OUR VISION FOR ZERO-CARBON EMISSION AIR TRAVEL

Realising 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.

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

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

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& Industrial Strategy

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Front cover image © ATI

FOREWORD

Decarbonising aviation is the challenge of our generation.

The aircraft being manufactured today are more efficient than ever before and will increasingly operate using fossil fuel alternatives representing great strides towards our global climate commitments on carbon emissions.

But what if we could eliminate carbon emissions altogether? This question was the catalyst for FlyZero, a 12-month research project which began in early 2021 to realise zero-carbon emission commercial flight by the end of the decade.

This report, as part of a suite of outputs, presents a vision for aviation which keeps businesses, cultures, families and nations connected without the carbon footprint.

Realising this vision for liquid hydrogen powered flight presents challenges for all facets of our aerospace and aviation sectors as well as wider industries and energy infrastructure. An integrated, collaborative, international approach is needed to protect our planet, maintain the benefits of aviation and secure economic growth.

There is a compelling case for taking action today.

The UK is ideally positioned to build on decades of expertise in aerospace innovation to develop, test and certify the advanced technologies which will propel a new generation of liquid hydrogen powered aircraft into our skies. As has historically been the case, the UK would need to work in collaboration with global OEMs, governments and regulatory bodies to deliver the technologies, policies and certification at pace.

The project has made some initial conclusions that require further investigation and investment to understand the feasibility and approach to innovation for the next phase. To this end the Aerospace Technology Institute (ATI) will incorporate the findings from the project into its Technology & Portfolio Strategies and look to pursue opportunities for the UK.

FlyZero has generated a rich resource of learning that supports the transition to hydrogen technologies and would not have been possible without the support of BEIS and the ATI team, FlyZero's contributing companies and our supporting organisations.

A new era for aviation is on the horizon.

Chris Gear, Project Director – FlyZero

Gary Elliott, CEO - ATI

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EXECUTIVE SUMMARY

Zero-carbon emission flight can be a reality. The target to reach net zero by 2050 requires large zero-carbon emission aircraft to enter service by 2035. The scale of the challenge is huge, but the ambition to succeed is strong. It will require a collaborative and urgent approach, with aerospace companies, airlines, airports, governments, regulators and adjacent sectors such as energy working together at pace.

Zero-carbon emission aircraft will be powered by green liquid hydrogen. The UK can become a leader in the necessary technology, systems and processes, influencing how they are introduced across the world. To do so, it must rapidly develop its infrastructure, capabilities and regulatory framework for hydrogen. To enable large commercial aircraft to enter service by 2035, it must also commence an ambitious aircraft research programme on technologies such as cryogenic hydrogen fuel systems, gas turbines, and airframes for ground and airborne demonstration. In parallel, the UK must also continue to advance technologies required for sustainable aviation fuels (SAF). SAF and liquid hydrogen are both needed to achieve the net zero 2050 target.

The economic opportunity for the UK is also significant. By 2050, it could grow its market share in civil aerospace from 12% today to 19%, increasing the sector's gross value added to the economy from £11bn to £36bn, and expanding the number of aerospace jobs from 116,000 to 154,000.

FLYZERO CONCLUSIONS

1. FlyZero has compared zero-carbon emission energy sources such as batteries, hydrogen and ammonia and concluded that **green liquid hydrogen is the most viable**, able to power large aircraft utilising fuel cell, gas turbine and hybrid systems. For aviation to achieve net zero 2050 FlyZero determined that we must invest now in both the development of sustainable aviation fuel (SAF) and green liquid hydrogen technologies.
2. **Technology acceleration is key as industry and aviation can only afford one fleet refresh between now and 2050. This gives a window of opportunity to introduce zero-carbon emission aircraft** in the regional, narrowbody and midsize market segments. FlyZero has modelled these concepts and determined that it is feasible to design and **fly an experimental aircraft across the Atlantic by 2030 powered by hydrogen gas turbines.**
3. The optimum route to decarbonising aviation is through acceleration of a large (narrowbody and midsize) commercial aircraft into service. **FlyZero's midsize aircraft is able to reach all destinations in the world with a single stop.** Less commercially risky than developing a narrowbody first, it would allow infrastructure development to be focused on fewer, but larger international hub airports.
4. **Global cumulative CO2 emissions from aviation could be reduced by 4 gigatons (Gt) by 2050 and 14 Gt by 2060.** This requires 50% of the commercial fleet to be hydrogen-powered by 2050 and assumes midsize hydrogen-powered aircraft are operating by 2035, with hydrogen-powered narrowbody aircraft in service by 2037. It is critical to achieve these dates to hit the net zero 2050 goal.
5. **Revolutionary technology breakthroughs are required in six areas** to achieve zero-emission flight: hydrogen fuel systems and storage, hydrogen gas turbines, hydrogen fuel cells, electrical propulsion systems, aerodynamic structures and thermal management. The UK has expertise and capability today in these, but little in liquid hydrogen fuels. **Climate science is also fundamental to aerospace research.**
6. From the mid-2030s, **liquid hydrogen** is forecast to become **cheaper as well as greener** than Power to Liquid SAF which is expected to be the primary SAF as demand increases. PtL SAF requires more electrical energy to produce than liquid hydrogen. Scalability of other SAFs is limited by availability of raw materials.
7. Hydrogen-powered aviation will require **new aircraft certification policies. New health and safety regulations** will also be needed for transporting and storing liquid hydrogen at airports and refuelling aircraft. Regulators will need to take a **global approach** to developing and adopting these.
8. By leading these developments, the UK could by 2050 grow its **market share** in civil aerospace from 12% to **19%**, its **gross value added (GVA)** from £11bn to **£36bn** and increase **aerospace jobs** from 116,000 to **154,000**. Failure to act could result market share reducing to 5%, with £14bn GVA and sector jobs declining to 74,000.
9. **Failure to decarbonise may result in measures to restrict aviation, impacting the UK economy heavily.** In 2019 aviation and aviation facilitated tourism worth some £77.5bn GVA to the UK, supporting over one million jobs. With decarbonisation, this is forecast to grow to £177 bn GVA and 1.5 million jobs in 2070. Without decarbonisation the project growth will be significantly reduced.

FLYZERO RECOMMENDATIONS

1. **Industry and government should work internationally to bring large zero-carbon emission aircraft to market as soon as possible.** Industry should demonstrate the potential of the technology to transform the global fleet and deliver environmental and economic benefits. Government should facilitate research as well as support the infrastructure and regulatory changes required for zero-carbon emission flight. Urgent investment in green energy infrastructure is required to deliver green hydrogen. There should be a rapid roll-out of SAF in the 2020s and early 2030s to deliver early decarbonisation.

2. **ATI and BEIS should create strategic partnerships to pursue mission-led R&D programmes** to demonstrate UK capability, maximise UK supply chain participation and broker international collaboration. They should cover early-stage industrial R&T (unproven higher-risk, higher-reward technologies), directed R&T (innovation in critical areas required for hydrogen aviation), test infrastructure and demonstrations.

3. **Critical technologies must be progressed to technology readiness level (TRL) 5-6 by 2025** if UK equipment is to stand a chance of making it on to the first liquid hydrogen-powered aircraft. The AGP and Jet Zero Council should consider how best to create a new hydrogen and zero emission supply chain in the UK. Stimulating industry access to private finance would help support the development of zero-carbon emission aircraft systems and components in the UK.

4. To address the UK's limited hydrogen-related skills and testing capabilities, **a cross-sector hydrogen technology centre** with open access facilities should be created to facilitate research into fundamental hydrogen behaviour (including cryogenics), requirements for safe handling, standards and regulations, material properties and test specifications. **It should act as a centre of excellence and provide an anchor for industry in the UK**.

5. The UK needs to create an **integrated approach with the global aviation community** that involves aerospace, aviation and energy industrials, academia and research and technology organisations. The engagement needs to be done jointly with government and aviation authorities to create the infrastructure, legislation, policies and regulations, to secure and enable the safe operation of hydrogen-powered aircraft.

6. The **UK Civil Aviation Authority (CAA) should establish strong links with EASA and the FAA to create a future sustainability committee**. This committee should focus on the introduction of commercial aircraft using SAF and hydrogen based fuels. It should become responsible with industry for developing new global aviation policies, regulations, certification and operational requirements. It will also need to have close links into government departments on infrastructure, health and safety and environmental impacts.

7. **Academic research into the climate impacts of hydrogen-powered aircraft should be prioritised**. It should focus on predicting and modelling the impacts of water vapour and contrails for different atmospheric conditions and assessing the impact of different fuels and propulsion systems on emissions and contrails, through laboratory tests and airborne research.

8. Consideration should be given to using **incentives, pricing and taxation to influence passenger behaviour and shift demand to sustainable forms of aviation**. Using aviation tax or levy receipts to support the development of a zero-carbon emission aircraft should also be explored.

9. FlyZero has identified the UK aviation's hydrogen demand over the next 30-50 years. It is important that the UK government along with Hydrogen UK utilises our recommendation on **ensuring aviation is recognised as an important use case for H_2 in future energy strategies**.

10. The ATI, BEIS, DfT, the Aerospace Growth Partnership and the Jet Zero Council should play a leading role to urgently consider and take forward these recommendations through a coordinated series of actions across the aerospace, aviation and energy sectors.

01. INTRODUCTION TO FLYZERO

The UK is a powerhouse of innovation, uniquely able to find solutions to complex engineering challenges. As an island we benefit disproportionately from aviation with the UK's aviation sector predominantly supporting international travel and business.

The UK was the first major economy to legislate to bring overall greenhouse gas emissions to net zero by 2050. Transport, including aviation, has a key role to play. The UK government's Transport Decarbonisation Plan [1] requires domestic traffic to achieve net zero by 2040. Internationally, the UK is pressing for global aviation to reach net zero by 2050. At COP 26 in November 2021, 23 nations joined the UK in signing up to net zero by 2050 [2]. The government has established the Jet Zero Council to drive progress and proposed a range of policies including improving aircraft efficiency, accelerating the use of sustainable aviation fuels (SAF), supporting the development of zero-carbon emission flight and promoting consumer transparency. Further initiatives are expected from the government's Jet Zero strategy, due to be released in 2022.

Against this background, the FlyZero project was initiated in late 2020 by the Aerospace Technology Institute (ATI) and the Department for Business, Energy, and Industrial Strategy (BEIS) to determine whether zero-carbon emission flight was feasible for large aircraft. The project scope was broad, covering economic, operational, infrastructural and regulatory challenges as well as identifying the aircraft technologies required, and creating three preliminary designs of zero-carbon emission aircraft. The timescale for reporting was 12 months.

Current thinking about aerospace decarbonisation is incremental, focused on blending SAF with kerosene. This enables existing aircraft to remain in service with minimal re-certification. Introducing SAF is an important part of the solution, but meeting the net zero 2050 target will require major developments in capacity for chemical processing and direct air capture. True zero-carbon emission aircraft provide an alternative pathway, with large aircraft entering into service from early to mid-2030s.

FlyZero has identified green liquid hydrogen as the optimal zero-carbon emission fuel able to power large aircraft [3]. It has higher energy by mass compared to alternative fuels and produces no carbon emissions.

Realising hydrogen-powered commercial aircraft will require major changes in aircraft technology as well as in regulations, policies and safety requirements. In addition, the global aviation community and governments will need to work closely together to build the infrastructure to enable their global operation.

This is a massive challenge, but it is achievable. Mobilising the UK's technical and research capabilities in engineering, manufacturing and materials science is needed to deliver it. At the same time, UK academia has a significant role in research to understand fully the climate impact of hydrogen-powered aviation.

Despite these challenges, FlyZero forecasts that hydrogen-powered aircraft will have superior operating economics over their kerosene or SAF-powered rivals from around 2035 due to carbon pricing and production inefficiencies relating to SAF.

FlyZero has focused on large commercial aircraft as these create the most carbon emissions and provide the greatest commercial opportunity. It has developed three concept aircraft, addressing the regional, narrowbody and midsize market segments. The regional concept uses a liquid hydrogen-powered fuel cell with electric motors while the narrowbody and midsize concepts both utilise hydrogen powered gas turbines. Together, the concept aircraft carry between 75 and 280 passengers with design ranges between 800 and 5750 nautical miles. Below the whole aircraft level, FlyZero has identified 13 technologies required to realise large zero-carbon emission commercial aircraft.

The project has identified several potential pathways for introducing hydrogen-powered aircraft, based on the capacity of airframers to launch new programmes. Pathway 1 assumes the midsize is developed first and enters service by 2035. These aircraft would introduce liquid hydrogen systems, operating from larger international airports which are able to fund the ground infrastructure and create a global aviation network for liquid hydrogen aircraft. With lower production rates, the midsize programme would enable the supply chain to develop and the technology to mature before launching the narrowbody. The narrowbody will ultimately require a much more extensive network of hydrogen-ready airports, but in the first instance can operate from large airports and, because of the much lower fuel weight of liquid hydrogen, fly shuttle services to regional airports without refuelling.

The UK currently has world-leading capabilities in wings and aerostructures, fuel systems, gas turbines and thermal management, giving the UK around 12% of the large commercial aircraft global market turnover in 2019 – equivalent to £11bn GVA. All these elements would need to be redesigned for a hydrogen aircraft, presenting the UK with both a threat and an opportunity.

If the UK acts ahead or alongside other nations, it can lead the development of new technologies where it is currently strong and secure a greater share of activity. This could see the UK securing:

- Up to a 19% stake in the global aerospace industry estimated to be worth £178bn per annum in 2050.
- £36bn GVA per annum in 2050.
- 38,000 jobs, growing sectoral employment from 116,000 today to 154,000 in 2050.

To succeed, the UK will need to ramp up technology development now to ensure that its technologies are incorporated onto the next generation of aircraft. Conversely, if the UK does not act, it will lose some of its market share as the industry transitions. In this scenario, the UK could see:

- Market share reduce from 12% to 9%.
- Job numbers reduce from 116,000 to 74,000 despite forecasts that the industry will more than double its output by 2050.
- Crown jewel technologies being re-located overseas.

Team FlyZero

The FlyZero team consisted of 100 engineers and aviation professionals made up of secondees from 13 industrial partners together with independent experts. The project was also supported by 16 universities and research organisations, a further 34 aerospace companies, five airports and three airlines.

Figure 1 – Participating organisations in the FlyZero project (Source: FlyZero)

Advisory groups and community workshops further validated the projects priorities and findings. The FlyZero team were located across all parts of the UK and utilised remote working to deliver the project's aims despite the COVID-19 pandemic.

Figure 2 – Team FlyZero (Source: FlyZero)

02. THE CASE FOR HYDROGEN

Eliminating carbon emissions in flight was the primary aim for the FlyZero project, going beyond sub-regional and regional aircraft to larger aircraft capable of mass transport. The project took a broader approach, looking at sustainability across the aviation supply chain, non-carbon emissions and the context of broader decarbonisation in the economy. A key first step was to identify the optimum fuel source for future flight to enable early and significant decarbonisation while being technically, operationally and economically practical. This chapter sets out the considerations leading to the conclusion that hydrogen offers the best way forward.

CO_2 emissions

Aviation must reduce its impact on the environment if it is to continue to transport people and goods around the world. In 2019, aviation emitted 920 Mt (Megatonne) of CO_2 [1], or 2.5% of global CO_2 emissions [4]. Without the development of zero-carbon emission aircraft, aviation's annual carbon emissions will grow to 1540 Mt in 2050 (+67%) reaching 1845 Mt by 2070 [5]. This would increase its contribution to climate change and its share of overall emissions as other sectors decarbonise rapidly.

Non-CO_2 impacts

Different emissions from aircraft have different and often complex impacts on the climate with varying lifetimes. Carbon emissions remain in the atmosphere for hundreds of years. Water vapour stays in the stratosphere for weeks, while contrails in the troposphere typically disperse within hours, but some may become persistent. Noise, NO_x, particulates and the materials used in manufacturing are also key considerations when assessing an aircraft's lifecycle impact.

Continued research into the climate impacts of hydrogen-powered aircraft is required and should focus on predicting and modelling the impacts of water vapour and contrails for different atmospheric conditions. Laboratory tests and airborne research are key to assessing the impact of different fuels and propulsion systems on emissions and contrails under different climate conditions.

Identifying the optimum future fuel

FlyZero considered the merits of SAF along with potential carbon-free energy sources – batteries, liquid hydrogen fuel cells, hydrogen combustion, with storage in liquid or gaseous form, and ammonia. This section discusses each against a range of technical, operational and cost criteria.

Sustainable aviation fuels

SAF have an important part to play in reducing aviation's climate impact. They can be added to conventional fuel as a blend with minimal alterations to today's commercial aircraft. Even if 100% SAF is deployed, no appreciable development in 'on aircraft' technology is required. They generally produce the same tailpipe carbon emissions as current aviation fuel, however, so are not zero-carbon emission fuels. They can achieve net-zero emissions when produced by a green feedstock and direct air carbon capture. The energy industry is developing the infrastructure to produce SAF at volume. However, current government targets show a slow anticipated introduction of blended SAF, with EU targets of 5% blend by 2030, 32% by 2040 and 63% by 2050 **[6]**, with targets limited by projected supply.

