work reported in this report is based on a desktop analysis and interviews with a number of systems suppliers.

## Challenges

Adopting liquid hydrogen as a fuel will drive significant changes to aircraft configurations. At an overall aircraft level, the difficulties of storing cryogenic fuel in the wings will lead to changes in wing design and most likely, the need to store the fuel in the fuselage. The fuel and propulsion systems will also need to be radically changed, albeit these are out of scope of this report.

At a systems level, the liquid hydrogen will need to be kept at an extremely low temperature of 20K (or -253°C) which will place new demands on the fuel storage and distribution network. These low temperatures may also need to be managed alongside heat generated from fuel cells meaning aircraft thermal management needs to be carefully considered.

With hydrogen replacing kerosene as the fuel, alternatives to traditional fueldraulic[1] systems used to actuate engine components will need to be found. Alternative solutions will also be needed for auxiliary power units (APU) which are today fuelled by kerosene.

This new category of aircraft will also give rise to requirements to improve the efficiency of high lift devices due to the higher landing weights[2] of hydrogen-fuelled aircraft. This will be a driver for improvements to actuation systems. Finally, although not directly related to liquid hydrogen technology, the trend of more electric aircraft will inevitably continue which will give rise to the challenge of minimising the electrical power consumption of all systems.

From an organisational standpoint, based on interviews with several suppliers, there is not yet a mutual understanding of the aircraft revolution that is already happening. In addition, large systems companies are predominantly international, not UK based. Both of these factors could impede the development and delivery of UK-led systems capability for this new class of aircraft.

## Recommendations

To address these challenges and to realise the vision of liquid hydrogen-fuelled aircraft, it is recommended that a number of key systems technologies are developed. These are:

- Cryogenic hydrogen containment and fluid control technology (pumps, filters, valves, seals, bearings, pipes etc).
- Hydrogen-specific leak detection, fire detection and suppression systems.
- Novel APU architectures including liquid hydrogen-fuelled gas turbines, internal combustion engines and fuel cells.
- Inerting systems for liquid hydrogen aircraft designed for the zones adjacent to the fuel tank(s).
- Engine component actuation system architectures to replace the today's fueldraulic systems.

In parallel with the above it is essential that the customary aircraft development process of improving efficiency, increasing reliability and reducing weight continues. In particular:

- Activities relating to the increasing electrification of aircraft including development of electrical actuation, control systems and sensors for flying controls should be prioritised. As part of this process every opportunity should be taken to reduce, electrical power demand, especially of the major consumers such as the environmental control system (ECS) and ice protection system (IPS).
- Development of novel landing gear architectures, performance improvements such as energy recovery and sustainability improvements such as noise reduction.

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*[1] Fueldraulics refers to a hydraulic system wherein the working fluid is fuel.*

*[2] Comparing a kerosene and hydrogen fuelled aircraft at a constant range, the required mass of hydrogen is three times less. This means that less mass is lost during a mission with the result that the landing weight compared to the take-off weight is higher for the hydrogen fuelled aircraft.*

The above recommendations relate to essentially mono-disciplinary activities – those related to the development of individual systems. However the integration of these systems at an aircraft level also needs to be addressed, both in terms of design, and verification and validation (i.e. physical testing). In support of this:

- A UK virtual systems network comprising systems suppliers, academia and the end customer(s) should be established for the sharing of information, development of systems requirements and the exploitation of system integration opportunities.
- To support the design work that will be produced in the above a systems test pyramid needs to be defined and new test facilities built where required. At the top of this pyramid a national wing systems 'plug and play' test rig should be developed for the integrated development of novel systems such as actuators, control systems, sensors etc.

Finally, all of the above will need to be done while the industry skill base is transitioning to a new fuel type and the airworthiness regulations and design standards are evolving. This means:

- A centralised authoritative database on all aspects of the use of hydrogen as a commercial aviation fuel and associated training courses should be established.
- For expediency, every opportunity should be taken to engage with the various standards organisations and authorities to drive the regulatory changes needed rather than to wait for new standards to emerge.

## Conclusions

The FlyZero project has identified that cryogenic liquid hydrogen is the most suitable fuel to enable zero-carbon tailpipe emission flight. The impact of this finding on aircraft systems has been investigated and recommendations for the requisite development activities made.

The global aviation community is already actively pursuing ways to reduce aircraft emissions with an intensity that has not been seen before. For example, in 2020 the French government announced its vision of a hydrogen-powered plane in the next 15 years supported by a €7 billion injection into the hydrogen power sector and a €15 billion support plan for the country's aerospace industry [5].

For the UK to remain competitive the time for investment is now, as the aspirational in-service date for a hydrogen-powered aircraft is just over a decade away which is a relatively short time to develop technology, design and certificate an aircraft.

For the systems community this offers opportunities to secure component or systems supply for their area of expertise or to establish a market position where there are currently gaps in the market or where the market does not currently exist.

# 01.
# INTRODUCTION

FlyZero is led by the UK's Aerospace Technology Institute (ATI) and sponsored by the UK government's Jet Zero Council as part of the Prime Minister's "Ten Point Plan for a Green Industrial Revolution" [6]. Jet Zero has two main delivery groups, a group that is looking at the adoption of sustainable aviation fuel (SAF) – carbon-based fuels that are drop-in alternatives to kerosene and FlyZero which is looking at energy sources with zero-carbon tailpipe emissions.

FlyZero has been tasked with assessing the feasibility of zero-carbon emissions commercial flight and defining the technology roadmaps needed to realise the vision. An early finding from this work has been that liquid hydrogen is the best future aviation fuel and can enable zero-carbon tailpipe emission aircraft.

To assess the implications of this finding in more depth, the team has identified 13 'technology bricks' which are required to enable hydrogen flight as shown in **Figure 1**. Of these, hydrogen aircraft roadmaps cover six bricks, which are the revolutionary aerospace technology developments fundamental to realising liquid hydrogen-fuelled aircraft. The remaining seven, which include systems[3], are seen as underpinning technology areas that will enable the realisation of future aircraft and ensure that these new products are more sustainable; these are covered by cross-cutting roadmap papers. This document is the Aircraft Systems cross-cutting roadmap paper.

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[3] *Excluding electrical power and fuel as these are covered in dedicated hydrogen aircraft roadmaps – see Figure 1 below.*

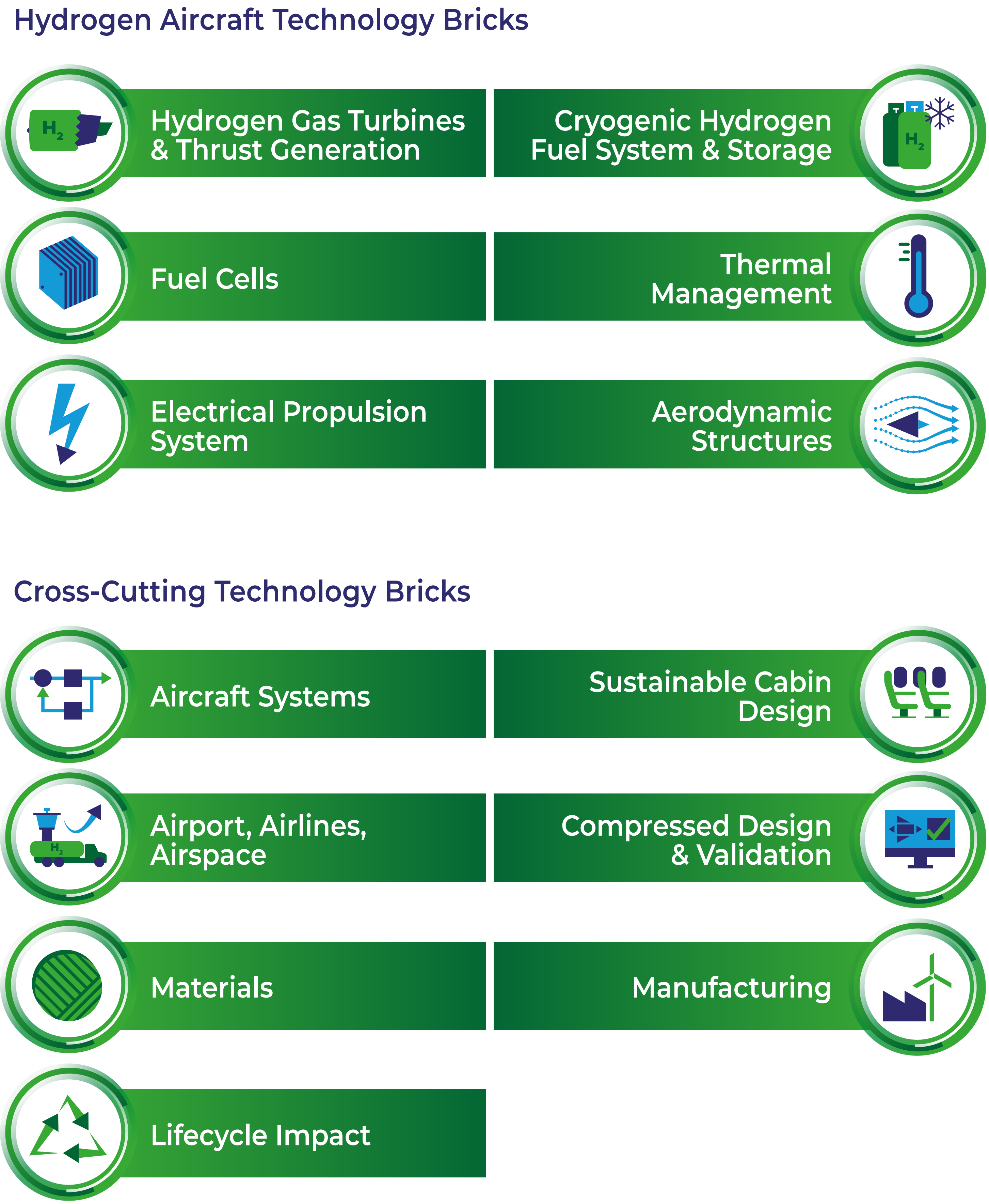

*Figure 1: Flyzero technology bricks*

The information in this report has been gathered through a combination of supplier engagements and desk-based research. The report is structured by first reviewing each system in turn (using the Air Transport Association of America (ATA) chapter list) and then reviewing and consolidating supplier feedback which often applies to more than one ATA chapter.

