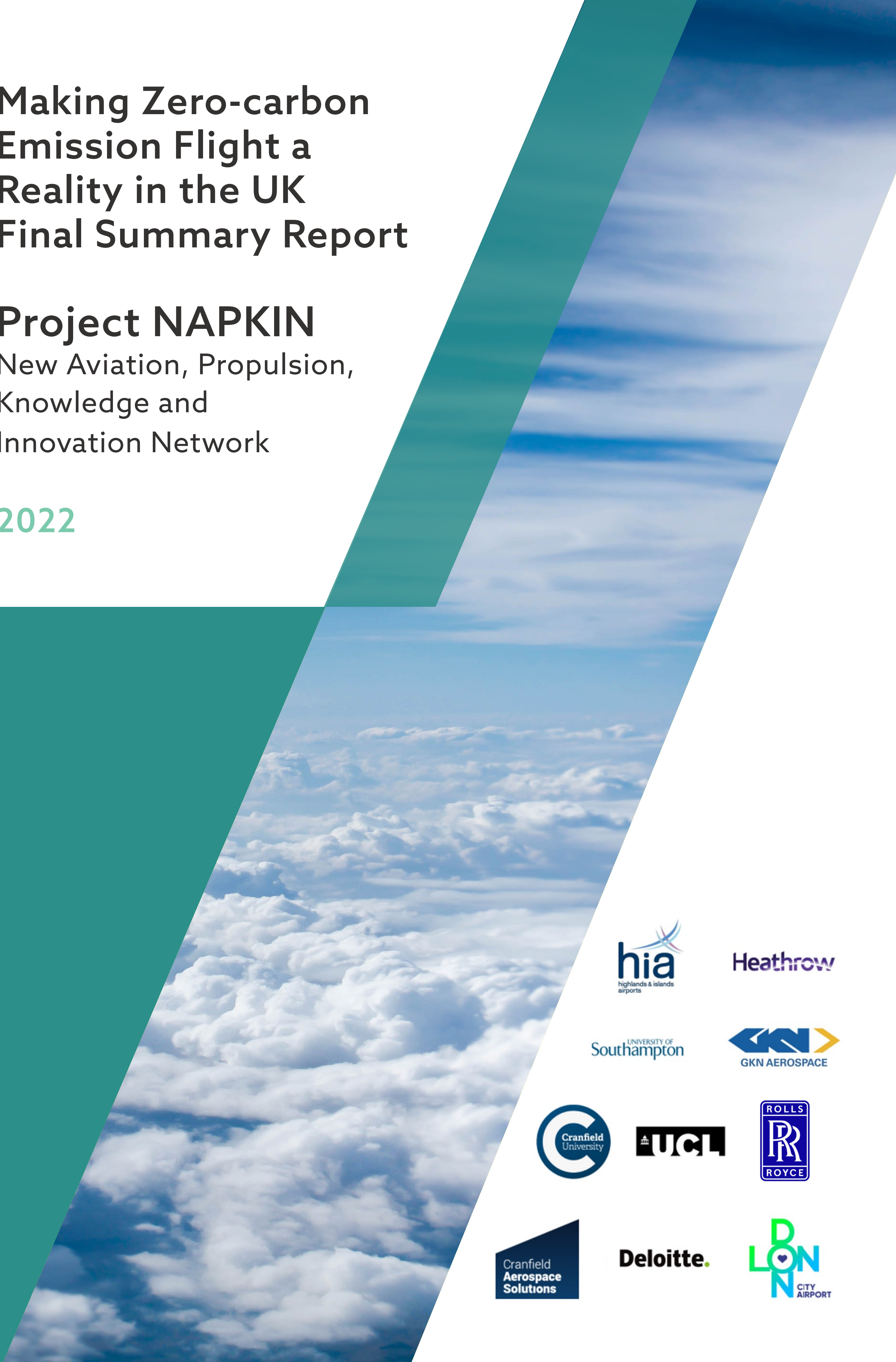
Making Zero-carbon Emission Flight a Reality in the UK Final Summary Report

Project NAPKIN

New Aviation, Propulsion, Knowledge and Innovation Network

2022



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Introduction

Current landscape

The UK has a long and storied role in the history of aviation. Today, as the world recognises the need to reduce, and ultimately eliminate its reliance on fossil fuels, the UK aviation industry is turning its focus to achieving Zero-carbon Emission Flight (ZEF).

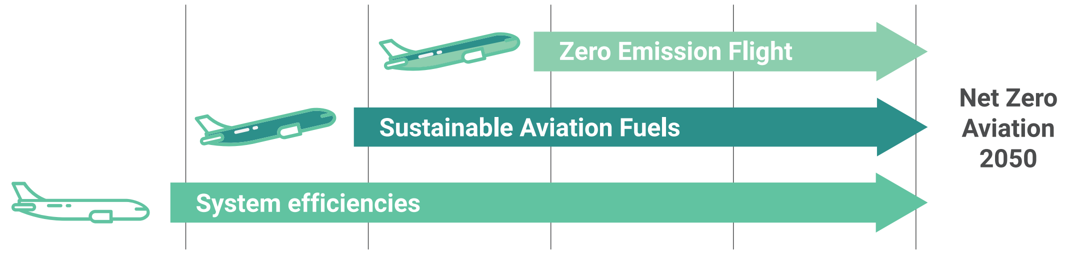
With the industry on course to generate 39% of the UK's greenhouse gas emissions by 2050 according to the Aerospace Technology Institute[1], and given the challenges to decarbonise the sector, it is a "must act now" situation.

Change will not happen overnight, but through a long-term industrial partnership with Government together with investment, dynamism and a recognition that we must re-engineer aviation.

Thanks to the UK Government and the Jet Zero Council, there is now a body that can work across Whitehall to establish the industrial strategy that will help us move furthest, fastest.

The recently launched Jet Zero Strategy, with its mission for all UK domestic flights to be net zero emissions by 2040, and for all of UK aviation to reach that target by 2050, is challenging but, with support, possible.

There is no silver bullet; Jet Zero will take time and progress may be slower than anticipated. But over time, improvements in systems efficiencies, including from: modernising airspace; continued renewal of the conventional aircraft fleet; the scaling up of Sustainable Aviation Fuels (SAF); the update of airline methods of operation and by embracing hydrogen technologies to unlock the potential of ZEF will contribute to achieving this goal.



1 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-PPL-0041-Case-for-the-UK-to-Accelerate-Zero-Carbon-Emission-Air-Travel.pdf

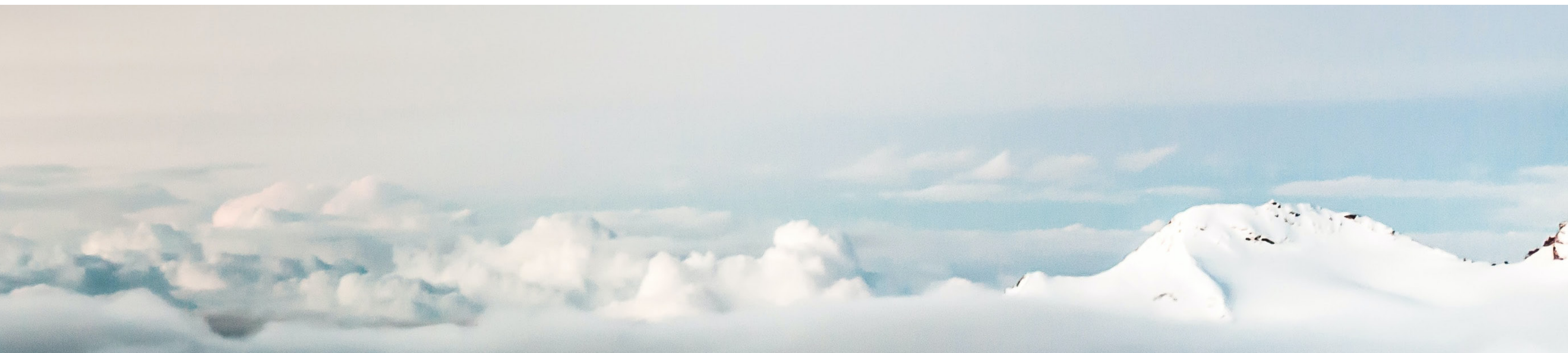
Current new aircraft are more than twice as fuel efficient as those operating in the 1960s[2] and, with the continued improvement in aircraft and engine design that is on-going, additional fuel savings will be delivered while the new zero emission technology develops and scales up. Additionally, airports and Air Navigation Service Providers, supported by aircraft and powerplant providers, improve efficiencies by working with airlines, enabling innovation in operations and the use of airspace in the most efficient way. Also, commitments like those made by the airports in this consortium to achieve net zero emissions by embracing renewable energy, pivoting to clean heating systems and deploying zero emissions operational fleets will help reduce emissions in the sector.

When compared to conventional jet fuel, SAF cuts around 70%[3] toady and theoretically up to 100% of CO_2 emissions over its lifecycle. Its potential is not yet being realised at scale due to limited supply. Although many dedicated SAF production facilities are in planning or construction around the world, we need to see many more. This is the policy priority now if we are to start demonstrating that aviation can cut emissions growth this decade.

However, to get to net zero by 2050 further new technologies must play a complementary role. Zero-carbon emissions flight, as the name suggests, has the advantage of releasing no carbon emissions in flight. Green hydrogen (produced by electrolysis using green electricity) has zero-carbon emissions in production as well as in flight. ZEF will initially operate on sub-regional and shorter routes, and in doing so demonstrate the use of hydrogen fuel and aircraft in the aviation system, facilitating the delivery of global, zero carbon connectivity (the thesis of Fly Zero[4]). This study looks at commuter and regional aircraft, focussing at this stage on the UK market and how it may evolve from there with the introduction of larger zero-carbon emission aircraft as a consequence.