Using SAF in the short term reduces carbon emissions compared to kerosene. But its supply chain is complex. Principal feedstocks initially will be biomass (e.g., sugary or oily crops, agricultural and forestry residues or algae) or waste (e.g., cooking oil, animal fat or municipal organic matter). Supplies of these are limited and are expected to deliver only up to ~20% of the SAF required to power the global fleet by 2040 (see **Figure 4**). Production beyond this will require power to liquid (PtL) SAF, made from carbon collected from atmospheric or industrial flue gases combined with electrically produced hydrogen. PtL production is inefficient and expensive. Despite the operational advantages of SAF, therefore, it has major disadvantages when used at scale. These are considered further below in comparison with liquid hydrogen.

Batteries

Battery electric solutions produce no in-flight emissions or local air quality impact. The renewable electricity demand per unit of propulsive power is much less than for hydrogen. The mass of batteries, however, currently limit applications to short-range aircraft. Battery power up to 450 kW/h was considered to be possible by 2030 but this is not enough progress to utilise them for the primary propulsion system in larger aircraft. Sourcing of raw materials and recycling are challenging, with the cobalt supply chain of particular concern due to geopolitical issues. Recycling processes have been developed to recover cobalt, lithium, and nickel, and are being commercialised. It is expected that by the late 2020s a strong recycling supply chain will have been established.

Hydrogen

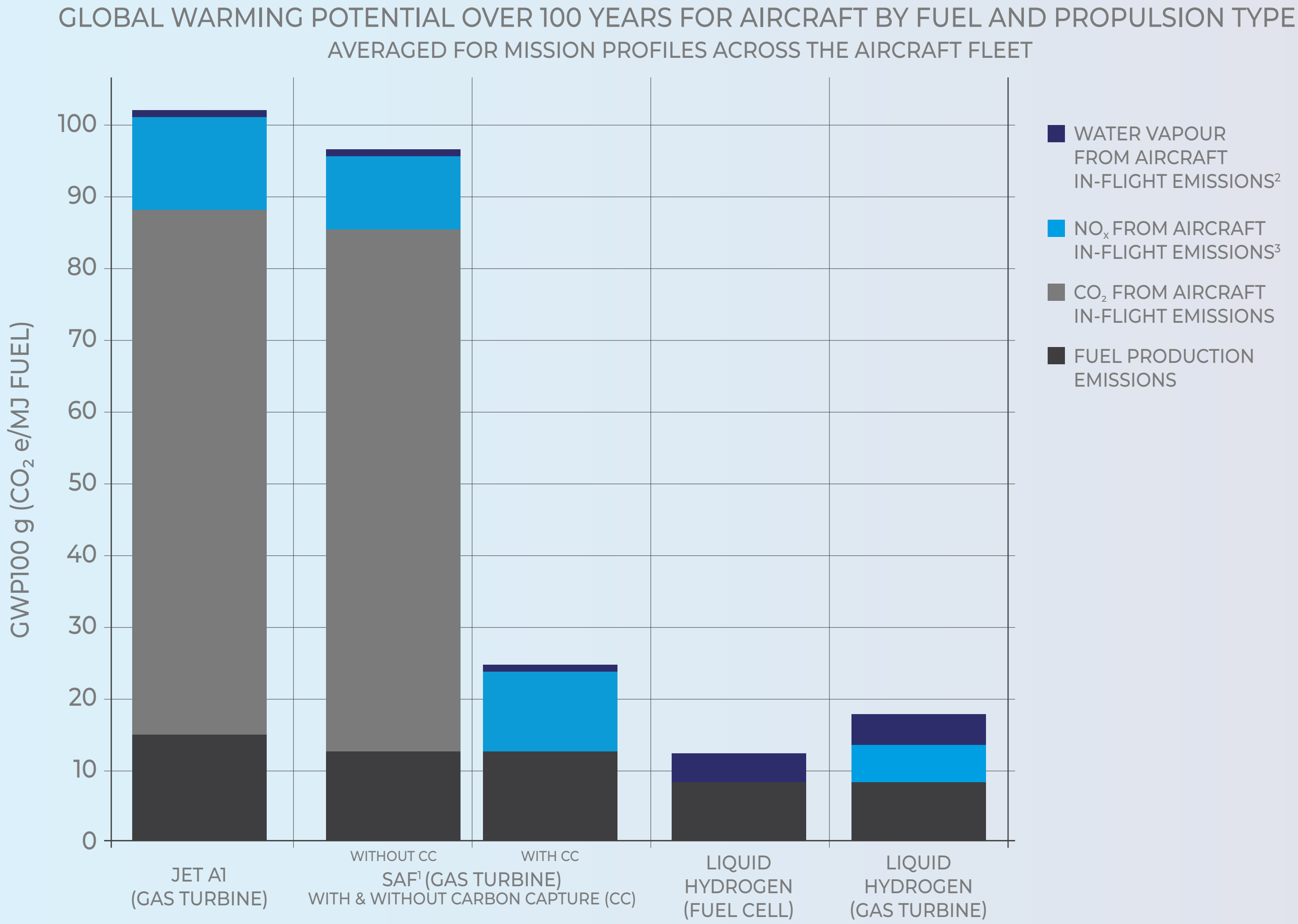
Hydrogen can be burned directly in a gas turbine or used to power a fuel cell. Hydrogen fuel can be stored on the aircraft in gaseous or liquid form. Gaseous hydrogen offers reduced complexity and a quicker route to market compared to liquid hydrogen, but the storage tank mass for gaseous hydrogen (needing heavy, high-pressure 700 bar tanks) limits its use to short-range aircraft. Liquid hydrogen poses many challenges, including storing and distributing a cryogenic fuel on an aircraft, achieving stable and reliable combustion in gas turbines, thermal management of fuel cells, minimising aircraft structural mass and drag, and developing a sustainable hydrogen fuel production infrastructure.

Water emissions will be 2.6 times that from aircraft running on kerosene or SAF [7], thus forming different contrails to kerosene. However, these are likely to be optically thinner and less persistent due to the absence of particulates in the exhaust. There is no published data to date, simulated or measured, to verify whether the overall climate impact from hydrogen-induced contrails would be less than that for kerosene. Contrail avoidance by re-routing around ice supersaturated regions would however be less polluting than with current aircraft as no CO_2 would be emitted. NO_x emissions from burning hydrogen could be around 50% lower compared to comparable kerosene-fuelled gas turbines, reducing impacts on climate and local air quality. There are no NO_x emissions from fuel cells. Hydrogen itself has indirect greenhouse gas effects, so it will be important to minimise venting of hydrogen, except for safety reasons [7]. In terms of recyclability, hydrogen fuel cells would present a new challenge with the main economic driver being the use of rare and expensive materials, such as platinum, that needs to be recycled.

Ammonia

Ammonia is toxic and corrosive and considered a major hazard if it leaks. The increased weight of ammonia fuel compared to kerosene / SAF and liquid hydrogen impacts on aircraft take-off mass, payload and range. Contrail impacts have not been assessed but a key issue is that NO_x emissions would be significantly higher than for hydrogen owing to the nitrogen content in the ammonia, in addition to the nitrogen in the air. This would impact on climate warming and local air quality. If ammonia were combusted directly, unacceptable amounts would be likely to be released unburnt. However, if ammonia is cracked into hydrogen to improve combustion, this would reduce any unburnt ammonia to acceptable thresholds.

Figure 3 makes a comparison of Jet A1, SAF and liquid hydrogen, considering their global warming potential. The green credentials of liquid hydrogen are clear.



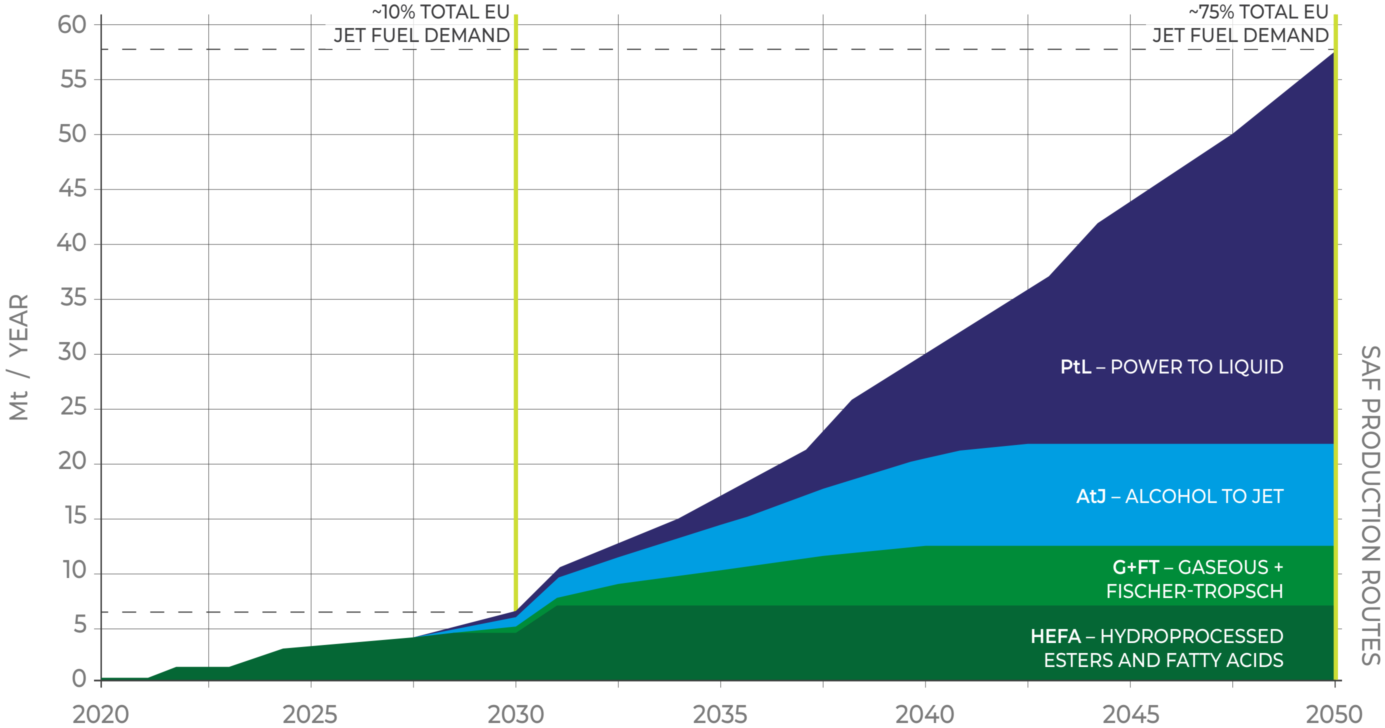
[1] *Assumes 80% PtL SAF and 20% Bio mix SAF.*
[2] *The direct impact of water vapour in the stratosphere increases. Further research taking into account flight altitude is recommended to inform design decisions.*
[3] *NO_x emissions estimated to be 50% to 70% less from hydrogen gas turbines and completely eliminated with hydrogen fuel propulsion cell aircraft.*
Note – Effect of contrails not included due to high uncertainty

Figure 3 – Global warming potential over 100 years for aircraft by fuel and propulsion type (Source: FlyZero)

Hydrogen compared to SAF

Having established the primacy of hydrogen over other potential zero-carbon candidates, a comparison between hydrogen and SAF is required to conclude the optimum approach. Cost is an essential element of this. Due to the predicted wide adoption of hydrogen as a future zero-carbon emission fuel, the cost of liquid hydrogen (per MJ of energy) is forecast to be below kerosene or SAF equivalents by the mid-2030s. Key to this is the anticipated role of Power to Liquid (PtL) SAF in future fuel production. As noted above, SAF production is limited by feedstock availability, requiring high levels of PtL particularly from around 2040. To achieve NetZero, the adoption of PtL SAF would have to be aggressive as outlined in the ATAG S2 scenario. [8].

Figure 4 presents a scenario for the ramp up of SAF production in the EU. Kerosene is progressively phased out as SAF volumes become available. Only PtL SAF has potential to scale up to address aviation demand. Hydrogen and CO_2 are main feedstocks for PtL. There is therefore a choice – directly power aircraft with hydrogen or convert the hydrogen to SAF. Note the EU has set a requirement of 5% SAF in all commercial flights by 2030 [6]. The UK is considering a 10% mandate by 2030 [9]. Today's aviation fuel standards allow for a maximum of 50% mix of SAF / kerosene so long as the fuels meet the appropriate specifications.



Source: World Economic Forum (2021), Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe

Figure 4 – Production capacity by feedstock for SAF

This reliance on PtL will make the cost of SAF uncompetitive compared to hydrogen, which involves a less complex and more efficient production process, as demonstrated in Figure 5 below. The production of PtL SAF requires 45% more renewable electricity and 22% more hydrogen.

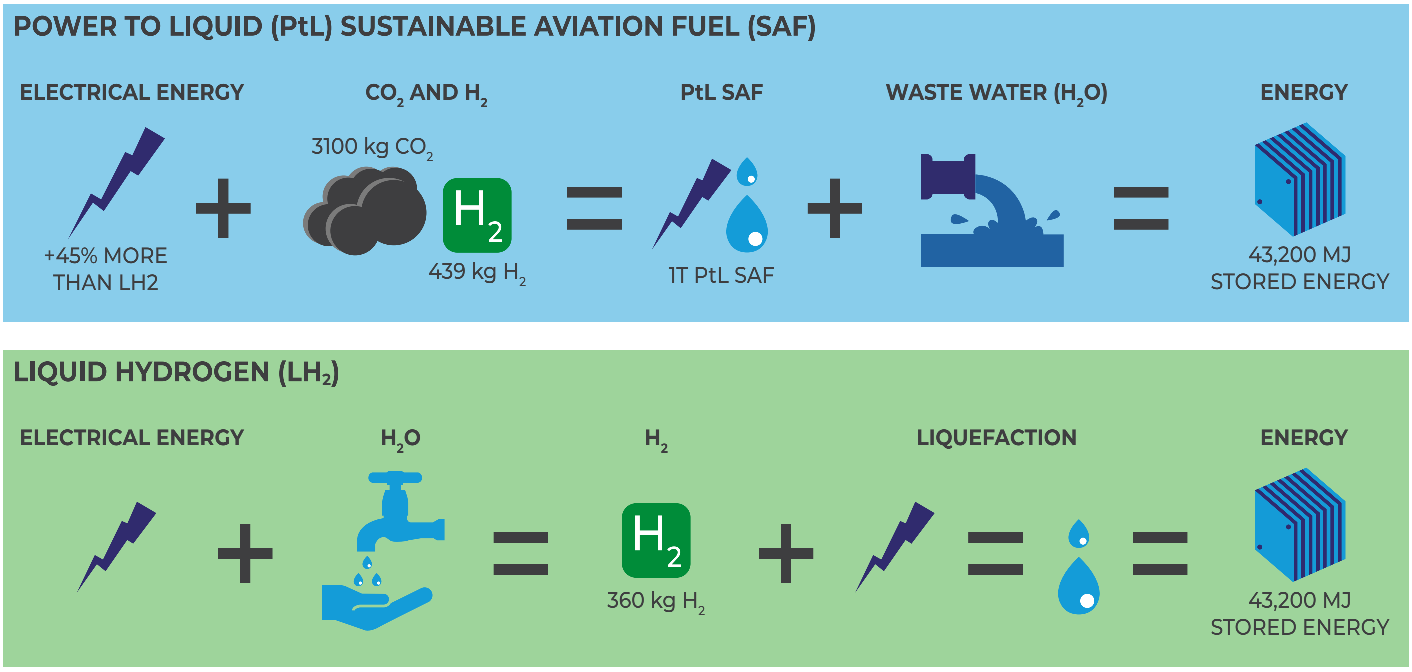


Figure 5 – Manufacturing process for PtL SAF and Liquid Hydrogen (Source: FlyZero)

Hydrogen aircraft operations are forecast to be cost competitive by the early 2030s as shown in Figure 6. A more detailed discussion regarding these forecasts can be found in [5].

