THE CASE FOR THE UK TO

ACCELERATE ZERO-CARBON EMISSION AIR TRAVEL

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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PURPOSE AND OVERVIEW

FlyZero was established by the Aerospace Technology Institute (ATI) and the Department for Business, Energy and Industrial Strategy (BEIS) to determine the technical, commercial and economic potential of large commercial zero-carbon emissions aircraft. The project aims to inform the direction of UK industry and government investment and take a global lead on zero-carbon emission aircraft technology.

FlyZero has conducted a 12 month programme of work drawing on more than 100 technical and commercial specialists from aerospace, aviation and other sectors, supported by extensive collaboration with universities and research centres.

This strategic case has been prepared by FlyZero to share its findings and set out the case for change for the UK to play a leading role in accelerating zero-carbon emissions aviation and for the UK aerospace sector to support the development of these aircraft.

This strategic case is presented over 6 chapters:

1. The strategic context for zero-carbon emissions aviation
2. The role of FlyZero and the programme's key findings and recommendations
3. An assessment of the optimal role for hydrogen in decarbonising global aviation
4. The case for the UK to play a leading role in hydrogen aviation, and the benefits to the UK's aerospace and aviation sectors
5. The challenges facing investment in hydrogen aviation, including the market failures at play
6. How the UK can de-risk and accelerate the launch of liquid hydrogen aircraft

To inform the strategic case an initial economic assessment has been conducted and is available as an accompanying document "The Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation".

EXECUTIVE SUMMARY

Aviation will become environmentally and economically unsustainable if it does not decarbonise. If current trends continue, aviation will be responsible for 39%[1] of the UK's total carbon emissions by 2050. This scenario is unacceptable for several reasons: the UK would miss its net zero targets; flights would become more expensive as carbon costs increase; and the UK economy would be damaged as environmentally conscious businesses and consumers choose to avoid air travel. Alternative scenarios that rely on suppressing demand would reduce the social and economic benefits the UK derives from aviation, which in 2019 transported nearly 300 million people and over 2.5 million tonnes of goods into and out of the UK – valued at £77.5 billion gross value added (GVA) to the UK economy [2].

This explains the UK government's new commitment at COP-26, alongside 23 other nations, to achieve net zero CO_2 emissions in aviation by 2050.

While this higher level of ambition is clearly needed, it is less clear what the right course of action should be. Over the last few years, more efficient aircraft and sustainable aviation fuels (SAF) have been the main focus of decarbonisation efforts; but achieving net zero aviation through SAF would rely on abatements from outside the sector, such as carbon offsets and greenhouse gas removals, approaches that are complex and uncertain.

FlyZero's analysis indicates another way as the optimum route for fast decarbonisation and maximum economic benefit. This involves a rapid roll-out of SAF to start decarbonising the existing fleet in the 2020s and early 2030s, and in parallel developing ambitious new liquid hydrogen aircraft that will enter service in the mid-2030s, thereafter delivering zero-carbon emissions flight and ultimately enabling full decarbonisation of aviation.

1 Assumes other sectors continue their decarbonisation activities and the aviation sector follows the "Continuation of Current Trends" as set out in the JetZero consultation [Jet zero: our strategy for net zero aviation – GOV.UK (www.gov.uk)].

FlyZero's findings include:

1	*Liquid hydrogen produced by renewable energy is the only aircraft fuel able to remove meaningful levels of carbon from commercial air travel*
2	*Liquid hydrogen powered aircraft are technically viable and are forecast to have superior operating economics compared to both jet fuel and SAF powered aircraft*
3	*A family of three hydrogen powered aircraft, with design ranges up to 5,750 nmi[3], has the potential to address up to 88% of all carbon emissions from aviation[4]*
4	*The optimal sequencing strategy for maximum decarbonisation would be to introduce a midsize aircraft first; this is more aggressive than other propositions and challenges industry and governments to act more swiftly to meet 2050 targets*

FlyZero has developed a family of three liquid hydrogen aircraft concepts (a regional, narrowbody and midsize) with design ranges up to 5,750 nmi (operational range 5,250 nmi), which could directly abate up to 88% of global emissions from large commercial aircraft. The strategy of introducing the midsize aircraft first would allow airport infrastructure investment to be focused on international hubs and high traffic routes such as UK-Middle East, UK-Far-East, or UK-North America, ultimately creating a "global network".

The cost savings of this approach for the global aviation industry and passengers could be worth $167 billion annually by 2050 compared to a SAF dominant pathway.

But the benefits could also be felt closer to home if the UK acts now to de-risk and accelerate a new aircraft development programme. The UK is home to one of the world's leading aerospace industries, supporting 116,000 jobs across all regions of the UK and generating £11 billion GVA from a diverse community of over 3,000 companies. By securing content on the first generation of hydrogen aircraft, the UK could create up to 38,000 highly productive, high wage jobs by 2050, providing employment opportunities in many centres outside of the south east and London, including the South West, the East Midlands, Northern Ireland, Scotland, and North Wales.

Whilst the opportunity is significant, the challenges should not be underestimated. Developing hydrogen powered aircraft would represent a major technology step and require a huge commitment from an original equipment manufacturer (OEM). Success would depend on a range of factors outside the OEM's control, such as the reliable supply of low cost, green hydrogen in sufficient quantities. In this report we set out a range of market failures with the potential to prevent the investment needed. These include the challenges of coordination across multiple stakeholders – airlines, airframers, engine makers, fuel providers, airports – who must act simultaneously if the market is to be realised.

[3] *5,250 nmi operational range is equal to 5,750nm ESAD (Equivalent Still Air Distance).*
[4] *FlyZero analysis indicates that these aircraft could directly address 88% of global tailpipe carbon emissions by 2070, and have the potential to address 100% of emissions if these aircraft expand into the long-haul market - with one stop to deliver global connectivity.*

Industry and government will need to work together to overcome these challenges. The window of opportunity for launching the development of these aircraft is short and could be closed by 2025 if the airframers decide to develop conventionally powered aircraft instead – aircraft that will continue operating until the end of the 21st century, preventing meaningful hydrogen aircraft penetration and associated carbon reduction by 2050.

FlyZero has developed a set of 13 'technology bricks' required to develop liquid hydrogen powered commercial aircraft. The UK already has world leading capability in technologies for conventional kerosene burning aircraft, giving it a head start in developing some critical components for hydrogen powered aircraft, including fuel systems and storage, gas turbines, thermal management and aerodynamic structures.

FlyZero has developed a four point action plan for de-risking and accelerating a liquid hydrogen aircraft programme and securing maximum UK content. It consists of four pillars and will require strong coordination across energy, industrial and fiscal policy:

1	*Accelerating the development of hydrogen aircraft technology bricks, their verification, integration and demonstration*
2	*Actively stimulating industry access to private financing, creating an environment to support the development of zero-carbon emissions aircraft systems and components in the UK's aerospace sector*
3	*Creating the enabling environment for zero-carbon emissions aviation through exploring new infrastructure requirements; shared enabling capability, and fiscal and broader policy measures*
4	*Enacting key enabling steps to deliver tangible progress quickly, forming international collaborations to develop zero-carbon aircraft and build a common approach to infrastructure and regulation to support their introduction*

FlyZero believes that the UK can drive the delivery of zero-carbon emissions flight. Success will require a sustained programme to catalyse and coordinate stakeholders from across the economy. But the prizes are great: abating emissions that, left unchecked, would represent 39% of UK emissions by 2050; maintaining the social and economic benefits of aviation; increasing the benefits associated with aviation, worth some £77.5 billion GVA in 2019; and securing greater UK content in the global aerospace sector – an industry worth around £100 billion in 2019.

01. STRATEGIC CONTEXT

It is essential to decarbonise aviation if the UK is to meet its net zero targets. It is also essential on economic and social grounds: £88 billion[5] of UK GVA and nearly 1.4 million UK jobs are supported by the aerospace and aviation industries; and 300 million passengers pass through UK airports every year, demonstrating the benefits many of us enjoy from the connectivity that air travel provides. A greater level of ambition and coordination is required if we are to meet our environmental responsibilities while at the same time safeguarding these economic and social benefits.

The ambition to decarbonise aviation

The UK was the first major economy to create a legally binding target to bring overall greenhouse gas emissions to net zero by 2050. The government has set out clear ambitions for the UK aviation sector to reach this goal through the Jet Zero Consultation and Net Zero Strategy [6], and it is consulting on a range of policies, including improving aircraft efficiency, accelerating the use of sustainable aviation fuels (SAF), supporting the development of zero-carbon emissions flight, and promoting emissions transparency for consumers. A vision for the industry is set to be announced in the Jet Zero Strategy in 2022.

COP-26 demonstrated that the UK is not alone in wanting to decarbonise aviation. Twenty three nations, responsible for almost 40% [7] of carbon emissions from air travel today, signed a new declaration recognising the current climate impact of aviation and pledging to reduce CO_2 emissions consistent with global targets. This agreement set out three urgent priorities:

- Promoting SAF production while avoiding competition with food production for land use and water supply;
- Promoting low and zero-carbon emission aircraft; and
- Ensuring the maximum effectiveness of the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)[8].

[5] Total aerospace, core aviation and aviation-based tourism in 2019
[8] The global carbon trading scheme for aviation, enabling airlines to buy offsets from other sectors

Over recent years, improved aircraft efficiency and SAF have been the main focus of decarbonisation efforts in aviation, whilst more recently, a number of programmes exploring zero-carbon emission aviation have been launched (see definitions below).

Overview of Zero-Carbon and Sustainable Aviation Fuels

Zero-carbon aviation fuels generate no carbon emissions at the aircraft tailpipe. Examples include liquid hydrogen, hydrogen fuel cells or green electricity. Governments around the world have launched several programmes to explore zero-carbon aviation, and the role and contributions of FlyZero are explored in more detail in Section 2.

Sustainable aviation fuels (SAF) are renewable or waste derived aviation fuels that meet certain sustainability criteria. These are generally hydrocarbons that can be blended with kerosene to reduce net emissions and these currently account for <1% of jet fuel demand [9]. They can be manufactured via various processes and inputs, including organic feedstocks and industrial products. The decarbonisation potential of SAF differs across these methods but none are currently able to reduce aviation emissions to zero. Recent research indicates that updates to the airport fuel system, aircraft fuel systems and engine will be required to accommodate SAF blended at above 50% [10]. 100% SAF is not currently certificated. As biomass feedstocks are limited, they will not be able to satisfy global demand for SAF (maximum ~40% of 2050 requirement). The widely perceived view (Clean Skies / ATAG) is that scale up of SAF demand will be focused on producing a near net-zero power-to-liquid (PtL) SAF where zero-carbon electricity is used to produce hydrogen through water electrolysis; hydrogen then reacts with CO_2 captured from the air or waste industrial exhaust streams to produce a synthetic fuel.

Source: FlyZero analysis of UK Net Zero Strategy and Jet Zero Consultation data

Preserving economic advantages

As outlined in the Jet Zero consultation, the government has made clear that these decarbonisation approaches must preserve, if not improve, the economic benefits that stem from the UK's aerospace and aviation sectors [11]. These sectors are integral strategic assets for the UK, supporting global connectivity and high value employment whilst boosting productivity and exports (see Figure 1).

The UK is a major player in global aerospace, with the sector currently employing 116,000 people and generating £11 billion of gross value added (GVA) for the UK [12]. These capabilities are widely distributed across the UK, generating significant spill over benefits to other parts of the economy and supporting the government's aspirations for levelling up. The UK has a particular strength in complex, high value systems such as wings, engines, fuel systems, landing gear and avionics systems. The UK hosts major companies in the sector including Rolls-Royce, Airbus, GKN, and Spirit AeroSystems, as well as more than 3,000 companies in the supply chain [13].

The UK **aviation sector** has the third largest passenger carrying capacity globally [14], playing a vital role in global connectivity and supporting a services industry as well as tourism, maintaining over 1 million jobs in the UK [15].

Aviation (2019 Estimates)

587,000 JOBS SUPPORTED

£48 BILLION GVA BENEFITS

Aviation Enabled Tourism (2019 Estimates)

561,000 JOBS SUPPORTED

£29 BILLION GVA BENEFITS

Source: The Sensitivity of Aviation's Economic Impact to Decarbonisation Restrictions, Oxford Economics (2022)

Aerospace (2019 Estimates)

116,000 JOBS SUPPORTED

£11 BILLION GVA BENEFITS

Source: FlyZero Macroeconomic Model

Figure 1 – UK economic impact of aviation, aviation enabled tourism and aerospace

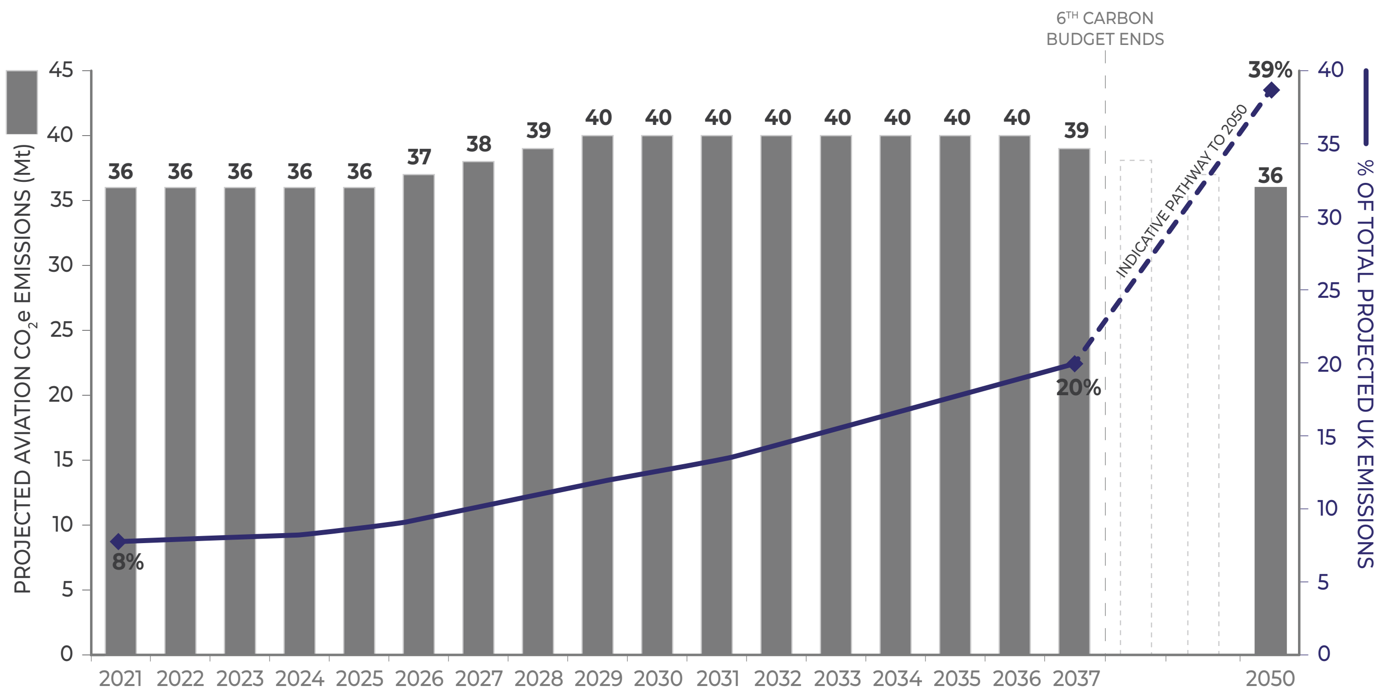
What happens if current trends in aviation continue

The Jet Zero consultation set out four illustrative scenarios for carbon emissions from the UK aviation sector by 2050, based on different technological pathways.