Project NAPKIN (New Aviation, Propulsion, Knowledge and Innovation Network) brings together three aerospace manufacturers, three airports and three academic institutions. It takes a whole systems approach to the ZEF challenge – understanding how the market will work from all perspectives in the aviation value chain. NAPKIN focuses on the UK market and how the ZEF opportunity will evolve there. Its research and findings have also been critiqued by British Airways, easyJet and Loganair as part of the Project's Advisory Board.

2 https://theicct.org/sites/default/files/publications/ICCT_Aircraft_Efficiency_final.pdf
3 https://www.sustainableaviation.co.uk/wp-content/uploads/2020/02/SustainableAviation_CarbonReport_20200203.pdf
4 https://www.ati.org.uk/flyzero/



> PROJECT NAPKIN (NEW AVIATION, PROPULSION, KNOWLEDGE AND INNOVATION NETWORK) BRINGS TOGETHER THREE AEROSPACE MANUFACTURERS, THREE AIRPORTS AND THREE ACADEMIC INSTITUTIONS. IT TAKES A WHOLE SYSTEMS APPROACH TO THE ZEF CHALLENGE – UNDERSTANDING HOW THE MARKET WILL WORK FROM ALL PERSPECTIVES IN THE AVIATION VALUE CHAIN.

The strength of the consortium is a recognition that no one part of the industry has all the answers. To realise the potential of new propulsion systems and concept aircraft, the requisite infrastructure needs to be in place at airports like Heathrow, London City and Inverness – the subject of specific project case studies in NAPKIN. Also, suitable market conditions must exist in order for airlines to invest in aircraft, and sufficient supply of green hydrogen available in the economy to serve the demand.

The consortium believes that ZEF is possible, potentially from the second half of this decade, starting from 7-19-seat aircraft operating subregional lifeline routes between the Scottish mainland and islands.

While this phase may be small in scale, it could play an important role in enabling learning and development on critical issues such as safety compliance and regulation. The first step will involve retrofitting aircraft, which while imperfect from design and performance perspectives, provide insights for the development of new, clean sheet aircraft for 2035.

This will give the industry and travelling public the confidence to embrace an exciting period of change. From 2035 onwards, entirely new aircraft, designed specifically for hydrogen, could be flying the whole of London City's domestic schedule and connecting into the UK's only global hub, Heathrow.

The work of NAPKIN is instructive and gives us cause for optimism. But included within it are significant challenges and areas that require further research. For example, with an estimated demand of 300,000 tonnes of green liquid hydrogen by 2040, the industry will need to work closely with Government and the energy sector to ensure enough supply around the country to propel zero-carbon emission flight. Furthermore, the cost of hydrogen will heavily influence how quickly progress accelerates. By 2040, NAPKIN modelling suggests that large regional zero-carbon aircraft (modelled as a 90-seater in NAPKIN) could cost-effectively serve almost the entire UK domestic network given favourable fuel price conditions.

Lastly, this sector connects everyone globally. We, in the UK, see a future where that is increasingly possible through hydrogen fuelled ZEF. We sincerely hope this work can inform and inspire more studies globally and we look forward to collaborating with partners, new and established, on building an aviation network that meets the needs of society and the planet.

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About NAPKIN

The project has built an understanding of the conditions required to enable the successful introduction of zero-carbon emission flight in UK domestic air travel to support zero carbon regional connectivity. Within its scope of advancing the regional civil aviation network, NAPKIN has brought together expertise from the entire aviation ecosystem. Airports, academia, manufacturers and aviation specialists have combined efforts, with advice from airlines, to build a comprehensive picture of the factors that will enable the transition to regional hydrogen aviation.

NAPKIN has evaluated 25 modified and original aircraft concepts to explore their impact on the five 'As' of Aircraft, Airport, Airspace, Airline, and Air Passenger. By taking a whole systems approach, it is shedding light on the ground infrastructure, energy demand, noise performance, and emerging passenger sentiment.

Using a modelling tool developed at University College London, it sets out how a UK hydrogen flight network can be achieved, taking account of aircraft capability, routes and commercial viability and scale. This, in essence, illustrates where green hydrogen powered aircraft can successfully be adopted in realistic market conditions.

NAPKIN aims to help inform Government, and the industry more broadly, to better understand the opportunities, challenges and conditions required to enable zero-carbon emissions flight.

It is also the shared view that hydrogen aircraft represent a credible solution to reach zero carbon flight and is the natural complement to Sustainable Aviation Fuels. While other solutions were looked at initially, such as electric and hybrid propulsion, the consortium concluded that hydrogen technologies provide the path to zero-carbon emission flight for "mainstream" commercial services and elected to concentrate its research and analysis in this area.

The consortium has focused on means of removing carbon emissions[6]. The impact of contrails from hydrogen powered aircraft (fuel cell or combustion) as well as implications of NOx emissions from hydrogen combustion has not been considered in this study. It is recognised there is considerable uncertainty around the influence on these emissions from the use of hydrogen as a fuel and that further studies are necessary to improve understanding.

5 AGS, Ferrovial, IAG, Jacobs, Manston, NATS, UK Power Network, Deloitte and CAA.

6 By "carbon emissions" we refer to the gas carbon dioxide – CO_2 – not "all greenhouse gases" – CO_2e

Findings are presented across three distinct periods:

- From 2025 with the introduction of small aircraft on sub-regional routes;
- the introduction of new clean sheet aircraft by 2035 and finally;
- by presenting a vision for what the UK domestic aviation network could look like by 2040

Each section details key information on aircraft range, payload, commercial performance and CO_2 savings. It also plots a potential route network, required airport infrastructure, insights and challenges that could inspire further work. The potential net zero route network presented by NAPKIN is based on existing routes. How ZEF could drive new routes and help redefine regional connectivity should be further explored, as opportunities may arise for new and established airlines.

To access and download the full report and associated technical reports, please visit https://www.heathrow.com/company/about-heathrow/future-flight-challenge/napkin

Hydrogen Fuel Cell: A hydrogen fuel cell converts hydrogen into electricity. Fuel cell technology has the potential to deliver zero-emission aircraft as they do not emit CO_2 or NOx. While it is an immature technology for aerospace applications, it presents significant potential for performance and efficiency gains.

Hydrogen Gas Turbine: In a similar way to how gas turbines in operation burn kerosene, they are also able to run on hydrogen. This technology produces no CO_2 emissions and shows potential to be more efficient than current kerosene systems, though further research is needed in this area to reduce the risk of NOx emissions and manage contrails.

Liquid Hydrogen: Liquid hydrogen results from cooling gaseous hydrogen to temperatures below -253oC. Liquid hydrogen has a higher volumetric energy density than gaseous hydrogen, which makes it more suitable for larger aircraft. However, liquid hydrogen production, handling and storage requires significant amounts of electricity and introduces complexities that may make it more expensive.

Gaseous Hydrogen: While it has lower volumetric density than liquid hydrogen, it has some production, handling and cost advantages compared to liquid hydrogen, which makes it the preferred option for smaller aircraft, especially operating from remote locations.

Retrofit Aircraft: An aircraft that uses an existing airframe as a basis to install a new propulsion system.

Clean Sheet Aircraft: A new aircraft which has been specially designed around the type of propulsion system and fuel selected to suit the operating requirements.

Study Aircraft: An aircraft concept loosely based on an existing airframe, featuring a new fuel storage and propulsion system. It differs from a retrofit design as it is unconstrained by spatial and structural integration limitations of an existing aircraft.

Findings and Recommendations

1: Zero-carbon flight will arrive this decade

Zero-carbon emission flight could be possible from the second half of this decade with 7-19 seat aircraft on sub-regional lifeline routes. Although the shorter routes that ZEF will initially operate will not solve the net zero challenge, they could be a useful first step for zero-carbon emissions flight. Using this as a stepping stone, the government and industry must exploit the opportunity and accelerate the practical learning that arises in a whole host of areas including regulation, safety, ground support equipment development, airspace modernisation, infrastructure design and propulsion system technologies.

Recommendation: Ensure that alongside continued funding for the Aerospace Technology Institute, further funding for whole aviation system R&D and the development of specific systems, technologies and processes is available.

2: The Government "Jet Zero" 2040 net zero target is possible but contingent on supply

It will be potentially cost-effective for airlines to replace the entire UK regional fleet with safe, certified, zero carbon aircraft by 2040, provided sufficient aircraft and green hydrogen production capacity exists.

Recommendation: Accelerating the production of green hydrogen at scale should be a major focus for the Government. As green hydrogen can be used for the production of SAF and also used directly to power hydrogen aircraft, continued expansion of supply is a critical prerequisite for net zero aviation.

3: National supply, and the price of green liquid hydrogen, will be critical

The price of liquid hydrogen relative to fossil kerosene is a critical factor in determining profit-optimal uptake of ZEF by airline operators. Modelling shows that, if hydrogen prices meet US[1] and EU[2] ambitions for gaseous green hydrogen prices to approach $1/kg, ZEF uptake could cover almost 100% of the UK domestic market. This could fall away to very little if hydrogen prices remain closer to present-day values. NAPKIN aircraft uptake levels for different hydrogen and kerosene prices are analysed in the detailed 'NAPKIN Final Report'.

1 https://www.energy.gov/eere/fuelcells/hydrogen-shot
2 EC, 2022. RePowerEU. https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

Recommendation: Government industrial strategy on liquid hydrogen is critical and should target achieving the lowest possible production costs. Government will have various levers at its disposal to provide price certainty to airlines and to close any price premium above fossil kerosene, by creating price incentives or intervening through the taxation system. Implicit in this is the need to assess the necessary energy, production and distribution infrastructure to help ramp up and meet such a possible demand.

4: Airport infrastructure requirements will be key by 2040

Depending on the size of airport and the airline hydrogen operations using it, airport infrastructure requirements are relatively limited until the mid-2030s, with hydrogen (whether gaseous or liquid) largely delivered by truck. However, to enable regional uptake, the right level of distribution infrastructure needs to be in place.