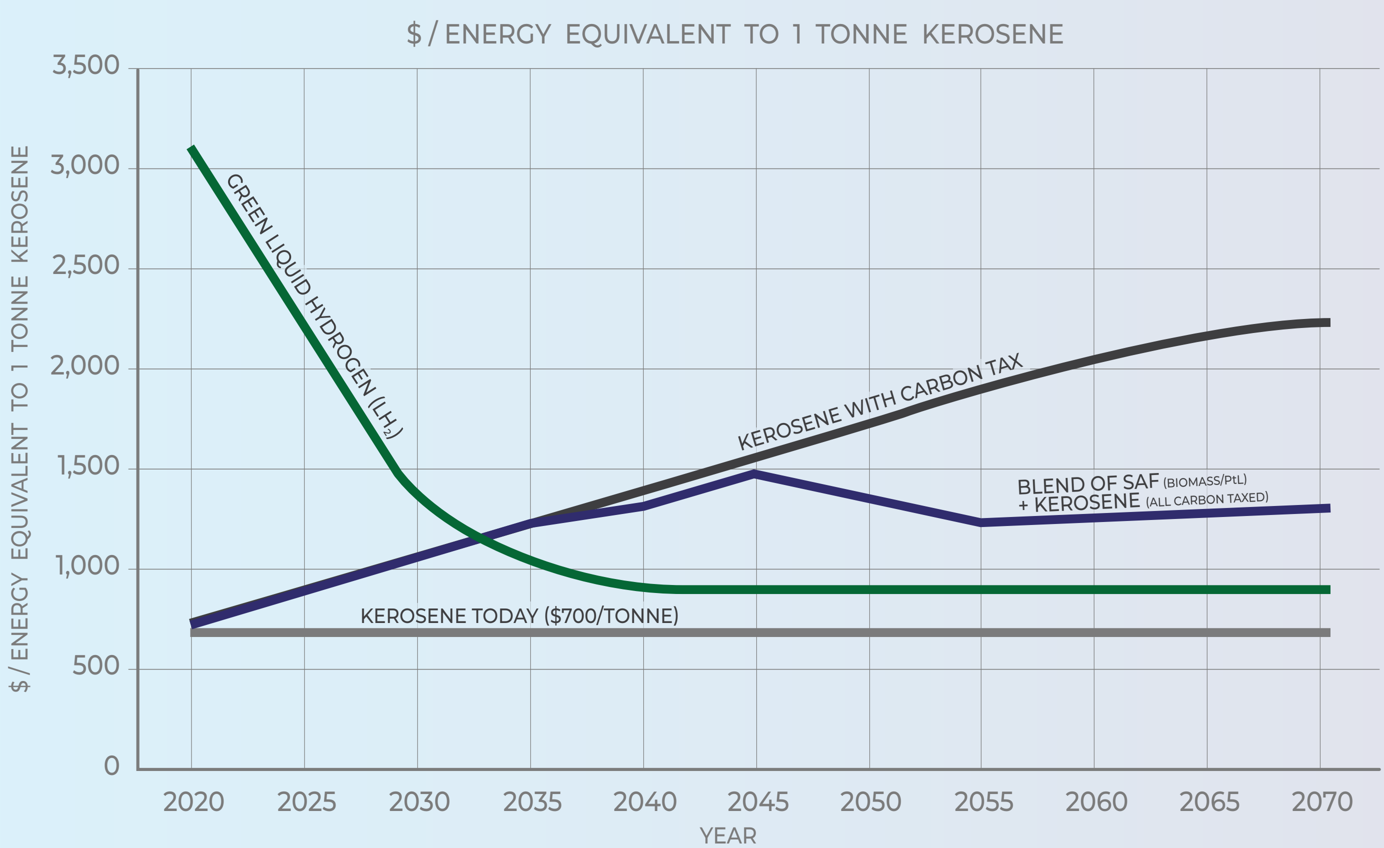


Figure 6 – Future cost of fuels (Source: FlyZero)

Figure 7 below shows a projection of mission fuel costs comparing an existing Airbus A320 aircraft with a baseline 2030 design powered by SAF and a hydrogen gas turbine powered narrowbody. A concept for the hydrogen powered narrowbody is outlined in this report.

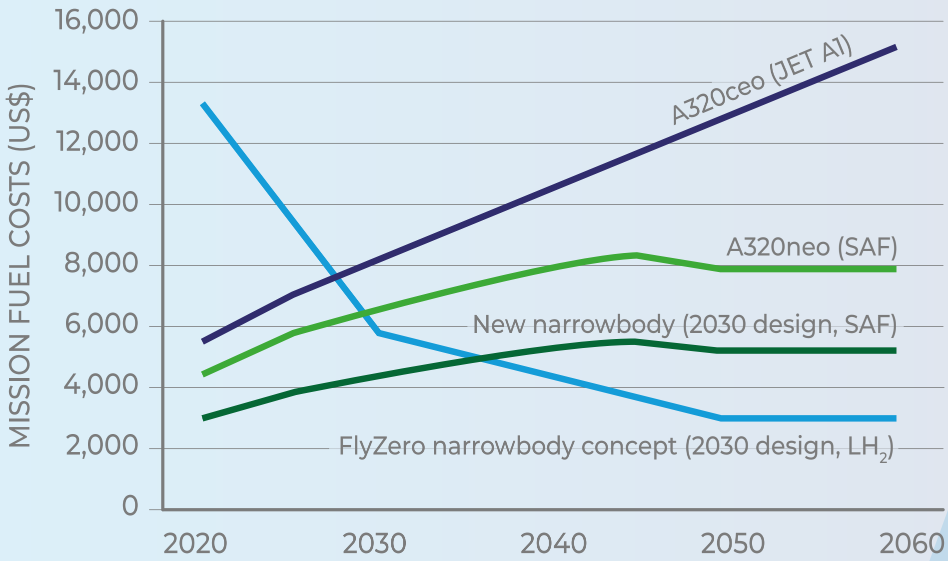


Figure 7 – Projection of mission fuel costs (Source: FlyZero)

When compared with the alternatives, considering climate impacts, economics and means of supply, there is a strong case to pursue liquid hydrogen as a fuel for aviation.

03. INTRODUCING THE FLYZERO AIRCRAFT CONCEPTS

FlyZero has developed three aircraft concepts which set out a vision for the next generation of commercial aircraft. They address the regional, narrowbody and midsize markets, offering similar capability to today's aircraft while eliminating in-flight carbon emissions. The concepts represent the art of the possible in demonstrating zero-carbon emission technologies in the context of an aircraft configuration capable of operating in the air traffic system.

The concepts were informed by developing 27 initial designs, called scouts, created with no constraints. A comprehensive and independently audited assessment selected the design features from these scouts which were then incorporated into the FlyZero concepts.

Objectives

The objectives for the FlyZero concepts were:

- Regional concept: demonstrate the maximum potential of a fuel cell primary powered aircraft.
- Narrowbody concept: explore the opportunity for hydrogen to replace carbon-based fuels in the largest and most competitive sector of commercial aviation.
- Midsize concept: assess the potential for hydrogen to address longer haul routes which have traditionally been served by larger twin-aisle aircraft.

In addition, the concepts were developed against a set of requirements and compared against baseline aircraft specifically modelled for the purpose. These are clean sheet SAF-powered aircraft with anticipated 2030 technology, their payload and range matched to the concept aircraft, but other parameters optimised. Some examples of the requirements are shown in **Table 1**.

Figure 8 – FlyZero scout aircraft (Source: FlyZero)

Non-CO_2 emissions	*Minimise or eliminate all non-CO_2 operational emissions including NO_x, non-volatile Particulate Matter (nvPM), water, hydrogen and contrails*
Noise	*No worse than current equivalent aircraft*
Range and payload	*Equal or better than current equivalent aircraft maximum range at maximum payload*
Aircraft service life	*No worse than current aircraft in the relevant market sector*
Maintenance intervals	*No worse than current aircraft in the relevant market sector*
Turnaround time (target time between flights)	*Equal or better than current aircraft in the relevant market sector*

Table 1 – Simplified examples of concept requirements (Source: FlyZero)

It is likely the configuration and performance of hydrogen aircraft will change significantly as research continues, for example in key areas such as hydrogen storage efficiency. It is therefore important that the FlyZero concepts continue to be updated.

Figure 9 below shows the key market segment and primary propulsion energy sources for the FlyZero concepts.

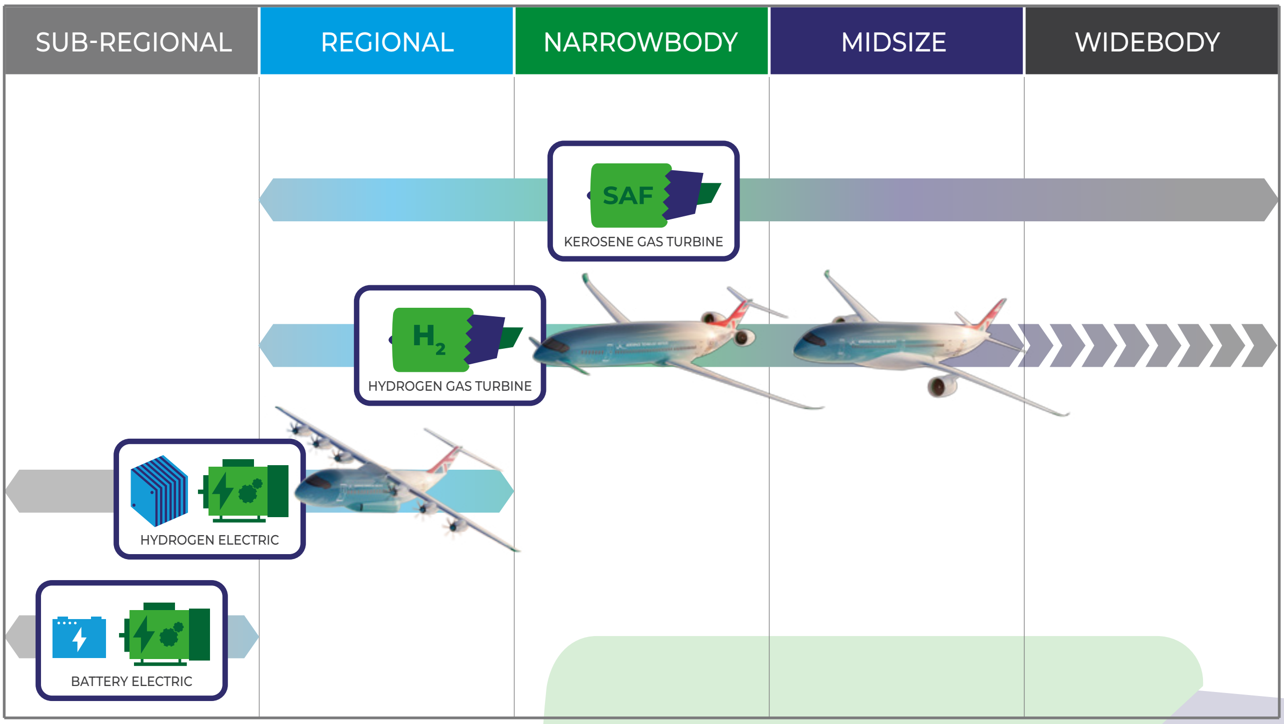


Figure 9 – Market segments and primary fuel sources (Source: FlyZero)

The Concepts

Regional Concept Aircraft

The regional concept carries 75 passengers up to 800 nautical miles (nmi) at a speed of 325 knots, which makes it more capable than existing comparable turboprop aircraft such as the ATR72 or Q400. It is positioned to bridge the gap between regional turboprops and jets. It has a wider fuselage than current regional propeller aircraft due to the liquid hydrogen being stored in tanks at the rear of the fuselage. It has six propulsors, each with an independent electrical system for high levels of redundancy, and the wingspan is 15% larger than comparable existing regional aircraft.

The main advantage of fuel cells is that they only emit water, eliminating other emissions such as CO_2, NO_x and particulates. Power density and thermal management are however key to the competitiveness of a fuel cell aircraft. A fuel cell system has lower power density than a gas turbine, so weighs more for the same power. A fuel cell is thus likely to be more competitive on smaller aircraft than the FlyZero regional concept.

When assessed against the design mission of 800 nautical miles, the concept uses 2% more energy than a comparable baseline SAF-powered aircraft, primarily due to the weight of the fuel cell system.

Figure 10 – FlyZero regional concept aircraft (Source: FlyZero)

Parameter	FlyZero Concept	FlyZero Baseline	Delta
Max Take-off Weight (tonnes)	28.8	25.8	-10%
Operational Empty Weight (tonnes)	19.8	15.0	-24%
Mission Fuel Mass (tonnes)	1.2	3.0	+155%
Mission Energy (GJ)	139	136	-2%
Aircraft Length (m)	28.0	28.5	+2%
Propulsion System	H_2 FC	SAF GT	N/A

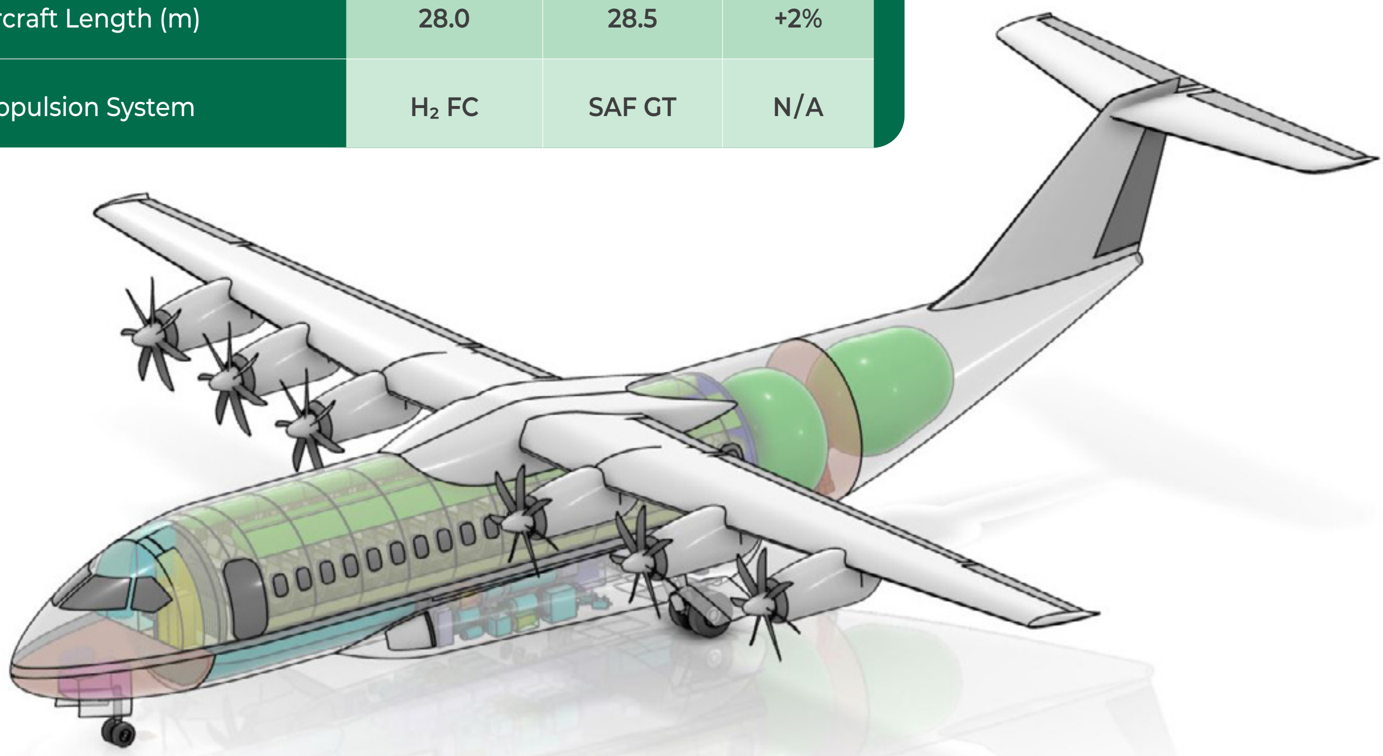


Figure 11 – Regional concept hydrogen fuel cell electric aircraft comparison with baseline aircraft (Source: FlyZero)

Narrowbody Concept Aircraft

The narrowbody concept carries 179 passengers up to a design range of 2400 nmi at a speed of 450 knots. These design points were chosen to match the maximum payload range of existing narrowbody aircraft such as the Airbus A320 or Boeing 737. When assessed against the design mission of 2400 nmi, the concept uses the same amount of energy relative to a comparable baseline SAF-powered aircraft.

The concept has the energy storage and propulsion system located at the rear of the aircraft, including the fuel tanks, fuel system and gas turbines. This location is well placed to manage ventilation requirements and helps keep fuel lines short. The architecture has the disadvantage that a lot of weight is at the rear, so canards (the small wings near the nose of the aircraft) have been added to provide additional pitch control. The concept also illustrates a low drag fuselage configuration with varying diameter which also allows a novel cabin configuration.