Jet Zero Consultation Scenarios

1. Continuation of current trends: 60% increase in passenger numbers by 2050 and 5% uptake of SAF
2. High ambition: 60% increase in passenger numbers by 2050 and 30% uptake of SAF
3. High ambition with a breakthrough on SAF: 58% increase in passenger numbers by 2050, 75% uptake of SAF and 21% of air traffic movements for aircraft <150 seats are zero emission
4. High ambition with a breakthrough on zero emission aircraft: 58% increase in passenger numbers by 2050; 30% uptake of SAF and 53% of air traffic movements for aircraft <150 seats are zero emission

If aviation follows the Jet Zero **'Continuation of Current Trends' scenario**, there will be no carbon reduction from aviation over the next 30 years (see Figure 2). Decarbonisation efforts will be offset by continuing growth in air travel, despite the rising global carbon price assumed in that scenario. In 2050, aviation would be responsible for 39% of UK carbon emissions, which would be in stark contrast to decarbonisation expected in other parts of the economy.



Source: FlyZero analysis of UK Net Zero Strategy and Jet Zero Consultation data

Figure 2 – UK aviation emission forecasts under 'Continuation of Current Trends' scenario, 2021-2050[16]

[16] Source: FlyZero analysis of HM Government data. Note: This analysis assumes that aviation follows the 'Continuation of Current Trends' pathway set out in the Jet Zero consultation (and is not able to offset this through greenhouse gas removals) whilst other industries follow the delivery pathway set out in the UK Government Net Zero strategy. Shipping sector data is isolated from IAS by assuming the Net Zero strategy aviation delivery pathway follows Jet Zero 'High Ambition' pathway. 2050 non-aviation emissions is taken as the average of the 'High Electrification', 'High Resource' and 'High Innovation' scenarios.

This scenario is likely to be unacceptable to policymakers for a number of reasons: the UK would miss its net zero targets; flights would become more expensive as carbon costs increase; and the UK economy would be damaged as environmentally conscious businesses and consumers choose to avoid air travel (see accompanying document "The Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation" for a fuller analysis).

A more ambitious approach is therefore required. However, even the **'High Ambition' scenario** would result in a minimum of 21 million tonnes of CO_2 being emitted in 2050. Achieving net zero in aviation would therefore rely on complex and uncertain abatement approaches from outside the sector, such as carbon offsets and greenhouse gas removals.

FlyZero's analysis indicates another way as the optimum route for fast decarbonisation and maximum economic benefit. This involves the rapid roll-out of SAF to start to decarbonise the existing fleet in the 2020s and early 2030s, and in parallel developing ambitious liquid hydrogen aircraft that will enable zero-carbon flight. This approach far exceeds even the **'High Ambition with a Breakthrough on Zero Emission Aircraft'** scenario set out in the Jet Zero consultation.

02. THE ROLE OF FLYZERO AND OUR KEY FINDINGS

FlyZero has concluded that liquid hydrogen is the only fuel able to deliver aviation decarbonisation. Liquid hydrogen aircraft are not only technically viable, but also commercially attractive, with superior operating economics compared to both kerosene and SAF powered aircraft. FlyZero has identified 13 'technology bricks' required to develop liquid hydrogen powered commercial aircraft. The UK already has leading capabilities in many of these areas, providing a strong platform for an accelerated and coordinated technology development programme, however there are gaps associated with cryogenic hydrogen that need to be urgently addressed.

The FlyZero project

FlyZero was established by the Aerospace Technology Institute (ATI) and the Department for Business, Energy and Industrial Strategy (BEIS) to determine the technical, commercial and economic potential of large commercial zero-carbon emission aircraft. The project outputs were to inform the direction of UK industry and government investment and set out the opportunities for the UK to take a global lead on zero-carbon emission aircraft technology.

To address this challenge, the programme assembled more than 100 specialists in aerospace, aviation and engineering from across leading industry organisations. This has been supported by a broad range of collaborations with universities and research centres, airports and airlines (see **Figure 3**). The programme has validated its findings through a dedicated advisory board, several advisory groups, and through extensive discussions and workshops with experts.

FlyZero is a detailed and holistic study of the design challenges, manufacturing demands, operational requirements and market opportunities of potential zero-carbon emition aircraft concepts.

Source: FlyZero

Figure 3 – FlyZero's collaboration with industry organisations and academia

Zero-carbon aviation concepts

FlyZero has developed three aircraft concepts to demonstrate the technical and commercial feasibility of liquid hydrogen powered aircraft. These concepts have been positioned to target maximum CO_2 abatement in their respective market segments. (See **Figure 4**).

FlyZero Regional
75 pax (1 class)
800nmi range

FlyZero Narrowbody
180 pax (1 class)
2400nmi range (ESAD)

FlyZero Midsize
279 pax (1 class)
5750nmi range (ESAD)

ESAD: Equivalent Still Air Distance

Figure 4 – FlyZero Concepts targeting up to 5,250 nmi Operational Range

Through a process of technology assessment, concept aircraft design and commercial assessment, FlyZero has reached four important conclusions:

1. Liquid hydrogen is the only aircraft fuel able to remove meaningful levels of carbon emissions from commercial air travel
2. Liquid hydrogen powered aircraft are not only technically viable, but also forecast to have superior operating economics compared to both jet fuel and SAF powered aircraft
3. A family of three hydrogen powered aircraft, with design ranges up to 5,750 nmi[17], has the potential to address up to 88% of all carbon emissions from aviation[18]
4. Timing is critical to prevent a next generation conventional narrowbody being launched, tying the sector to a slow transition to net-zero

Figure 5 below shows the relative sizes of the market and growth rates in each of the market sectors that the FlyZero archetypes could operate in.

Market Sector	*Sector Seat Range*	*Sector Share of CO_2 Emissions (2019)*	*Forecast Sector Growth Rate (2030-2050)*	*Forecast Sector Value (2030-2050)*	*Sector Size by Aircraft Numbers*	*Comment*
Regional	*20 - 120*	*7%*	*3%*	*$100bn - $140bn*	*11%*	*Smallest value sector, retrofit is an opportunity for turbo prop aircraft*
Narrowbody	*120 - 220*	*49%*	*67%*	*$1800bn - $2000bn*	*65%*	*Largest value and highest growth sector*
Midsize	*200 - 300*	*19%*	*71%*	*$700bn - $800bn*	*10%*	*High value and high growth, potential to take share in adjacent market sectors*
Widebody	*300+*	*25%*	*54%*	*$800bn - $900bn*	*7%*	*Opportunity for midsize to replace a portion of widebody flights*

Figure 5 – Assessment of the potential size and growth of key market sectors (Source: FlyZero Market Strategy report)

[17] 5,250 nm operational range is equal to 5,750 nm ESAD (Equivalent Still Air Distance).
[18] FlyZero analysis indicates that these aircraft could directly address 88% of global tailpipe carbon emissions, and potentially 100% if they expand into the long-haul market - with one stop to deliver global connectivity.

Hydrogen ‘Technology Bricks’

Developing liquid hydrogen powered aircraft will require new technologies in the areas of fuel storage and distribution, propulsion, aircraft architectures and underpinning capabilities. FlyZero has identified 13 technology bricks (see **Figure 6**) and created roadmaps for each.

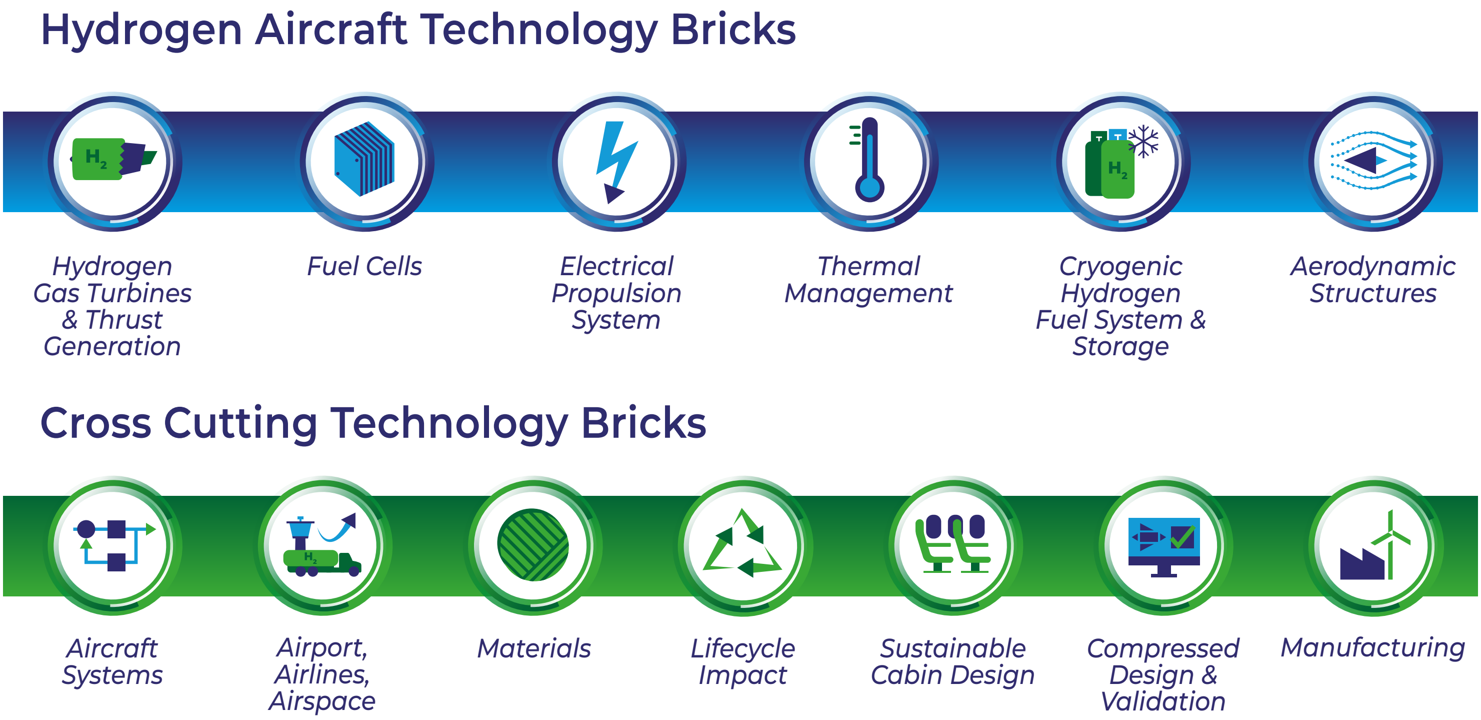


Figure 6 – FlyZero technology bricks

The UK has world leading capability in technologies for conventional kerosene burning aircraft that can be brought to bear on the development of hydrogen aircraft, including fuel systems and storage, gas turbines, thermal management and aerodynamic structures. UK aerospace has substantial experience in the certification challenges associated with these systems and so can provide the technical leadership required to compress the development cycle and accelerate the delivery of hydrogen aircraft to market. Fuel cells and electrical systems 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 other sectors, such as energy and automotive, to address aerospace applications.

The pathways to zero-carbon emissions aviation

FlyZero has identified several potential pathways for introducing hydrogen powered aircraft, based on the capacity of airframers to launch new programmes. Two are assessed here:

- **Pathway 1: FlyZero Midsize First, Accelerated**

In this scenario, SAF from bio-derived and industrial feedstocks is rolled out rapidly in the 2020s and 2030s, until capacity constraints require PtL SAF to be deployed as well. Introducing the midsize aircraft in the mid-2030s allows liquid hydrogen to play a greater role in the fuel mix and avoids a significant requirement for PtL SAF. The midsize is closely followed by a narrowbody, allowing high levels of CO_2 to be abated early.

- **Pathway 2: FlyZero Regional First, Unaccelerated (SAF dependent to 2050)**

Zero-carbon emission aviation happens at the rate implied by current industry statements and ambitions. This constitutes a slow rollout, beginning with regional aircraft and no meaningful market penetration by zero-carbon emission aircraft before 2050. As in Pathway 1, there is a rapid rollout of SAF in the 2020s and 2030s, but in this scenario PtL SAF production has to expand significantly to remove kerosene from the fuel mix.

Additional pathways considered fall between the two described above, and are therefore not analysed further in this strategic case.

For Pathways 1 and 2, FlyZero has projected market penetration rates and the fuel composition mix. These are outlined in **Figure 7** on the following page, and show that a 'Midsize First, Accelerated' scenario would see zero-carbon emissions aircraft representing nearly all of the fleet mix by 2070 and contributing to over 90% of passenger flight capacity.

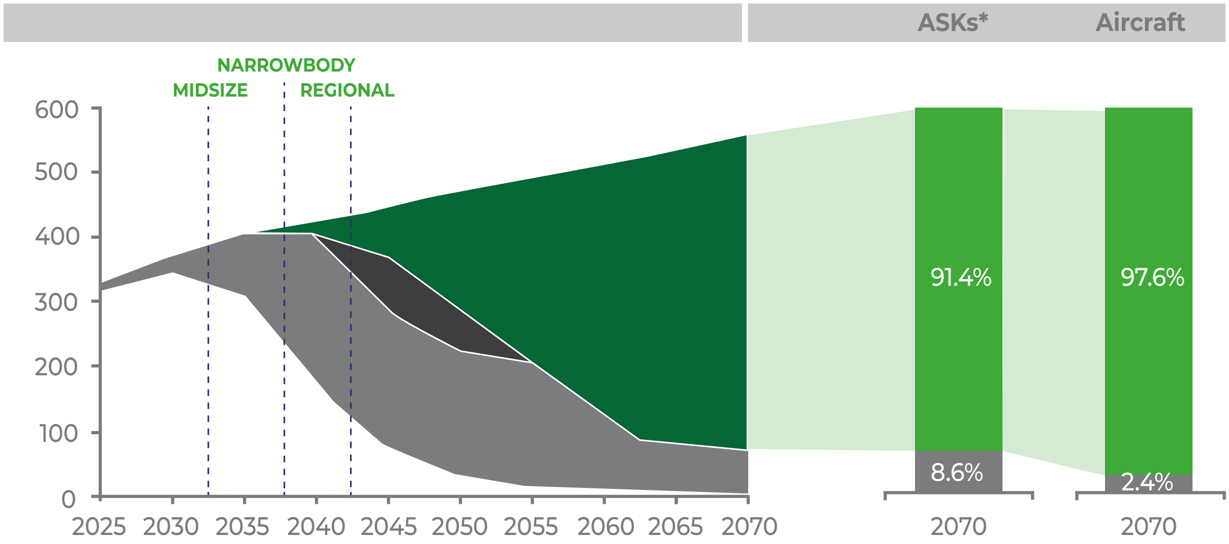
Energy in Fuel Mix, equivalent to MT of kerosene 2019 - 2070

Hydrogen PtL-SAF Non-PtL-SAF Kerosene

2070 Market Composition

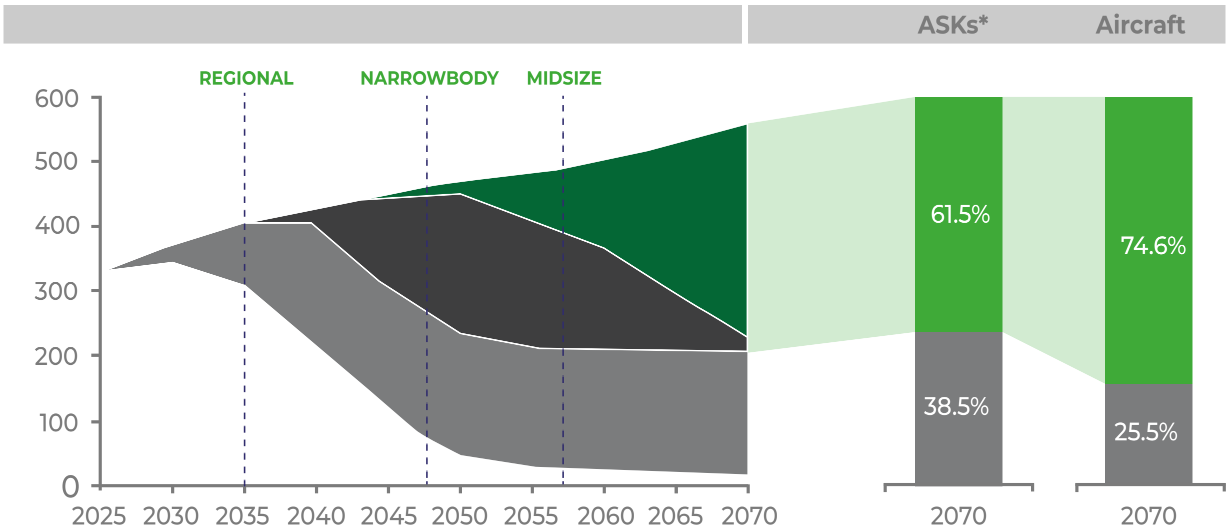
Zero-emissions Conventional

Pathway 1: FlyZero Midsize First, Accelerated



*Avaliable seat kilometers (ASKs) captures total flight capacity i.e. total number of seats on aircraft multiplied by the kilometres that those seats were flown

Pathway 2: FlyZero Regional First, Unaccelerated (SAF-dependent beyond 2070)



Minimal hydrogen aircraft market penetration in 2050, high dependancy on PtL SAF

Source: FlyZero Market Modelling

Figure 7 – Fuel and market outputs from modelled FlyZero decarbonisation pathways[19]

FlyZero has also analysed the environmental and economic outcomes for the UK from these pathways. These findings are set out in **Section 3**.