## In-scope

- An appraisal of the systems changes needed to help realise zero-carbon aircraft
- Consultation with systems suppliers[4] to understand the current development landscape in the UK and how closely it aligns with the above

## Out-of-scope

- Electrical power systems and fuel systems as these are covered in dedicated roadmaps of their own
- System design activities, such as flight control architecture, environmental conditioning systems etc, due to limited resources

The purpose of this cross-cutting roadmap paper is to:

- Review the challenges and opportunities for civil aircraft systems brought about by the unique characteristics of a zero-carbon aircraft, in particular the opportunities for UK industry
- To publish this to the wider aerospace community
- To make recommendations for systems technology and organisational development to ensure that the UK plays a leading role in realising this next generation of aircraft

*4 Note: time and resource limitations meant that other centres of excellence e.g. universities and research organisations were not consulted during this exercise.*

# 02.

# ZERO-CARBON AIRCRAFT

## 02.1

## AIRCRAFT FUEL TYPE AND PROPULSION SYSTEM

To investigate the possibility of zero-carbon aircraft, several different fuel types were studied as reported in **[1]**. One of the conclusions of this study was that cryogenic liquid hydrogen was the most appropriate "fuel source to enable zero-carbon emissions flight for larger aircraft". It was also noted that "low and net-zero carbon solutions such as sustainable aviation fuel are not in scope but will be considered as reference points of comparison as the programme progresses".

Given that cryogenic liquid hydrogen was deemed the most suitable fuel for a zero-carbon aircraft, a suitable propulsion system is needed to consume this fuel, with the following three options being studied:

- Combine it with oxygen in a fuel cell
- Burn it in a gas turbine engine
- Burn it in an internal combustion engine

Based on these studies and parallel conceptual studies of regional, narrowbody and midsize aircraft, known as FZR, FZN and FZM respectively[5], the most suitable pairings of propulsion system and aircraft category were found to be:

- Regional aircraft powered by fuel cells
- Narrowbody and midsized aircraft powered by gas turbines

It would also be possible to power a regional aircraft with gas turbines, but the decision was taken to configure the FlyZero regional aircraft with fuel cell-powered propellers in order that the design challenges of a fuel cell aircraft could be investigated.

Images of FZR, FZN and FZM are shown in **Figures 2**, **3** and **4** respectively for reference. Although only limited details of the systems are shown, the hydrogen fuel tanks can be seen, installed in the aft fuselage of all three concepts. For FZM there are also hydrogen tanks in the wing root fairings ahead of the wing root which can be seen in **Figure 4**. In addition, for FZR, the fuel cell installation in the belly fairing can be seen with the air intake visible.

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[5] *FlyZero Regional (FZR), FlyZero Narrowbody (FZN), FlyZero Midsize (FZM).*

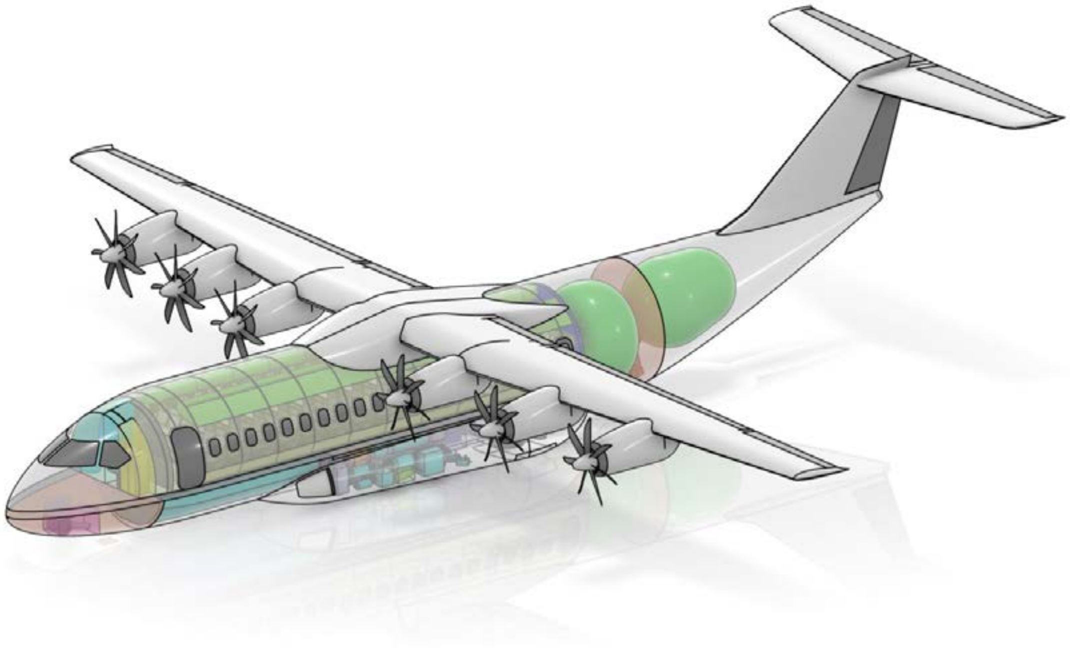

*Figure 2: FlyZero regional aircraft concept, FZR*

*Figure 3: FlyZero narrowbody aircraft concept, FZN*

*Figure 4: FlyZero midsize aircraft concept, FZM*

# 02.2

# CONSEQUENCES OF A LIQUID HYDROGEN-POWERED AIRCRAFT

Having selected liquid hydrogen as the fuel source, several fundamental challenges arise which lead to design differences from a kerosene-fuelled aircraft, the main ones being:

- Hydrogen needs to be stored in the fuselage or external pods since a much greater fuel volume is required compared to kerosene-powered aircraft: for example, comparing the two aircraft types at a constant range, the required mass of hydrogen is three times less but the required volume around four times more.
- As a lower mass of liquid hydrogen fuel is required for a given mission, then the difference between the maximum take-off weight (MTOW) and maximum landing weight (MLW) will be much less for a liquid hydrogen aircraft which could influence the aircraft design. For example, a traditional fuel jettison system to reduce the landing weight may not be permitted; or a more efficient high lift system could be required to achieve an acceptable approach speed.
- As the fuel is no longer stored in the wing, the wing now becomes 'dry', which could create design opportunities. Conversely, not being able to store fuel in the wing could lead to potentially radical aircraft architectures. For example, the need to store fuel in the fuselage could compromise capacity and create new systems integration challenges.
- The work reported in [1] notes that the maximum temperature needed to keep the hydrogen liquid is 20K. Maintaining and distributing fuel on board an aircraft at these temperatures will be a particular challenge.
- The current certification regulations have been written around kerosene-fuelled aircraft and will need to be revised to also cover liquid hydrogen-fuelled aircraft.

While the above gives an overview of some of the consequences of having liquid hydrogen as a fuel, there are also some additional consequences of not having kerosene on board, these being:

- There will be no fueldraulic power available to move such things as engine variable inlet guide vanes for example, due to the thermal design challenges of keeping hydrogen fuel in its liquid state in the hot engine environment.
- The fuel will not be available as a heat sink to cool hydraulic fluid via a heat exchanger situated in the fuel tank as is the case with some existing aircraft.
- The bending moment relief that is inherent when fuel is stored in the wings will not be available, which could lead to a heavier wing structure.
- There will be reduced opportunity (or increased complexity) for centre of gravity (CG) control compared to kerosene-fuelled aircraft where fuel is often pumped between the wing and tail tanks to adjust the CG in flight.

These notable differences between the commercial aircraft of today and future liquid hydrogen powered aircraft form the backdrop to changes needed in the systems environment.

# 03.

# IMPACT ON SYSTEMS

## 03.1

## SYSTEMS OVERVIEW

To understand the effect of the aircraft changes mentioned in **Section 2** it is convenient to look at the various systems by means of the systems ATA chapter list – see **Table 1**.

| Number | ATA Chapter Name |
|---|---|
| ATA 21 | Air Conditioning |
| ATA 22 | Auto Flight |
| ATA 23 | Communication |
| ATA 24 | Electrical Power |
| ATA 25 | Equipment / Furnishings |
| ATA 26 | Fire Protection |
| ATA 27 | Flight Controls |
| ATA 28 | Fuel |
| ATA 29 | Hydraulic Power |
| ATA 30 | Ice and Rain Protection |
| ATA 31 | Indicating / Recording System |
| ATA 32 | Landing Gear |
| ATA 33 | Lights |
| ATA 34 | Navigation |
| ATA 35 | Oxygen |
| ATA 36 | Pneumatic |
| ATA 37 | Vacuum |
| ATA 38 | Water / Waste |
| ATA 39 | Electrical - Electronic Panels and Multipurpose Components |
| ATA 40 | Multisystem |
| ATA 41 | Water Ballast |
| ATA 42 | Intergrated Modular Avionics |
| ATA 43 | Not used |
| ATA 44 | Cabin Systems |
| ATA 45 | Onboard Maintenance Systems (OMS) |
| ATA 46 | Information Systems |
| ATA 47 | Inerting |
| ATA 48 | In-flight Fuel Dispensing |
| ATA 49 | APU |
| ATA 50 | Cargo and Accessory Compartments |

*Table 1: Systems ATA chapter list*

By reviewing these chapters while considering the characteristics of a liquid hydrogen aircraft, it is possible to see where 'revolutionary' i.e. pertaining to liquid hydrogen in this discussion, changes to a system are necessary and where 'evolutionary' or incremental changes to reduce weight or cost, improve reliability etc, are needed. This overview is provided in **Table 2**.

| *Number* | *ATA Chapter Name* |
|---|---|
| *ATA 21* | *Air Conditioning* |
| *ATA 22* | *Auto Flight* |
| *ATA 23* | *Communication* |
| *ATA 24* | *Electrical Power* |
| *ATA 25* | *Equipment / Furnishings* |
| *ATA 26* | *Fire Protection* |
| *ATA 27* | *Flight Controls* |
| *ATA 28* | *Fuel* |
| *ATA 29* | *Hydraulic Power* |
| *ATA 30* | *Ice and Rain Protection* |
| *ATA 31* | *Indicating / Recording Systems* |
| *ATA 32* | *Landing Gear* |
| *ATA 33* | *Lights* |
| *ATA 34* | *Navigate* |
| *ATA 35* | *Oxygen* |

| *Number* | *ATA Chapter Name* |
|---|---|
| *ATA 36* | *Pneumatic* |
| *ATA 37* | *Vacuum* |
| *ATA 38* | *Water / Waste* |
| *ATA 39* | *Electrical - Electronic Panels and Multipurpose Components* |
| *ATA 40* | *Multisystem* |
| *ATA 41* | *Water Ballast* |
| *ATA 42* | *Intergrated Modular Avionics* |
| *ATA 43* | *Not used* |
| *ATA 44* | *Cabin Systems* |
| *ATA 45* | *Onboard Maintenance Systems (OMS)* |
| *ATA 46* | *Information Systems* |
| *ATA 47* | *Inerting* |
| *ATA 48* | *In-flight Fuel Dispensing* |
| *ATA 49* | *APU* |
| *ATA 50* | *Cargo and Accessory Compartments* |

*Table 2: Revolutionary and evolutionary changes needed*

KEY

☐ *Evolutionary changes needed*

🟦 *Revolutionary changes needed*

🟩 *Revolutionary changes needed and being assessed in depth by FlyZero team*

⬛ *Will not feature on FlyZero aircraft*

As can be seen from **Table 2** there are only a limited number of revolutionary changes needed at a systems level but even so some, for example a fuel system that needs to manage cryogenic liquid hydrogen fuel, will undoubtedly throw up many significant challenges before development can be completed and certification achieved.