Figure 12 – FlyZero narrowbody concept aircraft (Source: FlyZero)

Parameter	FlyZero Concept	FlyZero Baseline	Delta
Max Take-off Weight (tonnes)	70.7	70.6	-0.1%
Operational Empty Weight (tonnes)	48.0	41.5	-14%
Mission Fuel Mass (tonnes)	3.9	10.3	+164%
Mission Energy (GJ)	445	474	+7%
Aircraft Length (m)	44.8	37.6	-16%
Propulsion System	H_2 GT	SAF GT	N/A

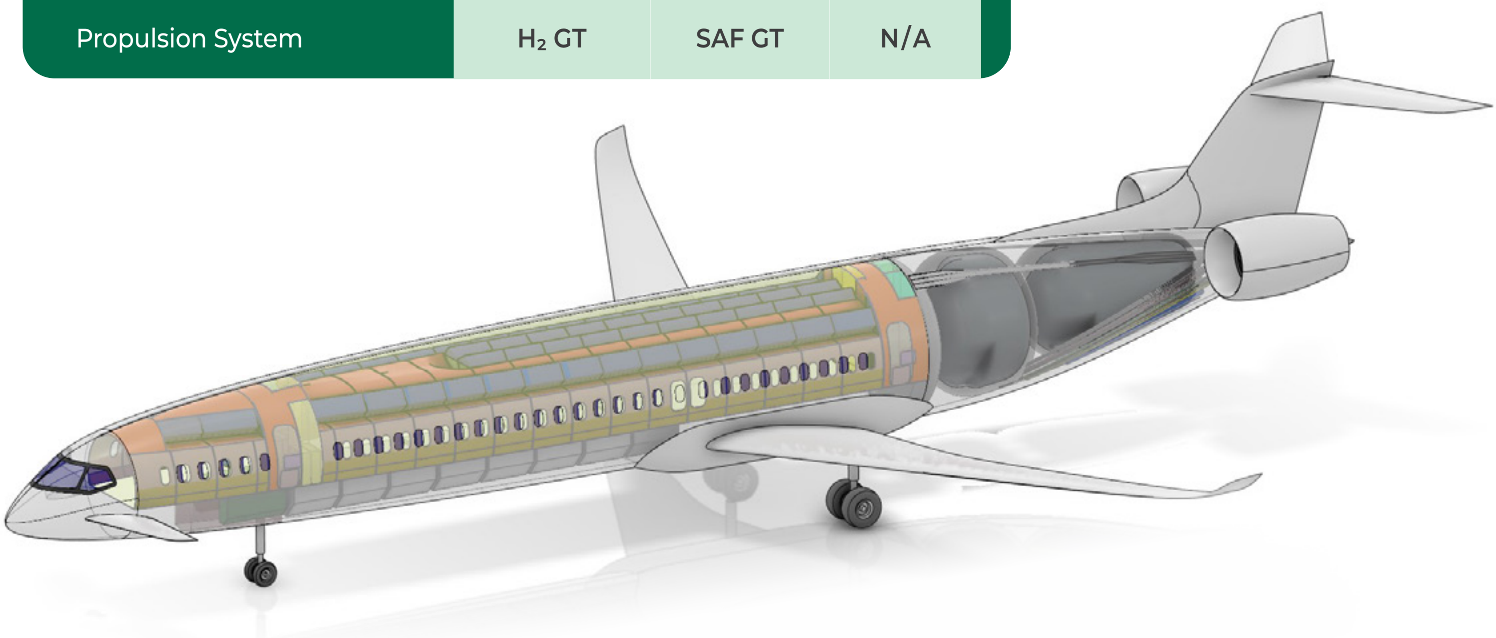


Figure 13 – Narrowbody concept comparison with baseline aircraft (Source: FlyZero)

Midsize Concept Aircraft

FlyZero analysis concluded that a midsize hydrogen aircraft could efficiently address 93% of existing long haul scheduled flights and, therefore, the majority of emissions in this market sector. A midsize aircraft could be introduced harmoniously into the "middle of the market" currently served by older aircraft designs or larger aircraft operating below their design points.

The midsize concept carries 279 passengers with a design range of 5750 nmi at a speed of 473 knots and an operational range of 5250 nmi. Its maximum payload capability is similar to the Boeing 767. When assessed against the design mission of 5750 nmi, the FlyZero concept uses 7% less energy than a comparable baseline SAF-powered aircraft. Its operational range means destinations including San Francisco (4664 nmi) and Beijing (4414 nmi) are within reach from London direct while Auckland (9991 nmi), Sydney (9198 nmi) and Honolulu (6289 nmi) are in reach with just one stop.

The concept has a larger fuselage diameter than a typical twin-aisle midsize aircraft, akin to that of a large widebody aircraft like the Airbus A350 or Boeing 777. This enables more efficient hydrogen storage. The required volume of hydrogen cannot be located solely in the rear of the fuselage as it would cause weight and balance challenges. The chosen solution is to use 'delta' tanks in the fuselage in front of the wing, which is a compromise between hydrogen storage efficiency and other design factors such as flight crew access to the cabin and refuelling safety zones.

Figure 14 – FlyZero midsize concept aircraft – one-stop global connectivity (Source: FlyZero)

Parameter	FlyZero Concept	FlyZero Baseline	Delta
Max Take-off Weight (tonnes)	150.8	170.0	+13%
Operational Empty Weight (tonnes)	104.8	96.5	-8%
Mission Fuel Mass (tonnes)	16.7	44.4	+165%
Mission Energy (GJ)	1909	2041	+7%
Aircraft Length (m)	59.6	51.7	-13%
Propulsion System	H_2 GT	SAF GT	N/A

Figure 15 – Midsize concept comparison to baseline aircraft (Source: FlyZero)

04. FLYZERO FORECASTS AND MARKET SCENARIOS

Forecasts

Air travel is here to stay in our globally connected world. It connects families and friends, allows us to explore and experience different cultures, and enables business to be done face-to-face. Air travel allows affordable mass transportation between regions, countries and continents, but its contribution to climate change requires it to decarbonise urgently.

The COVID-19 pandemic has had a profound impact on aviation since March 2020. Nonetheless, air travel has proven resilient to previous crises and demand has recovered, driven by more affordable air travel alongside income growth.

FlyZero's baseline scenario forecasts average growth of 3.2% a year, reaching 22.9 trillion revenue passenger kilometres (RPKs) by 2050. The FlyZero conservative scenario is 10% lower by 2050 at 20.7 trillion RPK, taking account of incomplete post-pandemic traffic recovery due to passenger behaviour changes, increasing environmental concerns, post-pandemic gross domestic product (GDP) growth and increased surface mode competition. The FlyZero conservative scenario lags the baseline scenario growth trajectory by about five years – the growth still occurs but comes later.

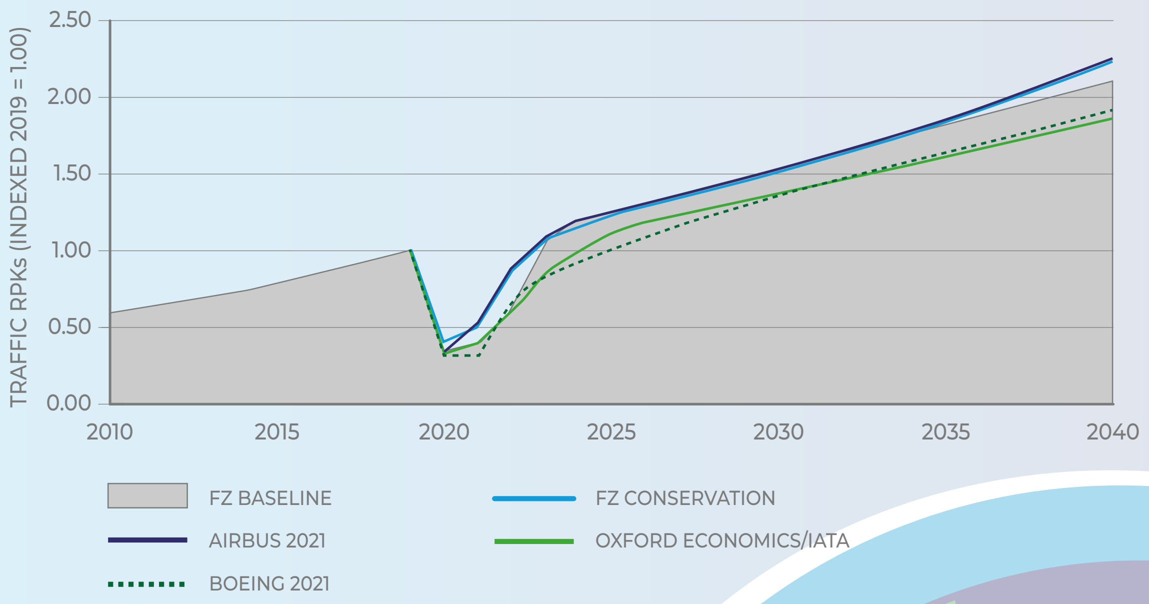


Figure 16 – Global air traffic growth forecast comparisons (Source: FlyZero & Market forecasts as shown)

As seen in **Figure 16**, growing passenger demand as aviation recovers from the current downturn will drive the need for more aircraft globally **[5]**, **[9]**, **[10]**, **[11]**. The in-service fleet is expected to more than double from its 2019 pre-pandemic level of 29,900 aircraft to 69,090 aircraft in 2050, an average growth rate of 2.7% per year. Fleet growth and aircraft retirement cycles will result in new aircraft delivery demand averaging about 2,600 aircraft per year during the 2030s, rising to 3,000 aircraft per year in the 2040s. The value of these deliveries is estimated to be worth £3.6trn in the period 2030-2050. The make-up of fleet deliveries is expected to remain dominated by narrowbody aircraft, as shown in **Figure 17** below:

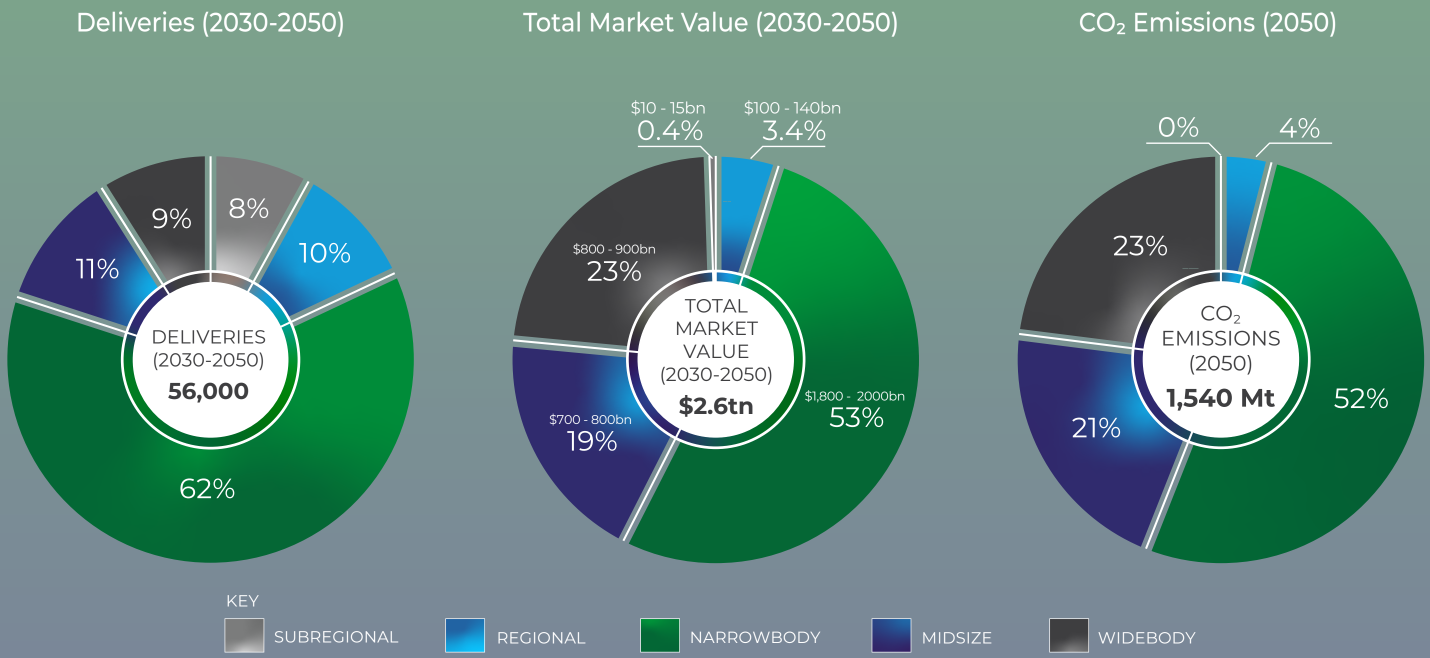


Figure 17 – Market forecasts in terms of deliveries, total market value and CO_2 emissions (Source: FlyZero)

Market Scenarios

FlyZero reviewed its three concepts and considered how each of them could be introduced into the market within the existing constraints around the investment of aircraft in service and associated infrastructure. The aviation industry has flagship aircraft, such as the new widebody planes, but also the work horses of the industry, the narrowbody aircraft. FlyZero determined the narrowbody market needs careful management as it represents 91% of all commercial aircraft flights, hence has the biggest fleet and operational infrastructure. With the predicted growth in traffic demand this narrowbody fleet will hit 150 aircraft a month production rates. The best economic pathway is to focus on the larger international airports, and with the higher value midsize aircraft, introduce this new technology into a global aviation network.

Based on the aircraft concepts discussed in the previous chapter and market forecasts above, FlyZero has developed two contrasting scenarios for the entry-into-service of zero-carbon emission aircraft:

- Regional first
- Midsize first

Regional first

In this scenario, a regional aircraft enters the market in the mid-2030s. This involves lower investment in new technology than introducing a larger (narrowbody or midsize) aircraft, but the low value of the regional market limits returns. Addressing the regional market first also does little to reduce CO_2 emissions as it generates only 7% of aviation's total carbon emissions (2019), with a lower share projected by 2050.

As pressure builds during the 2030s to deliver decarbonisation, airframers would be likely to respond by introducing an upgraded conventional narrowbody aircraft capable of being powered by SAF, delaying the arrival of a zero-carbon narrowbody by 10 to 15 years.

Midsize first

In this scenario, a midsize aircraft enters the market in the early 2030s, closely followed by a zero-carbon-emission narrowbody aircraft. This delivers the fastest and highest reduction in carbon emissions and yields a larger return on investment. Fifty percent of the commercial fleet could be hydrogen-powered by 2050 – with the potential to scale to 92% in the following 20 years, as shown in Figure 18. The newer widebody aircraft in service today would be operating to 2060 with a midsize hydrogen-powered aircraft replacing them between 2045 and 2060.

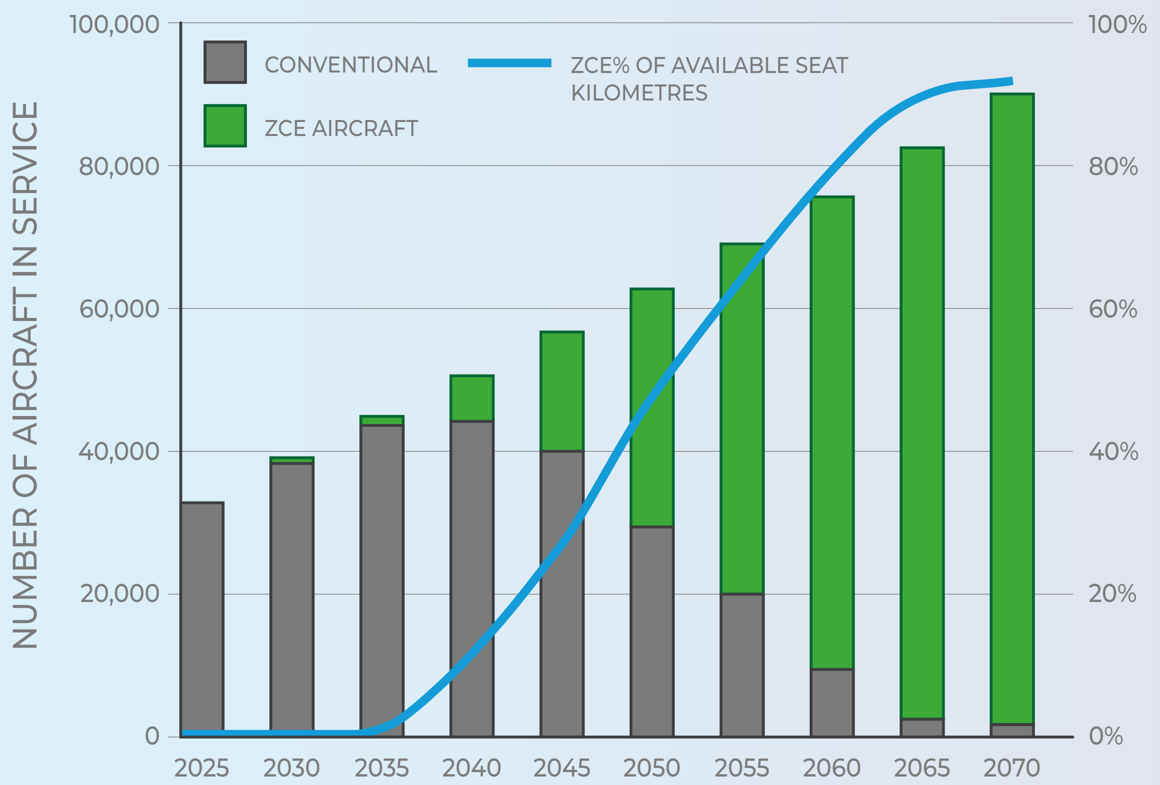


Figure 18 – Zero-carbon emission (ZCE) aircraft market penetration (Source: FlyZero)

Introducing a midsize first allows the gas turbine propulsion and fuel systems to be proved and certified in a larger aircraft, facilitating the engineering integration challenges involved. This would also de-risk subsequent development of similar technologies required for a narrowbody aircraft, which could thus enter the market soon after the midsize. Narrowbodies are by far the main revenue earners for the airframers, so it is essential to reduce the risk on a new generation of narrowbodies as much as possible.

The midsize first scenario would also enable one-stop global connectivity with zero-carbon emission aircraft, initiating a global approach to developing the regulations, legislation and policies needed to operate airports and aircraft safely and efficiently. It would further concentrate the need for new infrastructure on fewer but larger international airports initially, phasing the investment burden.

This scenario can only be achieved by accelerated investment in technology development and concerted global action on infrastructure development.

Comparison of pathways

Figure 19 compares expected annual carbon emissions if no action is taken with emissions expected to be abated under FlyZero's two market scenarios. This shows that under the midsize first scenario, hydrogen-powered aircraft in 2050 could reduce CO_2 emissions that would otherwise be generated by around 50%, and in 2070 by around 90%.