Recommendation: There is concern that airport infrastructure could quickly become the limiting factor for the growth of ZEF. Programmes such as the Department for Transport's Zero Emissions Flight Infrastructure "ZEFI" need to be further developed[3] and place a big focus on infrastructure-preparedness and standardisation. Additionally, planning and delivery of a national H2 infrastructure network should go in hand with the production of hydrogen at scale, to ensure there will be sufficient supply and avoid limiting the potential for regional uptake, which could delay the introduction and scalability of zero-carbon emission flight.

5: There is a potential noise benefit and opportunity

Noise performance of hydrogen aircraft is comparable with that expected for future conventional aircraft with potential of noise reduction in the proposed technologies. Airport noise impact can eventually benefit from the introduction of hydrogen concepts once their market share becomes significant (>10% of total airport movements) and their operation optimised.

Recommendation: While the broad outlook for noise from hydrogen powered aircraft is optimistic, it needs to be recognised that these aircraft will still produce a level of noise sufficient to impact a large number of people. It is therefore important that those likely to be affected are informed as to realistic noise expectations as well as continue funding R&D programmes focusing on opportunities for noise reduction.

3 https://cp.catapult.org.uk/programme/preparing-uk-airports-for-zero-emission-aircraft/

Currently, the aviation industry is on course to generate **39%** of the UK's greenhouse gas emissions by **2050.**

Demand for liquid hydrogen is estimated to reach **300,000 tonnes** per year by **2040.**

By **2040**, we estimate **aircraft fully powered by hydrogen** could serve the entire UK domestic network.

The **first zero CO_2 emission hydrogen aircraft** could be in service before **2030.**

6: Passengers will accept zero-carbon emissions flight

From surveys conducted as part of this study, passengers show a willingness to take ZEF flights so long as they don't excessively impact the flight experience. More than 50% of passengers would be willing, for instance, to have slightly longer journey times if the trade-off benefit of zero carbon was sufficiently clear.

Recommendation: There is a wealth of research to be done to understand consumer attitudes further, including whether particular market segments, such as large corporations, could be among early adopters, and how ZEF availability could alter the patterns of leisure sector demand.

Acknowledgements

The consortium would like to acknowledge the support of UK Research and Innovation (UKRI). Innovate UK drives productivity and economic growth by supporting businesses to develop and realise the potential of new ideas.

We would also like to acknowledge the expertise provided by the Advisory Board, comprising the following organisations: AGS, British Airways, easyJet, Ferrovial, IAG, Jacobs, Loganair, Manston, NATS, UK Power Networks.

Finally, thanks to the Civil Aviation Authority (CAA) for the support and expertise provided by a group of subject matter experts it convened on NAPKIN's behalf to explore key regulatory considerations associated with zero-carbon emissions concepts for air transport.

The NAPKIN Fleet

The table below presents the main characteristics of the NAPKIN fleet used on the project case studies.

Table 1: NAPKIN fleet

NAPKIN Aircraft	CAeS-7	CAeS-19	GKN-40	RR-50	RR-90
Seats	7	19	40	50	90
Manufacturer	Cranfield Aerospace Solutions	Cranfield Aerospace Solutions	GKN Aerospace	Rolls-Royce	Rolls-Royce
Airframe Type	Retrofit	Retrofit	Clean Sheet	Clean Sheet	Study Aircraft
Propulsion System	Fuel Cell	Fuel Cell	Fuel Cell	Gas Turbine	Gas Turbine
Fuel System	Gaseous H2	Gaseous H2	Liquid H2	Liquid H2	Liquid H2
Range (Max Payload)	230 km (124 nm)	300 km (162 nm)	1,506 km (813 nm)	1,111 km (600 nm)	2,654 km (1,433 nm)
Total Cost of Ownership/ Flight Hour[1]	650 - 850 £/FH	1,000 - 1,300 £/FH	2,500 - 3,050 £/FH	2,600 - 3,050 £/FH	5,900 - 7,600 £/FH


CAeS-7


GKN-40

1 Figures rounded to the nearest £50

2025-30: Small Hydrogen Retrofit Aircraft

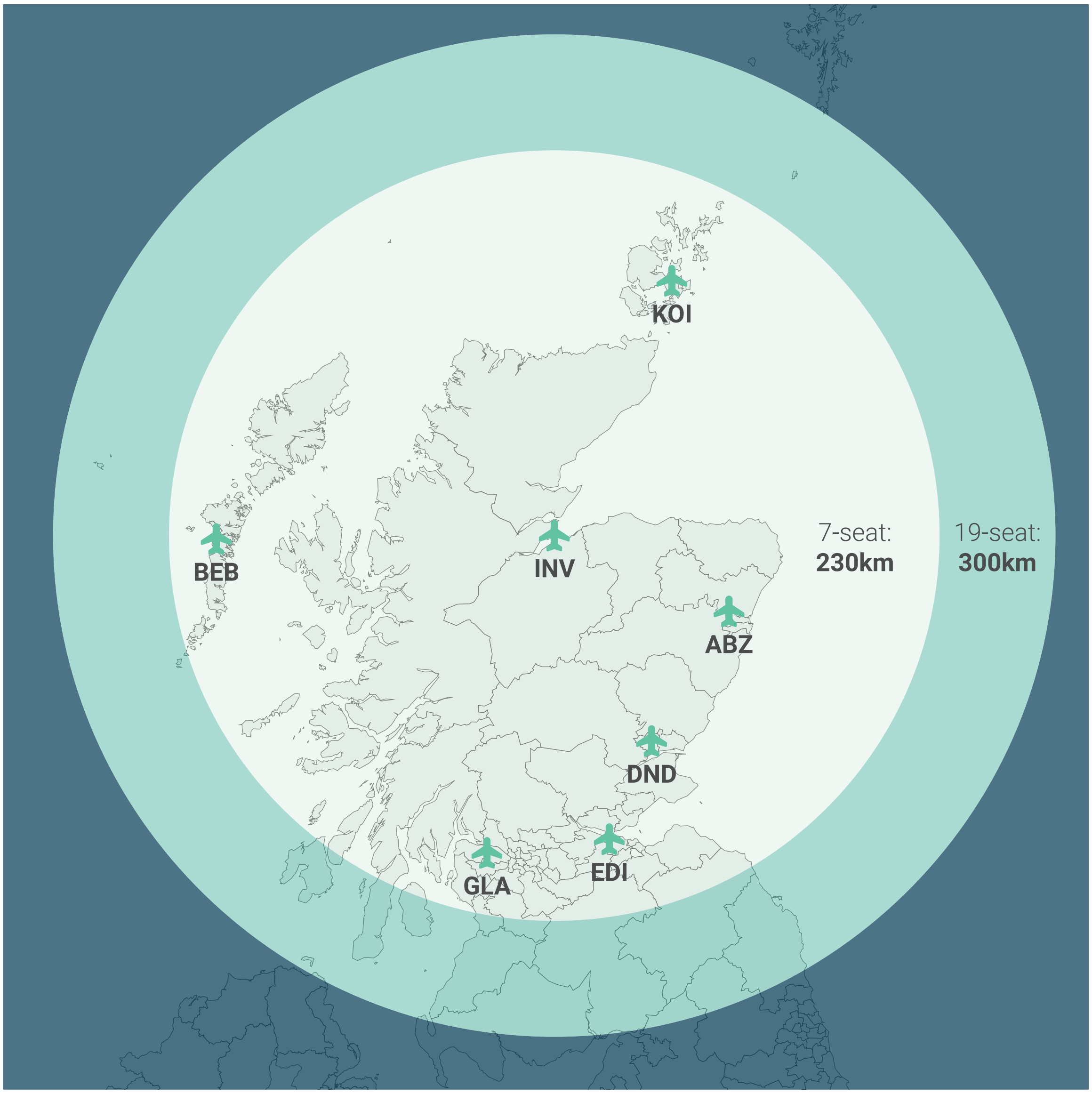
The NAPKIN Fleet

By 2025, 7-19-seater aircraft capable of flights around 200-300km could be operating from small regional airports. In this section we have modelled performance from Inverness Airport, operated by Highlands and Islands Airports Limited (HIAL).

The first hydrogen aircraft are likely to be retrofit. They will not have the performance of new aircraft, but will provide a good basis for the development of new, clean sheet aircraft by 2035.

Due to the reduced volume limitations and short range requirements for sub-regional aircraft, gaseous hydrogen provides a more feasible solution than liquid hydrogen, which is less likely to be available at remote airfields in the near future. For aircraft above 19 seats, there is likely to be a transition to liquid hydrogen storage as the impact of gaseous storage (e.g. weight and volume) become too costly to the aircraft performance.

Figure 1: Range of the 7- and 19-seat NAPKIN aircraft



> THE RANGE CAPABILITIES OF THIS AIRCRAFT CAN COVER INTER-ISLAND AND "PUBLIC SERVICE OBLIGATION" ROUTES, WHICH IS THE MAIN MARKET FOR THIS TYPE OF AIRCRAFT IN THE UK.

In this scenario, retrofitting aircraft such as the Britten Norman Islander (7-seat gaseous hydrogen fuel cell aircraft) and the de Havilland Twin Otter (19-seat gaseous hydrogen fuel cell aircraft) provide the UK with the opportunity to operate commercial zero emission routes inside this decade. NAPKIN modelling suggests that all existing 9-seat aircraft flying scheduled services could be cost-effective to replace by zero carbon alternatives starting in 2025.

Due to the use of existing airframes, these aircraft do not yield the same degree of noise and performance benefit that would be seen from a clean sheet aircraft. Nevertheless, they will help to establish a foundation that the industry can build upon in terms of aircraft certification, fuel handling and distribution, government policy and consumer confidence.

In terms of cost, these aircraft perform competitively as zero carbon alternatives, with maintenance and capital costs being key to their success.