The following sections discuss the various revolutionary and evolutionary systems developments that will be needed, considering each ATA chapter in turn. Also included is a brief commentary on UK supplier capabilities for each ATA chapter.

In the following section, **Section 4**, an analysis of discussions with suppliers is presented which complements this ATA chapter analysis by giving a more holistic and integrated view of future system developments.

# 03.2
# REVOLUTIONARY CHANGES

Designating system changes as either revolutionary or evolutionary is subjective and this being so, for the purposes of this discussion, it is considered that revolutionary changes will be necessary for the following systems:

- ATA 24 Electrical power
- ATA 26 Fire protection
- ATA 28 Fuel
- ATA 49 APU

Of these, ATAs 24 and 28 are covered by **[2]** and **[3]** respectively and so only ATAs 26 and 49 will be discussed in what follows.

# 03.2.1
# ATA 26 – FIRE PROTECTION

The fire protection system for a liquid hydrogen-fuelled aircraft would be similar to that of a kerosene-powered aircraft in that the key functional elements would be the same; these elements are:

- Fire and overheat detection system for:
    - Engines, APU compartment, main landing gear bay, for example
- Smoke detection system for:
    - Avionics bays, cargo compartments, lavatories, crew rest compartments for example
- Fire extinguishing system for:
    - Engines, APU and cargo compartments, lavatories for example

When considering detection, traditional systems are mostly configured to detect heat (in order to detect fires, bleed air duct rupture, battery fires etc) and in some instances to detect the presence of (hydrocarbon) fires via optical flame detection (OFD) **[7]**. However, although hydrogen and kerosene are both flammable, they have, among other aspects, different flammability ranges[6], molecular sizes and flame colours, which will necessitate changes to the leak and flame detection system: this is the revolutionary aspect.

To extinguish a fire, fire suppression systems in general rely on the principle of displacing oxygen or the extinguishing agent chemically combining with the oxygen to prevent combustion: this is equally applicable to hydrogen and kerosene. However, the 'traditional' agent, halon[7] has been prohibited for some years and hence a replacement will be needed, for any future aircraft, whatever the fuel source.

There are several suppliers[8] with conventional fire protection capability within their overall business group: these suppliers include Meggitt and Collins, however their capability resides overseas leaving a limited UK supplier footprint. The only supplier identified with conventional capability in the UK to date is Marshall. Furthermore, there is a mixed level of technology development activity aligned to hydrogen applications, with some suppliers having actively explored this topic and others positioning themselves to commence.

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*[6] The flammability range is the range of concentration of hydrogen (in this case) in air (minimum to maximum) over which ignition will occur.*
*[7] Halon is short for halogenated hydrocarbon.*
*[8] The supplier assessments shown throughout this report have been generated by consolidating feedback from supplier discussions and desktop research.*

A replacement solution for halon will be needed for any future aircraft irrespective of fuel source. There are several companies already developing potential alternatives which include:

- US-based Amerex have recently (June 2021) introduced halon-free systems (Halotron BrX) for portable extinguishers
- US-based Ventura aerospace has introduced an argon foam system for the main decks of cargo aircraft
- Germany-based Diehl have developed a technology that uses fine water mist coupled with nitrogen
- Meggitt have developed a green fire suppression solution, VERDAGENT™ at their US-based facility
- The EU-funded ECOSYSTEM project was launched in 2019 under funding from Horizon 2020 to develop a halon-free fire suppression system for safe aviation; the consortia for this include the United Technologies Research Centre in Ireland and Kidde Graviner in Solihull

While the above list shows good progress in the elimination of halon, it remains to be confirmed whether or not these would be suitable for extinguishing a hydrogen fire.

## 03.2.2

## ATA 49 – AUXILIARY POWER UNIT (APU)

Any discussion of an APU for a zero-carbon aircraft needs to be done in light of an understanding of the aircraft's main propulsion system. As discussed in **Section 2**, the FlyZero team has designed:

- A regional aircraft powered by fuel cells
- A narrowbody and a midsize aircraft both powered by liquid hydrogen gas turbines

For the regional aircraft, solely powered by fuel cells, an APU as such would not be needed as the power to run the aircraft systems before take-off would come from the same power source as that used to propel the aircraft. For the larger aircraft however, several options for an APU are possible as discussed in what follows.

Most large civil aircraft contain an APU as a means of:

1. Providing power for key aircraft systems like lighting, avionics, air conditioning etc before engine start
2. Starting the engines
3. Emergency backup power in the event of engine failure

Requirements one and two in the above list could of course be provided by ground carts. However, it is assumed that reliance on ground carts would not be acceptable to airlines and so all three requirements need to be satisfied by an APU.

Until the advent of the Boeing 787, APUs provided both pneumatic and electrical power for modern civil aircraft. For the 787, the APU only provides electrical power as part of its more electrical architecture. For a liquid hydrogen gas turbine powered aircraft it is probable that the same bleedless architecture will be used to improve engine core efficiency and reduce fuel burn: this then modifies the second requirement above to 'starting the engines (electrically)'.

Hence, with the onboard fuel source being liquid hydrogen and the need to start the main engines electrically, the options for the APU are:

- A liquid hydrogen gas turbine ($LH_2$GT)
- A liquid hydrogen internal combustion engine ($LH_2$ICE)
- Fuel cells

## $LH_2GT$

A $LH_2GT$ APU would be much the same as today's APUs in principle, in that it would be a gas turbine albeit fed with a different fuel. As the $LH_2GT$ concept is the baseline for the propulsion system of the FlyZero narrowbody and midsized concepts, it has been studied in some depth and is considered a viable propulsion concept. In principle, the same concept should be suitable for an APU, although the key design requirements would be a little different. For example, the key driver of optimum efficiency for the main propulsion engine might not be the key driver for an APU application where minimal size, weight, noise etc could well be more important. While the detailed requirements still need to be defined, it is clear that development work would be required to produce a $LH_2GT$ APU which would have a similar development pathway to a $LH_2GT$ main propulsion unit.

## $LH_2ICE$

As an alternative to a $LH_2GT$, the liquid hydrogen could be burned in an internal combustion engine. As ICEs are very mature machines and can be designed to burn liquid hydrogen this is an attractive option. Studies of hydrogen-fuelled ICEs have been done for the automotive industry and show promising results. Adapting these to aviation could offer a quick route to market and could be done in the UK according to [8]. Indeed [8] notes that the automotive sector in the UK is very mature with around 2,350 original equipment manufacturers (OEMs), tier 1 and tier 2 suppliers operating in the sector of which the majority are small and medium enterprises (SMEs). It is also noted is that both Cummins and JCB are developing engines in the UK capable of running on hydrogen in partnership with other UK-based suppliers. However, adapting this technology to work over an aircraft flight profile, including the balance of plant (BOP) components such as intakes and compressors needs to be addressed alongside noise and reliability issues.

## Fuel cells

Unlike the above two options where the fuel is burned to drive a shaft which then drives a generator, fuel cells directly convert hydrogen to electricity via a chemical process. In so doing they are more efficient and quieter than the other two options with zero emissions apart from water and heat (both the combustion options will emit a small amount of NOX (oxides of nitrogen) in comparison). However, when the BOP components such as batteries, compressors and inverters are added to the system, the specific power drops significantly (from around 9 kW/kg[9] to around 2 kW/kg) making it a less attractive option. In addition, it is likely that the purity of hydrogen for a fuel cell needs to be 99.995% which is higher than that required for a liquid hydrogen gas turbine so this might impose additional constraints on the system. That being said, fuel cells are still a viable option for an APU, but further development of the fuel cells and the BOP would be required for them to become the APU 'solution of choice'.

At the time of writing, it is not clear which of the above options would be a clear winner (or indeed what is the driving requirement e.g. specific power, efficiency, low noise etc). What is clear however, is that each needs to be further developed which presents a new opportunity to secure the technology for this system for future aircraft.

Finally, while the discussion thus far has centred on the systems ATA chapters, it should be noted that the propulsion system is also covered by its own ATA chapters – see **Table 3**. While a discussion of the propulsion system is outside the scope of this paper, it is interesting to consider two chapters, ATAs 82 and 85, highlighted in blue. Engine thrust can be increased by water injection which if part of the baseline could improve the efficiency of the engine. If a fuel cell were selected as the APU, this would provide the water for the injection system. Hence, the final choice for the APU must be made in conjunction with the decisions made around the engine architecture.

| *Number* | *ATA Chapter Name* |
|---|---|
| *ATA 71* | *Power Plant* |
| *ATA 72* | *Engine* |
| *ATA 73* | *Engine - Fuel and Control* |
| *ATA 74* | *Ignition* |
| *ATA 75* | *Bleed Air* |
| *ATA 76* | *Engine Controls* |
| *ATA 77* | *Engine Indicating* |
| *ATA 78* | *Exhaust* |
| *ATA 79* | *Oil* |
| *ATA 80* | *Starting* |
| *ATA 81* | *Turbine (reciprocating engines)* |
| *ATA 82* | *Water Injection* |
| *ATA 83* | *Accessory Gear Box (engine driven)* |
| *ATA 84* | *Propulsion Augmentation* |
| *ATA 85* | *Fuel Cell Systems* |

*Table 3: Propulsion ATA chapter list*

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[9] *Estimate of fuel cell specific power in 2030.*

Within this (APU) ATA chapter, there were no identified UK suppliers with the capability to supply conventional civil aircraft APU systems. Honeywell is a major supplier of these systems from their US facility with a presence on circa 150 airframes and with over 36,000 units in service. Safran Power Units business delivers over 500 units per year from facilities in France and the USA and currently has over 22,000 units in service. Another major supplier in this sector is Pratt and Whitney Canada, part of Raytheon Technologies, who have developed APUs for the A380 and 787 along with units for the A320 and various other Boeing applications.

With changes to aircraft architecture necessary to accommodate liquid hydrogen this may present an opportunity to utilise alternative APU solutions, potentially enabling the UK to harness existing capabilities repurposed for aerospace application. These include fuel cells or liquid hydrogen ICE technology or alternatively a small-scale liquid hydrogen gas turbine. The potential UK supply chain for these technologies includes Intelligent Energy, Ricardo and Rolls-Royce although there are other suppliers well placed to align themselves to these alternative technologies.