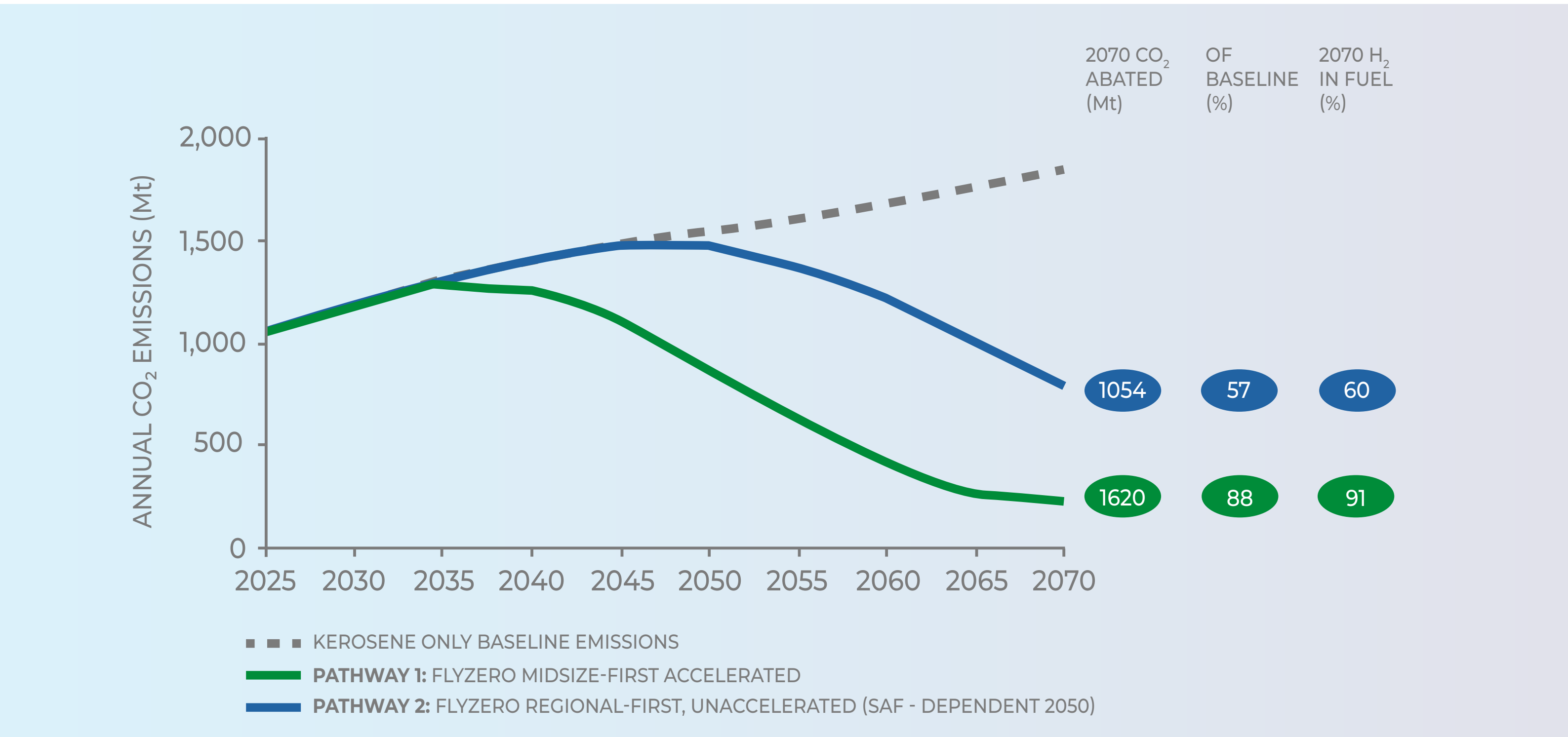


Figure 19 – Annual CO_2 emissions and the impact of Fly Zero scenarios (Source: FlyZero)

The emissions modelled above reflect the anticipated penetration rates of zero-carbon emission aircraft under the two scenarios. **Figure 20** demonstrates that the midsize first scenario delivers significantly greater numbers of zero-emission aircraft and consequently available seat kilometers from 2040 onwards than the regional first scenario. The fuel mix required under the two scenarios is also signifcantly different, the midsize first eliminates the need for PtL SAF in 2060, whereas the regional first requires significant volumes of PtL SAF out to 2070.

Figure 20 – Penetration rates of zero-carbon emission aircraft & associated fuel demand (Source: FlyZero)

In addition to emissions and market penetration, the price differential between hydrogen, SAF (particularly PtL) and kerosene discussed in **Section 2** 'The Case for Hydrogen', would see both scenarios deliver major savings for both the global aviation industry and passengers as shown in **Figure 21**.

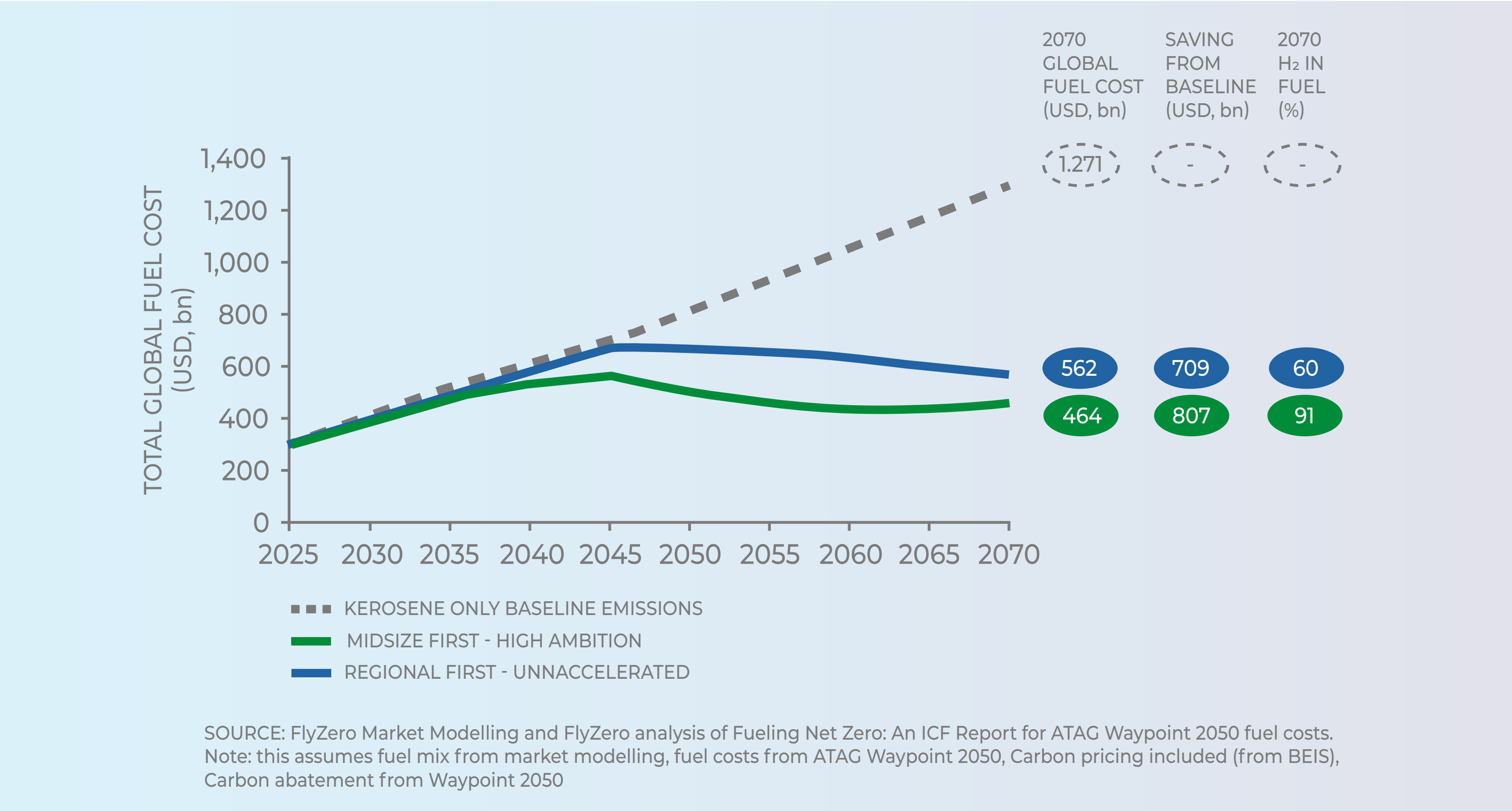


Figure 21 – Fuel costs forecasts by fuel composition pathway

This cost competitiveness will increase the probability of zero-carbon emission aircraft dominating sales from the late 2030s. Public concerns about climate change and anticipated emissions legislation from many nations are expected to reinforce this trend [5], [13], [14].

The two scenarios also offer very different opportunities for the UK economy. This is discussed further in **Section 5**.

Carbon Pricing, Taxation and Consumer Choice

Achieving net zero in aviation through carbon pricing and taxation measures alone would damage UK productivity and growth. However, where carbon pricing is applied globally and accompanied by a zero-carbon emission flight alternative, it could help to shift demand to sustainable forms of air travel and reduce emissions without lowering demand.

Other non-price measures to incentivise consumers to fly more sustainably include improved flight carbon emissions transparency, for example, mandating that this information is provided to customers when booking.

Opportunities also exist today to use the tax system to support the development of a zero-carbon emission aircraft. For example, air passenger duty could be used to help fund a portion of the investment required to stimulate zero-carbon emission aviation. This would be a highly coherent approach, using the proceeds of carbon taxation in aviation to support decarbonisation in the sector.

05. INVESTING IN HYDROGEN AVIATION FOR THE UK ECONOMY

The UK benefits hugely from aviation through its world-leading aerospace and airline industries and wider benefits such as tourism and business. As both an island and an active trading nation, aviation is particularly important to our connectivity with the rest of the world. This chapter considers how to ensure that the UK maximises the opportunities afforded by zero-emission flight.

With an estimated 12% of the global aerospace market turnover, UK aerospace generates turnover of around £36bn and GVA of £11bn annually. It supports 116,000 high value jobs. Aircraft systems in which the UK has strength will change significantly in hydrogen-powered aircraft. The industry must therefore lead in developing new technologies if it is to retain its position. Indeed, if it can exploit its potential to the full it stands to gain much more than that. The UK can seek leadership in new hydrogen technologies and climate science research areas, and the opportunity is enhanced by anticipated growth in the market - in the midsize first scenario, the total size of the zero-carbon emission aircraft market is worth $2.0trn cumulative from 2030 to 2050.

A major research effort now could result in market share increasing from 12% to 19% by 2050, GVA from £11bn to £36bn, and jobs from 116,000 to 154,000. Failure to act, conversely, could establish a pattern of decline over coming decades with market share reducing to 5%, GVA growing only to £14bn (the impact here cushioned somewhat by the overall growth in the market), and jobs declining to 74,000. The aircraft product lifecycle is 30 to 50 years. Thus, if the UK fails to establish its position, it could be locked out of the aerospace sector for the next generation. The growth potential is demonstrated in **Figure 22**.

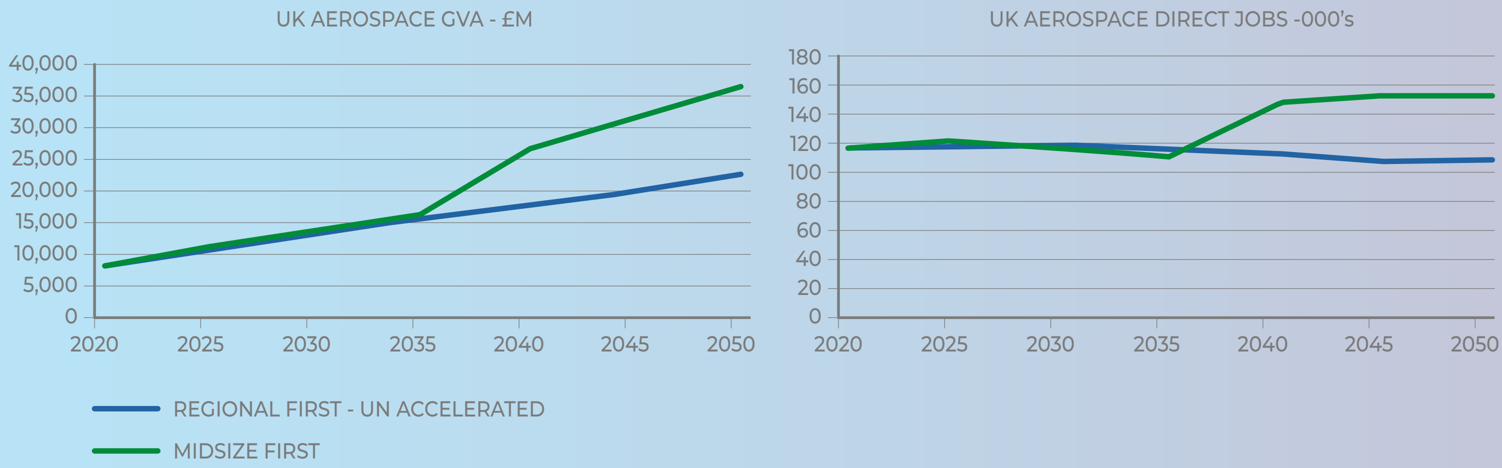


Figure 22 – Growth potential in terms of GVA and jobs (Source: FlyZero)

The risk to the UK from inaction is real. Many nations are investing heavily in sustainable aviation technology as they see the opportunity from the current technology upheaval to change their position in the industry. **Figure 23** shows estimated overseas spend on green aircraft technologies.

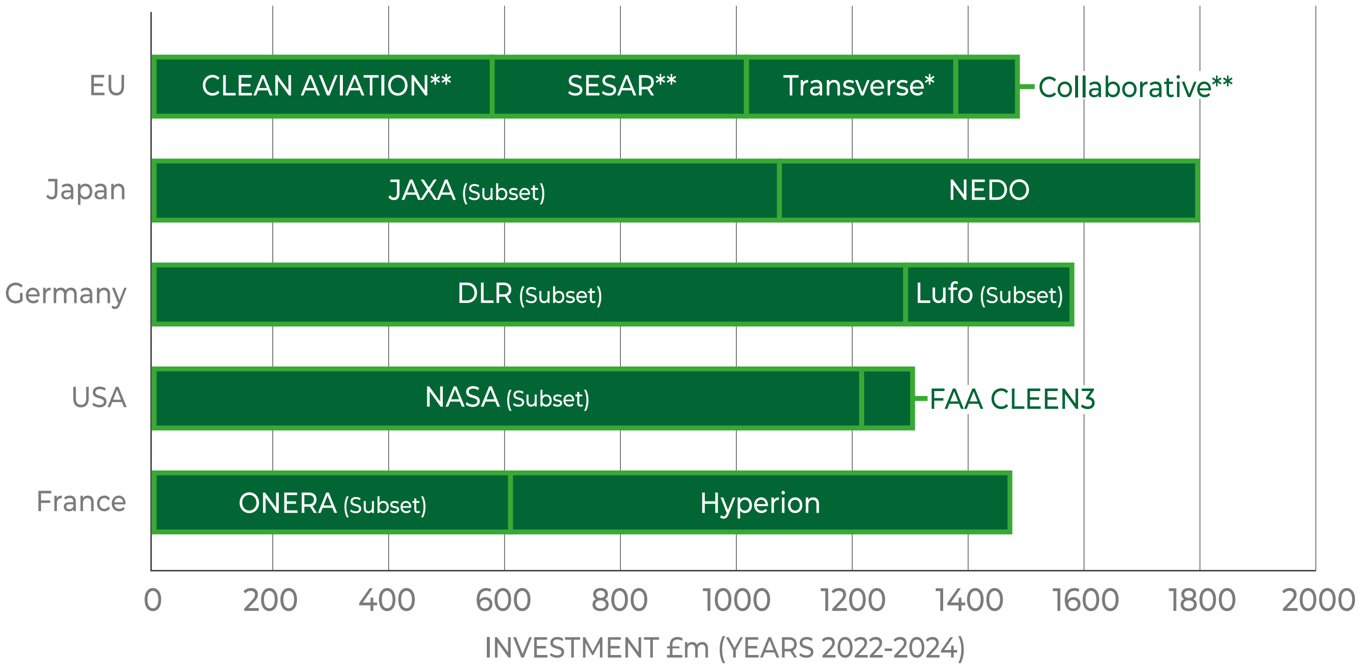


Figure 23 – Estimated overseas spend on green aircraft technologies (Source: FlyZero)

Achieving the FlyZero midsize first scenario assumes that the UK invests in critical technologies at similar scale and pace as Japan, Germany and France.

The technology pathway to hydrogen flight

FlyZero estimates that an ambitious technology and demonstration programme into zero-carbon aerospace technologies would require investment in the order of £270m per annum for at least the next five years [15]. The first sub-regional hydrogen fuel cell electric aircraft is expected to enter service in the late 2020s. The first hydrogen gas turbine powered aircraft may enter service by the mid-2030s. To win content on it, UK companies must be ready to demonstrate new systems by 2025. Airframers will not proceed with development programmes in the absence of proven technologies. This activity would build UK capability at pace raising the UK aerospace sector's profile internationally and increasing opportunity for collaboration. Continued fundamental research into climate science is also required.

FlyZero assessed a broad range of technologies relating to the aircraft, operational factors and underpinning capabilities, ultimately focusing on 13 technologies. All these technologies present significant challenges, requiring high levels of research, development, testing, integration and validation. The UK is well placed to lead this work but must develop its cryogenic hydrogen capabilities and infrastructure.