[19] *Each scenario assumes that non-PtL SAF production ramps up to reach capacity constraints, replacing kerosene in the fuel mix. Hydrogen replaces power-to-liquid SAF as they are likely to be competing for hydrogen feedstocks.*

03. THE OPTIMAL ROLE FOR HYDROGEN IN DECARBONISING GLOBAL AVIATION

Economically, liquid hydrogen is likely to be the lowest-cost alternative fuel by the mid 2030s and could be cheaper than untaxed kerosene by 2050. Collectively, this would deliver $167 billion of global savings annually by 2050 compared to a SAF dominant pathway and $295 billion annually compared to a kerosene only pathway. These savings demonstrate the commercial feasibility of the investment into liquid hydrogen powered aircraft and their supporting fuel infrastructure.

The delivery of the maximum pace of decarbonisation whilst minimizing the cost to the economy is determined by a range of factors:

- The carbon emission reductions that could be achieved
- The cost of producing each fuel, including any additional costs due to higher global carbon pricing
- The availability of the fuel and the requirement for new infrastructure to transport it to airports and deliver it to aircraft

This chapter explores each of these factors in turn, using them to compare the outcomes from the two main decarbonisation pathways set out in **Section 2**. FlyZero has concluded that the most advantageous route for the UK (and globally) to achieve the fastest pace of decarbonisation in aviation at minimum cost is expected to be the 'Midsize First, Accelerated' scenario, explained in **Figure 8**, below. These findings have been drawn from a range of market, environmental and economic analysis that FlyZero has undertaken, each set out in more detail in FlyZero accompanying documents [20] [21] [22]. It should be noted that FlyZero was commissioned to assess zero carbon emissions aviation and not to undertake primary research on SAF, so our analysis has drawn upon major industry studies already published, such as those produced by ATAG Waypoint 2050 [23] and Clean Skies for Tomorrow [24].

Reduction in Carbon Emissions	
1	*Green hydrogen offers a greater CO_2 abatement potential than any form of SAF (minimum ~8%)*
2	*A pathway with greater hydrogen penetration abates more CO_2 sooner than alternatives*
3	*Of the pathways modelled by FlyZero, the greatest CO_2 abatement is delivered by 'Pathway 1: Midsize First, Accelerated'*

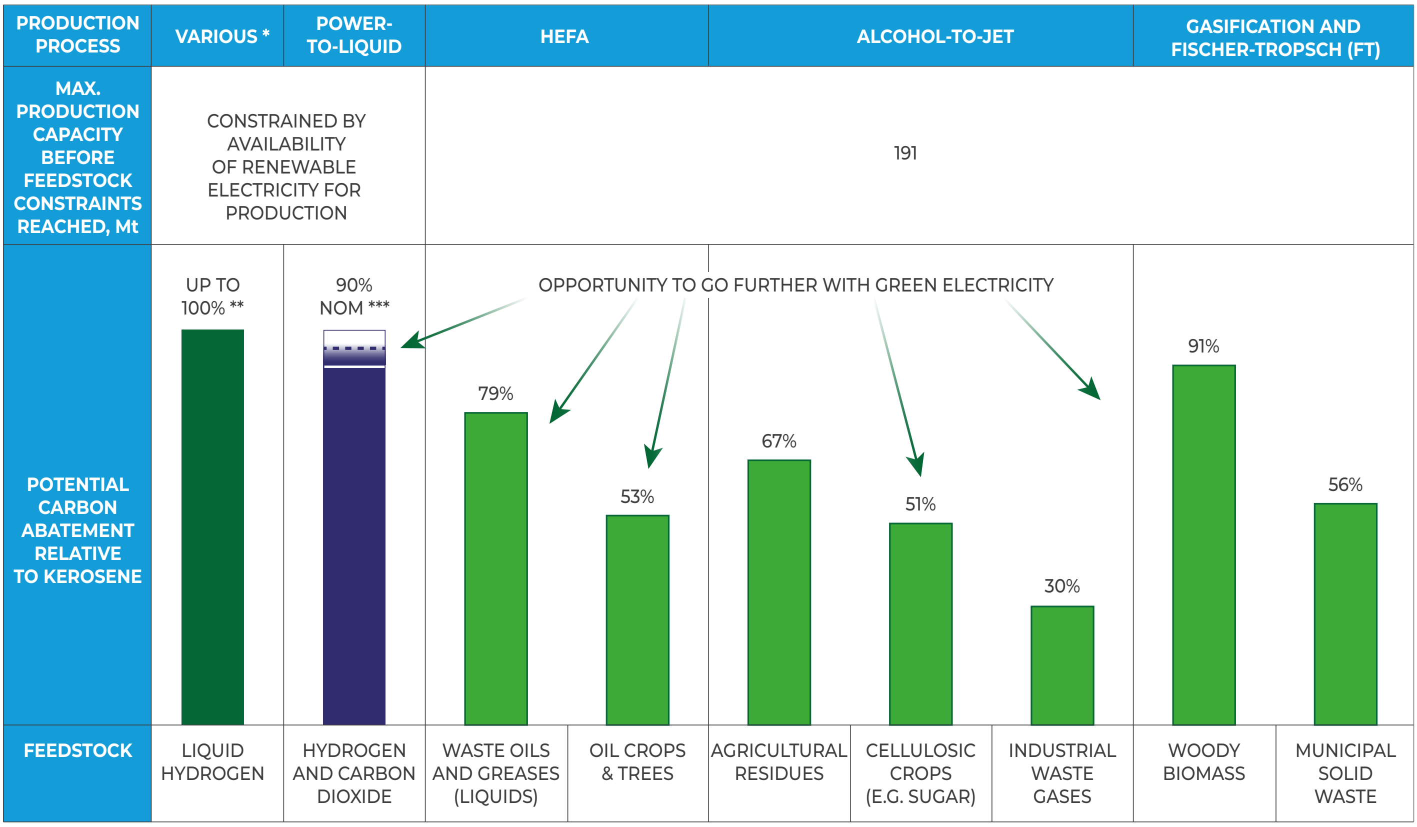
Costs of Fuel Production	
1	*Hydrogen is projected to be the lowest cost fuel capable of decarbonising aviation by the mid-2030s, and could be cheaper than kerosene by 2050*
2	*A pathway with greater hydrogen penetration has the potential to significantly reduce overall global fuel costs*
3	*Of the pathways modelled by FlyZero, the greatest cost reduction is delivered by 'Pathway 1: Midsize First, Accelerated'*

Rollout of Hydrogen	
1	*Rolling out a liquid hydrogen aircraft will require three key constraints to be overcome - aircraft availability, infrastructure and fuel availability*
2	*Much of the infrastructure required to deliver pathways with a greater role for liquid hydrogen powered aircraft is also likely to be needed in pathways that include significant power-to-liquid (PtL) SAF volume, although additional investment for airport infrastructure will be required*
3	*FlyZero's 'Pathway 1: Midsize First, Accelerated' achieves the maximum feasible penetration of liquid hydrogen aircraft in the market segments that emit the most carbon per aircraft today*

Figure 8 – Key findings from FlyZero analysis

The carbon emission reductions achievable

Zero-carbon liquid hydrogen (i.e. produced from green electricity) offers a 100%[25] reduction in lifetime CO_2 emissions relative to kerosene. As a result, the fuel offers the maximum possible potential to decarbonise aviation. SAF too can provide significant carbon reductions versus kerosene but production methods available today result in residual carbon emissions of up to 70% as they rely on carbon rich, organic or industrial feedstocks (see **Figure 9**, below). While the life-cycle emissions of SAF shown in **Figure 9** could be reduced by the use of renewables (as assumed for green hydrogen), SAF will still be required to be blended with conventional kerosene even by 2050. Today, the maximum blending ratios for SAF and jet fuel are 50% depending on the SAF and the base jet fuel. Aircraft manufacturers have committed to delivering 100% SAF capable aircraft from 2030 onwards, which means that by 2050 20% of the active fleet would still not be fully compatible with 100% SAF. SAF alone can therefore not deliver net zero aviation without abatements outside the sector, such as carbon offsets and greenhouse gas removal.



** Zero-carbon hydrogen is expected to be predominantly produced by water electrolysis with green electricity in future but can also be produced through other methods such as from natural gas through the process of steam methane reforming (SMR) with carbon capture.*

*** Through green electricity there is an opportunity to deliver 100% carbon abatement - the banding below the nominal value illustrates the exclusion of CO_2 associated with infrastructure.*

**** In the ATAG study, it is acknowledged that the values for PtL SAF would increase if produced with 100% renewable energy too, but "unlikely to achieve a complete reduction". The banding around the nominal value illustrates both the opportunity of green electricity and exclusion of CO_2 associated with infrastructure.*

Emissions associated to infrastructure ignored.

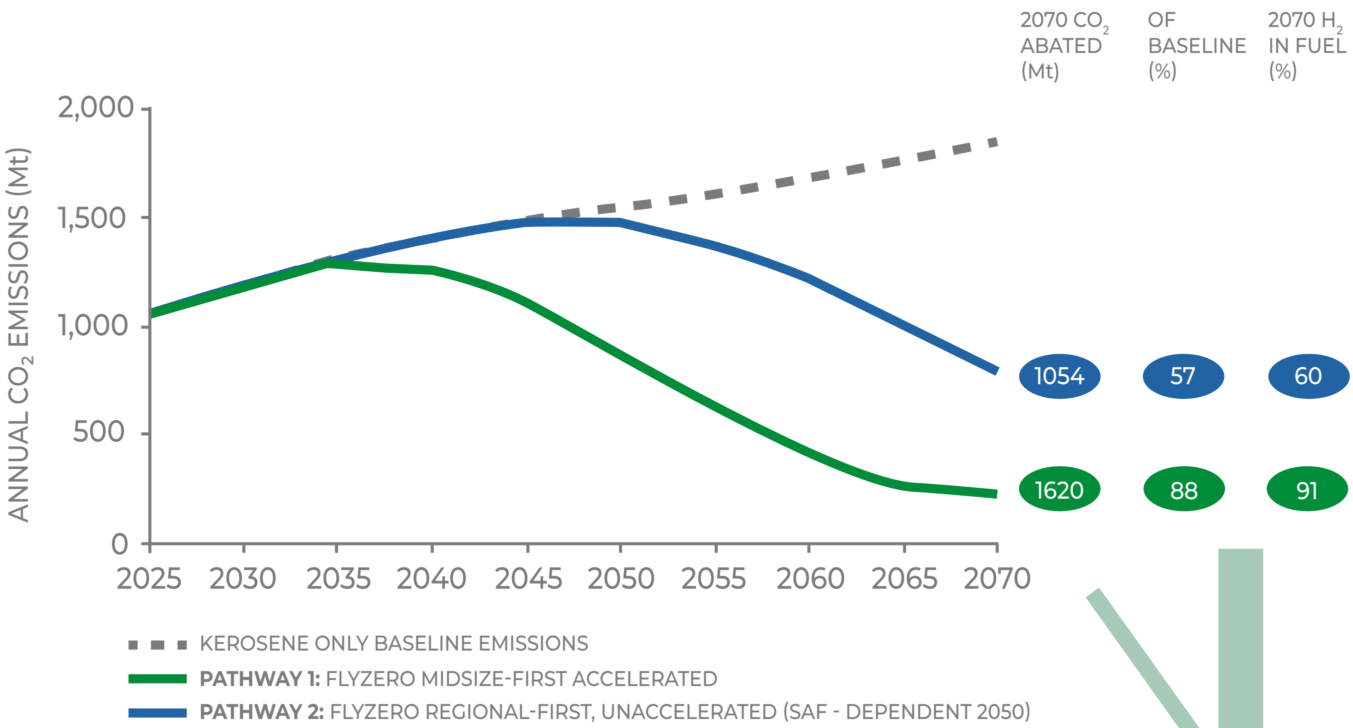
Figure 9 – Summary of key sustainable aviation fuels, as identified by ICF for Waypoint 2050 (Source: Fueling Net Zero: An ICF Report for ATAG Waypoint 2050)

[25] *Excluding CO_2 emissions related to infrastructure*

SAF industry sources predict that feedstocks will be limited and that significant amounts of power-to-liquid (PtL) SAF will therefore be needed to reach high overall abatement levels. PtL SAF is produced from gaseous hydrogen that is generated by green electricity and synthesised with CO_2. There is the potential for PtL SAF to overcome production constraints of SAF derived from organic and waste feedstocks, where production is expected to plateau to avoid competition for water, land, food and other sectors' needs for the same feedstocks. Leading industry consortia, including ATAG and Clean Skies for Tomorrow, all forecast this plateau, with ATAG estimating this limit to be 191 Mt, 41% of total 2050 fuel demand. Expansion of SAF beyond this level is expected to be feasible only through a roll out of PtL SAF that, critically, relies on hydrogen as a feedstock.

SAF has the potential to deliver significant short-term decarbonisation across all pathways analysed by FlyZero. Around 510 Mt of CO_2 could be abated by the maximum use of SAF from HEFA, Alcohol-to-Jet and Gasification & Fischer-Tropsch in 2050, equivalent to 34% of kerosene-only emissions. Beyond this, large amounts of hydrogen are needed, either as feedstock for PtL SAF or to be liquified and used directly in hydrogen powered aircraft.

FlyZero's 'Midsize First, Accelerated' Pathway 1 results in a greater level of CO_2 abatement than the 'Regional First, Unaccelerated' Pathway 2, and at a quicker pace (see **Figure 10**, below). It is expected to deliver annual CO_2 abatement of 1,620 Mt per year by 2070, equivalent to an 88% reduction relative to a kerosene only baseline. (668Mt per annum in 2050).