# 03.3

# EVOLUTIONARY CHANGES

As noted earlier, most system changes will be evolutionary and driven by the customary demands of reducing weight, improving reliability etc. With this in mind, the following systems are not considered further in this report as they are not directly related to a zero-carbon aircraft:

ATA 22 – autoflight
ATA 23 – communication
ATA 25 – equipment / furnishings
ATA 29 – hydraulic power
ATA 31 – indicating / recording system
ATA 33 – lights
ATA 34 – navigation
ATA 35 – oxygen
ATA 37 – vacuum
ATA 39 – electrical – electronic panels and multipurpose components
ATA 42 – integrated modular avionics
ATA 44 – cabin systems
ATA 45 – onboard maintenance systems
ATA 46 – information systems
ATA 50 – cargo and accessory compartments

As explained later, there are a small number of systems, however, that may be directly affected by the change to a liquid hydrogen aircraft these being:

ATA 32 – landing gear
ATA 38 – water / waste
ATA 47 – inerting

Additionally, a small number of systems may be indirectly affected by a change to liquid hydrogen, for example where the change in fuel type and propulsion system pushes the aircraft architecture towards more electric aircraft, the affected systems being:

ATA 21 – air conditioning
ATA 27 – flight controls
ATA 30 – ice and rain protection

The next sections review these systems, in numerical ATA chapter order, and indicate where changes will need to be made for future aircraft.

# 03.3.1

# ATA 21 – AIR CONDITIONING

Today's civil aircraft, for the most part, feature pneumatically powered air conditioning or environmental control systems (ECS). The notable exception to this is the 787 which has an electrically powered system to avoid taking bleed air from the engines.

It is considered that this will become the de facto architecture for future aircraft, regardless of fuel type, as part of the overall industry momentum towards more electric aircraft – see **Figure 5**.

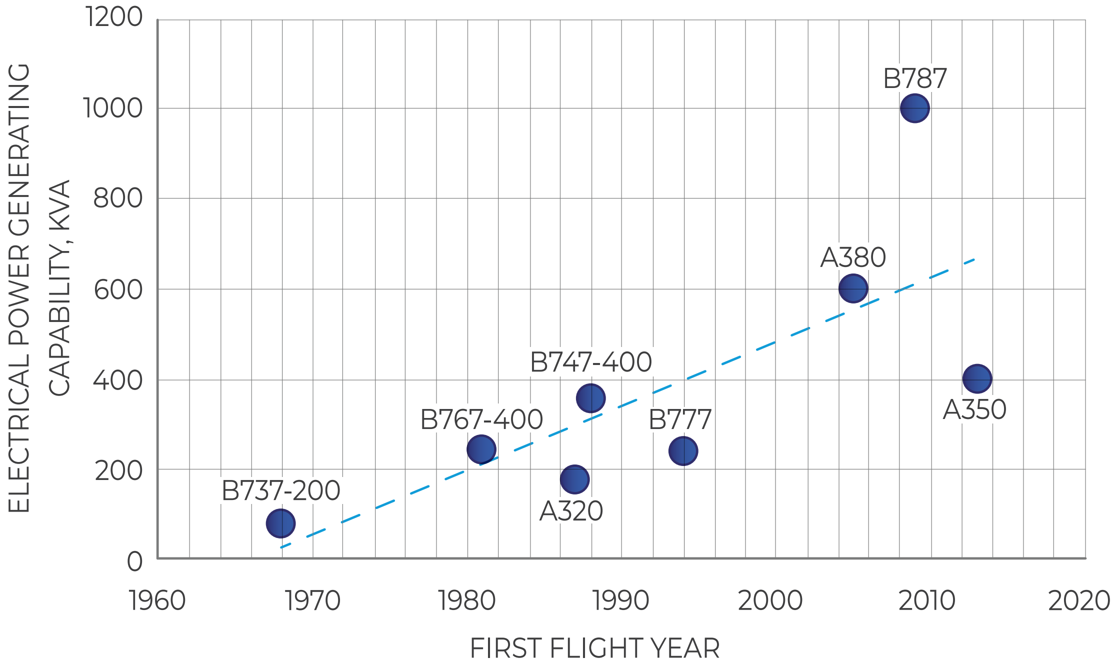

*Figure 5: Electrical power generating capacity by first flight year [kVA]*

The electrical ECS on the 787 was a radical departure from the norm and its power demand is high, consuming around half of the non-propulsive power according to **[9]**. Hence, for future systems, there needs to be a drive to reduce power including the evaluation of different architectures e.g. vapour cycle[10].

The expectation is that the technology will be evolutionary and thus existing suppliers will be well positioned to support liquid hydrogen aircraft. There are a number of global suppliers in the UK with existing system capability that could support future requirements. These include Honeywell, Collins and Ultra Precision Control Systems, however not all manufacture at their UK facilities. Other UK suppliers with aerospace exposure, but not currently with their air conditioning product, include Ametek who supply air conditioning capability for military vehicle applications. Filtration capabilities, both for air conditioning and wider aircraft requirements are also well supported by the UK supply chain. Suppliers in this area include Porvair and Pall who both supply to a wide range of civil aircraft applications.

*10 A vapour cycle is a thermodynamic cycle during which the working fluid is in, and passes through, the vapour state: it is the thermodynamic cycle utilized in refrigerators and heat pumps.*

## 03.3.2

## ATA 27 – FLIGHT CONTROLS

Aircraft primary flight controls i.e. ailerons, elevators and rudders and secondary flight controls i.e. spoilers, slats and flaps, have long been powered by hydraulics on commercial aircraft, typically using three hydraulic circuits with a mechanical backup.

On more recent Airbus aircraft, namely the A380 and the A350, this traditional baseline has changed to two hydraulic and two electrical circuits, the so-called 2H+2E architecture. While the remit of FlyZero was not specifically to study flight control architecture, as the related technology is unrelated to fuel type, it seems inevitable that the move towards more electric aircraft and flight controls will continue. This drive for aircraft electrification and related developments to improve aerodynamic performance and to reduce loads will likely lead to the introduction of new flight control technology. Such developments could include, among others, more use of electro-hydrostatic actuators (EHAs), the commercial introduction of electro-mechanical actuators (EMAs), distributed power arrangements, independent control of moveable devices and wireless position sensors.

In addition, some of the new airframe technology currently being developed, such as the semi-aeroelastic hinge folding wing concept by Airbus **[10]**, will lead to new challenges and opportunities in actuator design. Therefore, it is important that these components are developed in conjunction with the control systems and aircraft electrical power distribution and communication networks. Furthermore, as previously mentioned, a characteristic of a hydrogen-fuelled aircraft is that the maximum landing weight will be much closer to the maximum take-off weight than on conventional aircraft. One consequence of this is that more effective high lift devices may be needed which could drive further innovations in systems weight and efficiency.

This technology is again seen as evolutionary and current systems suppliers would be well positioned to support future hydrogen aircraft requirements, with many of the technology developments already being underway. The UK supply chain has numerous suppliers with elements of flight control capability, these include Meggitt, Cobham, Moog, Collins and Thales, each offering different technology developments and what on the surface appear to be complementary capabilities. Again, although these suppliers have UK presence, not all manufacture flight controls in the UK. However, those that do have extensive cross sector exposure in space, military, civil aircraft and helicopters positioning them well to supporting the development of technology for hydrogen-powered aircraft.

## 03.3.3

## ATA 30 – ICE AND RAIN PROTECTION

With large commercial aircraft moving away from a pneumatic bleed system, the baseline power source for the ice and rain protection system (IPS) will most probably be electrical for the aerodynamic surfaces while continuing to use engine bleed air for the engine nacelles. That being said, there is an argument that with a fuel cell powered aircraft the waste heat generated by the fuel cells could be utilised in the IPS (for every kW of electrical power generated a kW of waste heat is generated) so this possibility should not be overlooked.

For an electrical IPS, the 787 implementation can be considered as state-of-the-art. In this design several heating blankets are bonded to the interior of the slat leading edges and can either be energised simultaneously for anti-icing protection or sequentially for de-icing protection[11] to heat the wing leading edge. However, as with the ECS this is a major power consumer and so ways of reducing power demand should be investigated. This could be done in numerous ways and alternative technologies such as electro-impulsive, shape memory alloys or ultrasound systems should be investigated. Improved ice detection systems should also be developed to overcome inherent limitations in existing mechanical and optical systems. In addition, not only should these technologies be investigated and developed but also the integration into the aircraft structure e.g. a slat or a component such as an intake duct, should be addressed.

As with previous ATA chapters, this technology space is considered evolutionary, with current technology developments being potential options for future hydrogen-powered aircraft. This supply chain has a number of suppliers with UK presence, however not all of these support ATA 30 technology in the UK, which is a consistent theme with other systems. Suppliers with group capability include Meggitt, Honeywell, Collins, GKN and Ultra Precision Control Systems. There are differing technology development routes being explored within these suppliers which will hopefully offer alternative technologies which can be assessed as the available aircraft electrical power availability levels become more clearly understood.

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*[11] Anti-icing is the process of preventing ice from forming on an aircraft: de-icing is the process of removing ice that has already formed.*

## 03.3.4

## ATA 32 – LANDING GEAR

ATA 32 encompasses landing gear structure, brakes, steering, control and wheels and tyres.

The transition to hydrogen-fuelled aircraft has the potential to radically change landing gear architectures. The drive across industry to reduce all emissions and improve product sustainability could also drive significant changes. While the focus of the FlyZero project is primarily on the revolutionary technology, it is recognised that landing gears are an area of importance in improving overall product sustainability, which evolutionary technology can enable.

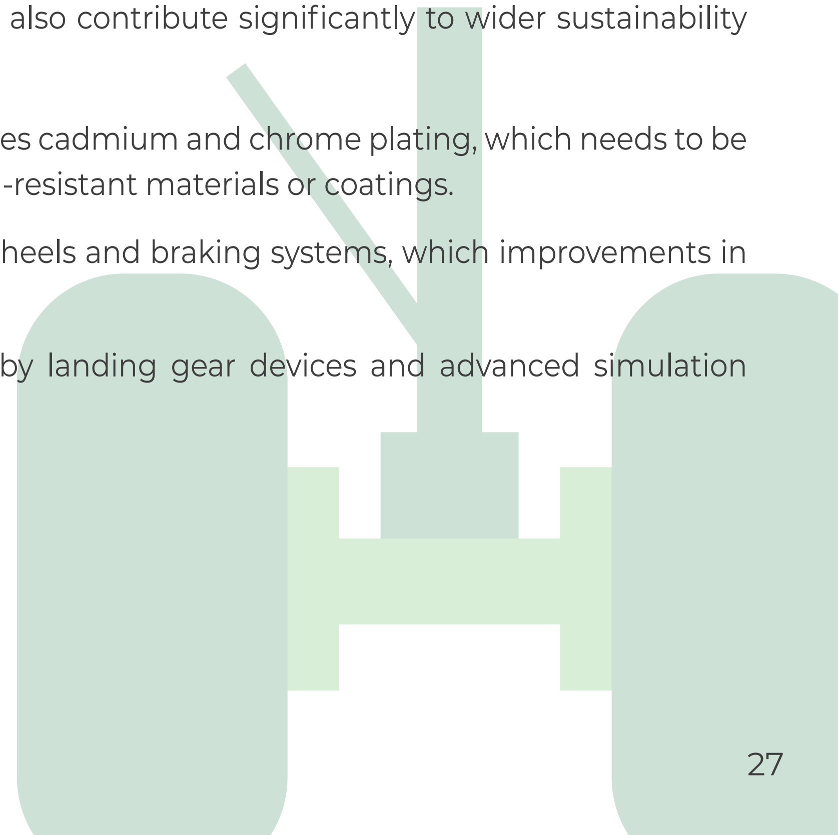
The positioning of aircraft landing gear is both driven by, and has a considerable influence on, aircraft architecture. At this point in the transition to hydrogen fuel the final aircraft configurations are yet to be decided. Novel architectures under consideration, such as blended wing body, thin high aspect ratio wings and morphing wings could have significant impacts on landing gear positioning and configuration. These new architectures could:

- Prevent on-wing gear mounting.
- Drive the need for lengthening or shortening of landing mechanisms, increasing the importance of light-weighting.
- Increase landing weights (relative to the take-off weight) as the fuel on board becomes a smaller percentage of overall aircraft mass.