Figure 24 below identifies six technologies fundamental to hydrogen fuel cell or hydrogen gas turbine aircraft along with seven cross-cutting technologies critical to ensuring that hydrogen aircraft are commercially and operationally viable and deliver tangible sustainability improvements.

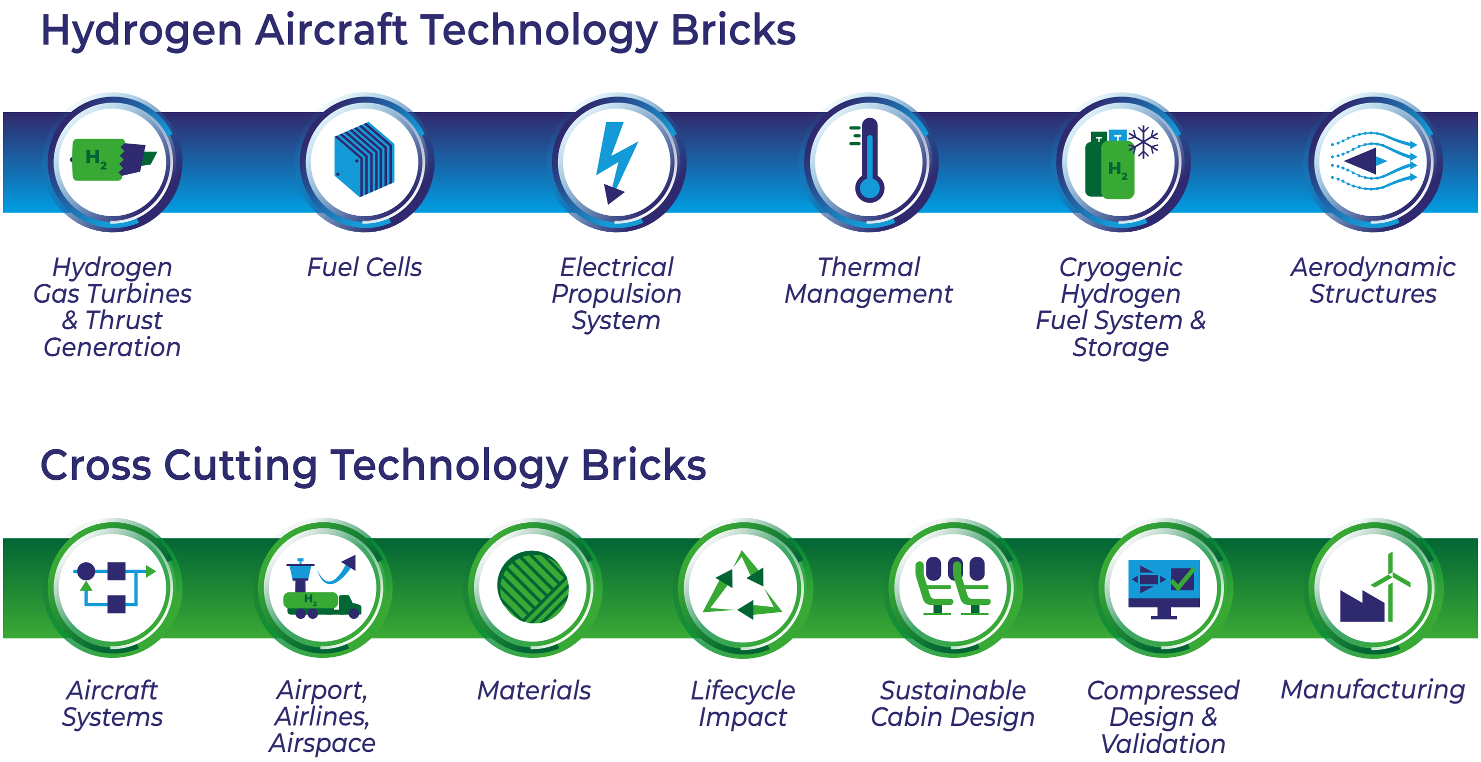


Figure 24 – FlyZero technology bricks

The UK has leading capability in these technologies including gas turbines, fuel systems, aerodynamic structures, thermal management and electrical systems. With its deep understanding of the certification challenges associated with these systems, UK aerospace can also provide the know-how required to compress the development cycle and accelerate the delivery of hydrogen aerospace technologies to market. **Figure 25** on the following page identifies technology challenges and developments needed for the six hydrogen aircraft technology bricks.

Taking forward the FlyZero technology bricks

Underpinning Research and Technology

Work is required to generate data on materials suitable for designing fuel tanks and thermal management and propulsion systems which are exposed to liquid hydrogen. This should explore the risk to materials from hydrogen permeation and embrittlement over a range of cryogenic temperatures. This work would benefit the whole UK aerospace community and should be centrally coordinated to avoid duplication.

Hydrogen Gas Turbine - Technology Pathway

The UK has a strong position in gas turbine technology and an associated research network.

FlyZero considers that burning hydrogen in a gas turbine is feasible and potentially more efficient than kerosene or SAF. The gas turbine is the most power dense propulsion solution and so advancing this technology is critical to realising the full potential of hydrogen-powered aircraft.

This requires the adaptation and advancement of the combustion system within the gas turbine. Early work should be launched rapidly to test and validate hydrogen combustion computer modelling methods.

Figure 25a – Rolls Royce 'Ultrafan' gas turbine engine

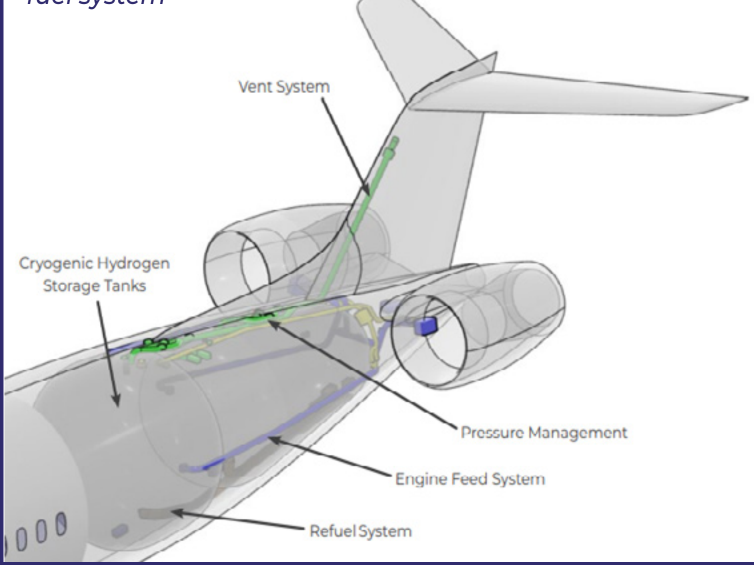
Cryogenic Fuel System - Technology Pathway

The UK has a strong position in conventional aerospace fuel systems and pumps but cryogenic hydrogen introduces a high degree of novelty and risk.

FlyZero studies show that the mass of the fuel system is dominated by heavily insulated pipework, complexity of pumping systems and the distance between tank and engine in the airframe. The technology to provide lightweight insulation is therefore a vital development challenge.

One major driver of the fuel system design is the management of the pressure and temperature of the liquid hydrogen inside the tank and the system. This is a key area of research as it is a trade between weight, reliability and complexity.

Figure 25b – FlyZero representation of a cryogenic fuel system



Liquid Hydrogen - Cryogenic Fuel Tanks - Technology Pathway

Cryogenic tanks must manage a number of variables during the cycle of refuel and flight as shown in Figure 25c, right.

Light and well insulated fuel tanks are essential to any liquid hydrogen fuelled aircraft. The performance of such tanks is measured by the gravimetric efficiency, which is driven by the shape, plus the structural and thermal technologies. A major opportunity exists to improve tank gravimetric efficiency and aircraft capability by introducing composite materials in the walls of the tank.

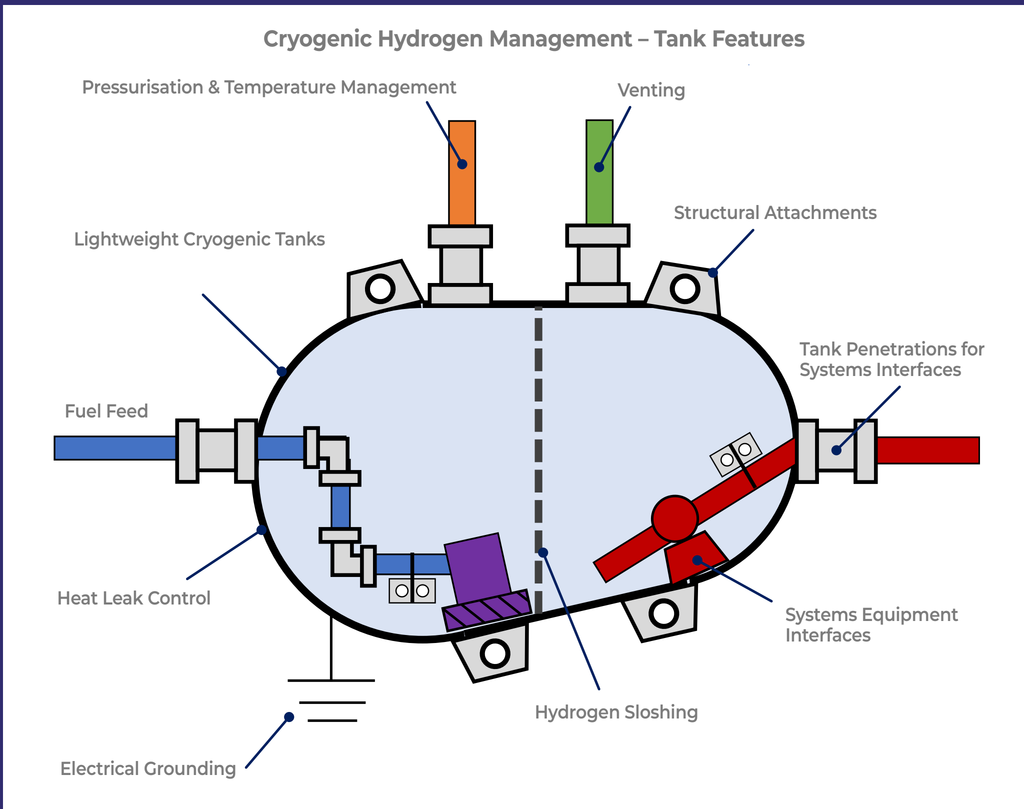


Figure 25c – Overview of cryogenic fuel tank (conceptual illustration of tank only to highlight key design parameters)

Fuel Cell and Electrical Powertrain - Technology Pathway

The first generation of electrical powertrains will use low temperature proton exchange membrane (LT-PEM) fuel cells. These reject heat at a relatively low temperature (~80°C) and require complex thermal management systems. Reducing the weight of these is an important focus. Next generation high temperature (HT-PEM) fuel cells will be lighter but require substantial research into new materials to realise them.

Fuel cells produce electrical power at around 50% efficiency, so power density of the electrical powertrain is the technology challenge. Creating a competitive hydrogen electric powertrain will require advances in high voltage power electronics and power dense electrical motors.

Figure 25d – Example fuel cell (Source: iStock)

Thermal Management System - Technology Pathway

As noted above, LT-PEM fuel cells require complex vapour compression cycle thermal management systems and large heat exchangers, increasing mass and drag. Next generation HT-PEM fuel cells will use a simpler, lighter liquid thermal management system

Improved heat exchanger technology will be needed to create more competitive second-generation hydrogen gas turbine powered aircraft.

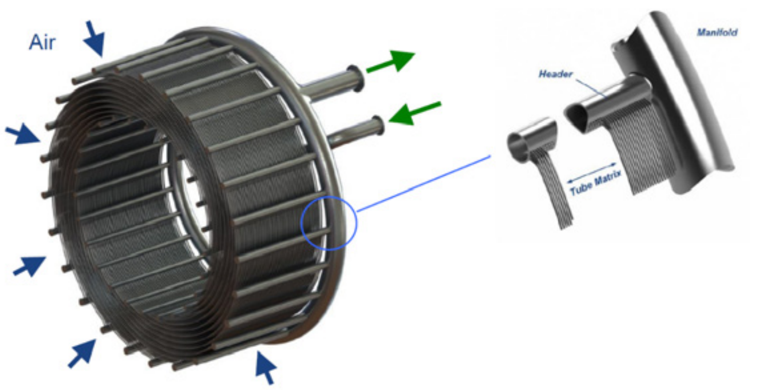


Figure 25e – Reaction Engines heat exchanger

Aerodynamic Structures- Technology Pathway

The UK has a strong position on aerodynamic structures, particularly wings and moveable devices.

Liquid hydrogen-powered aircraft will store fuel in the fuselage rather than in the wings as conventional aircraft do. Maximising the benefits of a dry wing is therefore an essential area of research.

Continued research into reducing drag and weight will enhance the performance of all aircraft, including those powered by liquid hydrogen.

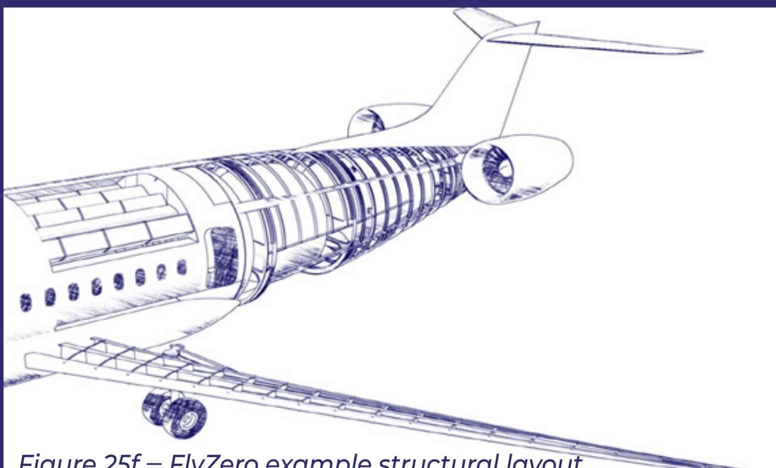


Figure 25f – FlyZero example structural layout

Figure 25 – Technological challenges and key developments needed to realise hydrogen fuel cell electric and hydrogen gas turbine powered aircraft

The opportunity for the UK afforded by each technology brick is shown in **Figure 26** below. The greatest potential contribution comes from liquid hydrogen gas turbines, fuel systems and wings.

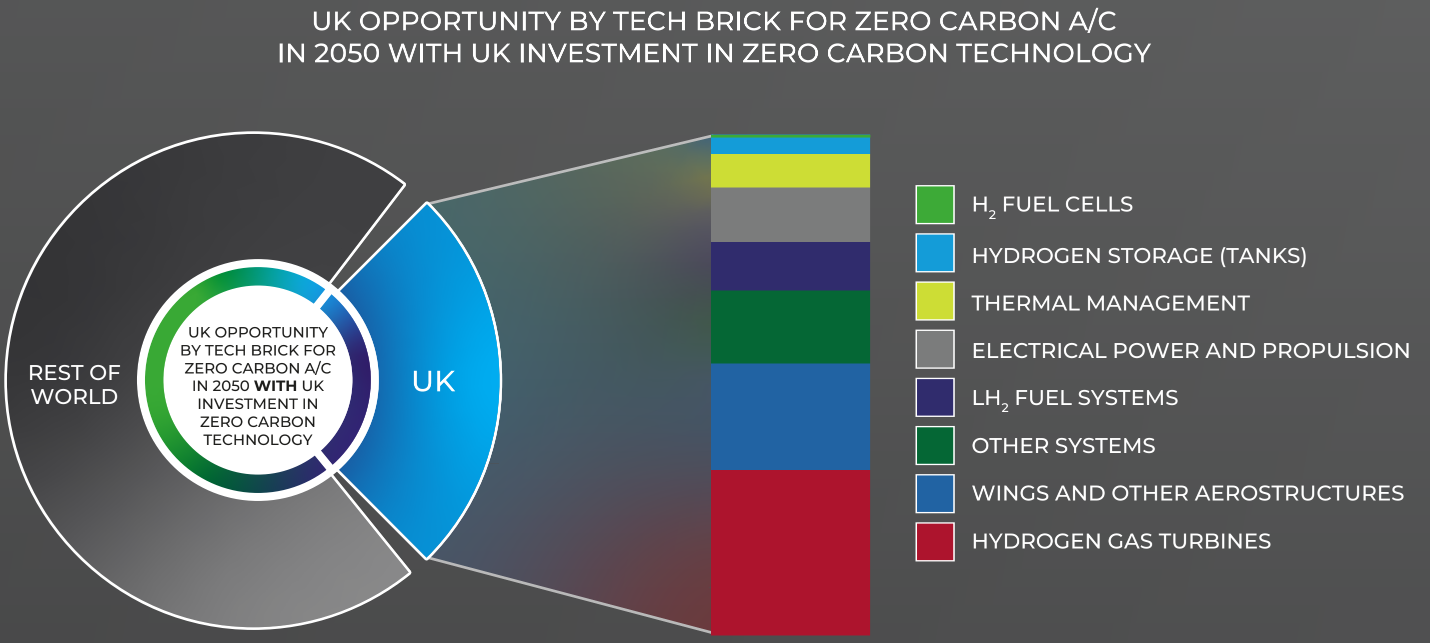


Figure 26 – Potential UK contribution to liquid hydrogen aircraft manufacture in 2050 (Source: FlyZero)

Building UK capability for hydrogen aerospace technologies

While the UK sector has great strengths in the critical technologies for hydrogen powered flight, it will rapidly have to adapt to manage the transition to hydrogen. The UK has leading capability in gas turbines, fuel systems, aerodynamic structures and thermal management for conventional kerosene-burning aircraft. To develop these systems for hydrogen aircraft, new capabilities are required particularly in cryogenics and hydrogen handling, safety and materials interaction. These are limited in the UK, with some specific knowledge within some sectors (space, medical imaging, chemical processing) and within some organisations such as the UK Health and Safety Executive's Science and Research Centre. Other sectors (automotive, maritime, energy) are also setting out to learn.