Table 2: Reference and 7-19 seat NAPKIN concept characteristics and performance comparison

NAPKIN Aircraft | Reference aircraft

Concept	CAeS-7	CAeS-19	BN2B-26	DHC-6-400
Seats	7	19	9	19
Airframe Type	Retrofit	Retrofit	-	-
Propulsion System	Fuel Cell	Fuel Cell	Turboprop	Turboprop
Fuel System	Gaseous H2	Gaseous H2	Kerosene	Kerosene
Range (Max Payload)	230 km (124 nm)	300 km (162 nm)	700 km (378 nm)	750 km (405 nm)
System CO_2 Savings per annum (kilotons)	2 – 12 kt CO_2		-	
Total Cost of Ownership/Flight Hour	650 - 850 £/FH	1,000 - 1,300 £/FH	880 £/FH	1,503 £/FH

The Network

The aviation market model utilised in NAPKIN shows a number of examples of where small retrofit gaseous hydrogen fuelled aircraft, carrying between 7 and 19 people can enter the market in the 2020s.

At this stage, and with this technology, there is the potential to operate on key UK lifeline routes as well as connect island economies to the mainland and better serve remote communities. This means that around 9% of flights and 1% of UK domestic passengers could be served by zero carbon aircraft in this decade if the rate of fleet turnover keeps pace with available ZEF aircraft.

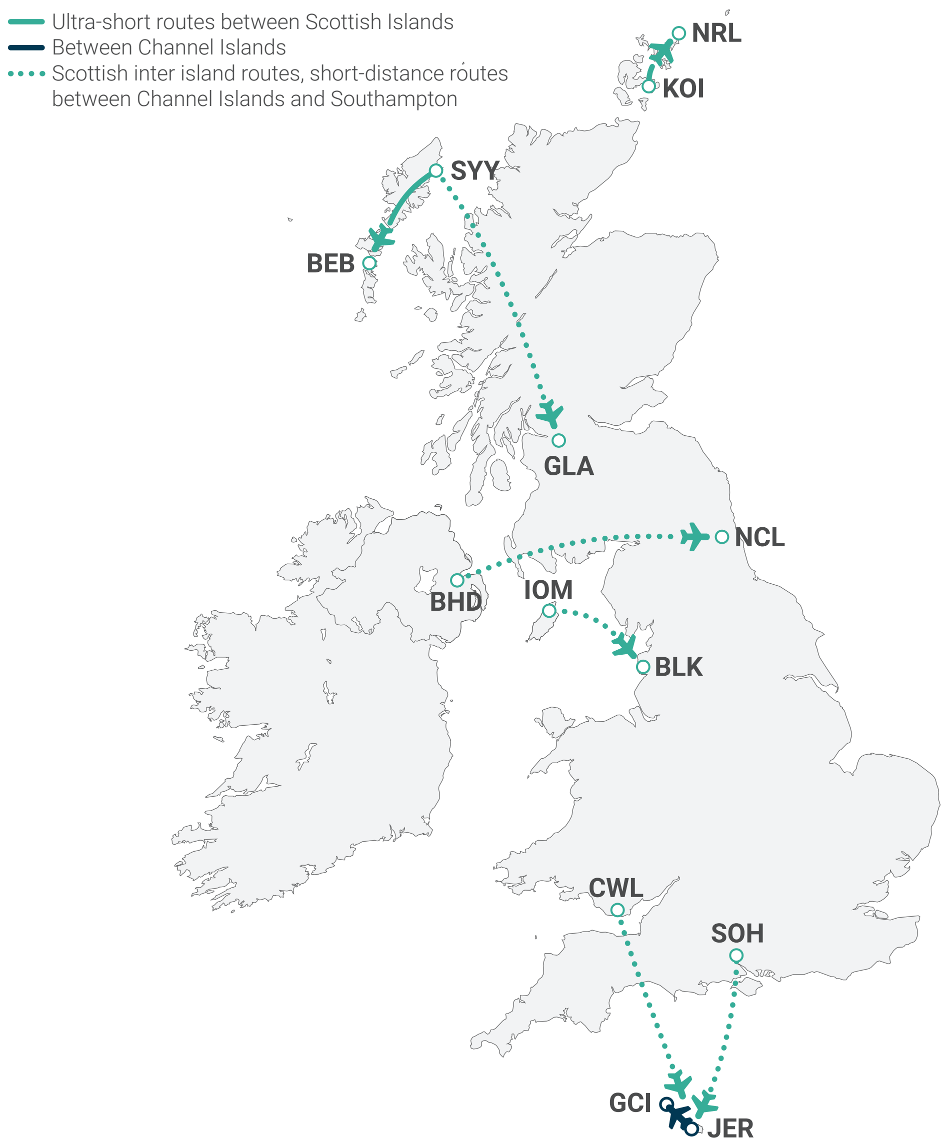


Figure 2: Example routes of the 7- and 19-seat NAPKIN aircraft

Upstream Infrastructure

As hydrogen powered aircraft uptake in the short-term will be limited to ultra-short routes operating from regional airports, demand for hydrogen is expected to start low. Under the NAPKIN 'baseline scenario', annual hydrogen demand at the UK airports studied grows from a low base of nearly 550 tonnes per year in 2025 to 1,600 tonnes by 2030.

It is vitally important that the distribution infrastructure is available to enable this regional uptake. A lack of immediate investment in the necessary upstream infrastructure will directly inhibit the zero carbon opportunity afforded by the NAPKIN aircraft.

For instance, most of the hydrogen being produced in the Scottish Highlands is currently not used within the region but sold to other regions of the UK due to the lack of local distribution infrastructure, which in turn increases the distribution costs. To ensure smaller airports, such as those within the Scottish Islands, have access to this green hydrogen, national distribution infrastructure needs to be the clear focus.

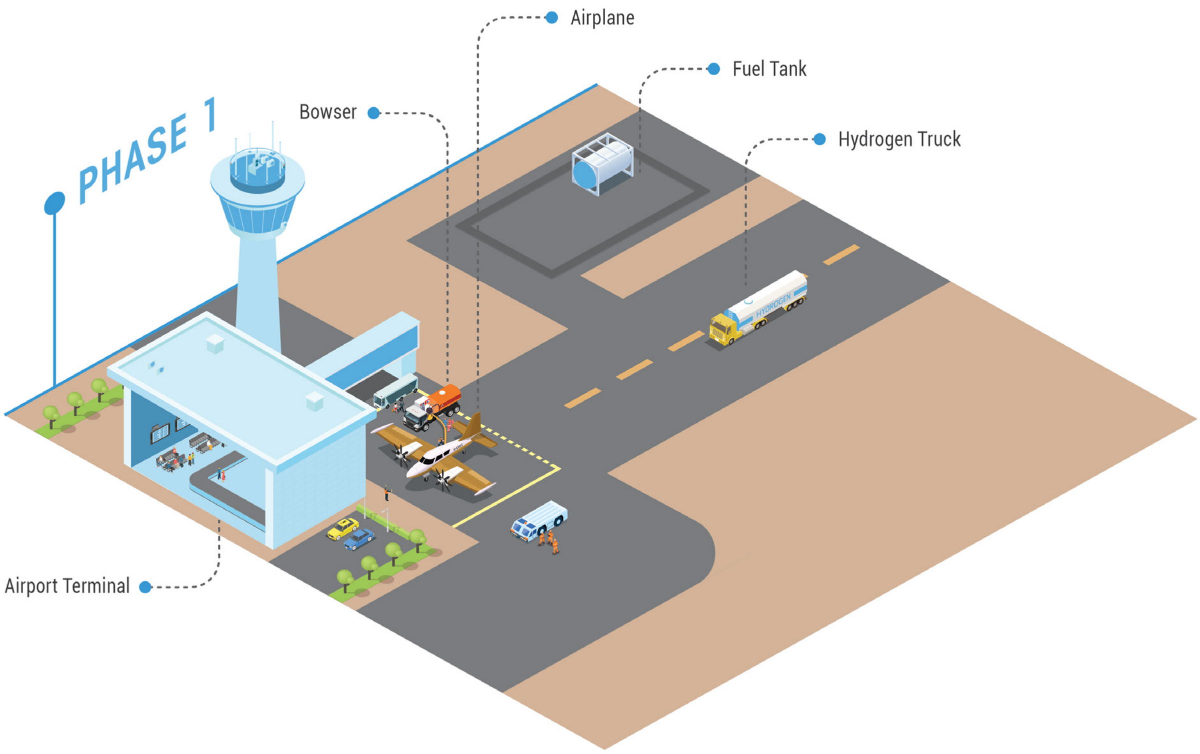
Airport infrastructure

The expected level of hydrogen demand in the early years of adoption will not require extensive or intrusive infrastructure at airports, with road delivery and storage being sufficient. For the smaller airports, road tankers could also be used to refuel the aircraft, avoiding the need for bowsers.

From an airport infrastructure perspective, the limited nature of additional requirements means that hydrogen flight could be integrated into existing operations. During the timeframe presented, this would be particularly viable at airfields and smaller regional airports where there are limited capacity constraints. However, given the financial legacy of the COVID-19 pandemic and the smaller-scale nature of these airports, investment in new infrastructure, as well as training for staff, would have to be carefully considered.

Turnaround times for hydrogen aircraft are likely to increase initially as specific procedures are being developed. However, given the small scale of operations and small size of the aircraft, refuelling challenges associated with this new type of operation should be manageable for airports, given sufficient advanced planning. Moreover, these initial hydrogen refuelling operations will be source of key learning for the future, once the scale of operations increases.

Figure 3: Gaseous or liquid hydrogen delivered to the airport by road and aircraft refuelling using tankers



Carbon impact

While 7-19-seat aircraft represent under 2% of current UK domestic aviation emissions, for smaller airports they can represent the entirety of operations and therefore this is an exciting place from where to launch pivotal new technology. It is anticipated that between 2,000 to 12,000 tonnes of CO_2 emissions per annum could be reduced with the introduction of these zero carbon aircraft into the UK network. This represents around 0.2% to 1.1% decrease in UK aviation CO_2 emissions compared to a scenario with no hydrogen aircraft.