All of these will require UK technology development to enable current landing gear performance to be maintained or improved.

Landing gear technology development must also contribute significantly to wider sustainability topics such as:

- Corrosion protection which currently requires cadmium and chrome plating, which needs to be replaced over time with ’greener‘, corrosion-resistant materials or coatings.
- Local particulate matter at airports from wheels and braking systems, which improvements in braking technologies could reduce
- Noise emissions which can be improved by landing gear devices and advanced simulation capability.



The FlyZero team, in consultation with UK industry, has identified the following developments as critical to securing high value landing gear activities on future aircraft:

- Architecture development.
- Alternatives to large forging technology such as additively manufactured structures and welded tailored material blanks.
- Performance improvement e.g. energy recovery, e-taxying, more electric actuation, loads management, materials development, topology optimisation, multifunctional sensing, rapid cooling brakes.
- Sustainability improvements including noise reduction, reduced carbon brake wear, electrical braking, chrome and cadmium replacement.

UK facilities such as the Noise Technology Centre in Southampton will support the development and test pyramid which will be critical to maintaining and growing UK capability. It is important to note that these evolutionary technologies, although not considered in detail for FlyZero, will drive performance and be required for the future fleet, including zero-carbon aircraft, and these technologies present a significant opportunity for UK companies.

Landing gear is a strategically important supply capability for the UK. The UK is very well positioned in this technology sector, with thousands of jobs supporting landing gear manufacture in the UK supply chain. There are several UK system and component manufacturers also supporting this sector including Safran with landing gear systems, Meggitt with braking systems, Triumph with hydraulics, Dunlop with tyres, Heroux-Devtec Inc with surface treatment, component manufacture and assembly along with Ultra Precision Control Systems with position sensing and controls. Additionally, there are other UK-based systems suppliers who have capability in landing gear which is not located in the UK, which include Honeywell and Collins.

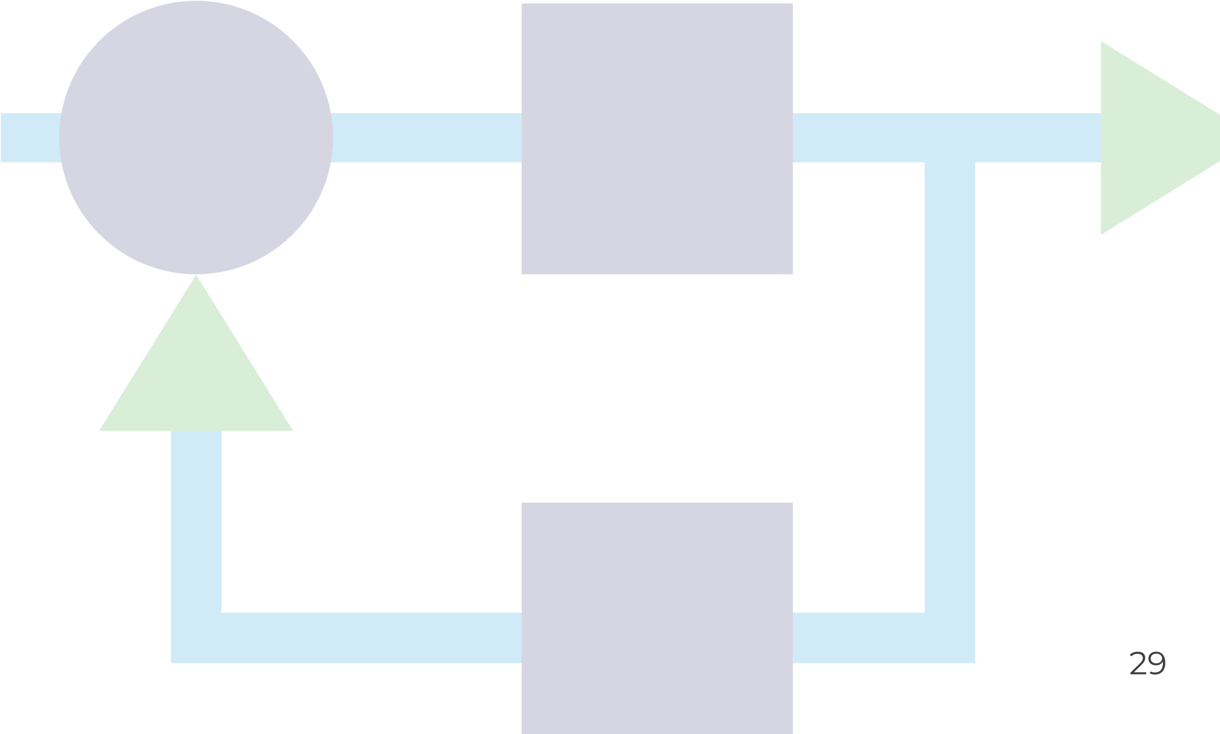
# 03.3.5
# ATA 38 – WATER-WASTE

Whatever the aircraft fuel type, there should be no fundamental differences in the water-waste system. However, if the liquid hydrogen aircraft features fuel cells, either as the main propulsion system or APU, this gives rise to the opportunity to use one of the by-products of the fuel cells, water, for other purposes.

In the case of ATA 38, the waste fuel cell water can be used to supply either all or some of the aircraft's potable water. This would have the benefit of being able to install a smaller tank, upload less (or no) water during a turnaround and potentially remove one turnaround operation.

At a systems level, this opportunity should be straightforward to implement as long as the development of ATA 38 and ATA 85 (fuel cells) is integrated.

This technology area is again seen as evolutionary. As the technology is extremely niche it is expected that incumbent suppliers are likely to evolve this capability, with limited opportunities for other industry suppliers to enter this sector. In the UK there were no identified suppliers with this product range, however suppliers with group footprint in the UK that have this capability overseas include Collins and Safran, who both manufacture in the USA.



# 03.3.6
# ATA 47 – INERTING

In 2008, the Federal Aviation Administration (FAA) mandated operators and manufacturers to incorporate a flammability reduction means (FRM) or ignition mitigation means on fuel tanks having a flammability exposure exceeding certain thresholds. This mandate resulted in the inerting systems that are 'standard fits' on today's aircraft.

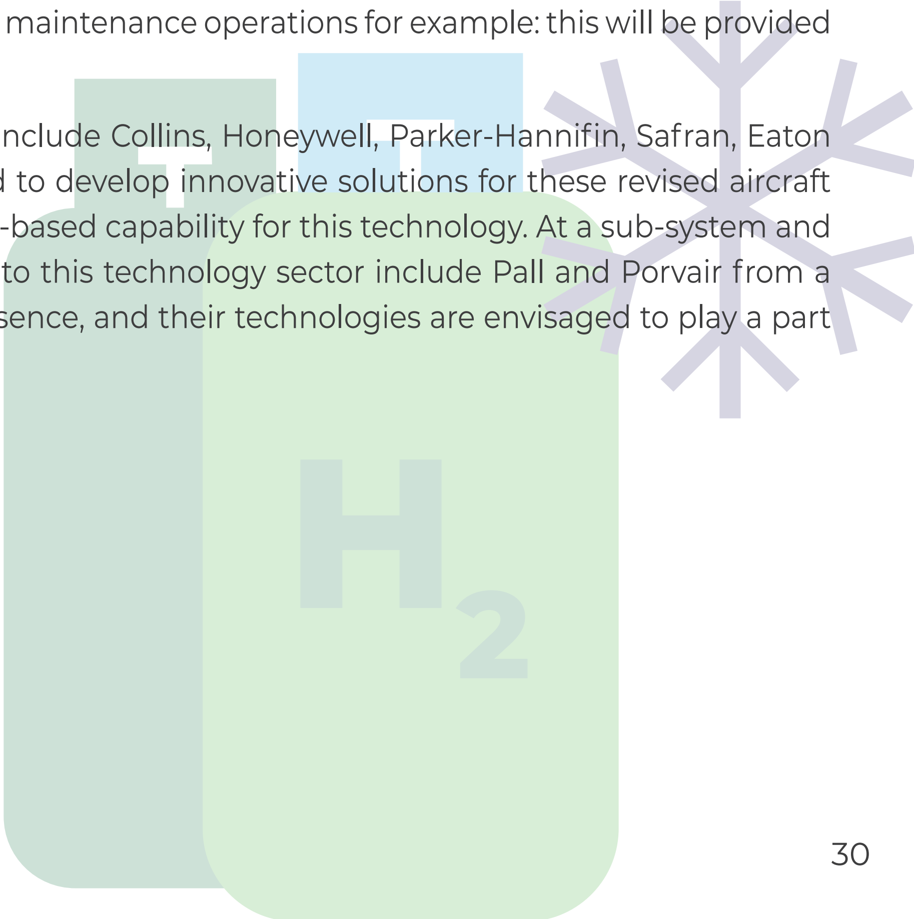
An initial assumption therefore might be that an inerting system would be a standard fit for a liquid hydrogen aircraft, but this is not necessarily the case. It is noted that there is currently no certification basis for liquid hydrogen aircraft in place.

For ignition to occur, all three elements of the 'fire triangle' - fuel, oxygen and an ignition source need to be present. For a liquid hydrogen aircraft the fuel tanks will contain liquid hydrogen with the ullage being gaseous hydrogen to maintain the required pressure in the tank. Hence, as there is no oxygen in the tank, ignition will not occur, and the fuel tanks will not require inerting.

However, it can be assumed that areas adjacent to the tanks and fuel pipework will contain a percentage of hydrogen due to leakage and hence there is a fire and explosion risk in those areas. The risk mitigation or 'means of compliance' (MOC) for these areas could be achieved in several ways, one of which would be inerting i.e. keeping the oxygen content below a prescribed level. Hence for a liquid hydrogen aircraft an inerting system could be required for areas adjacent to the fuel tanks, rather than the tanks themselves.

It is worth noting that although inerting of the fuel tanks is not needed in flight it will be needed on the ground for purging the tanks during maintenance operations for example: this will be provided by ground support equipment (GSE).