One route to accelerate cross-sectoral collaboration would be to establish a UK hydrogen technology centre, or to leverage a network of existing centres. This could research and disseminate hydrogen fundamentals, provide test infrastructure for end-use applications and help develop critical enabling capabilities across multiple sectors. It is needed urgently. Without it, UK companies will act independently, incurring high capital costs and creating unnecessary duplication. Alternatively, some may choose to conduct research overseas.

UK aerospace and the ATI understand the facilities required and recognises the need to create the enabling capabilities in an open access environment, serving the needs of multiple sectors to accelerate the UK position. To address this, the Catapult network and other key organisations have launched the Hydrogen Innovation Initiative (HII[1]), created with the purpose of working with government, industry and academia to create a focal point of collaboration. Bringing together relevant cross-sector actors, with access to the right resources to address the capabilities gap as part of a co-ordinated national programme for hydrogen innovation. Collaboration between actors such as the ATI, HII and the UK's Health and Safety Executive Science and Research Centre in the near term could help address the capability gap and deliver for UK aerospace.

Fuel cells and electrical motors are newer to aerospace and a new supply chain will have to be built. There is opportunity for companies with experience in these technologies from energy and automotive to move to aerospace applications. For new entrants the cost of achieving aerospace levels of compliance could act as a barrier. This could be overcome through collaboration with aerospace incumbents or by upskilling new companies on aerospace processes.

The size of the market for proton exchange membrane (PEM) fuel cells for aerospace is forecast to be around £110m per annum by 2035 or £135m per annum by 2050. By comparison, the overall PEM market is projected to exceed £15bn by the late 2020s **[16]**. The UK has capability in integrating fuel cells into aircraft. Research in fuel cells themselves might best be conducted through a cross-sector initiative similar to the Faraday Battery Challenge.

Transition to production

The FlyZero 'midsize first' scenario assumes that production ramps up to around 250 hydrogen aircraft per month by 2050 (**Figure 27**), the majority of which would be narrowbody aircraft. During the 2030s and 40s both kerosene and hydrogen aircraft will be produced. New factories and production lines will be needed. Once built these factories could anchor production for the lifecycle of the aircraft - potentially for decades. To win this work the UK must compete on productivity as well as technology, meaning that new factories should be highly automated. Currently, only a small proportion of carbon emissions associated with an aircraft over its lifecycle occur during production. For hydrogen aircraft, however, the proportion will be higher because tailpipe emissions will have been eliminated. There will therefore need to be more focus on the sustainability of factories **[17]**.

[1] The HII participants are the High Value Manufacturing Catapult, Energy Systems Catapult, Offshore Renewable Energy Catapult, Connected Places Catapult, Digital Catapult, Compound Semiconductor Applications Catapult, Net Zero Technology Centre (NZTC), National Physical Laboratory (NPL), Aerospace Technology Institute (ATI) and the Advanced Propulsion Centre UK (APC).

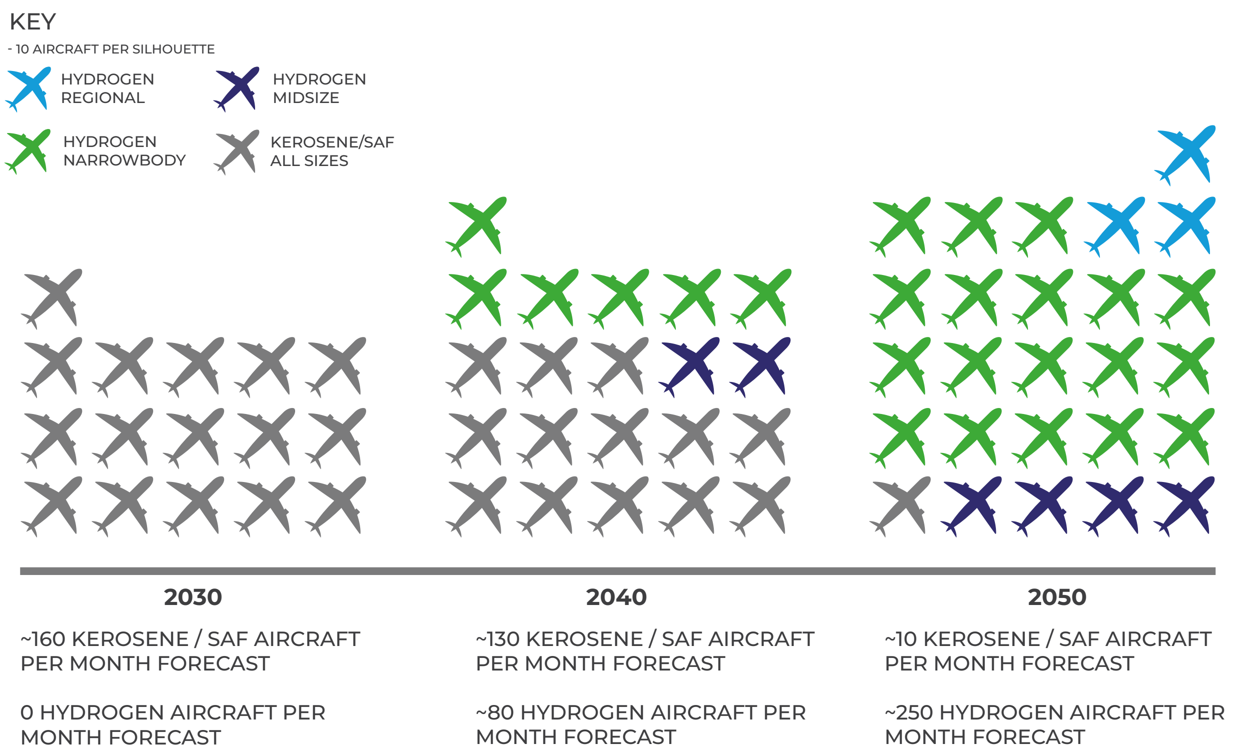


Figure 27 – Forecast production rate per month for the FlyZero midsize first scenario (Source: FlyZero)

While R&D investment develops technology, builds critical skills and secures intellectual property, it is production that anchors long-term jobs. Figure 28 indicates the relative level of investment needed at each stage of an aircraft development cycle. Costs increase by an order of magnitude on the transition into production. This will occur for large aircraft in the 2030s, and sooner for sub-regional aircraft. Ahead of that, the UK government should consider what mechanisms can be provided to support industrialisation post TRL 6 (see also FlyZero 'The Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation' [18]).

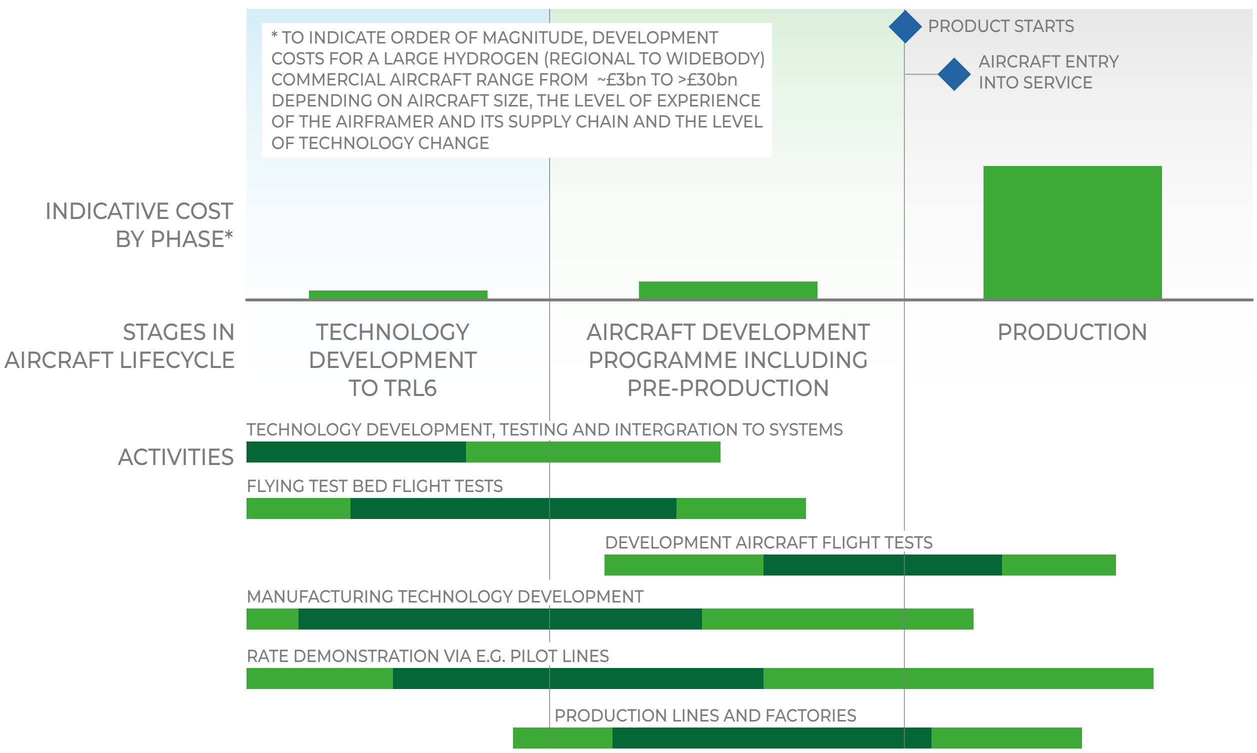


Figure 28 – Activities and indicative cost (investment needed) at different stages in the aircraft lifecycle (Source: FlyZero)

International collaboration on technology development

Aerospace is a global industry. The technology challenges, barriers to entry and market risks associated with new large aircraft programmes indicate that only an existing aircraft manufacturer is likely to be able to bring a new large aircraft to market. Decisions about the next generation of aircraft, whether powered by SAF or hydrogen, will therefore be taken by global companies headquartered outside the UK. It is therefore fundamental that the UK does not operate in isolation as it develops technology but collaborates with industry leaders to attract investment to the UK, helping them to share costs and risks and create better opportunities for UK technology to win a place on multinational platforms.

This collaboration needs to recognise that:

- A hydrogen-powered aircraft would be a greater technological challenge than any recent whole aircraft development.
- Fuelling aircraft would depend on a global supply of green liquid hydrogen.
- Aircraft operations will rely on the secure distribution of hydrogen to targeted hub airports and new airside infrastructure to deliver fuel to airlines.

These risks mean that financing will be crucial to any programme to develop a hydrogen aircraft. Traditional finance routes, company funded and government repayable launch investments, may not be best suited or feasible in this context. If adequately de-risked, however, private investors with record levels of capital to deploy may be willing to participate. Government should therefore consider how to de-risk investments across aerospace and aviation. This could take different forms, including offering attractive levels of early-stage R&D funding, supporting whole aircraft demonstrations, providing asset value guarantees, price guarantees, debt raising or equity capitalisation of special purpose vehicles, and risk-sharing agreements with industry and private capital.

Other nations are already working in partnerships to accelerate their respective positions for technology maturity of national strategic importance. This includes:

- European programmes such as Clean Aviation and the Clean Hydrogen Joint Undertaking.
- Bilateral programmes such as the Hy2Sky programme between DLR and NASA.
- Bilateral cooperation between the national funding programmes, such as LuFo in Germany and Innovair in Sweden.

The opportunity to establish strategic relationships between the ATI and overseas bodies to secure a leading UK position in the next generation of technologies is closing quickly.

The wider economic benefits of hydrogen aviation

Hydrogen aircraft will avoid carbon taxation and market-based restrictions on aviation, in turn maximising the economic benefits of air travel such as through international business and inbound tourism. Lower levels of international air travel could cause significant damage to the UK economy. The UK's aviation sector contributed £48.1bn in GVA to the UK in 2019. In the same year, the sector sustained 587,400 jobs, employing 266,030 people directly and supporting many more indirectly from fuel suppliers to food and beverage providers, and financial and business services firms. Including tourism, it is estimated that UK aviation supported GVA of £77.5bn to the UK in 2019, equivalent to 3.4% of GDP. In contrast, reduced demand due to taxation or legislation could cause significant economic damage. The reduction in GDP associated with restricting aviation is estimated to be £35bn annually by 2070 **[19]**.

The economic benefits of zero-carbon aviation far outweigh the shorter-term investment considerations to secure the technology to enable an accelerated hydrogen aircraft launch in the early 2030s.

FlyZero analysis of the expected costs, benefits, risks, and uncertainties of the investment show this activity is expected to deliver high value for money for UK taxpayers - this analysis is presented in more detail in the FlyZero report (Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation) **[18]**.

06. THE HYDROGEN ECOSYSTEM: FUEL SUPPLY, AIRPORTS & AIRSPACE

As noted in the previous chapter, hydrogen-powered aircraft will require a globally accessible supply of fuel and infrastructure provision at airports to be operational. This will have to be underpinned by a network of international agreements concerning fuel standards, and safe distribution, storage and handling of hydrogen.

Hydrogen supply

Hydrogen as a future energy source is gaining credibility, with strategies emerging for generation and exploitation across many countries and sectors. FlyZero forecasts that aviation will be a significant use case, given forecast demand for hydrogen in both zero-carbon emission aircraft and in the production of SAF.

The UK has signalled its intention to develop domestic hydrogen supply through the UK Hydrogen Strategy published in August 2021. The National Grid has also published its view on future energy scenarios [20], providing further forecasts on hydrogen availability. Overlaying the FlyZero market scenarios on these supply forecasts shows aviation to be a significant use case, but only one part of a broader and very challenging energy transition.

The National Grid future energy scenarios can be summarised as:

- **Consumer transformation**: widespread electrification
- **System transformation**: blue hydrogen[2] replacing natural gas
- **Leading the way**: green hydrogen[3]

[2] Blue hydrogen is produced mainly from natural gas, using steam reforming. The output is hydrogen, but also carbon dioxide as a by-product. Carbon capture and storage (CCS) is essential to trap and store this carbon.

[3] Green hydrogen is produced using clean electricity from surplus renewable energy sources to electrolyse water. Electrolysers use an electrochemical reaction to split water into its components of hydrogen and oxygen, emitting zero-carbon dioxide in the process.

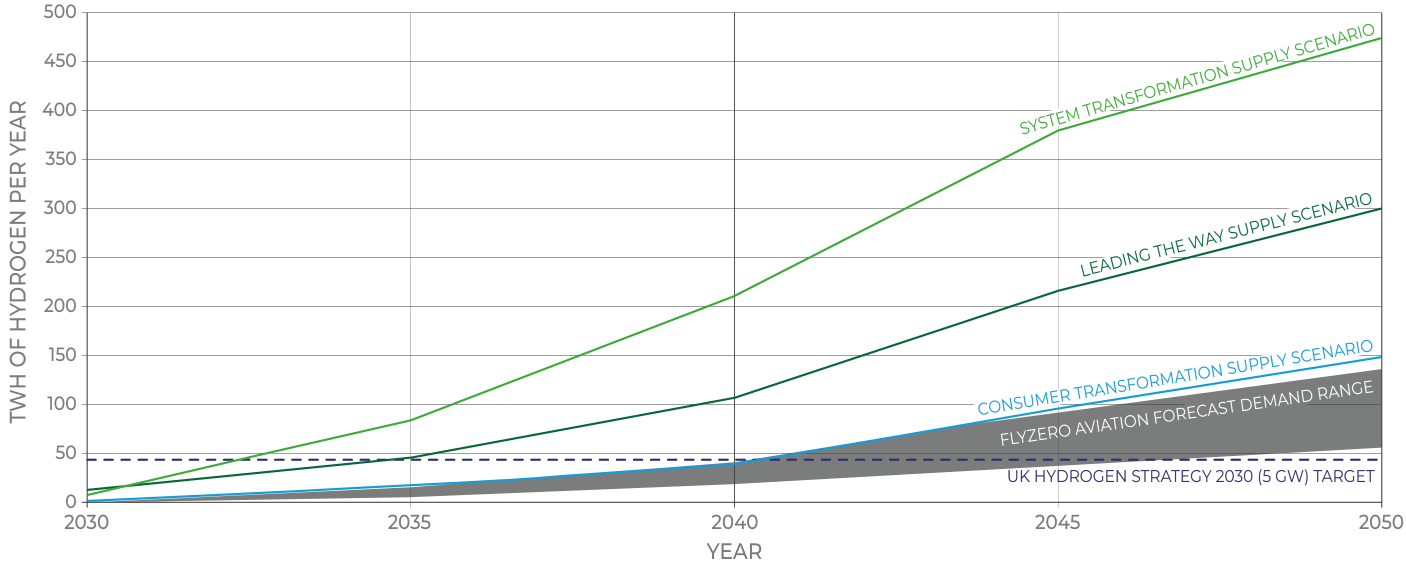


Figure 29 – UK hydrogen production scenarios (Source: FlyZero)

The government's commitment to hydrogen and specifically green hydrogen is a positive early step in accelerating this transition. The potential for hydrogen as an aviation fuel needs to be prominent in future hydrogen strategies and the sector prioritised for hydrogen supply given its status as difficult to decarbonise.