Source: FlyZero Market Modelling. Note: This assumes fuel mix as set out in ***Section 2****, kerosene and all forms of SAF emit 3.15 t of* CO_2 *per t of fuel into the atmosphere*

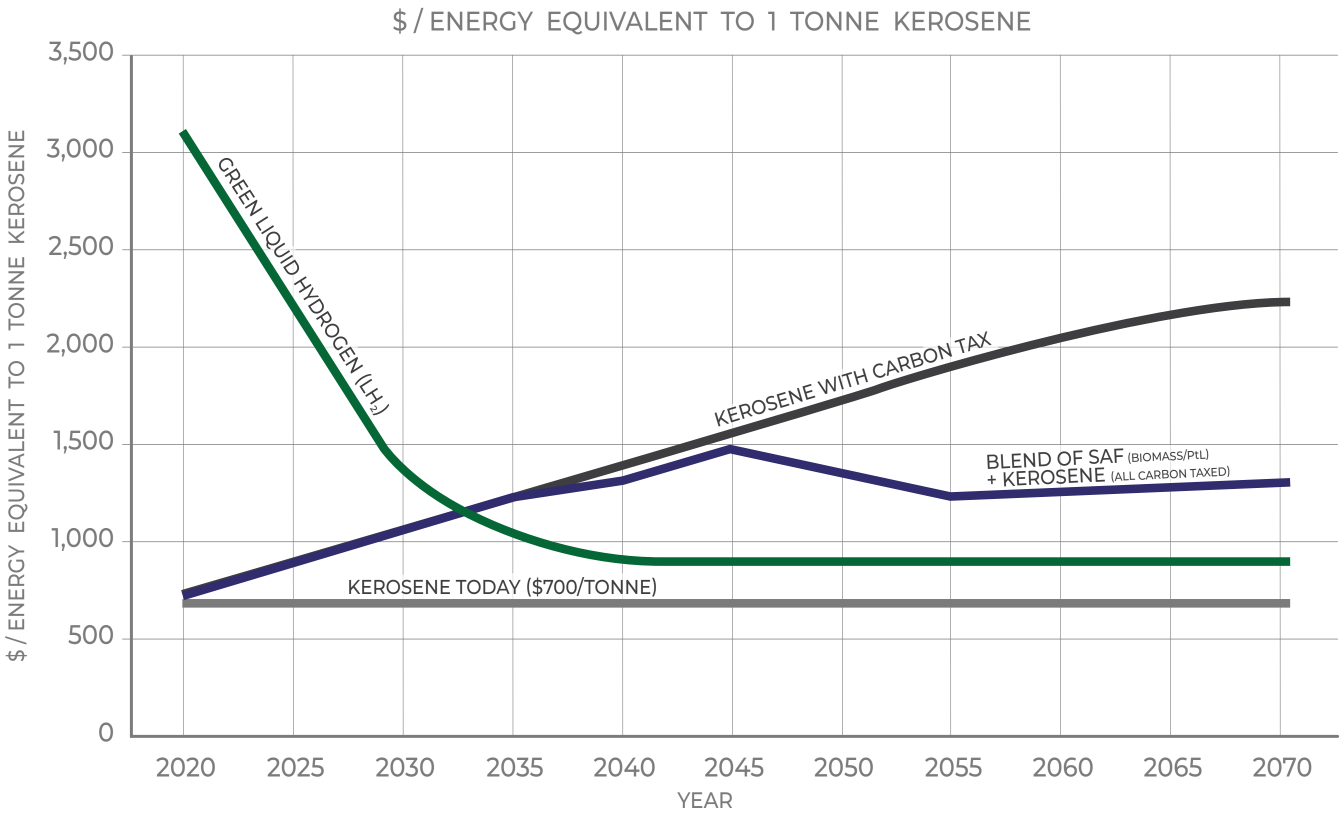
Figure 10 – Atmospheric CO_2 *emissions from FlyZero pathways*

The costs of fuel production

As emerging fuel technologies, SAF and liquid hydrogen are significantly more expensive than kerosene today. However, production costs are expected to fall rapidly as supply increases and production efficiencies are found as the technology advances. **Figure 11** presents FlyZero forecasts for these fuels compared to kerosene, with and without the impact of carbon pricing.

Cost scale is $ per unit energy equivalent to the stored energy in 1 Tonne of Kerosene (note liquid hydrogen is ~x3 lighter than kerosene so cannot be compared on a $/Kg basis).

SAF blend costs are based on the blended cost of kerosene and different types of SAF (biomass / power-to-liquid), with carbon prices (BEIS forecasts) applied to the residual carbon in the blend. The share of SAF versus kerosene in the blend increases over time (based on ATAG2 aggressive SAF scenario).



Source: FlyZero "Study of Studies" aggregating results from 1. Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation 21st April 2021, World Economic Forum in collaboration with McKinsey & Company.; 2. ATAG/ICF Waypoint 2050 - Fueling Net Zero September 2021. 3. ICCT – The cost of supporting alternative jet fuels in the European Union March 2019. 4. Meggitt plc – Cost of Green Fuel for Aviation – (commissioned by FlyZero but taking an energy usage approach to cost comparisons so lacking capital cost contributions). 5. BEIS Hydrogen Production Costs August 2021. 6. ARUP commissioned analysis for FlyZero. 7. Clean Skies for Tomorrow: Guidelines for a Sustainable Aviation Fuel Blending Mandate in Europe. 8. Proposal for a Regulation of the the European Parliament and of the Council on ensuring a level playing field for sustainable air transport - 14th July 2021 (EU SAF mandate proposal). Energy density of hydrogen 120 MJ/kg, SAF and kerosene energy density of 43.15 MJ/kg. Costs beyond 2050 have been estimated based on FlyZero assumptions.

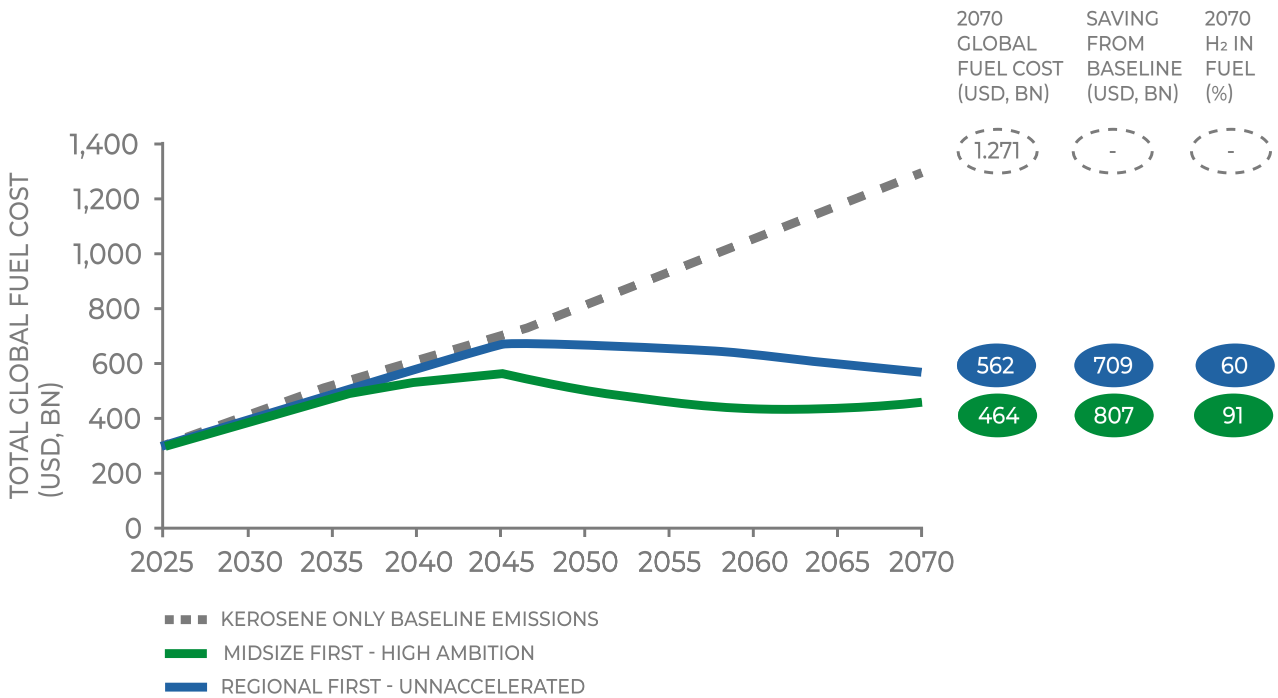
Figure 11 – Production cost forecasts for aviation fuel, USD per Te of kerosene energy equivalent, with and without carbon pricing

Liquid hydrogen is projected to be the cheapest of the fuels capable of decarbonising aviation by the mid-2030s and could be cheaper than kerosene by 2050. A number of industry research papers also conclude that hydrogen could be the cheapest decarbonising aviation fuel in future[26], driven predominantly by substantial production cost reductions for gaseous hydrogen, as the renewable energy on which it depends becomes cheaper and production volumes increase rapidly.

PtL SAF is expected to see similar, rapid reductions in costs as it also uses gaseous hydrogen as feedstock, although it is expected to be consistently more expensive than liquid hydrogen. In contrast, non-PtL SAF which are dependent on less scalable, high carbon feedstocks are expected to fall in cost more slowly.

If aviation fuel is subjected to higher levels of carbon pricing globally, in line with the carbon cost assumptions in the Jet Zero consultation, hydrogen's cost advantages would be accelerated.

The global impact of the lower fuel costs delivered by hydrogen could be considerable, with a 'Midsize First, Accelerated' pathway delivering savings for the global aviation industry and passengers that could be worth $167 billion annually by 2050, compared with a SAF dominant decarbonisation pathway, and $295 billion, compared with a kerosene only pathway (see **Figure 12**).



Source: FlyZero Market Modelling and FlyZero analysis of Fueling Net Zero: An ICF Report for ATAG Waypoint 2050 fuel costs. Note: this assumes fuel mix from market modelling, fuel costs from ATAG Waypoint 2050, Carbon pricing included (from BEIS), Carbon abatement from Waypoint 2050.

Figure 12 – Fuel costs forecasts by fuel composition pathway

[26] *Sources include: "Hydrogen-powered aviation: A fact-based study of hydrogen technology, economics, and climate impact by 2050", Clean Sky 2 Joint Undertaking (May 2020), "Clean Skies for Tomorrow: Sustainable Aviation Fuels as a Pathway to Net-Zero Aviation", "Fueling Net Zero: An ICF Report for ATAG Waypoint 2050". The UK also recently signed up to the Clean Hydrogen Mission that is targeting $2/kg clean hydrogen by 2030: http://www.mission-innovation.net/missions/hydrogen*

The rollout of a liquid hydrogen aircraft

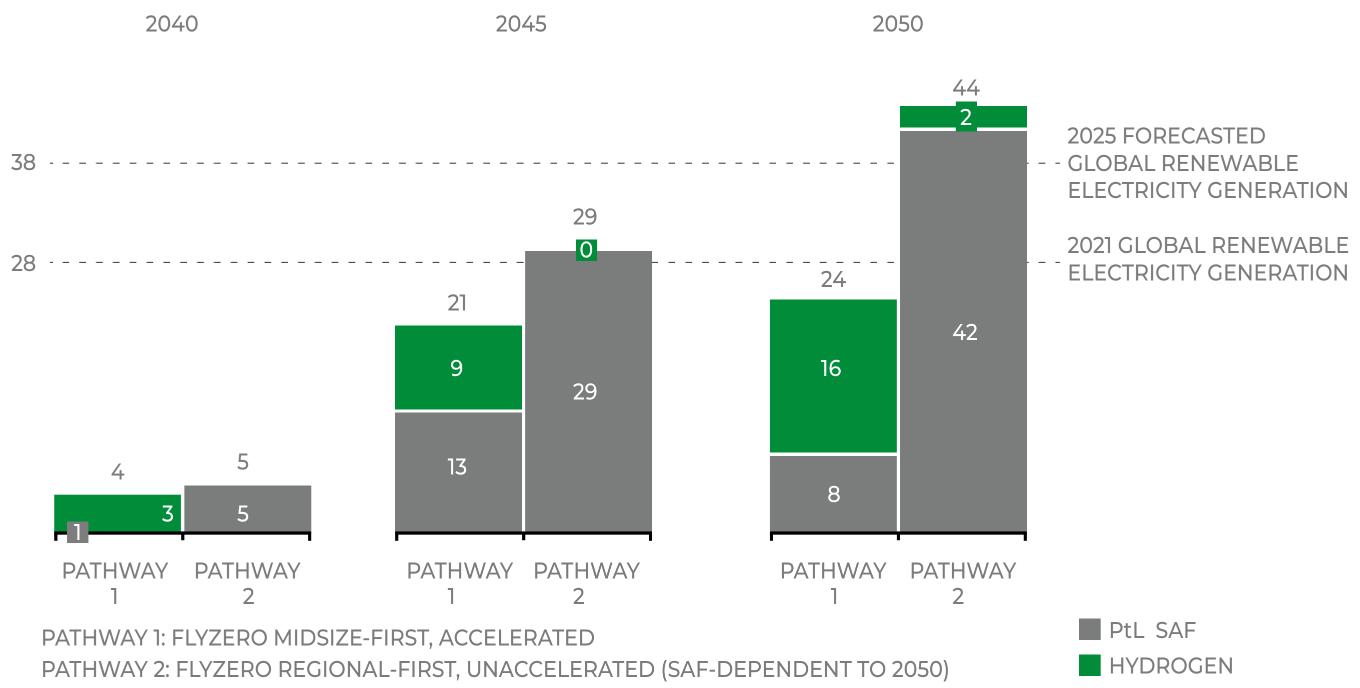
The ambition of a faster roll-out of liquid hydrogen aircraft, entering into service sooner, to achieve the maximum pace of decarbonisation whilst minimising fuel costs, is not without risks. There are a number of potential constraints, the availability of fuel, aircraft and the existence of supporting infrastructure. This section analyses these constraints and finds evidence that these can be overcome.

Availability of fuel

Sustained decarbonisation of aviation will require significant volumes of green hydrogen, regardless of the pathway chosen. Once feedstock constraints cap the production of non-PtL SAF, green hydrogen will either be required to produce liquid hydrogen or PtL SAF to continue progress on decarbonisation. Efficient use of this hydrogen will be important as its zero-carbon production will face competition with other uses of renewable electricity[27].

Using hydrogen as the end fuel rather than using it to produce SAF is a more efficient use of both hydrogen and renewable energy. **Figure 13**, below, shows the expected demand for electricity across the pathways analysed by FlyZero.

This indicates that a 'Midsize First, Accelerated' pathway would require around 45% less electricity by 2050 than a High SAF pathway, reducing the strain placed on renewable electricity production.



Source: FlyZero analysis note: This assumes: water electrolysis for H_2, efficiency factors from hydrogen-powered aviation: A fact based study of hydrogen technology, economics, and climate impact by 2050, Clean Sky 2 Joint Undertaking (May 2020). PtL from direct air capture). Energy density of H_2 120 MJ/kg, energy density of PtL SAF 43.15 MJ/kg. Fuel mixes set out in ***Section 2****.*

Figure 13 – Global electricity demand for the production of liquid hydrogen and PtL SAF required to fuel FlyZero pathways, exajoules

[27] *For example, FlyZero analysis has found that aviation could represent a 10-17% share of UK hydrogen demand by 2050, dependent on whether hydrogen is used for domestic heating*

The UK could supply the hydrogen that it would need for aviation through domestic production or energy imports from abroad. The production potential of green hydrogen is analysed in more detail in FlyZero's report "Airports, Airlines and Airspace – Hydrogen Infrastructure and Operations", where we set out the important role played by the government's hydrogen strategy [28], alongside other future hydrogen use cases (road transport, industrial energy etc.).