The existing suppliers of such systems include Collins, Honeywell, Parker-Hannifin, Safran, Eaton and Cobham, should be well positioned to develop innovative solutions for these revised aircraft needs however none appear to have UK-based capability for this technology. At a sub-system and component level suppliers delivering into this technology sector include Pall and Porvair from a filtration perspective, both have UK presence, and their technologies are envisaged to play a part of any overall system solution.



# 04.
# SUPPLIER CONSULTATIONS

## 04.1
## SUPPLIER ENGAGEMENT

An essential part of preparing this systems roadmap paper was to engage with the supply base and following a review of the supplier landscape, suppliers were contacted to:

- Explain the scope and purpose of the FlyZero project to the supply chain.
- Gain an understanding of the suppliers' views on and activities related to zero-carbon flight.
- Solicit supplier inputs to feed into this roadmap paper.

Eighteen were contacted, and meetings ultimately arranged with eleven:

- Collins Aerospace
- Eaton
- GKN Aerospace
- Honeywell Aerospace
- Marshall
- Moog
- Oxsensis
- Pall Aerospace
- Porvair Filtration Group
- Thales
- Ultra Precision Control Systems

## 04.2
## SUPPLIER KEY THEMES

As a result of these discussions, a number of key themes arose which summarise the systems work underway, or work needed to realise hydrogen-fuelled aircraft; these themes being:

- The hydrogen-specific technology that will be needed for this new class of aircraft (i.e. the revolutionary items).
- The 'fuel agnostic' technology development that will be needed to enhance or upgrade today's systems (i.e. the evolutionary items).
- The overall systems design and integration aspects.
- The enablers needed to support and underpin the above.

As will be seen, several of the points noted reinforce what has been highlighted in **Section 3**. In contrast, some additional points and interdependencies between systems are highlighted which are not apparent in the monodisciplinary review discussed previously.

## 04.2.1

## HYDROGEN-SPECIFIC TECHNOLOGY

Various suppliers are already working on the assumption that hydrogen will be a future fuel. Some of them are also working on cryogenics but not necessarily of hydrogen e.g. they are looking at cryogenic carbon dioxide ($CO_2$). Other suppliers are more focused on SAF and one in particular is not yet convinced about hydrogen fuel and wanted to see the physics proven before investigating hydrogen further. Overall, it seems fair to say that the possibility of using hydrogen as a future fuel is reasonably well understood in the supply chain. However, a centralised authoritative database on all aspects of the use of hydrogen as a commercial aviation fuel and potentially associated training courses would be beneficial for the systems community.

One FlyZero project assumption is that cryogenic hydrogen will be uploaded to the aircraft in a liquid state with the temperature being maintained via use of insulated tanks and pipes. No on-board cryogenic cooling is required, but if this capability were to be needed, it is available in the supply chain where systems are already available for spacecraft and defence applications.

Filtration of hydrogen is also being looked at, in some cases leveraging knowhow from other sectors such as pharmaceutical or nuclear. However, with a lack of aircraft specific liquid hydrogen standards, it is not clear if the exacting purity requirements for fuel cell purposes (i.e. 99.995% pure) are being used as a requirement. This absence of standards for hydrogen purity requirements for fuel cells in aviation use is one example where development is needed in the transition to liquid hydrogen aircraft.

Replacement of fueldraulic functions, for example to provide alternate means of motive power to move engine guide vanes was highlighted as an area needing development. This would have to be a dedicated system, suitable for high temperature environments, with at least one supplier working on an electrical system for this application.

At the other end of the temperature spectrum the need for low temperature seals, bearings and valves for cryogenic systems associated with the fuel and propulsion systems was discussed. In particular the nature of couplings and seals was highlighted which need to be suitable for two phase systems, such as where the fuel transitions from a liquid to a gas.

# 04.2.2
# FUEL-AGNOSTIC TECHNOLOGY

As will have been seen from previous sections of this report, the majority of systems technology developments for future aircraft do not depend on fuel type and so a discussion of these has not been included here – see **Section 3.3** for further details. However, a few of these systems such as actuation, flight controls and more electric aircraft were discussed with several suppliers and hence it is useful to note the key points from these discussions.

While primary flight controls systems for large civil aircraft are not designed and built in the UK there is the opportunity and willingness from suppliers to do so if adequate government support were provided. Development of secondary flight controls is likely to form the precursor to this work.

Several suppliers are looking at new actuator technology e.g. fault tolerant EMAs while others looking at actuation control systems (both in UK and overseas facilities). Such systems would enable direct drive of flaps and eliminate the current technology torque tubes and associated components. EMA development has progressed to the point that the results are already being introduced in Federal Aviation Regulations (FAR) Part 23 (i.e. small) aircraft.

It was also apparent that much of the aviation community is already considering the benefits of high aspect ratio, thin wings (which contain no fuel in the case of a hydrogen-fuelled aircraft) and this was seen as another driver to keep actuator size to a minimum.

A discussion of aircraft electrical systems is outside the scope of this report and a FlyZero report on this subject can be found in [2]. However electrical systems were mentioned several times in supplier discussions and the following points were noted:

- There is a need to develop more efficient electrical energy storage.
- There is also a need to improve electrical cable insulation (due to environment such as areas adjacent to the engine and also to mitigate the effects of corona discharge if the system architecture demands high voltages).
- The opportunity of replacing copper wires with optical fibres for communications should be investigated.
- Reducing the power demand of electrical systems should be pursued, in particular for the high-power consumers such as the ECS and IPS.

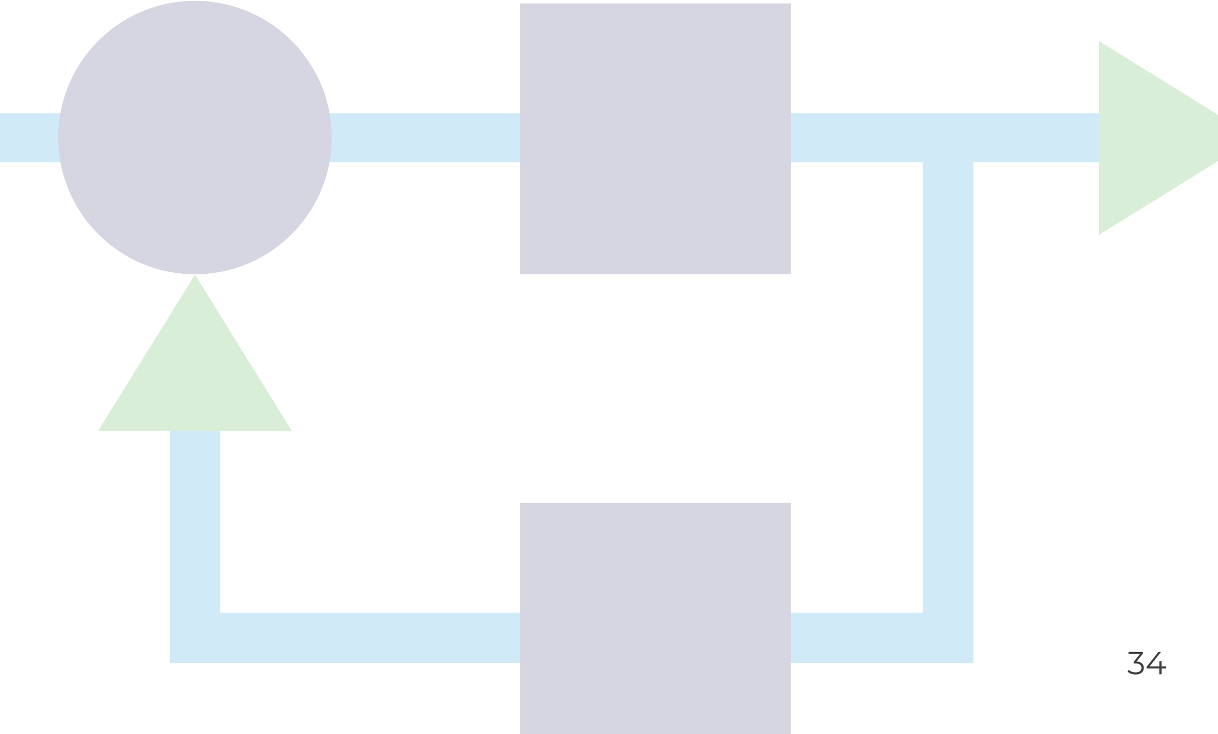
# 04.2.3
# SYSTEMS DESIGN AND INTEGRATION

The discussion so far has focused on the revolutionary and evolutionary changes needed in designing the various sub-systems of a liquid hydrogen-fuelled aircraft. While these developments are fundamental to realising such an aircraft, the integration of these technologies is equally important.

Not surprisingly, systems companies are focused on their own areas of expertise. This being the case an aircraft level integrated-systems approach, and the benefits this can bring, was not always apparent from the discussions as this is usually the preserve of the aircraft manufacturers. However, aspects of systems interdependencies and whole aircraft integration were discussed.

In the case of a fuel cell propulsion system, several points were noted:

- It is important to consider the entire system - not just the fuel cells but also the balance of plant including the air intakes, compressors, thermal management system and inverters etc.
- The trend towards more electric aircraft and electrically powered ECS systems, gives rise to the possibility to combine the ECS air compressor and the fuel cell compressor.
- If fuel cells were chosen for the APU then potentially they could drive the engine low speed shaft and fan to provide on-aircraft taxi power at the airports without starting the engines: this would mean zero emissions, apart from water, during taxi. To achieve this would undoubtedly need a high degree of integration between the airframer, engine supplier and APU suppliers.
- The by-products of the system need to be considered for potential exploitation, for example:
    - Could the fuel cell water be used in the water-waste system or for injection into the engine?
    - Could the heat generated be used as part of the IPS or to condition air that is used in the ECS?