Airport infrastructure

The system requirements for future aviation need to be considered in parallel with aircraft technology and development. Radical changes to airport infrastructure are needed in preparation for hydrogen-powered aircraft including supply to the airport, liquefaction and on-airport distribution.

Therefore, in parallel to the development of aircraft technology and climate science, the introduction of hydrogen aircraft will have significant requirements for new infrastructure and ways of working at airports.

The midsize first scenario consolidates initial infrastructure requirements while creating a global zero-carbon network. Initially, it would require a small, global network of hydrogen-ready airports, acting as hydrogen hubs from which more local networks could be grown. It is estimated that this will require a minimum viable initial network of six to 10 hydrogen-ready airports, increasing to 50 or 60 airports once the global in-service fleet reaches 100 aircraft.

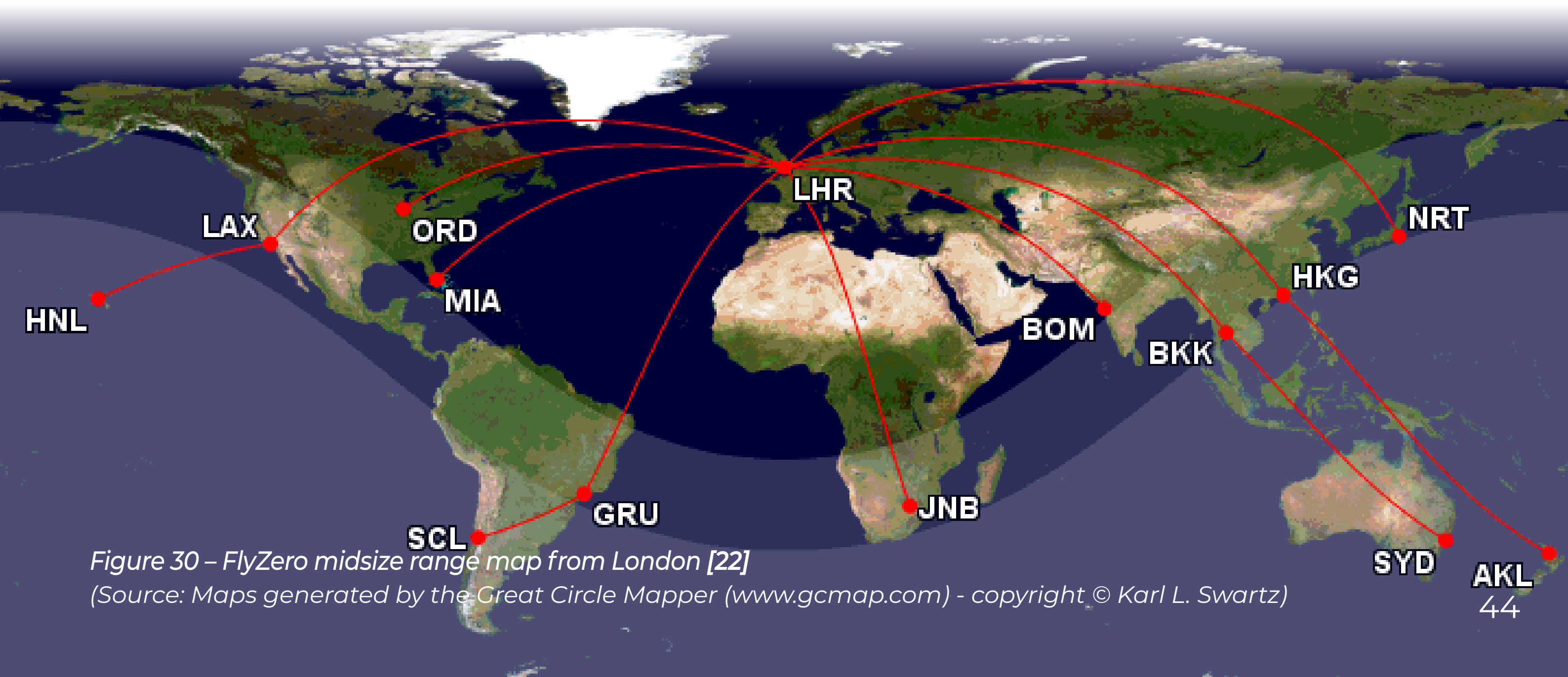


*Figure 30 – FlyZero midsize range map from London **[22]***
(Source: Maps generated by the Great Circle Mapper (www.gcmap.com) - copyright © Karl L. Swartz)

Liquid hydrogen has four times the volume of kerosene so will require more storage space at airports as well as presenting the challenge of keeping it cold. FlyZero has determined three potential ways to deliver liquid hydrogen at airports as shown in **Table 2**.

1. Road delivery by fuel tanker.
2. Delivery as a gas via a pipeline, followed by liquification at the airport.
3. Hydrogen generation at the airport. This final option is considered unlikely due to the associated on-site energy requirements.

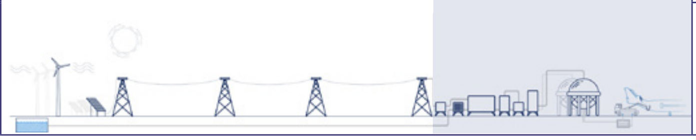
On-airport infrastructure option	*Representation*	*Airport suitability*	*H_2 supply*	*Estimated capital cost (£m)*
1. Storage only		*Small*	*Tanker*	*Small: 20 - 55* *Medium: 100 - 250* *Large: 325 - 775*
2. Liquefaction & storage		*Medium, large*	*Pipeline*	*Small: 25 - 75* *Medium: 200 - 450* *Large: 625 - 1375*
3. Electrolysis, liquefaction & storage		*None**	*N/A*	*Small: 100 - 165* *Medium: 850 - 1350* *Large: 2500 - 4050*

Table 2 – Airport infrastructure options (Source: FlyZero)

Note: Estimated capital costs display the median and upper estimates for airports of various sizes in the UK.
** Scenario may be suitable if demand is very low but the airport is close to a large supply of renewable electricity.*

For alignment of zero-carbon aircraft, the hydrogen production and distribution at scale, and hydrogen refuelling infrastructure at airports will be a significant global coordination challenge. It is essential that the aircraft, airport and energy infrastructure are developed in tandem.

Airspace Management

There remains an immediate opportunity to address airspace management and provide immediate sustainability benefits through improved management both in the air and on the ground benefiting both current fleet operations and in time, next generation aircraft. Typical measures and initiatives that facilitate this include optimised trajectory-based flight paths in free route airspace, collaborative decision making between airspace managers, airport operators and airlines, and defined benefits of high-resolution weather data for headwind and contrail avoidance as well as formation flying. (See also FlyZero: 'Airports, Airlines and Airspace – Hydrogen Infrastructure and Operations') [22].

Safety and Operations

Ensuring exceptionally high safety standards is expected of any new aircraft or technology. While many of the existing regulations can be read across to hydrogen aircraft, there are some key areas where no regulations are currently defined. FlyZero worked with the UK CAA to identify where existing regulations were not applicable or suitable to arrive at a solution at least as safe as an existing aircraft. As the behaviour of cryogenic hydrogen, when tanked in a commercial aircraft, is not well understood, the FlyZero concepts may incorporate features incompatible with future safety standards. Substantial further work is needed in this area and global collaboration on safety standards will be required.

The ability to ready an aircraft for its next flight safely and efficiently will be critical to airlines and will require specific ground support equipment. Initial studies for FlyZero by the Health and Safety Executive suggest that a 20-metre safety zone would be required during connection and disconnection of fuelling hoses, but this could be reduced to 8-10 metres once the connection is secured, subject to testing and risk assessments. Critically, fuelling and passenger boarding in parallel is considered feasible once the connection is secured.

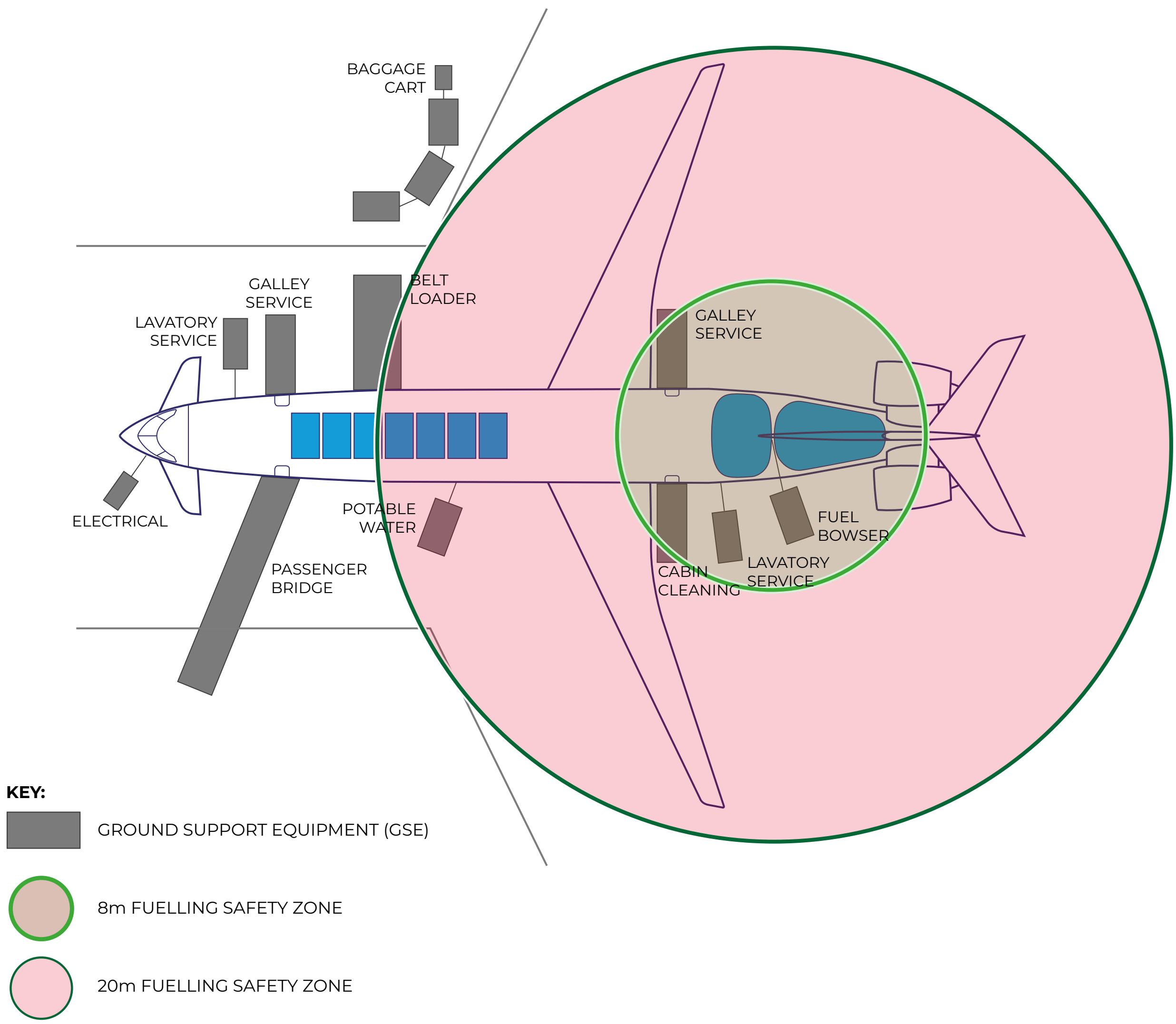


Figure 31 – Narrowbody aircraft concept fuel safety zone (Source: FlyZero)

07. CONCLUSION

Global aviation is at a turning point, requiring new aircraft technologies, airport and energy infrastructure, global regulations and policies to deliver next generation aircraft based on liquid hydrogen technology. UK industrial leadership and technology strengths in wings, propulsion and fuel systems are all going to be impacted by these disruptive technologies to meet the worlds' drive for net zero aviation by 2050.

The UK risks losing considerable jobs and investment in high technology industry unless we invest in both sustainable aviation fuels and liquid hydrogen now to ensure we protect our markets and UK Aerospace industry.

UK industry and government must decide whether to invest and secure a role in hydrogen aviation or risk being locked-out. Relying purely on SAF being the fuel of choice in the longer term is a high-risk strategy.

The implementation of hydrogen-powered aircraft in aviation is not going to be easy, hence we need to start now to understand it and apply the right engineering solutions to deliver it to protect our environment and the global aerospace industry. The aviation sector must play its part in limiting the impacts of climate change and given the development times for new aircraft we must act now.

Ultimately, an integrated approach is needed, and the UK must build strong links across global aviation with international partners to ensure we can play our role to secure future hydrogen technology. The global community has already launched several new projects to develop hydrogen aircraft technologies, with plans for ground and flight test. It is vital that the UK launches ambitious hydrogen projects or we will lose our position in the global aviation sector.

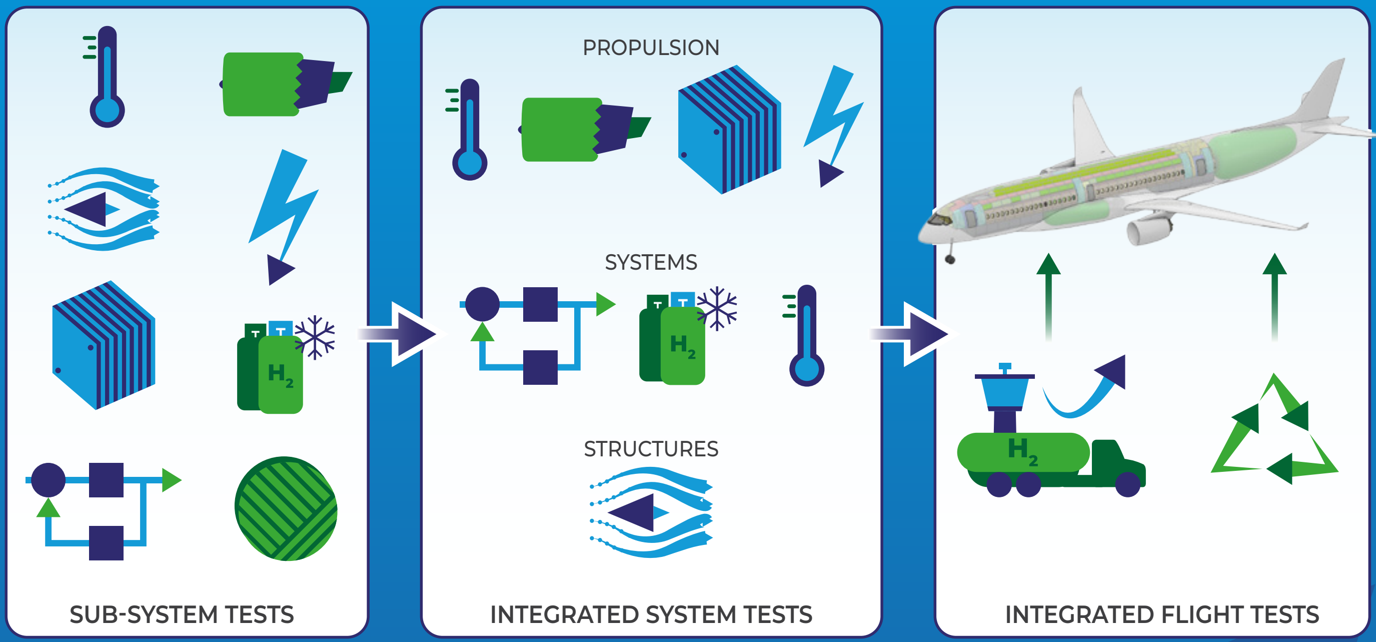


Figure 32 – Example of integrated test elements (Source: FlyZero)

The ATI already runs calls for industry on zero carbon and this fits within the scope of the UK Aerospace Technology Strategy, funding both R&D programmes and infrastructure. The ATI is ideally positioned to deliver these initiatives, leveraging existing infrastructure and programmes such as FlyZero. It can develop capability and skills to oversee the hydrogen R&D activity and help coordinate this across the UK aerospace sector.

APPENDIX A – LIST OF ABBREVIATIONS

ATAG	*Air Transport Action Group*
ATI	*Aerospace Technology institute*
CAA	*Civil Aviation Authority*
COP	*Coefficient of Performance*
EASA	*European Aviation Safety Agency*
FAA	*Federal Aviation Administration*
GDP	*Gross Domestic Product*
GE	*Gravimetric Efficiency*
GMF	*Global Market Forecast*
GTP	*Global Temperature change Potential*
GVA	*Gross Value Added*
GWP	*Global Warming Potential*
LH_2	*Liquid Hydrogen*
Mt	*Megatonne*
MTC	*Manufacturing Technology Centre*
NATS	*National Air Traffic System*
nmi	*Nautical miles*
NO_x	*Nitrogen Oxides*
OEM	*Original Equipment Manufacturers*
PEM	*Proton Exchange Membrane*
PtL	*Power to Liquid*
RPK	*Revenue Passenger Kilometres*
SAF	*Sustainable Aviation Fuel*
TRL	*Technology Readiness Level*
ZCE	*Zero-Carbon Emission*

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NATS
Reaction Engines
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