Availability of supporting infrastructure

All decarbonisation pathways will require new infrastructure to be built. Much of the infrastructure required to deliver pathways with greater hydrogen is also likely to be needed in a high PtL SAF scenario. This includes infrastructure relating to fuel production, transportation and storage of gaseous hydrogen, given its role as an input in both production processes. As explored in the previouse section, a pathway with greater adoption of liquid hydrogen is likely to place less strain on this infrastructure overall.

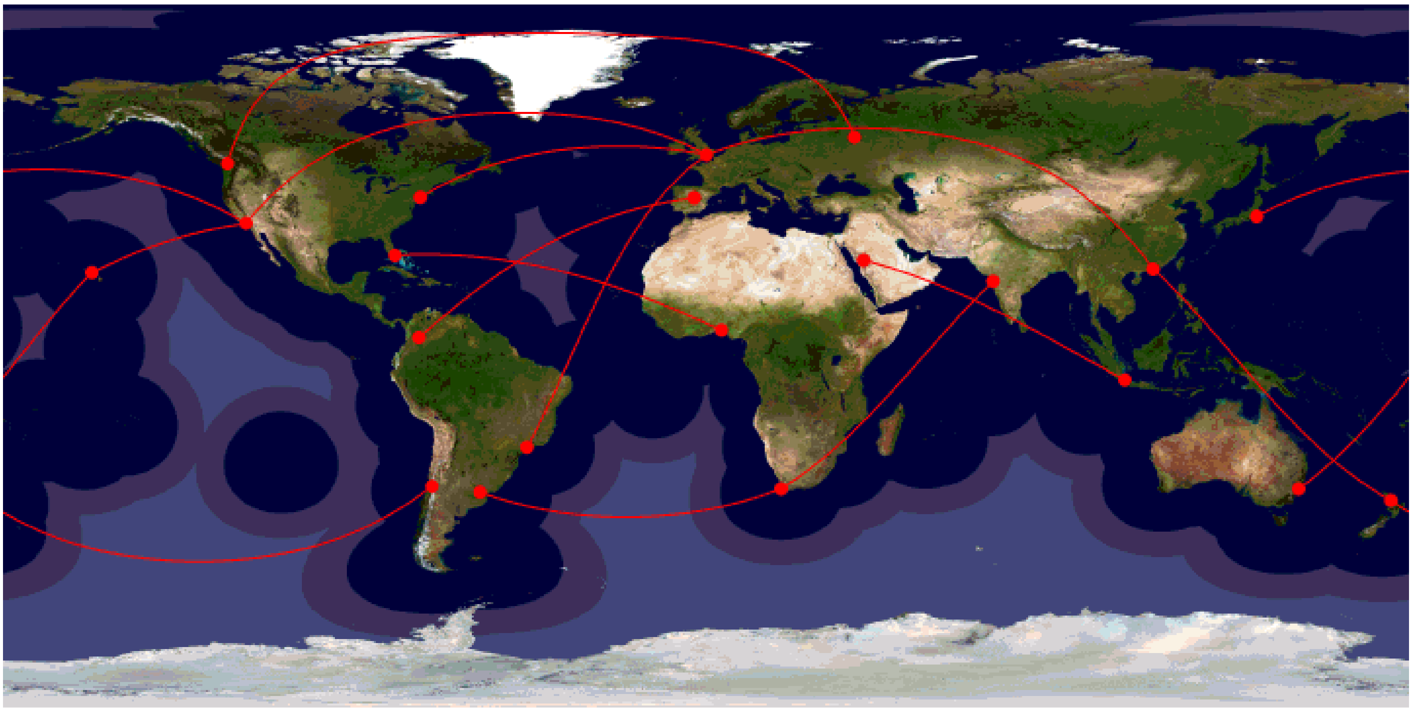
There is the potential for these additional infrastructure costs to be spread over other industries that will require this core hydrogen production and distribution infrastructure, such as building heating, power generation and heavy industry. FlyZero analysis has also shown that major UK airports are close to industrial clusters which are the main locations for hydrogen production today[29], increasing the likelihood that infrastructure can be shared across industries.

Beyond this, liquid hydrogen will require liquefaction, cryogenic distribution and refuelling infrastructure at airports. FlyZero has explored these potential costs across five major UK airports and for a large airport this could amount to $1.1 billion - $1.9 billion in new capital expenditure based on initial assessments[31]. Upper estimates of infrastructure costs would only account for 50% of the annual difference in total global fuel cost between the maximum and minimum hydrogen scenarios set out earlier in this section[31]. Potential models for airport infrastructure are explored in more detail in FlyZero's report: Airports, Airlines and Airspace – Hydrogen Infrastructure and Operations.

PtL SAF will also require additional infrastructure such as blending facilities, although the final output fuel can largely use existing transportation, storage and airport refuelling infrastructure. More work is needed to assess the costs to build and operate additional infrastructure across SAF and liquid hydrogen pathways.

Adoption of a midsize first strategy would focus initial airport investments on large international hubs, in advance of a diverse range of medium and smaller sized regional airports. Through this network of hubs and the 5,750 nmi design range of the midsize, zero carbon aircraft could enable global reach with a single stop, creating a "One Stop Zero Carbon Global Network".

[29] *Hydrogen Supply Infrastructure, Arup (2021)*
[30] *Airport Infrastructure for Hydrogen Aircraft, Jacobs (2021) - assumes supply of gaseous hydrogen by tanker and pipeline and a $1.36 to £1 exchange rate*
[31] *Assuming that 50 airports would each need $1.9 billion of infrastructure for a global zero-carbon aviation network of hydrogen hubs by 2050*



Shading shows ETOPS 120 min and 180 min exclusion zones; Maps generated by the Great Circle Mapper (www.gcmap.com) – copyright © Karl L. Swartz.

Figure 14 – FZM Example Routes (within 5,250 nmi operational range)

These international hubs could act as feeders for regional networks as zero carbon aircraft become established.

Availability of aircraft

Liquid hydrogen aviation will only achieve its potential if there are aircraft available for airlines to buy. With a limited feasible build rate in the aerospace sector, the focus should be on replacing aircraft classes that emit most CO_2 per aircraft today. As described in **Section 2**, the three hydrogen powered aircraft concepts developed by FlyZero have the potential to address up to 88% of all carbon emissions from aviation; the emissions abatement profile will be significantly slower with a 'Regional First' strategy.

FlyZero's market modelling reveals that the 'Midsize First, Accelerated' pathway to de-risk the technology introduction, closely followed by a narrowbody with scaled down technology, achieves the maximum possible penetration of liquid hydrogen aircraft in these market segments and therefore also delivers the greatest pace of decarbonisation. Launching a midsize aircraft first also allows the concentration of new infrastructure in fewer, larger international airport hubs, accelerating the rollout of a global network of zero-carbon emission flights.

Decision Timeframe, Coordination and Commitment

Airlines are expected to replace their fleets once more before 2050, beginning in the mid-2030s. Introducing a hydrogen fuelled aircraft will present a choice between buying a zero-carbon emissions aircraft with a fuel cost expected to decrease or a conventionally fuelled aircraft with fuel that is likely to remain relatively more expensive[32], particularly if carbon pricing is introduced.

Their decision will also depend on availability of hydrogen infrastructure to support their route network. The ability to coordinate fuel, supporting infrastructure and capable aircraft will be a challenge for actors in the aerospace, aviation, energy and policy making arenas, requiring a common vision and coordinated action plan to deliver the zero-carbon future.

FlyZero conclusions - the optimal role for hydrogen aviation

The analysis in this section further demonstrates that the '**Midsize First, Accelerated**' scenario is the optimal route to achieve zero carbon emission aviation, because it:

- Abates significantly more CO_2 by 2050 and in the following years, delivering 5GT total abatement by 2050 and increasing thereafter to deliver an annual CO_2 abatement of 1,620 Mt by 2070, equivalent to an 88% reduction relative to a kerosene-only baseline
- Results in the cheapest fuel becoming available to the global aviation industry, delivering savings of $167 billion annually by 2050, relative to the '**Regional First, Unaccelerated**' pathway that relies on SAF to 2050
- Requires new infrastructure, but much of this is also likely to be needed in a high PtL SAF scenario
- Achieves the maximum possible penetration of liquid hydrogen aircraft in the market segments that emit the most carbon per aircraft today

To deliver any pathway with a greater role for liquid hydrogen, new aircraft developments will need to be accelerated, demanding coordinated activity across the industry and governments. The scale of investment required is significant. The ambitious approach outlined by FlyZero would be extremely challenging for the airframers and their supply chains. But the prize of CO_2 abatement, affordability of flight and keeping the world connected is very valuable. Section 4 explores the economic opportunity this presents for the UK.

[32] *As previously outlined, non-PtL SAF are expected to make limited cost reductions once production processes are efficient as they rely on feedstocks which are unlikely to become cheaper. PtL SAF is likely to remain more expensive than hydrogen given its less efficient use of hydrogen and electrical inputs.*

04.
THE CASE FOR THE UK TO PLAY A LEADING ROLE IN HYDROGEN AVIATION

Decarbonising aviation is an opportunity for the UK to defend and grow its position in the global aerospace industry by leading on content for the first generation of hydrogen aircraft. FlyZero estimates that acting now to de-risk and accelerate a new aircraft development programme could increase UK content on commercial aircraft from 12% today to 19% in 2050, worth £39 billion annually in 2050 for manufacturing alone, creating or securing 154,000 highly productive, high wage UK jobs (an increase of over one third on today) in over 3,000 companies across the country.

In **Section 3**, FlyZero concluded that early and fast hydrogen adoption, together with acceleration of SAF, is the optimum approach for the UK to achieve maximum decarbonisation of aviation whilst minimising the economic and social downside of reduced / restricted aviation. In this section, we assess the outcome of this approach from the perspective of the UK aerospace sector and wider economy.

The development of a liquid hydrogen commercial aircraft would be a big opportunity for the UK aerospace industry and the economy at large. It could only be realised through UK industry and government working together to make a significant investment in the technology bricks described in **Section 2**, followed by participation in an international aircraft development programme, with both offering the potential to attract substantial new economic activity to the UK.

Importantly, to maximise CO_2 abatement, a midsize commercial aircraft must come to market by the early 2030's, closely followed by a narrowbody in the late 2030's. The UK government can help accelerate the timeline and position the UK sector to succeed by supporting industry in developing hydrogen technology bricks and capability (severely lacking in the UK); airframers are unlikely to risk launching an aircraft programme until the technology is sufficiently mature.

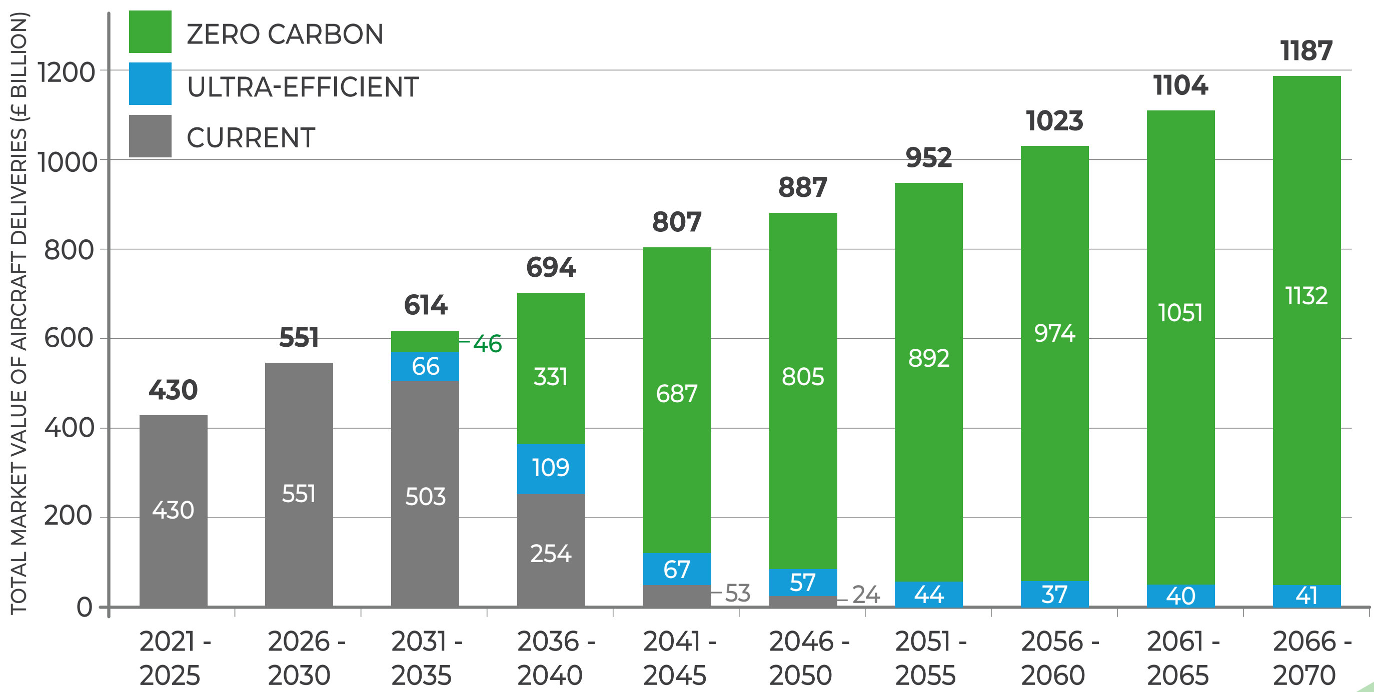
This section assesses the scale of the economic opportunity by analysing four key areas:

- The commercial benefits for airframers
- The spillovers from new R&D investment
- The employment and growth opportunities in the UK's aerospace industry
- The economic impacts on the aviation sector and the tourism industry it enables

We also consider how these benefits might be spread throughout the UK.

FlyZero conclusions - the optimal role for hydrogen aviation

FlyZero market modelling indicates that a liquid hydrogen aircraft could account for 50% of the global fleet and ~91% of aircraft sales by 2050 (figure 15, below). As explained in **section 3,** such an aircraft would offer the potential for lower fuel costs compared to kerosene, and help airlines drive greater demand.



Source: FlyZero Market Modelling. Note: this figure captures the total market value of the deliveries of aircraft made in each five year period assessed

Figure 15 – Total market value of aircraft deliveries following FlyZero's 'Midsize First, Accelerated' pathway

Airlines could potentially achieve higher sales and margins by flying on hydrogen, particularly if the public placed a premium on zero-emissions travel or was willing to travel more frequently[33]. Decarbonisation could also create competition between airlines, driving investment in their fleet and providing consumers with more choice. Ultimately, this would increase demand for aircraft.

[33] The Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation evidences the rising awareness of consumers and businesses of the environmental impact of air travel and how they are responding to this in their decisions to fly.

The benefits for jobs and growth of the UK's aerospace industry

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

If the UK invests ahead of other nations, or at least alongside given the ambitions outlined by the EU, it can lead the development and maturation of new technologies where it has current strength and secure a greater share of activity. This could see the UK securing:

- Up to a 19% stake in the global industry estimated to be worth £178bn per annum in 2050
- £36.5 billion GVA per annum in 2050
- 38,000 jobs, growing sectoral employment from 116,000 today to 154,000 in 2050

If the UK does not invest, it will lose some of its current share of aircraft programmes as the industry transitions. In this scenario where a hydrogen aircraft is launched but the UK has not secured a stake, the UK could see the industry decline with:

- The UK reduces its sector stake from 12% to 5%, the losses predominantly in the Aerospace manufacturing sector
- Reducing jobs to 74,000 (from 116,000) in an industry that is still forecast to more than double its output by 2050 (an average growth rate of 2.7% per annum 2021 to 2050)
- Crown jewel technologies being re-located overseas

To deliver these benefits, the UK would need to leverage its existing strengths and accelerate the development of its hydrogen capabilities and the technology bricks. This would attract more investment into the UK from airframers and their major suppliers and could allow a hydrogen aircraft to be brought to market sooner, enabling the environmental and fuel cost benefits set out in **Section 3** to be delivered.