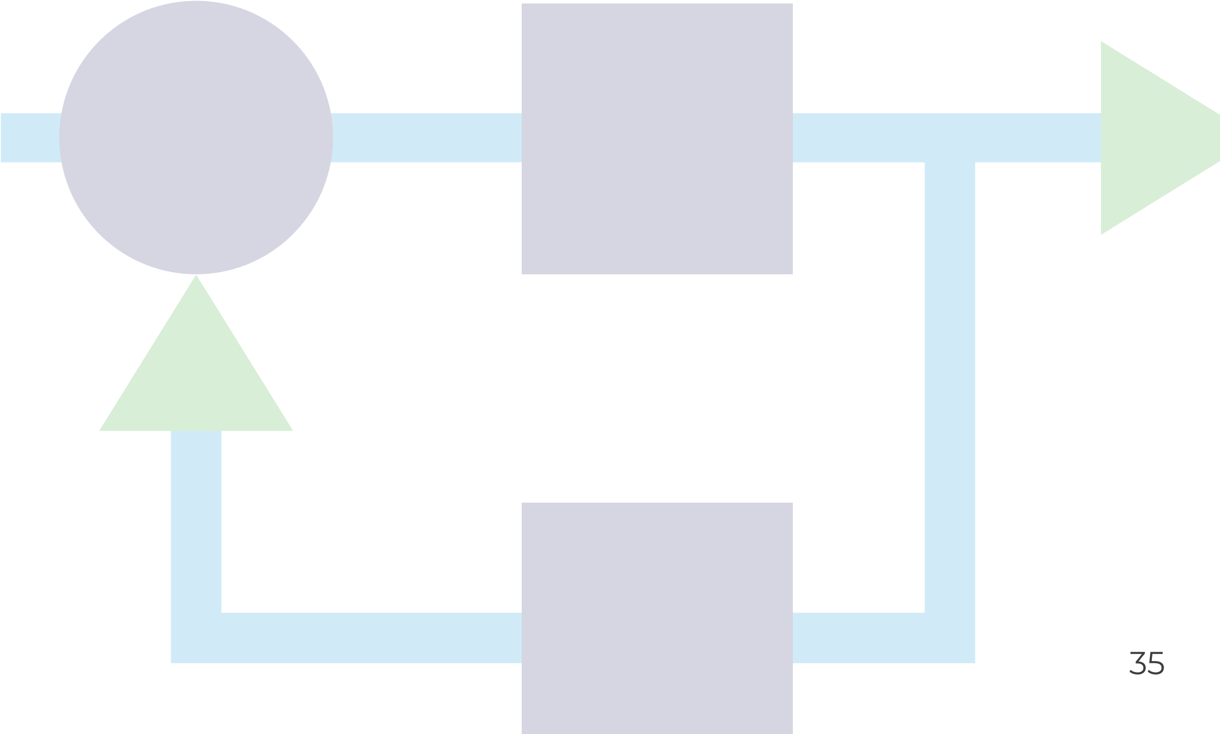


This last point is also an example of thermal management which was a recurring topic, with work underway in several companies on heat exchangers. While this topic is covered by a separate roadmap, 'heat repurposing' and 'energy harvesting' was highlighted as an important topic to evaluate in order to maximise use of unwanted heat and minimise aircraft energy demands.

The topic of sensing and sensors was mentioned on several occasions. New developments are planned related to wireless sensing (to reduce the amount of aircraft wiring), the sensing of hydrogen and multi-functional sensors to reduce the overall number of sensors onboard an aircraft. In addition, at least one supplier is also developing optical pressure and temperature sensors which by nature are resistant to electro-magnetic interference (EMI).

Lastly, it is well known that the efficiency of electrical components can be improved if they can be cooled to very low temperatures - the phenomenon of superconductivity. While a discussion on this topic is beyond the scope of this paper, it is important to note the integration aspects and opportunities that might be available given that the fuel system is now based around a cryogenic fluid. Given that the aircraft baseline architecture would now feature cryogenic systems this should remove, at least, any conceptual blockers to cryogenic electrical systems.

In summary, the above examples illustrate that while different suppliers will provide different components and sub-systems, an integrated systems approach will be needed to deliver an optimum aircraft.



# 04.2.4
# ENABLERS

Underpinning the above technology developments and with hydrogen replacing kerosene as the fuel, a number of enablers will be needed in order that aircraft certification can be achieved. The following is a list of some of these enablers, some of which are already being addressed by industry:

Firstly, the certification basis itself, based on kerosene-fuelled aircraft, needs to be updated. This work has been started as part of FlyZero and is reported in [11]. In support of this certification and product development activity, various aerospace standards will need to be updated, for example:

- RTCA DO 160 (“Environmental Conditions and Test Procedures for Airborne Equipment”).
- ARP994 (“Design of Tubing Installations for Aerospace Hydraulic Systems ARP994B”).

From a commercial standpoint, reducing the cost of certification will be important with at least one company developing a new approach to satisfying RTCA DO 178 (“Software Considerations in Airborne Systems and Equipment Certification”) and RTCA DO 254 (“Design Assurance Guidance for Airborne Electronic Hardware”).

Design software will also need to be developed or updated to account for the physics of liquid hydrogen and multi-phase fluids. These changes would be needed for in-house software and potentially existing commercially available software.

In addition to software and simulation capability developments, physical integration and test facilities will need to be updated or developed, the outputs of which will be used to verify the above simulation outputs in many cases. More specifically:

- Several fuel systems test rigs exist in the UK but none, to the knowledge of the FlyZero team, are configured for liquid hydrogen. As a minimum, at least one such facility would need to be constructed to enable testing of liquid hydrogen fuel systems.
- While the above would cover the overall system, there will also be a need for smaller test chambers for the purpose of testing individual components at temperatures around 20K and pressures equivalent to typical cruise altitudes: this testing would need to cover both functional testing of the components and also mechanical vibration testing.
- Furthermore, due to the close coupled nature of a liquid hydrogen fuel system and a liquid hydrogen gas turbine (both architecturally and physically on an aircraft) the fuel test rig should ideally be coupled with an engine test rig.
- With changes likely to be made to ECS design, a suitable test rig would need to be developed (or an existing facility such as the Honeywell test facility in Yeovil) modified.
- Thermal management is a significant challenge with liquid hydrogen aircraft and is covered by another FlyZero report [12]. Part of this challenge will be addressed by heat exchangers which, amongst other things, would need to be wind tunnel tested and at least one supplier is planning to build a dedicated tunnel for this purpose.

Suppliers are clearly working on various technologies which would ultimately be offered to other systems suppliers or airframers. However, it would beneficial, from an optimal aircraft point of view, if these were developed and tested in an integrated way. For example, actuator suppliers, control system designers, airframe and wing 'moveables' architects could work alongside each other to design and test integrated systems. To enable the testing a ground-based 'iron bird' or 'plug and play' test rig would be developed. This could take many forms but should allow the test of new actuators, control systems, anti-ice technology, wing morphing features and local power systems (for landing gear extension / retraction). This would then act as a 'pull' for systems technology development in the UK and at the same time, reduce costs for the participants. This approach would be akin to many of the previous wing design and manufacturing R&D programmes, the latest being the Airbus 'Wing of Tomorrow' programme which combines the inputs of several different companies.

Finally, the systems landscape is one where the large systems companies are multinational concerns with centres of competence spread throughout the world. If the aspiration to develop a specific technology in the UK happened not to coincide with a company's geographical centre of competence it would make realising that ambition difficult. However, several companies were willing to discuss this challenge. In particular, some companies made the point that US export controls and ITAR (international traffic in arms regulations) were very restrictive. Developing a UK capability could remove this restriction and hence be of interest to them, especially if UK government funding were available to support such activities.

# 05. SYSTEMS ROADMAP

Key: Technology Development | Essential Enabler

| | | |
|---|---|---|
| **Hydrogen-specific technology (revolutionary)** | Cryogenic hydrogen containment and fluid control technology developed. | Integrated cryogenic fuel and engine feed systems demonstrated. |
| | Engine component actuation system architectures developed (fueldraulics replacement). | Down-selected engine component actuator system developed and tested. |
| | Hydrogen specific leak detection, fire detection and suppression systems technologies developed. | Integrated fire detection and extinguishing system demonstrated. |
| | Novel APU architectures investigated. | Most promising architecture developed and tested. |
| | Development of inerting systems for liquid hydrogen aircraft validated by test. | |
| **Fuel-agnostic technology (evolution)** | Development of electrical actuation, control systems and sensors for flight controls. | Demonstration of fully electrical systems for primary and secondary flight controls. |
| | Electrical system & wiring developments e.g. higher voltage systems, cable insulation, power electronics etc. | |
| | Development of more efficient systems (e.g. ECS, IPS) to reduce electrical power demand. | Reduced power demand demonstrated by test. |
| | Development of landing gear novel architectures, performance improvement. | Validation of noise reduction technologies by flight test. |
| **Systems design and integration** | Fuel cell system development to reduce BOP losses. | Complete fuel cell system (air intake to power out) demonstrated. |
| | Cross ATA systems integration opportunities e.g. ECS, TMS (thermal management system), fuel cells etc established. | Cross ATA systems integration opportunities demonstrated by test. |
| | Enhanced modelling capability, software development for liquid hydrogen. | New modelling capability verified by test. |
| | Heat repurposing / energy harvesting opportunities investigated. | Heat repurposing opportunities embodied in systems design. |
| **Enablers** | Review of Part 25 airworthiness regulations instigated with airworthiness authorities. | Updated airworthiness standards issued. |
| | Updates of appropriate standards e.g., RTCA DO 160, DO-178, DO-254, ARP-4754 etc instigated. | Updated standards published. |
| | Development of component test rigs associated with liquid hydrogen, technology e.g. fuel systems. | Integrated test rigs delivered and commissioned. |
| | Wing systems 'plug and play' test rig(s) for integrated development of novel systems. | |

# 06.
# SUMMARY

**FlyZero has been tasked with assessing the feasibility of zero-carbon emissions commercial flight and defining the technology roadmaps needed to realise this vision. An early finding from this work has been that zero-carbon emissions flight is indeed feasible and that cryogenic liquid hydrogen is the best future aviation fuel.**

To assess the implications of this in more detail, the FlyZero team identified 13 'technology bricks' which are required to enable hydrogen flight, one of which is aircraft systems.

This paper has reviewed the challenges and opportunities for these systems brought about by the unique characteristics of a hydrogen-fuelled aircraft, in particular the opportunities for UK industry. This review has been performed by a desktop analysis of systems as defined by the ATA systems chapter list, supported by interviews with both UK and overseas based systems suppliers.

The identified challenges are summarised below, followed by a series of recommendations for technology and organisational developments to allow the UK systems community to take a leading role in the development of zero-carbon aircraft.

## Challenges

Adopting liquid hydrogen as a fuel will drive significant changes to aircraft configurations. At an overall aircraft level, the difficulties of storing cryogenic fuel in the wings will lead to changes in wing design and most likely, the need to store the fuel in the fuselage. The fuel and propulsion systems will also need to be radically changed, albeit these are out of scope of this report.

At a systems level, the liquid hydrogen will need to be kept at an extremely low temperature of 20K (or -253°C) which will place new demands on the fuel storage and distribution network. These low temperatures may also need to be managed alongside heat generated from fuel cells meaning aircraft thermal management needs to be carefully considered.

With hydrogen replacing kerosene as the fuel, alternatives to traditional fueldraulic systems used to actuate engine components will need to be found. Alternative solutions will also be needed for the auxiliary power unit (APU) which are today fuelled by kerosene.

This new category of aircraft will also give rise to requirements to improve the efficiency of high lift devices due to the higher landing weights of hydrogen-fuelled aircraft. This will be a driver for improvements to actuation systems. Finally, although not directly related to liquid hydrogen technology, the trend of more electric aircraft will inevitably continue which will give rise to the challenge of minimising the electrical power consumption of all systems.

From an organisational standpoint, based on interviews with several suppliers, there is not yet a mutual understanding of the aircraft revolution that is already happening. In addition, large systems companies are predominantly international, not UK based.