Key Insights

NOW

Zero carbon small retrofit aircraft could be flying by 2025. Modelling shows that once new aircraft enter fleets, they could be a cost-effective replacement for the legacy fossil fuelled fleet of a comparable size.

LEARNING PERIOD

Starting with small commuter aircraft provides airports and the wider industry the opportunity to gain expertise on the key regulatory and compliance issues. Civil Aviation Authority work with NAPKIN pointed to crashworthiness of aircraft, diversion capabilities and design of new refuelling procedures, as some of the key regulatory considerations the industry should focus on in the short-term. Being an active part of this learning and development process will allow regional airports to be at the vanguard of this transformation.

INFRASTRUCTURE

No major overhaul of airport infrastructure will be required in the short-term to accommodate the first ZEF services. However, off-airport infrastructure will need to be in place to enable hydrogen to be delivered to regional airports.

BUILD PASSENGER CONFIDENCE

Early introduction of hydrogen aircraft will help build confidence on this new technology through its safe use. Educating the public about the necessity, urgency and environmental benefit of hydrogen aircraft will be important to ensure future uptake.

TECHNOLOGY ROADMAP – FUEL CELLS

H_2

Fuel cells are a key technology for the NAPKIN aircraft. A novel technology for aircraft propulsion applications, they have the potential to provide zero CO2 and NOx emissions. However, there are some challenges associated with this technology. Further research is required on fuel cell degradation and both fuel cell system and thermal management system mass reduction.

NEED TO ACCELERATE PRODUCTION OF GREEN HYDROGEN

H_2

Accelerating the production of green hydrogen should be a critical focus for policymakers and industry if the hydrogen opportunity represented by NAPKIN is to be delivered. A key driver of this will be the high level of green energy infrastructure required to supply the power needed for both electrolysis and liquefaction.

2035: Liquid Hydrogen Aircraft

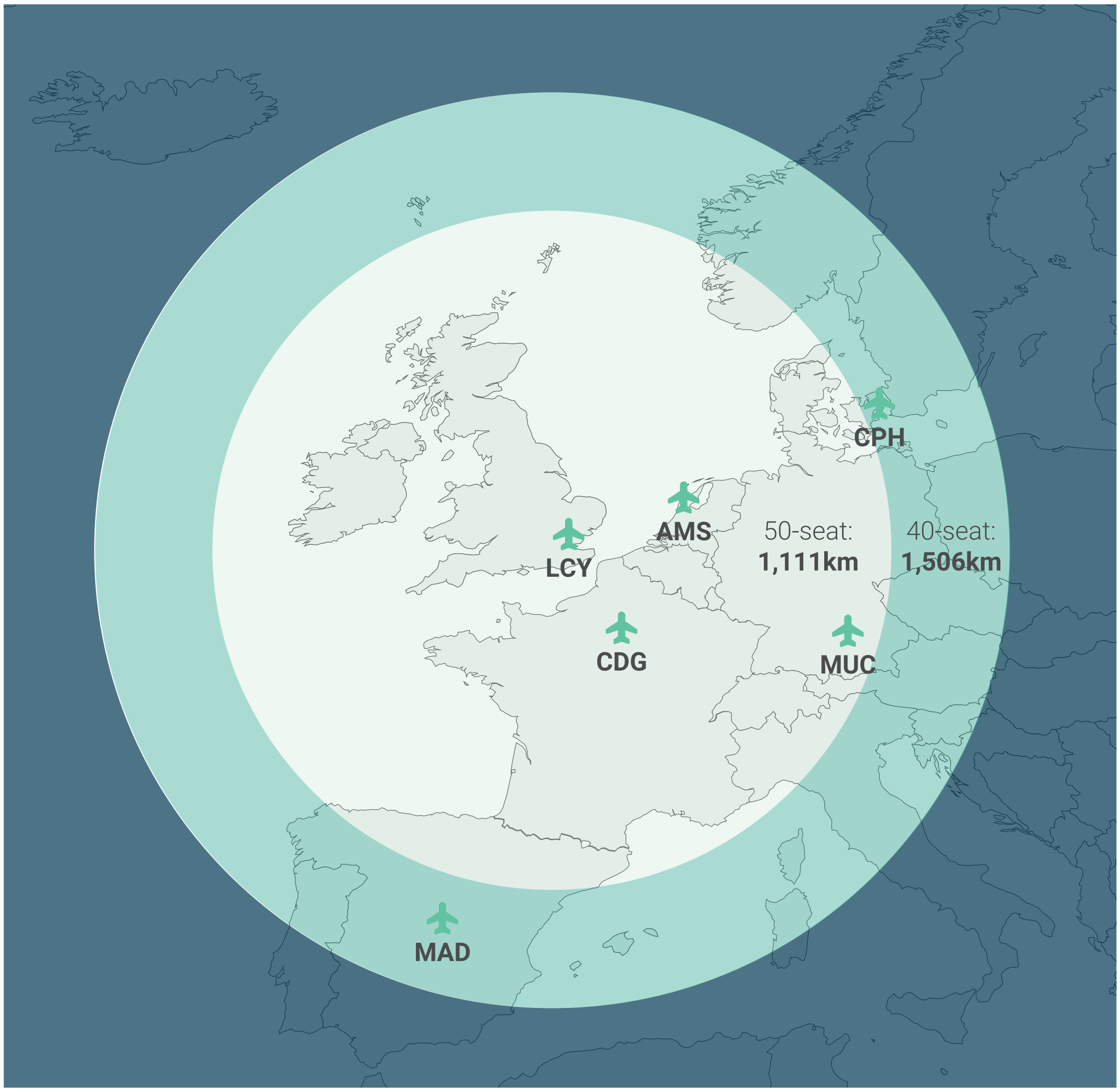
The NAPKIN Fleet

The mid-2030s is expected to be the period when regional hydrogen aircraft start to enter the market. While it may be possible to retrofit aircraft in the regional sector, such as the 48-seat ATR 42-600, earlier in the decade, the consortium believes that concentrating energy on designing, producing and certifying new, clean sheet aircraft should be the area of focus.

With better range, commercial and noise performance, clean sheet aircraft will provide a measurable step change in the potential of zero-carbon emission flight, going from representing around 9% of the UK domestic network up to around 50%. The uptake of the regional hydrogen aircraft has been studied using two clean sheet designs, a GKN 40-seat fuel cell and a Rolls-Royce 50-seat gas turbine aircraft, with performance assessed from London City Airport.

"MODELLING SHOWS THAT BOTH CONCEPT AIRCRAFT HAVE SIMILAR RANGE AND OPERATING COSTS AS THE ATR42-600, WHICH IS A STRONG INDICATOR OF THE POTENTIAL COMPETITIVENESS OF THESE AIRCRAFT."

Figure 4: Range of the 40- and 50-seat NAPKIN aircraft



While operating costs for a new propulsion system are inevitably liable to uncertainty, regional zero carbon aircraft present comparable operating costs to existing kerosene regional aircraft. Further investment and research on fuel cell and combustion related technologies is required to reduce this uncertainty and provide confidence to airlines and manufacturers of their economic viability.

Regional clean sheet aircraft present an overall noise benefit when compared to kerosene regional aircraft. The potential noise gains, however, may not be fully realised until some years later, once there has been enough time for a significant fleet penetration.

Table 3: Reference and 40-50 seat NAPKIN concept characteristics and performance comparison

NAPKIN Aircraft **Reference aircraft**

Concept	GKN-40	RR-50	ATR42 -600
Seats	40	50	48
Airframe Type	Clean Sheet	Clean Sheet	-
Propulsion System	Fuel Cell	Gas Turbine	Gas Turbine
Fuel System	Liquid H2	Liquid H2	Kerosene
Range (Max Payload)	1,506 km (813 nm)	1,111 km (600nm)	1,259 km (680 nm)
System CO_2 Savings per annum (kilotons)	Up to 500 kt CO_2		-
Total Cost of Ownership/Flight Hour	2,500 - 3,050 £/FH	2,600 - 3,050 £/FH	2,954 £/FH

The Network

The modelling work undertaken within NAPKIN shows its 40-50 seat aircraft concepts have the potential to cover around 50% of the UK domestic network and carry 40% of domestic passengers. The 40- and 50 seat aircraft show uptake in routes to outlying regions (Jersey – London City) and between regional airports. At lower hydrogen prices, they also supplement flight frequency on competitive London-Scotland and London-Northern Ireland routes alongside larger conventional aircraft, provided sufficient airport capacity is available. Routes where the 7-19 seat aircraft show an uptake unaffected by the introduction of 40-50 seat zero-carbon emission aircraft, reflecting the specialised nature of their network.

Figure 5: Example routes of the 7, 19, 40 and 50-seat NAPKIN aircraft

Fuel Infrastructure

With the introduction of hydrogen regional aircraft, the demand for hydrogen will increase. Once these aircraft have penetrated the market, the NAPKIN 'baseline scenario' projects that just under 22,000 tonnes of liquid hydrogen will be required to cover the needs of UK airports. This is equivalent to more than a 10-fold increase in hydrogen production from the quantity required in 2030.