The benefits from new R&D investment

R&D investment in the technology bricks for hydrogen aviation, and their integration, has the potential to generate new innovations which benefit the wider economy. The social return on aerospace R&D is four times higher than the private return - largely because of these spillovers benefiting adjacent sectors such as the automotive industry **[34]**.

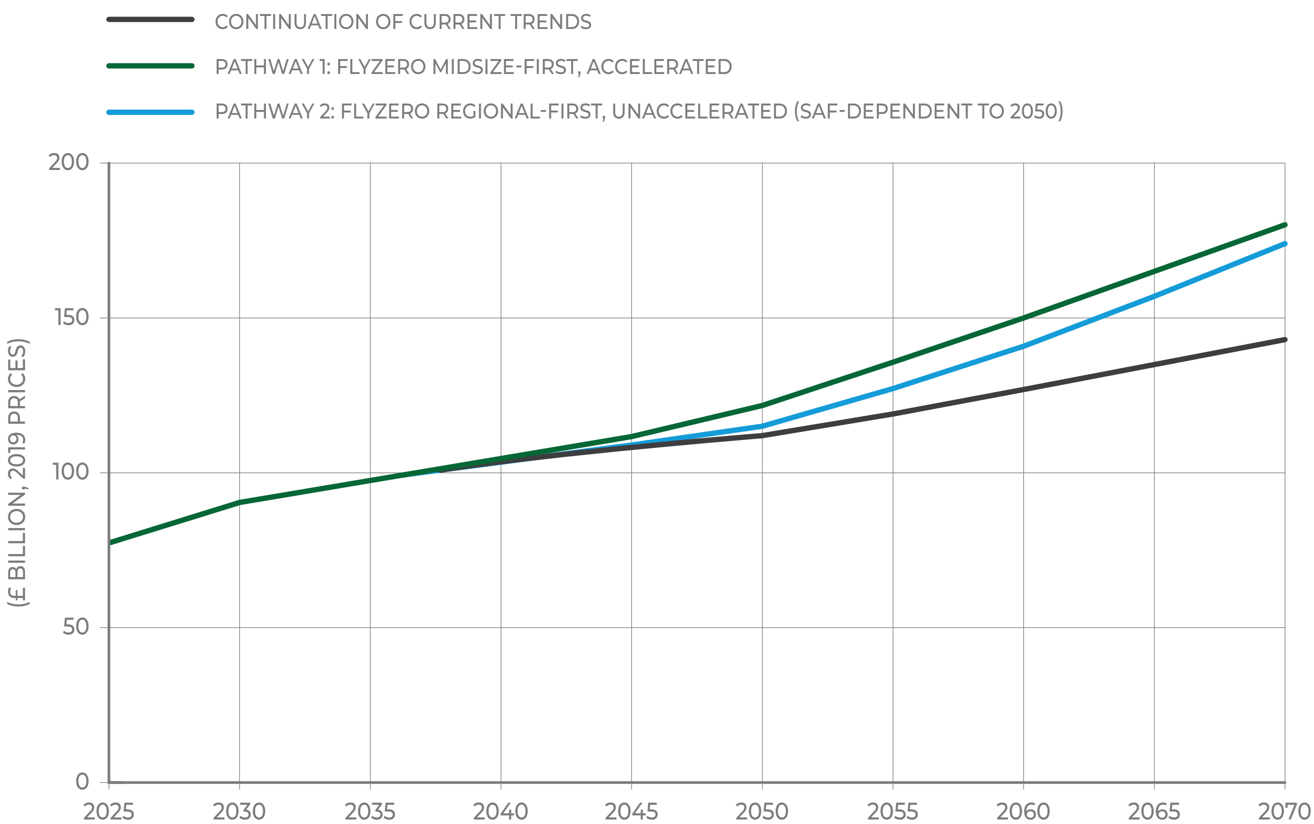
Given the early stage nature of the technology bricks, knowledge spillovers could be particularly valuable to society. For example, spillovers could emerge that benefit other hydrogen use cases that rely on the same transmission and distribution networks. By 2050, FlyZero analysis indicates that if a fleet of new liquid hydrogen aircraft were developed and the UK had a significant stake, the programmes could lead to an R&D investment of up to £21 billion and significantly more R&D investment occurring in UK civil aerospace programmes compared to the UK having a limited role (the consequence of a lack of capability and UK technology being available).

The benefits seen across the UK

These benefits would be felt across the UK, helping to support positive economic outcomes across a range of regions and local areas. The aerospace and aviation sectors are responsible for economic activity all over the UK, from international tourism that focuses on urban areas like London to aerospace design and manufacturing centred in industrial hubs outside the capital. In 2019, 88% of those employed in aerospace in the UK held jobs outside London and the South East [35]. For example, Airbus has major sites at Filton in Bristol, its main centre for wings, fuel systems and landing gear integration R&D, and at Broughton in north Wales, where over 5,000 people are employed at its main wing manufacturing centre, while Rolls-Royce employs over 12,000 people in Derby. GKN has established its Global Technology Centre also in Bristol, pulling in its supply chain; Spirit Aerosystems is also a large employer in Prestwick, Scotland, and has recently taken over Bombardier's wing manufacturing operations in Belfast, Northern Ireland.

The potential impacts on the aviation sector

As seen in **Section 3**, a liquid hydrogen aircraft has the potential to lower the cost of flying compared to SAF and kerosene alternatives, mitigating economic damage that might otherwise flow from higher prices and lower air travel demand. **Figure 16** shows that GVA contributed by aviation and the tourism it facilitates, would be £6 billion higher per year by 2050 if industry and government act to deliver the 'Midsize First - Accelerated' pathway, compared to the High SAF pathway.



Source: The Sensitivity of UK Aviation's Economic Impact Under Alternative Air Passenger Demand Scenarios, Oxford Economics (2021).

Figure 16 – Comparison of total GVA contributed to the UK Economy by the aviation sector and aviation facilitated tourism (£billion, 2019 prices).

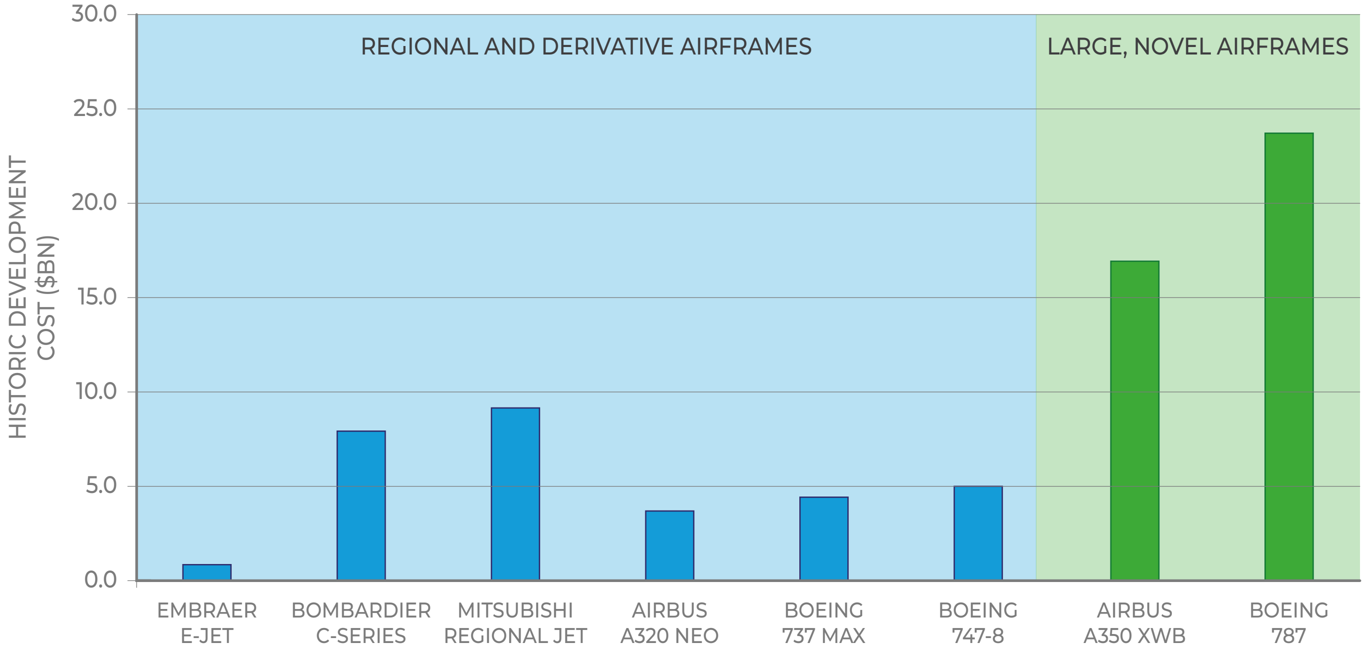
The economic advantages could be greater still. The availability of guilt-free, lower cost flying could well boost air travel demand overall, providing societal benefits, increasing connectivity and the economic activity would generate significant additional benefits for the economy. This may also strengthen economic resilience and energy security, as it is possible to produce hydrogen anywhere that affordable electricity and water can be supplied, potentially contributing to a more diverse, stable and resilient energy supply. **Section 5** will explore the production of hydrogen further and its potential to better insulate airlines from volatility in fuel and carbon markets.

05. THE CHALLENGES FACING INVESTMENT IN HYDROGEN AVIATION

Whilst the opportunity is significant, the challenges facing investment in hydrogen aviation should not be underestimated. Developing an aircraft with FlyZero's archetype characteristics would represent another major technology step in a constantly innovating industry. Its success would also depend on a range of factors outside an airframer's control, such as the reliable supply of low-cost, green hydrogen in sufficient quantities. In this section we set out a range of market failures which have the potential to prevent or limit the investment that could catalyse zero-carbon emissions aviation.

The challenges facing aircraft development programmes

Large whole aircraft development programmes involve airframers making large scale, long-term investments with significant technological risks. Whole aircraft development is highly capital intensive, particularly where the level of technology change is high (see **Figure 17**). Returns are long dated, taking several years before entry into service and longer still to sell enough aircraft to break even financially. These programmes are highly complex and operate at the cutting edge of technology, meaning delays and cost overruns are commonplace.



Source: FlyZero analysis of publicly quoted spend for past aircraft development programmes. Note: 'Complexity' has been based on the level of new technology introduction. These costs do not include the cost of developing technology to maturity prior to the launch of the aircraft programme. Also, these costs do not include Risk Sharing Partner (RSP) costs.

Figure 17 – Order of magnitude costs of past civil aircraft programmes (OEM costs only)

The incumbent global airframers, Airbus and Boeing, are the only companies with sufficient scale, capability and supply chain expertise to lead the development of large commercial aircraft. This is anticipated to remain the case in the medium to long term, whilst new entrants could play a role in spurring innovation in the regional or sub-regional market.

FlyZero's ambitious proposal with closely coupled development programmes, poses significant affordability challenges for the airframers. Only with coordinated international collaborations to develop both the technology and zero-emission aircraft can this vision be realised.

Additional challenges from developing a liquid hydrogen aircraft

In addition to the complexity associated with large scale, whole aircraft development, four additional challenges face an airframer considering a large hydrogen-powered aircraft:

First, a large-scale hydrogen aircraft, such as FlyZero's midsize or narrowbody concept, would be the largest technology step for a whole aircraft development programme over the last four decades.

Development would require breakthrough progress across a range of fundamental technologies, including gas turbines, cryogenic fuel systems and thermal management, aerodynamic structures, fuel cells and electric systems. There are also significant technical, regulatory, safety and certification challenges to overcome from working with a highly flammable fuel at cryogenic temperatures (-253 °C). These factors could exacerbate the cost and schedule risks seen in past development programmes[36].

[36] *This is analysed further in FZO-IST-MAP-0012 FlyZero Technology Roadmap report.*

Secondly, before airlines committed to purchasing aircraft, they would require confidence that future fuel costs would be affordable and stable.

As set out in Section 3, a pathway that involves a greater role for hydrogen could offer significantly lower fuel costs than one which is solely focused on SAF. However, this potential will only be realised if governments fulfil their commitments on hydrogen production (see next point), allowing low carbon forms of hydrogen to continue to move down their cost curves.

Fuel accounts for a large portion of airlines' operating costs. They will therefore require a degree of long-term price certainty between hydrogen and alternative fuels as purchasing new aircraft will lock them in for several decades. This could be achieved by a mechanism that allows airlines to limit their exposure to short-term fuel price volatility, similar to the role played by the hedging market for jet fuel. Whilst these challenges affect airlines directly, without government action they could also present a demand risk to airframers which might, in turn, deter them from investing in a new aircraft development programme.

Thirdly, a thriving market for hydrogen aircraft will be dependent on the global availability of green hydrogen at global airports.

Airline demand for aircraft will likely only focus on those routes where there is plentiful supply of hydrogen at both flight origin and destination. As described in Section 3, ambitious hydrogen production targets are being set globally and the biggest producers could be regions with plentiful and cheap renewable energy. Whilst global hydrogen production ramps up and a global distribution network emerges to support this, a 'One Stop Global Zero-Carbon Airport Network' concept focused on critical airport hubs such as JFK, Heathrow, Schiphol, Dubai, Beijing and Sydney could limit the number of airports worldwide requiring hydrogen supply and help mitigate fuel availability risks.

Finally, a traditional aircraft development financing approach may not be optimal for the development of a midsize or narrowbody liquid hydrogen aircraft.

The three main sources of financing that have been drawn on for whole aircraft development in recent years are: airframer balance sheet financing, supply chain financing and government support through R&D grants and repayable launch investment (RLI)[37], with all options facing new challenges today.

FlyZero analysis indicates that it is highly unlikely that an airframer and its supply chain will have the appetite and financial capacity to fund the launch of such a 'big bet' programme from its own balance sheet alone. The global aerospace industry is currently performing below its long-term trend, with airframers and their supply chains experiencing declining profits and margins alongside significant increases in debt and gearing (see FlyZero report "The Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation"). This has been exacerbated by the Covid-19 pandemic, which has resulted in a downturn in global air travel expected to persist for several years.