Both of these factors could impede the development and delivery of UK-led systems capability for this new class of aircraft.

## Recommendations

To address these challenges and to realise the vision of liquid hydrogen-fuelled aircraft, it is recommended that a number of key systems technologies are developed. These are:

- Cryogenic hydrogen containment and fluid control technology (pumps, filters, valves, seals, bearings, pipes etc).
- Hydrogen-specific leak detection, fire detection and suppression systems.
- Novel APU architectures including liquid hydrogen-fuelled gas turbines, internal combustion engines and fuel cells.
- Inerting systems for liquid hydrogen aircraft designed for the zones adjacent to the fuel tank(s).
- Engine component actuation system architectures to replace the today's fueldraulic systems.

In parallel with the above it is essential that the customary aircraft development process of improving efficiency, increasing reliability and reducing weight continues. In particular:

- Activities relating to the increasing electrification of aircraft including development of electrical actuation, control systems and sensors for flying controls should be prioritised. As part of this process every opportunity should be taken to reduce electrical power demand, especially of the major consumers such as the environmental control system (ECS) and ice protection system (IPS).
- Development of novel landing gear architectures, performance improvements such as energy recovery and sustainability improvements such as noise reduction.

The above recommendations relate to essentially mono-disciplinary activities – those related to the development of individual systems. However the integration of these systems at an aircraft level also needs to be addressed, both in terms of design, and verification and validation (i.e. physical testing). In support of this;

- A UK virtual systems network comprising systems suppliers, academia and the end customer(s) should be established for the sharing of information, development of systems requirements and the exploitation of system integration opportunities.
- To support the design work that will be produced in the above a systems test pyramid needs to be defined and new test facilities built where required. At the top of this pyramid a national wing systems 'plug and play' test rig should be developed for the integrated development of novel systems such as actuators, control systems, sensors etc.

Finally all of the above will need to be done while the industry skill base is transitioning to a new fuel type and where the airworthiness regulations and design standards are evolving. This means:

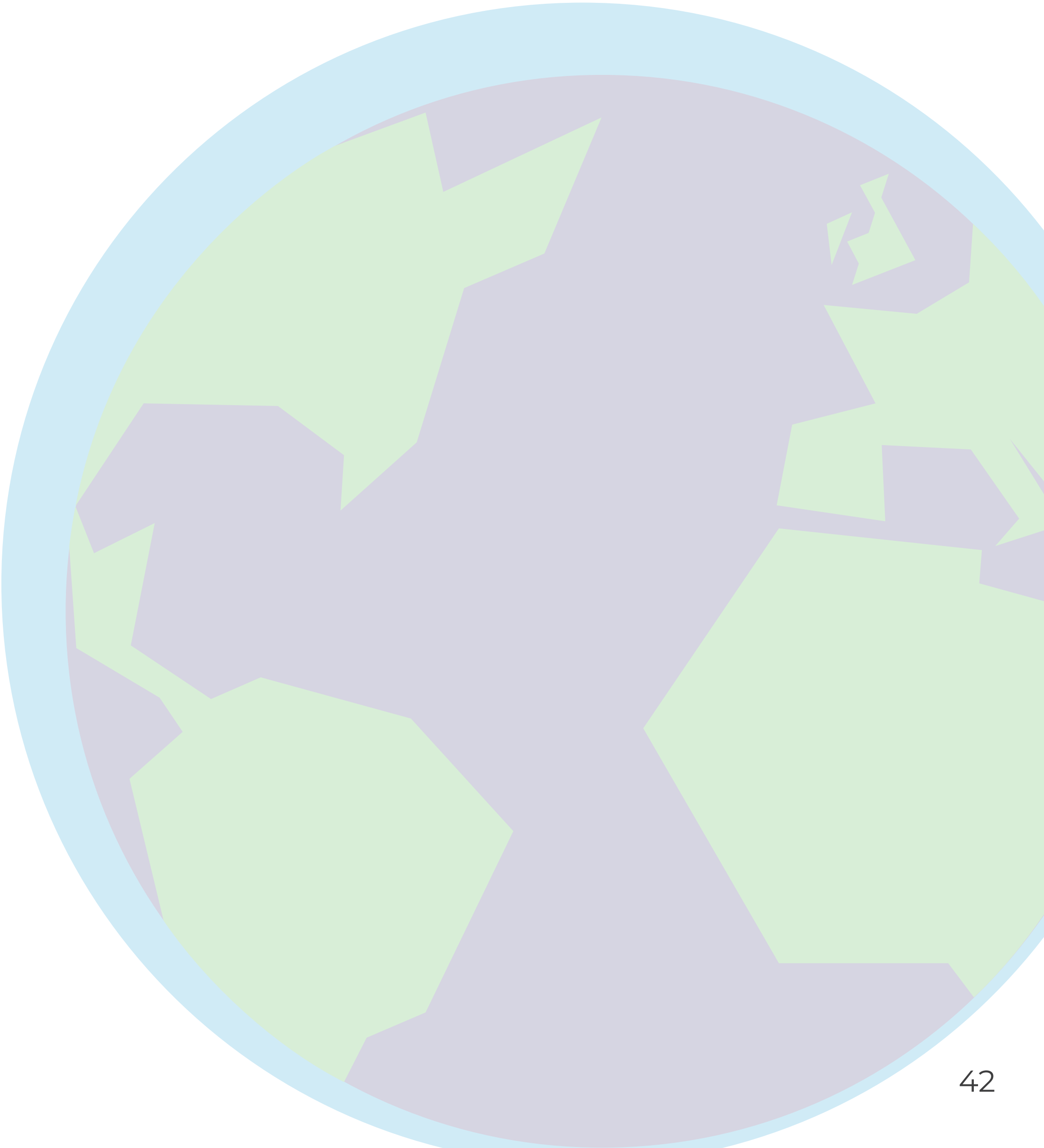
- A centralised authoritative database on all aspects of the use of hydrogen as a commercial aviation fuel and associated training courses should be established.
- For expediency, every opportunity should be taken to engage with the various standards organisations and authorities to drive the regulatory changes needed rather than to wait for new standards to emerge.

## Concluding remarks

The FlyZero project has identified that cryogenic liquid hydrogen is the most suitable fuel to enable zero-carbon tailpipe emission flight. The impact of this finding on aircraft systems has been investigated and recommendations for the requisite development activities made.

Systems technologies to support hydrogen aviation should begin development now, as the aspirational in-service date for a hydrogen-powered aircraft is just over a decade away which is a relatively short time to develop technology, design and certificate an aircraft.

For the systems community this offers opportunities to secure component or systems supply for their area of expertise or to establish a market position where there are currently gaps in the market or where the market does not currently exist.



# APPENDIX A – LIST OF ABBREVIATIONS

| *Abbreviation* | *Meaning* |
|---|---|
| *APU* | *Auxiliary Power Unit* |
| *ARP* | *Aerospace Recommended Practice* |
| *ATA* | *Air Transport Association of America (now known as Airlines for America)* |
| *ATI* | *Aerospace Technology Institute* |
| *CG* | *Centre of Gravity* |
| $CO_2$ | *Carbon Dioxide* |
| *ECS* | *Environmental Control System* |
| *EHA* | *Electro Hydrostatic Actuator* |
| *EMA* | *Electro Mechanical Actuator* |
| *EMI* | *Electro Magnetic Interference* |
| *FAA* | *Federal Aviation Administration* |
| *FRM* | *Flammability Reduction Means* |
| *FAR* | *Federal Aviation Regulations* |
| *FZN* | *FlyZero Narrowbody* |
| *FZM* | *FlyZero Midsize* |
| *FZR* | *FlyZero Regional* |
| *GSE* | *Ground Support Equipment* |
| *ICE* | *Internal Combustion Engine* |
| *IPS* | *Ice Protection System* |
| *ITAR* | *International Traffic in Arms Regulations* |
| $LH_2GT$ | *Liquid Hydrogen Gas Turbine* |
| $LH_2ICE$ | *Liquid Hydrogen Internal Combustion Engine* |
| *MOC* | *Means of Compliance* |
| *MLW* | *Maximum Landing Weight* |
| *MTOW* | *Maximum Take-Off Weight* |
| *NOX* | *Oxides of Nitrogen* |
| *OEM* | *Original Equipment Manufacturer* |
| *OFD* | *Optical Flame Detection* |
| *RTCA* | *Radio Technical Commission for Aeronautics* |
| *SAF* | *Sustainable Aviation Fuel* |
| *SME* | *Small and Medium Enterprise* |
| *TMS* | *Thermal Management System* |

# APPENDIX B – REFERENCES

1. *FlyZero, "Realising zero-carbon emission flight: Primary Energy Source Comparison and Selection", FZ_0_6.1, UK, Aerospace Technology Institute, 2021, available at:* www.ati.org.uk

2. *FlyZero, "Electrical Propulsion Systems Technical Report", FZO-PPN-REP-0028, UK, Aerospace Technology Institute, 2022, available at:* www.ati.org.uk

3. *FlyZero, "Cryogenic Hydrogen Fuel System Technical Report", FZ0-PPN-REP-0024, UK, Aerospace Technology Institute, 2022, available at:* www.ati.org.uk

4. *FlyZero, "The Route to Hydrogen Aviation - Airport and Airline Infrastructure and Operations", FZ0-CST-REP-0045, UK, Aerospace Technology Institute, 2022, available at:* www.ati.org.uk

5. *Aerotime hub, "France details new investment plan for hydrogen aircraft by 2035," [Online]. Available:* https://www.aerotime.aero/25821-france-details-new-investment-plan-for-hydrogen-aircraft-by-2035 *[Accessed 21 December 2021].*

6. *HM. Government, The Ten Point Plan for a Green Industrial Revolution, September 2020.*

7. *Anon, "Kidde Technologies Optical Flame Detection," Kidde Technologies (Collins Aerospace), [Online]. Available:* http://kiddetechnologies.com/products/detail/optical-flame-detection *[Accessed 6th December 2021].*

8. *Ricardo, "FlyZero ICE Feasibility Study," Ricardo, 16th September 2021.*

9. *Moir, I & Seabridge, A., "Aircraft Systems", 3rd Edition, John Wiley and Sons Ltd, 2008.*

10. *Warwick, G. & Norris, G., "Airbus X-Plane Will Test Inflight Folding Wingtips," 20th September 2021. [Online]. Available:* https://aviationweek.com/special-topics/sustainability/airbus-x-plane-will-test-inflight-folding-wingtips *[Accessed 6th December 2021].*

11. *FlyZero, "Safety and Certification of Zero-Carbon Emission Aircraft ", FZO-AIR-REP-0051, UK, Aerospace Technology Institute, 2022, available at:* www.ati.org.uk

12. *FlyZero, "Thermal Management Technical Report," FZO-PPN-REP-0017, UK, Aerospace Technology Institute, 2022, available at:* www.ati.org.uk

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