Airport Infrastructure

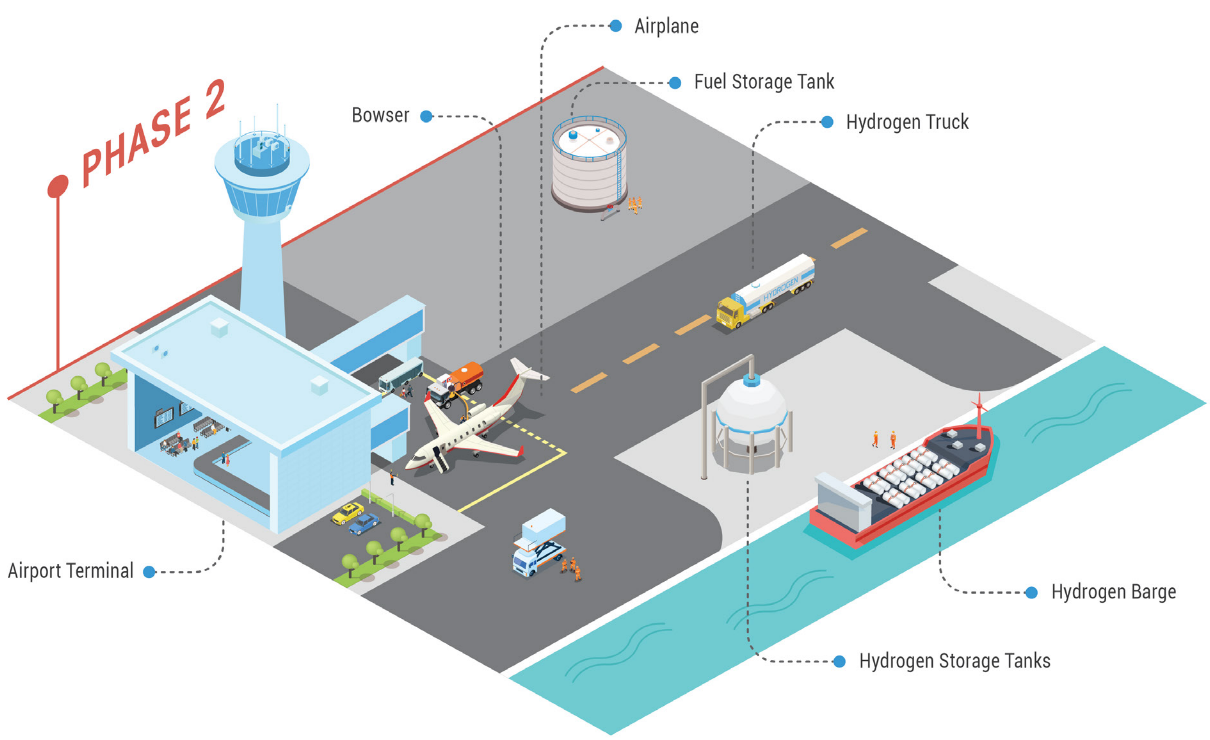
As hydrogen aircraft become more common, by the early 2030s airports will need to start preparing to support hydrogen aircraft movements. Medium-size airports will host quite a diverse aircraft fleet over time and will therefore need to continue to update their infrastructure.

NAPKIN hydrogen demand projections suggest that for most medium-size airports, road delivery, on-site storage and bowser aircraft refuelling will be sufficient to enable zero-carbon emission flight services up to 2035. For example, London City Airport will require just under 1,000 tonnes of liquid hydrogen annually by 2035 which could be delivered either by road or river and stored in cryogenic storage tanks before being delivered to aircraft.

Not withstanding NAPKIN's focus on regional connectivity and therefore aircraft up to 90 seats, some studies suggest that hydrogen narrow-body aircraft could also enter the market from 2035. For airports with a significant number of narrow-body operations, liquefaction on site and potentially parallel refuelling system could be required at later stages due to the higher cost of transporting large amounts of liquid hydrogen and also to avoid road congestion once frequency of daily deliveries is too high.

At this point, with the expected ramp-up of hydrogen demand, providing common hydrogen infrastructure across UK (and EU) airports will be key to ensure airports do not become the barriers for zero-carbon emissions aircraft uptake.

Figure 6: Liquid hydrogen delivered to airport storage tanks and aircraft refuelling using bowsers



Carbon Impact

With the introduction of the 40- and 50-seat aircraft, UK domestic aviation CO_2 emissions could be further reduced, by up to 51% compared with the equivalent conventional aircraft scenarios. This would represent a reduction of up to 500,000t of CO_2. However, the range of potential reduction in UK domestic aviation CO_2 emissions is quite large, reflecting the range in the uptake shown by the NAPKIN fleet, largely due to the uncertainty in future hydrogen, carbon and kerosene prices. Although not modelled within NAPKIN, the reduction in CO_2 emissions could be even higher if these aircraft were also used on some short range UK-EU routes.

By 2035, demand from other industries is likely to have increased, providing some airports the opportunity to establish 'hydrogen hubs' and create economies of scale in hydrogen production and delivery.

Key Insights

HYDROGEN REGIONAL CLEAN SHEET AIRCRAFT BY 2035

Zero carbon clean sheet aircraft could take-off from regional UK airports from 2035 and represent around 50% of the UK domestic network.

GOVERNMENT SUPPORT ON R&D

Operating cost is a key parameter for uptake of hydrogen aircraft. Given the novelty of some of these technologies and their application to the aerospace industry, investment should focus on fuel cell, fuel system and combustion related technologies. This is an area in which the Government can play a critical role. De-risking the economics of introducing ZEF aircraft into fleets is essential to provide airlines and manufacturers the required degree of confidence.

INFRASTRUCTURE

Intrusive airport infrastructure will not be required by 2035, with road delivery and storage tanks presenting the most cost-effective solutions for airports. However, infrastructure and operational changes required to accommodate zero carbon aircraft will need to be accounted for in airport Masterplans to get support and understanding from the local planning authorities.

TECHNOLOGY ROADMAP – LIQUID HYDROGEN STORAGE

Hydrogen regional aircraft will be fuelled with liquid hydrogen. The NAPKIN technology roadmap has identified the Gravimetric Index (GI) of liquid hydrogen storage as a key challenge to resolve to enable the aircraft concepts presented. Strong progress is being made here with sustained research and novel system designs which show promise for meeting the challenging fuel system requirements for aviation.

INTERNATIONAL POTENTIAL

Although the NAPKIN scope has focused on the domestic market, and hence not included larger aircraft designs such as those identified by FlyZero, the performance of the regional designs in the NAPKIN fleet suggests a strong potential for international uptake.

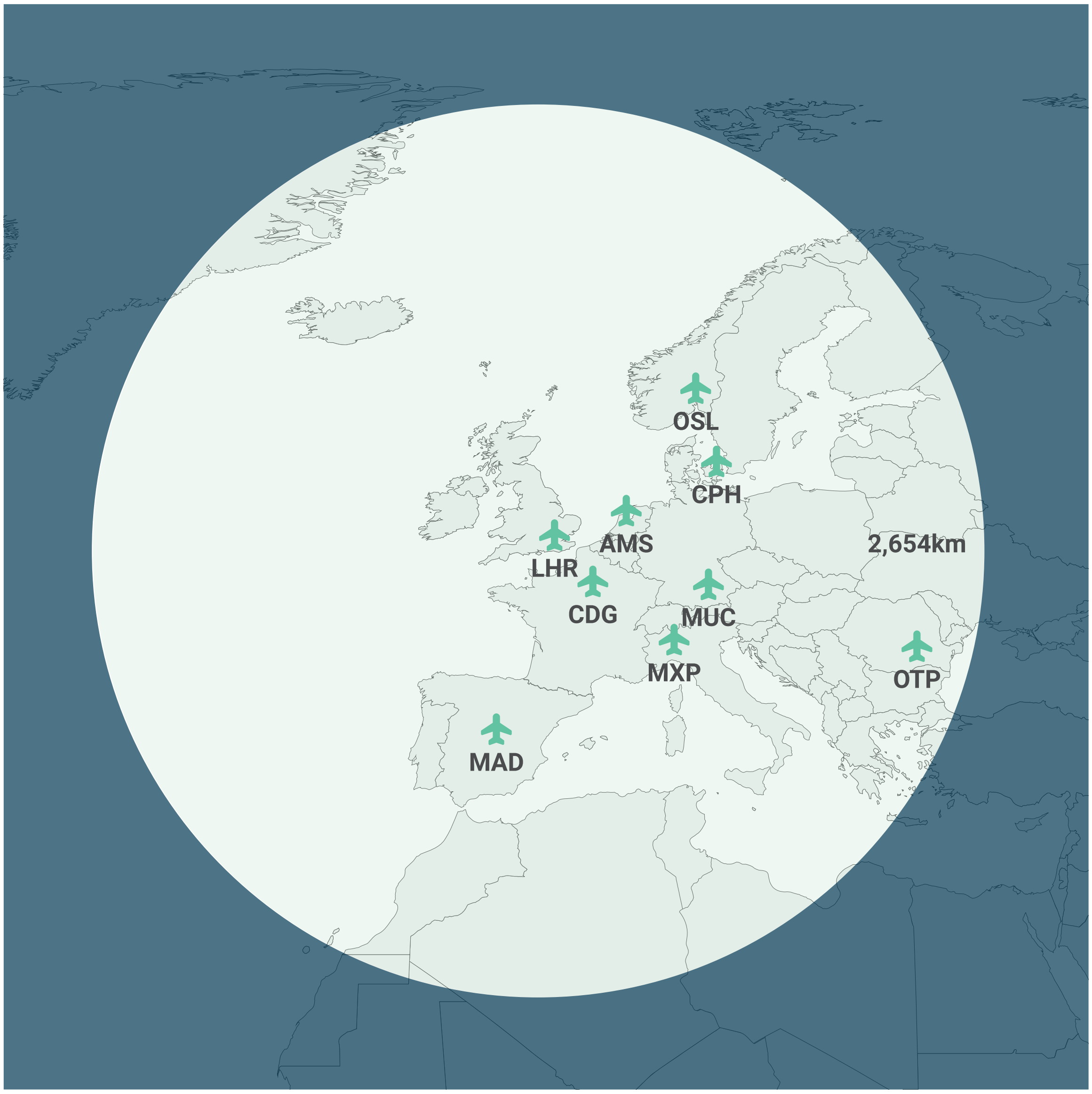
2040: Domestic Aviation Market

The NAPKIN Fleet

The largest NAPKIN aircraft is a 90-seat liquid hydrogen combustion aircraft. An aircraft of this size is likely to have a similar 2035 entry into service date as the 40- and 50-seat regional concepts presented previously. However, a 2040 horizon was chosen to demonstrate the impact on the market once there has been enough time for a level of penetration of at meaningful level of fleet penetration. Once 90-seat ZEF aircraft enter the market, they should be economically viable for airlines to operate at capacity constrained airports and become tangibly relevant for global hubs, such as Heathrow.