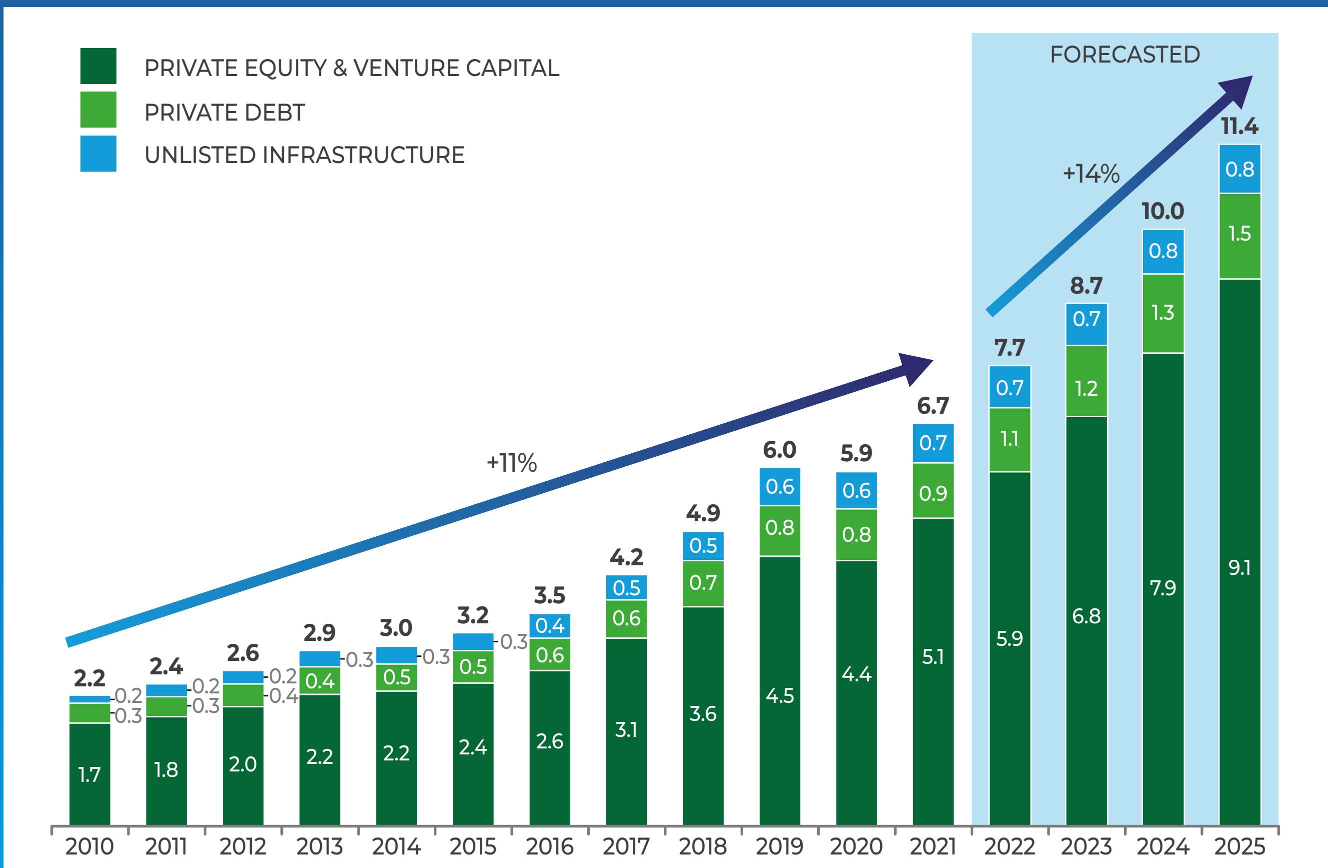
[37] Balance sheet financing is finance generated from an airframer's balance sheet; supply chain financing refers to risk and reward sharing agreements with suppliers during the development process and Repayable Launch Investment (RLI) schemes provided capital support to airframers launching aircraft, repayable after certain sales thresholds were met.

RLI is also unlikely to be popular with governments in its current form following the high profile US-EU trade dispute. Whilst new forms of repayable capital provision now might be possible following EU Exit, a significant new opportunity has been presented by growing private capital markets which now have record levels of capital to deploy (see **Figure 18**).

The value of the private capital markets has tripled in size over the last decade to $6.7 trillion globally (see below). The size and availability of private capital therefore represents a structural change in global markets since the launch of previous whole aircraft development programmes. This offers a new opportunity to mobilise capital for financing zero-carbon emissions aviation and potential investors include venture capitalists, private equity funds, infrastructure funds or private debt funds who, in general, are actively seeking participation in the energy transition and therefore participation in zero-carbon aviation would be of significant strategic interest.

However, private capital investors make investment decisions based on sophisticated analysis of the risk/return profile of the proposed investment and will only invest if they believe the parameters of the opportunity are directly in line with their investment mandate. Most of these investors do not tend to place 'all or nothing' bets; a clearer demand signal, such as a committed programme launched by an aircraft manufacturer, and greater demand and supply certainty is likely to be required to de-risk the business model and mobilise private capital. To help to unlock this circular challenge, government, industry and financing coordination is required.

Global Assets under management (AUM) by private asset class, 2010-2025



Source: FlyZero analysis of Preqin data

Figure 18 – The opportunity presented by private capital markets.

Market failures

These challenges are complex in nature, and many sit outside the direct control of an airframer or any single stakeholder. They are also likely to reflect more fundamental market failures that might require UK government support to overcome:

- **Negative externalities[38]:** Jet fuel is not taxed globally and carbon markets have not developed to the extent to capture the true cost to society of carbon emissions in the economy i.e. those induced by climate change. A liquid hydrogen powered aircraft avoids these negative externalities. Investment in this aircraft is expected to be under provided by the market and firms should be incentivised to invest more to extract the optimum level of social benefits.
- **Coordination failure at an industry and global level:** Multiple actors - airlines, airframers, engine makers, fuel providers, airports - must invest simultaneously for investment to be attractive for any one party (i.e. the first mover faces a prohibitive risk that no other element of the ecosystem will follow).
- **Asymmetric information:** Linked to coordination failure, organisations in the aerospace and aviation ecosystem do not have full knowledge of the issues facing others in the system, making it difficult for progress to occur in an integrated way.
- **Market power:** The market for large civil aircraft is dominated by Airbus and Boeing. As set out earlier in this section, barriers are high for new entrants meaning that new firms are unlikely to enter the market and compete.
- **Risk aversion:** Carbon emitting aircraft generate all airframer revenue and they might be reluctant to replace a high-volume product line with an uncertain hydrogen development, even if the commercial return could be larger.

[38] A negative externality is a cost experienced by society but that is not captured in the market price of the good or service.

Overcoming market failures

The UK government has a vital role to play in conjunction with industry to overcome these market failures and encourage investment. Analysis highlighted in **Section 6** illustrates that the window of opportunity for influencing an airframer is short and could be closed by 2025. FlyZero has developed a set of recommended actions to address these challenges and unlock the opportunity that hydrogen aviation could bring. These are comprehensively set out in **Section 6** but include:

- **Providing an early commitment signal:** Encouraging early investment in technology underpinning hydrogen aviation, helping to de-risk airframer development investment and ready supply chains for an aircraft development programme.
- **Providing greater demand and supply certainty:** For example through encouraging a plentiful global supply of green hydrogen, with the UK's hydrogen strategy playing an important enabling role (see **Figure 19**), and exploring mechanisms for establishing greater certainty of the price of this fuel.
- **Providing and de-risking financing where the market cannot:** Exploring innovative new avenues for financing of aircraft development programmes, including joint ventures backed by private capital markets.

In the UK, the Government's Hydrogen Strategy ambition to scale-up low carbon hydrogen production through blue hydrogen facilities using carbon capture and storage, whilst improving green hydrogen technologies, could help mitigate fuel availability risks domestically.

A number of use cases are envisaged around this strategy and aviation has the potential to represent a high profile and important use case. Demand for liquid hydrogen at UK airports could reach 1.7 Mt by 2050, representing a 38% share of the total energy demand from aviation in the UK. FlyZero analysis finds that aviation demand would represent 10-20% of total UK hydrogen in 2050, depending on whether the UK decides to prioritise hydrogen or electric power for domestic heating. Aviation would therefore represent a material share of total UK hydrogen demand, and in turn hydrogen would provide a path for decarbonising a hard to abate sector.

If hydrogen aviation were to be pursued, it might help to stimulate production capacity expansion. Hydrogen producers are faced with a 'chicken and egg' coordination problem - without demand that is visible in the long term (from aircraft manufacturers and airport infrastructure development), it is harder to invest into supply capacity. Equally, the aviation sector needs the assurance from hydrogen producers that the fuel will become abundant – mutually they could encourage investment into new hydrogen production facilities. However, it is reasonable to assume that large volumes of hydrogen will be required for aviation from the 2030s, be that for hydrogen aircraft or for use in power-to-liquid SAF.

Source: PwC Strategy& analysis of FlyZero and UK Government Hydrogen Strategy data sources

Figure 19 - Enabling role of the UK's Hydrogen Strategy

06. DE-RISKING AND ACCELERATING HYDROGEN AVIATION

Industry and government will need to work together and move quickly to avoid locking aviation into another generation of conventionally powered aircraft that will continue operating until the end of the 21st century. The opportunity to work with the airframers and investors to secure the development of these aircraft could be closed by 2025. It will be essential to secure commitments to hydrogen programmes before this point.

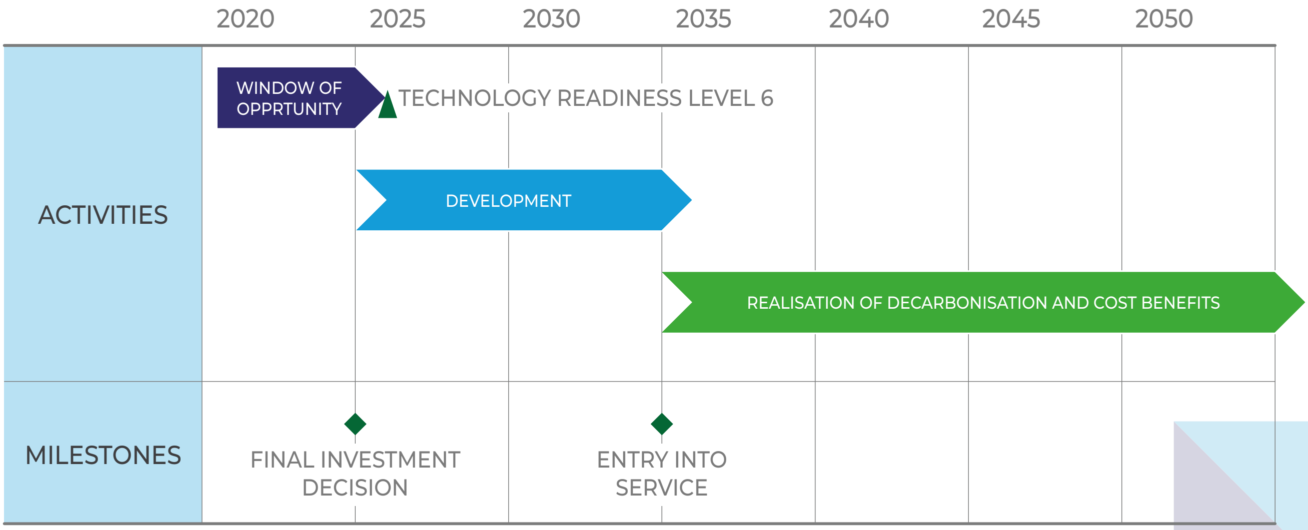
FlyZero has developed a four-point action plan for de-risking and accelerating a liquid hydrogen aircraft programme and securing maximum UK content. This roadmap consists of four core pillars and will require strong coordination across energy, industrial and fiscal policy.

The narrow window of opportunity

The global window of opportunity for launching a hydrogen aircraft development programme before 2050 is short and could be closed by 2025. A large hydrogen aircraft would need to be entering into service by the early 2030s, meaning a final investment decision would be required by the mid-2020s[39].

If this window is missed, airframers are likely to develop conventionally fuelled (kerosene/SAF) aircraft in the midsize and narrowbody classes, that would restrict their capability and incentive to invest in a hydrogen-powered competitor. Failing to secure commitments to hydrogen programmes before this point would lock aviation into another generation of hydrocarbon powered aircraft that continue operating until the end of the 21st century and prevent meaningful hydrogen penetration and carbon reduction until 2050 at the earliest (see **Figure 20**).

For the UK, winning content on the first generation of hydrogen gas turbine or fuel cell aircraft will likely require UK companies to be ready to demonstrate new, disruptive technologies within the next three years. Failure to de-risk technology, develop national industrial capabilities and make the UK an attractive location for development activity within this timeframe increases the threat that other countries will take share at the expense of the UK's aerospace industry if a programme is launched (see next page).



Source: FlyZero Market Strategy Report.

Figure 20 – Potential window of opportunity in a FlyZero 'Midsize First - Accelerated' scenario.

39 Entry Into Service (EIS) of a hydrogen aircraft is likely to take 7-10 years from Final Investment Decision (FID), based on analysis of past aircraft and technology and platform developments.

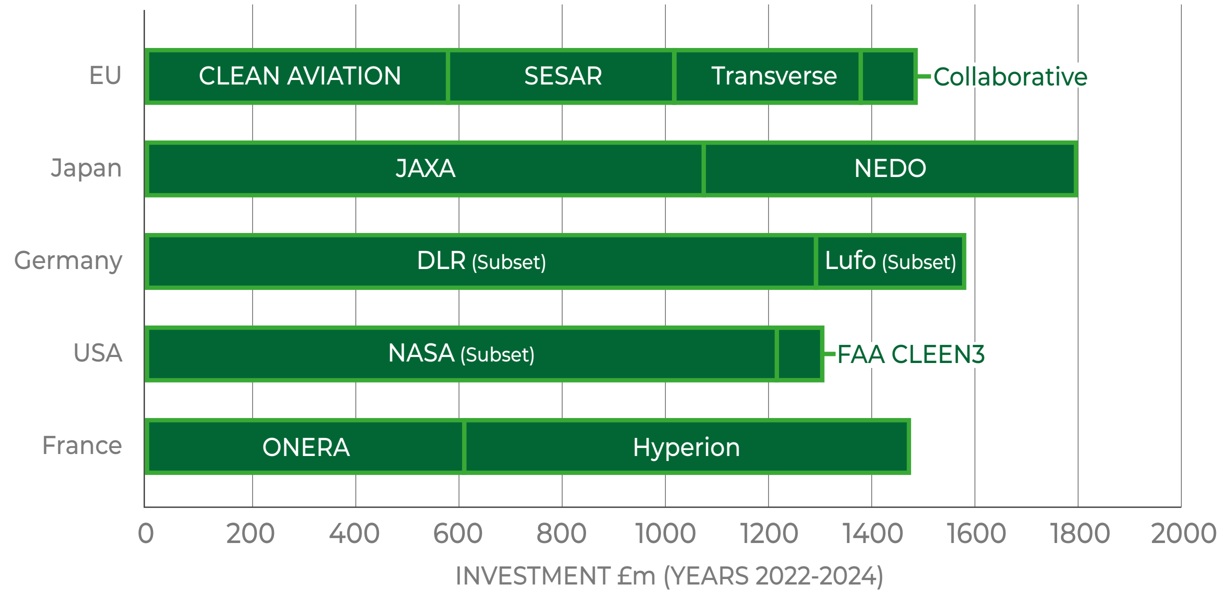
Global investment in zero-carbon emissions aviation

FlyZero has been successful in moving opinions forward regarding the feasibility of hydrogen-powered aircraft. The UK risks falling behind others globally (industrials, academia, research houses) who are investing more significantly into zero-carbon emissions aviation, increasing the chance a hydrogen aircraft development programme occurs without significant UK involvement.