Due to various constraints, the NAPKIN consortium has only investigated a hydrogen combustion aircraft of this scale. Further work is required on the viability of fuel cell aircraft at this scale – the focus of a number of other Government funded programs, including GKN Aerospace's H2GEAR programme.

Figure 7: Range of the 90-seat NAPKIN aircraft



> "RANGE AND PAYLOAD PERFORMANCE OF THIS AIRCRAFT ENABLE IT TO ADDRESS 95% OF THE EXISTING GLOBAL REGIONAL MARKET."

Modelling shows that hydrogen aircraft can have comparable operating costs to kerosene aircraft with the potential to be cheaper to operate once economies of scale are achieved and if projections of jet fuel and hydrogen prices are realised.

By 2040, NAPKIN noise analysis suggests it is possible for small and medium airports such as Inverness and London City to achieve lower levels of airport noise relative to a continous growth on movements with conventional kerosene aircraft.. For larger airports like Heathrow, the noise benefit coming from the NAPKIN fleet will be limited due to the dominance of larger aircraft than those studied within NAPKIN. However, other studies suggest that narrow-body and mid-size hydrogen aircraft would also bring noise benefits compared to kerosene aircraft and more research is needed in this area[1].

Table 4: Reference and 90 seat NAPKIN concept characteristics and performance comparison

NAPKIN Aircraft **Reference aircraft**

Concept	RR-90	A220-100
Seats	90	120
Airframe Type	Study Aircraft	-
Propulsion System	Gas Turbine	Gas Turbine
Fuel System	Liquid H2	Kerosene
Range (Max Payload)	2,654 km (1,433 nm)	6,390 km (3,450 nm)
System CO_2 Savings per annum (kilotons)	Up to 1,000 kt CO_2	-
Total Cost of Ownership/Flight Hour	5,900 - 7,600 £/FH	7,492 £/FH

The Network

With the introduction of 90-seat hydrogen fuelled aircraft, it is projected that the entire UK domestic air network could be operated using hydrogen aircraft. The 90-seat aircraft shows higher uptake on busy, competitive routes between London, Scotland and Northern Ireland given its higher seating capacity and thus lower cost per passenger.

It also provides the potential for illustrating the synergy between ZEF and SAF flights. For example, with a ZEF market penetration of 12% by 2040 at Heathrow, there would be the potential to fly in from Belfast on a ZEF flight and fly out to New

1 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

York on a service using SAF.

Figure 8: Example routes of the 7, 19, 40, 50 and 90-seat NAPKIN aircraft

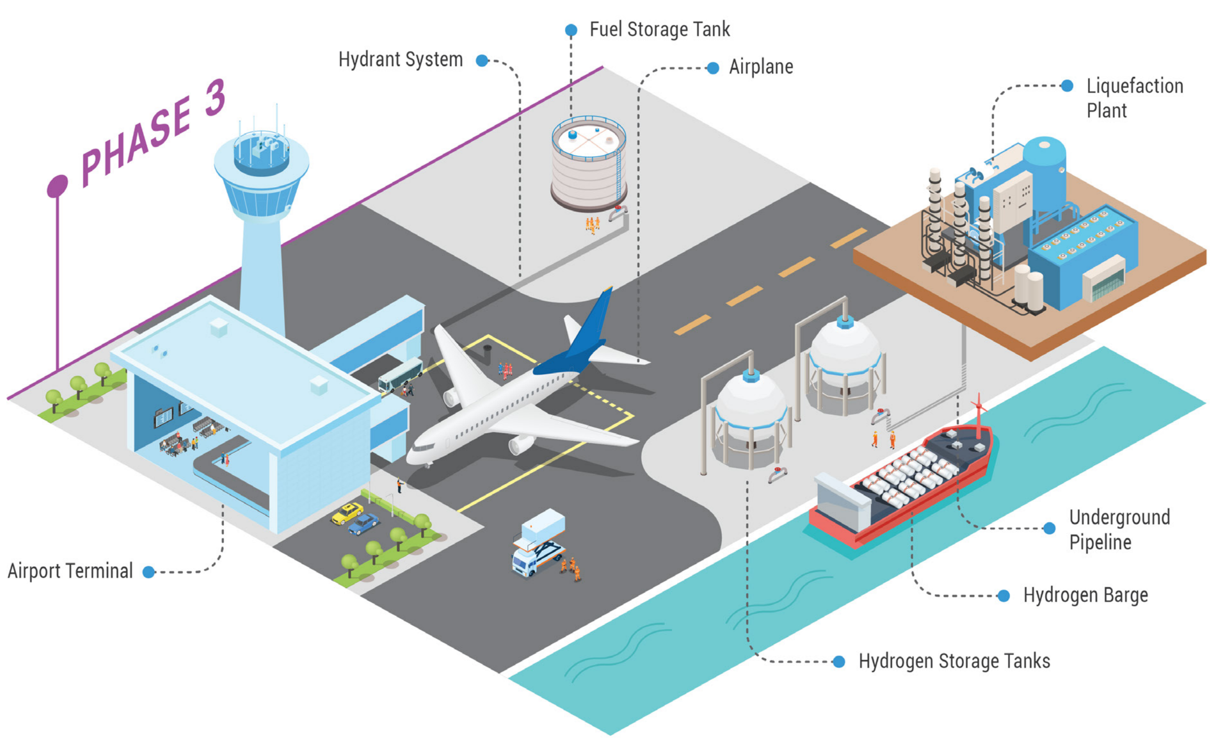
Carbon Impact

By 2040, NAPKIN modelling shows that, under favourable hydrogen, kerosene and carbon prices, effectively all UK domestic aviation CO_2 emissions could be eliminated, helping drive towards the UK government's 2040 net zero ambition. There are three particularly important caveats to this statement: firstly, even if advantageous from an operating cost point of view, airlines still need to acquire new aircraft which could require radically accelerated fleet renewal rates. Secondly, the aircraft production line capacity cannot be taken for granted, as well as the readiness for production of new technologies required for hydrogen powered aircraft. And finally, achieving this outcome without additional incentives to use hydrogen aircraft requires hydrogen prices on the lower end of those projected for 2035-40, and kerosene and carbon prices on the higher end. Therefore, practical achievability of full fleet replacement may occur after 2040 if aircraft enter service around 2035 (i.e., fleet replacement may take longer than 5 years).

Airport Infrastructure

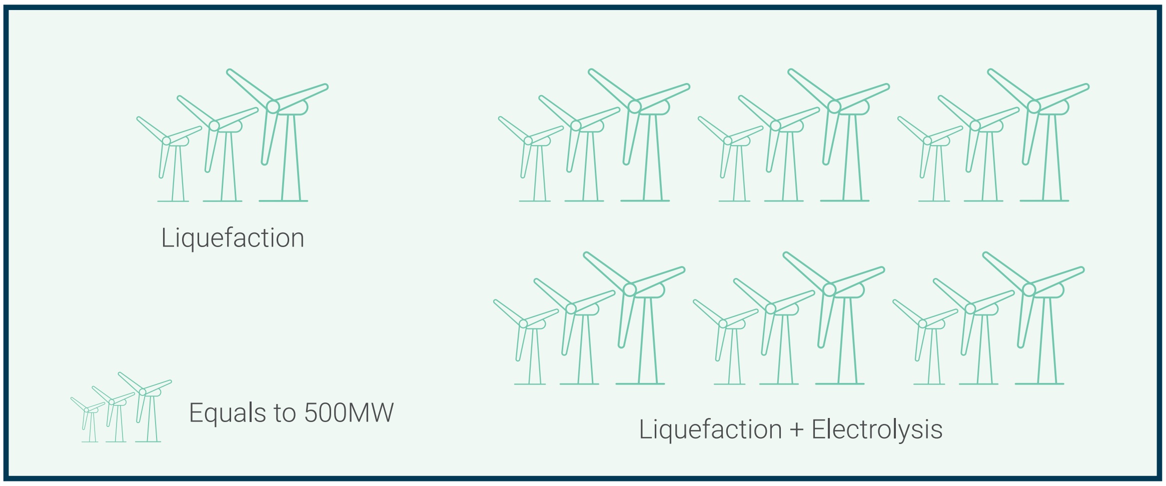
It is from 2040 that the projected hydrogen demand will have significant implications for larger airports around the country. Hydrogen delivery by road tankers will no longer be feasible at larger airports as they would be too costly and greatly increase ground traffic and pose logistical challenges. At that point, pipeline distribution and liquefaction on-site seems the most viable solution to avoid road congestion. For these airports, one of the main challenges will be securing the necessary space to locate these facilities as airports are often already space constrained

Figure 9: Gaseous hydrogen pipeline supply to the airport, on-site liquefaction, permanent storage tanks and aircraft refuelling via a hydrant system



Another factor to consider when it comes to liquefaction on site is the amount of electricity required. For example, by 2050, once there has been enough time for a reasonable level of fleet penetration of twin-aisle hydrogen aircraft, hub airports such as Heathrow could require almost 500MW for liquefaction, significantly higher than existing network capacities. Power requirements, along with space limitations, are also likely to be the main barrier to produce the hydrogen at the airport. Liquefaction and electrolysis would demand between 3.0 – 4.0 GW by 2050 for larger airports. To put these figures into context, the UK installed nuclear capacity in 2020 was c. 9 GW[2]. The complexity to implement the required scale of transmission grid work will most likely rule out the feasibility of hydrogen production at the airport, given current UK industrial strategy.

Figure 10: Energy requirements for on-site liquefaction only and on-site liquefaction and electrolysis



(figures based on NAPKIN 'baseline scenario' for Heathrow Airport in 2050)

Refuelling operations will also present some scalability challenges. Liquid hydrogen refuelling trucks could still be viable for smaller airports, but for larger airports would likely become unpalatable from a cost and local community point of view, and encounter space limitations airside. In the longer term, LH2 hydrant pipeline systems seems the most viable solution for aircraft refuelling, although aspects such as operational disruptions during the installation period, a potential requirement to divert some of the existing underground utilities, and the cost of this infrastructure will need to be carefully considered. Also, standardisation of refuelling infrastructure will be required to ensure compatibility with any hydrogen aircraft and thus, not limit its use to specific airports or regions.

When it comes to turnaround times, based on existing refuelling technology and processes, refuelling times would likely increase for larger aircraft. Automation of the refuelling process would create an opportunity to speed up the turnaround time as well as reduce the associated risks. It is not expected to be a feasible short-term solution as the technology is not available, but should be subject to future research.

2 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/789655/Nuclear_electricity_in_the_UK.pdf

Key Insights

UK NET-ZERO AVIATION NETWORK BY 2040

Safe, certificated zero carbon aircraft could be serving the entire UK domestic network from 2040.

BALANCE BETWEEN SUSTAINABLE AVIATION FUELS AND HYDROGEN

SAF and ZEF are complementary and will both be required to get to net zero. SAF powered aircraft can serve any market, including long-haul, but can equally power regional aircraft. With hydrogen likely to enter service on smaller aircraft, it presents the opportunity to focus available SAF on longer routes.

OPERATING COSTS WILL NOT BE A BARRIER FOR UPTAKE

For the NAPKIN fleet of hydrogen aircraft (both fuel cell and combustion), operating cost is not perceived to be a barrier to a zero-carbon emission UK domestic aviation system in the 2040s. This is provided that the price of hydrogen follows the current government predictions.

SIGNIFICANT NEW INFRASTRUCTURE WILL BE REQUIRED AT LARGE AIRPORTS

By 2040, new infrastructure will be required at large airports to introduce parallel fuel systems and liquefaction on site. To maintain turnaround times within existing standards, the refuelling process may need to be partially or fully automated.

POSITIVE IMPACT ON AIRPORT NOISE

Analysis of the noise footprints from the NAPKIN fleet provides optimism that local airport noise levels can be reduced, relative to the base case, once penetration levels are noticeable and operations optimised.

UK GOVERNMENT EMISSIONS TARGET

By 2040, UK domestic aviation CO2 levels could meet the UK Government’s 2040 net zero ambition if favourable hydrogen prices are achieved and the fleet can be renewed quickly – a policy opportunity.

UK HYDROGEN STRATEGY

Further development of UK hydrogen strategy, including how aviation will fit with demand from other sectors, is of fundamental importance and a top priority issue.

TECHNOLOGY ROADMAP – HYDROGEN GAS TURBINE

The larger NAPKIN aircraft, the 90-seater, has a hydrogen gas turbine as its propulsion system. Although gas turbine technology has been operating in an aerospace environment for more than 75 years, some key changes are required to allow current technologies to operate on pure hydrogen. For instance, due to a higher flame temperature, there is the risk of higher NOx emissions. Counteracting the potential NOx and contrail emissions will require further research and investment in advanced combustion technologies.

Hydrogen Demand

Understanding the level of hydrogen supply required to support hydrogen air transport over the coming years will assist with the planning and phasing of hydrogen production facilities in the UK and support efficient development of related supply and delivery infrastructure.

Given that future demand for hydrogen will not only come from aviation but also from other sectors, determining aviation's contribution to the overall demand landscape will assist in planning hydrogen production capacity and transportation at a regional level.

In order to provide a comprehensive picture of the volume of hydrogen demand at airports, national production requirements and national infrastructure, NAPKIN also modelled the hydrogen demand from larger concept aircraft developed by the FlyZero[1] project (i.e., short-haul and medium-size aircraft) as well as the demand coming from international services.

The table below presents the three scenarios generated reflecting hypothetical future outcomes of hydrogen aircraft uptake up to 2050.

Table 5: Scenarios for hydrogen supply

Scenario	Description
Upside	Optimistic, ambitious scenario that assumes more rapid uptake of hydrogen aircraft in the market and a preference for hydrogen over SAF up to 2050.
Baseline	A balanced scenario, where carriers adopt both hydrogen aircraft and SAF technology up to 2050. For those cases in which a mixed fleet operation is likely to not be cost effective for airlines, it is considered SAF aircraft will be chosen instead.
Downside	A more pessimistic, less ambitious scenario where penetration of hydrogen aircraft is far more limited, with a preference for SAF and current technologies predominating to 2050.

1 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

Under the 'baseline' scenario, NAPKIN projects that UK aviation could require just under 1.3 million tonnes (43 TWh) of hydrogen annually by 2050. This rises to 2.9 million tonnes (99 TWh) for the more 'optimistic' scenario, whereas the more 'conservative' scenario sees demand at 0.4 million tonnes (14 TWh).

To put these figures into context, the British Energy Security Strategy[2] doubled the UK target of low carbon hydrogen annual production to 10GW (88TWh[3]) by 2030. Although it is not clear how much of this supply will be available for aviation, this production could meet the demand coming from the UK air transport until 2050 under the 'baseline' scenario (Figure 11).

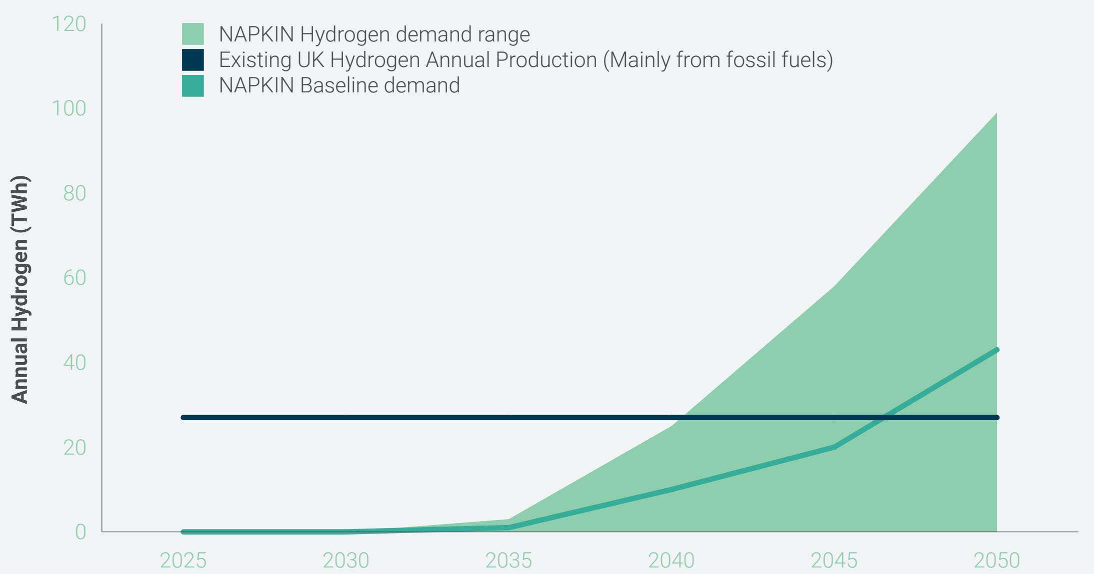
Demand for green hydrogen in the aviation sector, however, will not only come from hydrogen powered aircraft (as early as 2025) but also from the production of Power-to-Liquid (PtL) SAF. Accelerating the production of green hydrogen should therefore be a critical focus for policymakers and industry across UK-EU if the estimated timelines under NAPKIN and other studies are to be met. In this regard, other countries within the EU have also published national hydrogen strategies in which hydrogen production targets have been established.

For instance, Germany's hydrogen plan from 2021 sets a target of 5GW hydrogen generation capacity by 2030 with an additional 5GW of capacity by 2035, if possible, but no later than 2040[4]. The new German Government however, recently announced its intention to double this target to 10GW of green hydrogen electrolyser capacity by 2030[5].

France has also made its first regulatory steps towards increasing its hydrogen production capabilities with a target of 6.5 GW of electrolysis capacity by 2030[6]. With markets adjacent to the UK having similar production targets, the importance of scaling up green hydrogen supply is a clear necessity and economic opportunity.

2 https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy
3 Assumption: 8,765 hours full-load of electrolyser operation and an efficiency ratio of 100%
4 https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6
5 https://fuelcellsworks.com/news/germany-to-double-2030-hydrogen-production-target-to-10gw/
6 https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/090820-france-cranks-up-hydrogen-plans-with-65-gw-2030-target-plays-down-new-nuclear

Figure 11: Comparison between NAPKIN forecast hydrogen demand with UK existing hydrogen production



Over the years, the larger proportion of hydrogen demand will shift from regional airports to larger airports (Figure 12). To begin with, regional airports will attract the majority of the hydrogen demand, reflecting the nature of smaller, short-range hydrogen aircraft expected to enter the market first. By then, hydrogen is likely to be produced only in a few areas across the UK. To enable this regional uptake, however, distribution infrastructure will need to be planned and developed in advance.

Later, with the entry into service of the larger aircraft (i.e., narrow-body and mid-size), the overall hydrogen demand will be driven by the larger UK airports. By then, demand from other industries is also likely to have increased, providing the opportunity for some airports to create 'hydrogen hubs', minimising the cost of infrastructure and leveraging economies of scale in producing and delivering hydrogen to consumers.

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