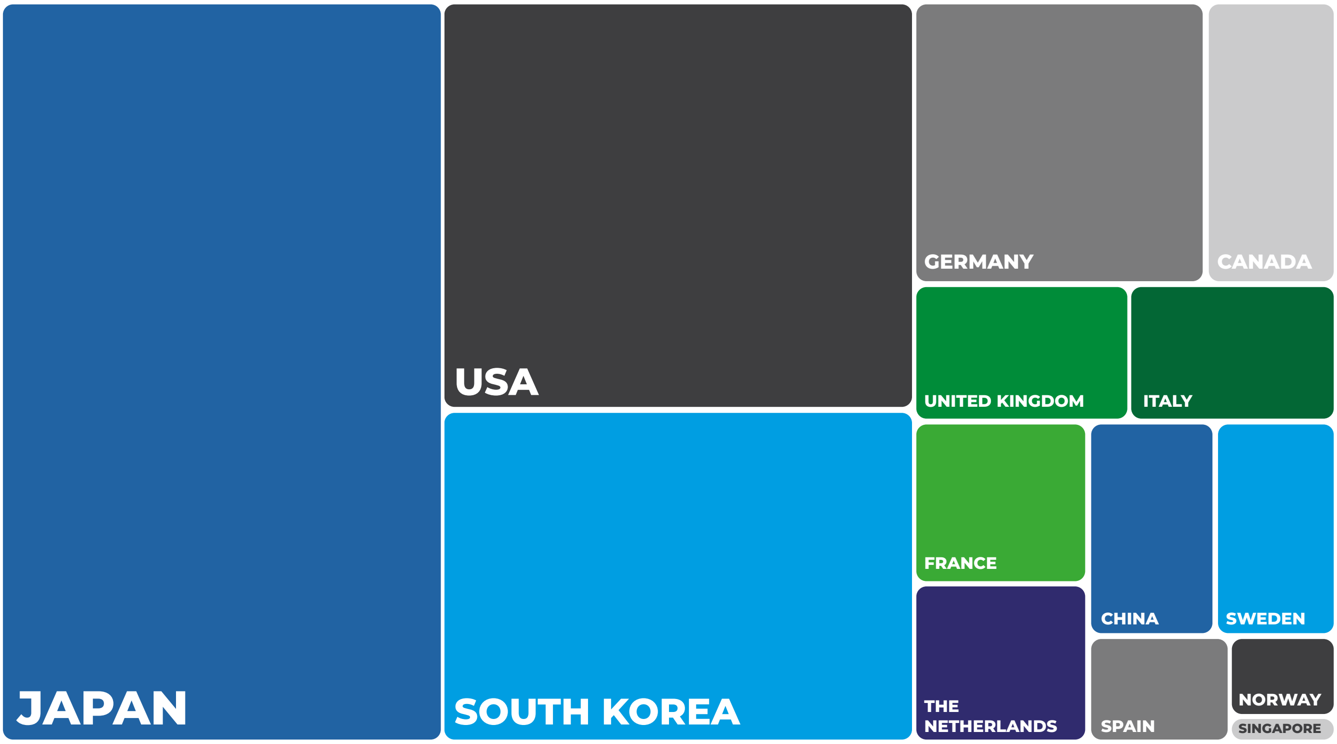
International activity and rising optimism about the potential of hydrogen as an aviation fuel is increasing the likelihood that other nations will take investment decisions to secure large shares of such a programme at the expense of the UK's aerospace industry. The EU, Japan, Germany, US and France are each investing over £1.3 billion in clean aircraft technologies over the next three years, and these countries are generating higher levels of intellectual property in this area than the UK (see figure 21). France has committed to support £1.5 billion worth of R&D over three years; €630 million of funding has been raised already including €200 million from the French government, €200 million from Safran (a competitor to Rolls-Royce), Dassault and Thales, and €230 million from the fund manager Tikehau [40]. All of these nations are taking a risk-based approach to secure the future.

Securing significant UK involvement in the next suite of aircraft development programmes will be key to preserving, and growing, the economic benefits from the UK aerospace sector described in **Section 4**.

Investment in zero-carbon emissions aviation programmes



Indication of relative level of patent activity by country in technology areas relevant to a hydrogen aircraft



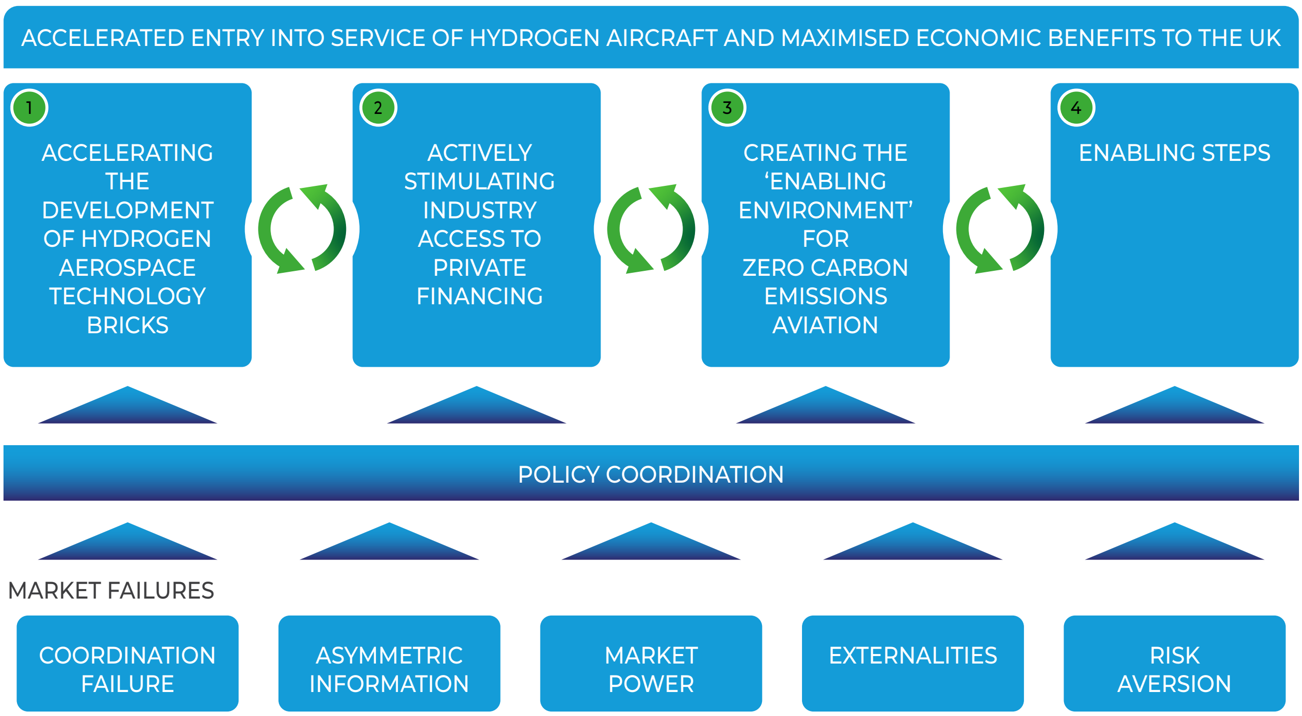
Source: FlyZero analysis.

Figure 21 – Global Investment and IP creation in zero-carbon emissions.

Action plan for de-risking and accelerating hydrogen aviation

Figure 22 presents FlyZero's action plan for de-risking and accelerating a liquid hydrogen aircraft development programme and securing maximum UK content. This roadmap consists of four pillars and will require strong coordination across energy, industrial and fiscal policy:

1. Accelerating the development of hydrogen aircraft technologies, their verification, integration and demonstration
2. Actively stimulating industry access to private financing, creating an environment to support the development of zero-carbon emissions aircraft systems and components in the UK's aerospace sector
3. Creating the enabling environment for zero-carbon emissions aviation through exploring new infrastructure requirements and broader policy measures
4. Enacting key enabling steps to deliver tangible progress quickly, including setting up a delivery unit supported by strategic partnerships and international collaboration



Source: FlyZero analysis.

Figure 22 – Action plan for de-risking and accelerating hydrogen aviation

Recommendation 1:

Accelerating the development of hydrogen aerospace technologies, their verification, integration and demonstration

Maturing and integrating hydrogen aviation technologies in the UK is the critical first step for developing a liquid hydrogen aircraft. Without this, it will be too risky for an airframer to launch a development programme. In contrast, achieving early breakthroughs across these technologies would encourage an airframer to bring forward investment and give confidence to policymakers.

The most effective way to maximise UK involvement in such an aircraft programme would be to stimulate technology development domestically. The R&D required for critical technologies must be accelerated for entry into service by the early to mid-2030s.The UK should focus efforts on its existing capabilities such as gas turbines, fuel cells, fuel systems and storage, wings and thermal management, and aim to achieve technology maturity by 2025. This would maximise the chance of the UK securing a significant share of overall platform development and gaining the associated benefits for GVA and jobs.

An ambitious, government supported R&D programme should direct more R&D into technology systems and test infrastructure which will be critical to demonstrating the performance and maturity of the technology, enhancing the likelihood of exploitation, and which could be used by a number of sectors (see recommendation 3, below).

The Aerospace Technology Institute (ATI) already runs calls for industry if they fit within the scope of the UK Aerospace Technology Strategy. For this emerging technology area, the UK could choose to take a more expansive and directive approach, considering:

- **Early stage industrial R&D:** research into technologies in the earliest stages of development such as those that are unproven or conceptual to accelerate development of higher risk, high reward technologies.
- **Directed R&D:** research projects given clear requirements by a government body or by a partnership between government and industry to target innovation in critical areas required for hydrogen aviation.
- **Test infrastructure and demonstrations:** development of environments for technologies to be trialled. This would deliver more credible evidence to validate technologies and provide a positive signal to other companies or investors, with the potential to bridge across aircraft and airports.

The ATI is ideally positioned to deliver these initiatives, leveraging existing infrastructure and programmes such as FlyZero to oversee the R&D activity required and help coordinate this across the UK's aerospace sector. These R&D actions will both develop product technology and develop UK skills and expertise in this growth area. This would establish the UK as a key location for developing hydrogen technologies. From FlyZero's initial analysis of the expected costs, benefits, risks and uncertainties of the investment, we expect this to deliver value for money for UK taxpayers – this analysis is presented in more detail in "The Economic and Commercial Case for Accelerating Zero-Carbon Emission Aircraft & Aviation".

Recommendation 2:

Actively stimulating industry access to private financing, creating an environment to support the development of zero-carbon emissions aircraft systems and components in the UK's aerospace sector

Section 5 sets out the significant challenge of obtaining the financing from the market to launch a new hydrogen aircraft development programme. This highlighted the balance sheet constraints facing airframers and the broader supply chain but identified a new opportunity from rapidly growing private capital markets, if the investment proposition can be tailored to investors' requirements. FlyZero believes that governments will need to play a vital role, both as a provider of capital, and as an enabler for unlocking this investment.

The first step will be for both government and industry to work together to stimulate technology investments, with R&D grants described in recommendation 1, above, playing a pivotal role to attract matched investment from industry. With breakthrough technological progress, this could offer a public success story for investment into hydrogen aviation that could encourage other investors, such as private capital, to engage with the industry and offer a bridge between R&D and a full aircraft development programme.

Whilst there are indications that this investment opportunity could be of interest to investors in private capital markets, a formal dialogue should also be opened between these investors, the UK aerospace industry and the government to formally assess the investment appetite, starting a journey to develop an attractive and viable commercial deal. This could take the form of equity capitalisation of a Special Purpose Vehicle (SPV) with a risk-sharing agreement with industry and private capital, similar to the approach taken to fund a Rolls-Royce led consortium to build small modular reactors in the UK[41].

Recommendation 3:

Creating the enabling environment for zero-carbon emissions aviation

This strategic case has identified four key areas where UK policy can create the environment for zero-carbon emissions aviation to flourish:

- Energy infrastructure

Hydrogen as a future energy source has global credibility, with strategies emerging for production and exploitation across many countries and sectors. As explored in Section 5, FlyZero analysis suggests aviation could be a significant use case. The UK's Hydrogen Strategy should be used to deliver a clear demand signal for hydrogen and incorporate the needs of the sector in its production targets. This should be aligned to production forecasts contained in the National Grid's Future Energy Scenarios (FES), with a longer term ambition towards green hydrogen.

41 https://www.gov.uk/government/news/uk-backs-new-small-nuclear-technology-with-210-million

Carbon pricing, taxation and consumer choice

An approach for attaining net zero in the aviation sector that relies heavily on carbon pricing and taxation measures would have a damaging impact on UK productivity and growth. However, where carbon pricing is applied to the aviation sector globally and this is accompanied with a zero-carbon emission flight alternative, this could help to shift demand to sustainable forms of aviation and reduce emissions without lowering demand for air travel overall.

Other non-price measures that could encourage consumers to make more informed choices about how they fly include improving flight carbon emissions transparency (e.g. mandating that this information is provided to potential customers at the point of booking).

Opportunities also exist to use the tax system to support the development of a hydrogen aircraft. For example, air passenger duty (APD) could be hypothecated to help fund a portion of the investment required to stimulate hydrogen aviation in the UK. This would be a highly coherent approach, using the proceeds of carbon taxation in the aviation sector to support decarbonisation efforts in the sector.

A clear time bound roadmap for any taxation and incentive changes would assist airlines and airports plan their green transitions.

Incentivising airport infrastructure investment

Section 3 set out the new infrastructure requirements for UK airports to receive, store and deliver large amounts of liquid hydrogen to aircraft. For a large airport, capital expenditure for this new infrastructure could amount to £850 million-£1,400 million. Whilst this would be lower cost than other airport infrastructure enhancements such as a new runway it is still a sizeable capex requirement and policymakers will need to consider how it should be financed. For large, regulated airports, it is likely these costs will be included in the regulated asset base (RAB) which is used to set airport landing charges. This should help to promote a level playing field between zero-carbon emission and hydrocarbon-powered aircraft, whereby new infrastructure charges should be spread over all landing slots, rather than penalising a particular type of aircraft.

In addition, where significant liquefaction or storage facilities are required airside, which might only be the case for the largest airports such as Heathrow, policymakers will need to consider the planning and regulatory considerations and develop appropriate policy responses.

Establish a UK hydrogen technology programme, centre or network of centres

There is significant, cross-sector activity to develop and bring to market hydrogen technologies. At the same time, due to the low technology readiness level (TRL) of these technologies, there are limited skills and testing capabilities in the UK. A centralised body with access to open access testing and infrastructure could research and disseminate fundamental hydrogen behaviour, requirements for safe handling, standards and regulations, material properties and test specifications to serve multiple use cases/sectors.

Recommendation 4:

Enacting key enabling steps to deliver tangible progress quickly

FlyZero has identified three key enabling steps to deliver and manage this strategy across industry and international partners:

- **Establish a Zero Emissions Delivery Group:**

to deliver a coordinated series of actions across aerospace, aviation and energy sectors. Ensure this group has authority to set national priorities and the support needed to set action in motion.

- **Establish a strategic partnership with industry:**

that has the autonomy to allocate mission-led R&D funding aligned to strategic priorities for the national interest. This partnership would set direction and priorities at the level below the Delivery Group, sharing requirements across supply chains with the aim of maximising UK supply chain participation and building international collaboration. It would provide integration across aerospace and aviation demonstrations and deliver a portfolio of actions that would demonstrate the UK's capability as a world leading player in hydrogen aviation.

- **Broker and support international collaboration:**

to ensure any UK programme signals, attracts, and enables international collaboration and sustains its UK 'seat at the table' in international programmes such as Clean Aviation. Discussions with global partners can help to seek consensus on regulatory issues raised by hydrogen aviation and other issues such as climate science, air traffic improvements and the development of a 'One Stop Zero Carbon Global Network ' of airports.

The importance of policy coordination

This section has summarised FlyZero's view on the recommended policy approach for de-risking and accelerating a liquid hydrogen aircraft development programme and achieving maximum UK involvement. It is clear that the interventions required are multi-dimensional in nature, crossing transport, energy, taxation and regulatory policy, and therefore the strong coordination of policy making will be vital to sending clear and consistent messages to airframers, the supply chain and wider potential investors and stakeholders considering investing in this space.

The ATI is well positioned to deliver the required coordination and bring the specific organisations and institutions together. Only with a sufficiently sized series of actions can the UK influence others globally – establishing a strategic and coordinated programme with industry partners to achieve the UK's net zero ambition.

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