Project NAPKIN

Interim Report

Making Zero Carbon Flight a Reality in the UK

- Project NAPKIN (New Aviation Propulsion Knowledge and Innovation Network) expects zero carbon emission flights (ZEF) to begin in the UK in 2025.

- ZEF can be scaled up to connect regions of the UK by 2030 and meet the Government's ambition of a zero-carbon emission flight network in the UK by 2040.

- This interim report shows that 9 and 19 seat aircraft can viably operate on 'lifeline routes' mid-decade, with 19 and 48 seat aircraft being deployed on regional routes, including between London City and Dundee Airports around 2030.

- The next phase of research will investigate the viability and carbon impact of up to 100 seat ZEF services on core UK trunk routes like Heathrow to Edinburgh and will include market ready future aircraft concepts.

- The first ZEF flights will most likely operate from small airports operating short hops, such as those in the Scottish Highlands and Islands and to and from the Isles of Scilly and the Channel Islands. They will use gaseous hydrogen, which can be delivered by truck using existing supply chains, with liquid hydrogen used for longer routes.

- Ultimately major new infrastructure will be required at larger airports potentially involving pipeline, liquefaction, storage, and upgraded delivery to aircraft, but at the point of introduction, a small number of deliveries by road will be sufficient to support core routes.

- The consortium will present its full findings in April 2022.

Introduction to Project NAPKIN

One year on from being selected by Innovate UK as a Future Flight Project, this interim report outlines progress made to date on establishing the conditions required to make zero emission flight in the UK a reality.

Formed in November 2020, the consortium features 3 airports/airport groups (Heathrow, London City, Highlands and Islands), 3 manufacturers (GKN Aerospace, Rolls-Royce, Cranfield Aerospace Solutions), 3 academic institutions (University College London, Cranfield University and the University of Southampton) and Deloitte.

NAPKIN is evaluating each part of the future aviation system, creating modified and original aircraft concepts to explore their impact on the five 'A's of Aircraft, Airport, Airspace, Airline, and Air Passenger. In doing so, it is shedding light on the ground infrastructure, energy demand, noise performance, and passenger response. It sets out a viable flight network, taking account of aircraft range, routes and the way in which commercial viability and scale can be achieved.

The work of the consortium is focussed on helping UK Government, and the industry more broadly, better understand the opportunities, challenges and potential timelines associated with zero carbon emissions flight (ZEF).

While the focus for the consortium is the UK market, it is expected that the learnings can be applied across markets globally. It is also the shared view that hydrogen-based ZEF solutions represent the best opportunity to reach zero carbon flight and are the natural complement to Sustainable Aviation Fuels (SAFs).

The UK's Aspiration and Potential to be a Global Leader

In the Department for Transport's 2021 Jet Zero Consultation the industry has been asked whether establishing a 'net zero' domestic aviation network in the UK is possible. International airline operators in the UK do not currently use a dedicated domestic fleet. However, the initial insight generated by the consortium is highly promising that it could be achieved, given the route network that exists today, the potential of the hydrogen fuelled aircraft studied so far and dedicated policy effort.

Based on retrofitting existing certified aircraft, preliminary findings from NAPKIN indicate that zero carbon emissions, hydrogen fuelled, aircraft could operate in the mid-2020s on lifeline services such as between Glasgow and Campbeltown. Later in the decade ZEF could make a meaningful contribution to UK regional connectivity, for example connecting Dundee and London City Airport, as well as, subject to viable commercial models, on some of the busiest domestic aviation routes in the UK.

And while UK regional aviation connectivity is comprehensive today, with the potential of zero emission aircraft with seat capacity ranging from 19 to 48 seats this decade, then there exists an opportunity to expand regional aviation connectivity as we know it. This may have the potential to boost small and regional airports such as Manston, Coventry and Carlisle, helping to drive economic equality across the UK and complementing other transport modes to deliver net zero. Taking the lead in the zero carbon emissions flight agenda could also be a boon for the UK's research and development industry, as the country pivots towards a low carbon economy.

It is also crucial for ZEF to be considered optimally within an overall UK decarbonisation roadmap and industrial strategy. Hydrogen has many existing or potentially competing uses, in other sectors such as road transport and home heating. Equally, hydrogen is expected to be a key requirement of future synthetic sustainable aviation fuels. Therefore, the outputs from NAPKIN need to be considered in this broader context as policymakers grapple with the question of which technologies to support in this area and investors consider options to both supply and, over time, further develop hydrogen infrastructure in the UK.

Aircraft

Project NAPKIN has so far considered a range of aircraft concepts covering sizes from 7 to 100 seats using various different hydrogen architectures for their propulsion. As Innovate UK's 'Future Flight' programme and project NAPKIN are focussed on regional and sub-regional aviation, its focus will extend only as far as 100 seats.

The following table shows the expected take-up of UK and inter-European routes using zero carbon and zero greenhouse gas-emitting aircraft. What is clear from our analysis is that one size and one technology will not fit all requirements. It is likely that a range of aircraft sizes will be in operation, more so than today. Smaller aircraft will serve shorter routes or those that are vital for connectivity, but with lower demand, with larger aircraft for the longer range or busier routes in the UK and into Europe for which the propulsion system will differ.

The level of take-up of these zero-carbon aircraft will depend on several factors, ranging from level of operational costs through to taxation and incentives. In its next phase NAPKIN intends to further explore sensitivity to these factors.

Aircraft	Passengers	Type of operation	Location	Fuel source	Emissions	Example routes
	7-9	Short hops, island-mainland, inter island, public service routes	Typically coastal/ island groups	Gaseous hydrogen (fuel cell)	Zero GHG	Land's End-Isles of Scilly Kirkwall-Orkneys Southampton-Channel Islands
	11-19	Regional - within UK countries & cross border (short trips) Island-mainland Public service routes	Coastal & inland	Gaseous or liquid hydrogen (likely fuel cell)	Zero GHG	Glasgow-Barra Norwich-Exeter Birmingham-Isle of Man Glasgow-Derry
	19	Regional - between UK countries on less busy routes due to number of passengers	Coastal, inland & to Europe	Liquid hydrogen (fuel cell or combustion)	Zero carbon / GHG	Birmingham-Inverness Aberdeen-Bristol Aberdeen-Dublin Derry-Stansted
	40-50	Regional - more busy routes within UK & into Europe	Coastal, inland & to Europe	Liquid hydrogen (fuel cell or combustion)	Zero carbon / GHG	London City-Rotterdam London City-Belfast Southampton-Edinburgh Hamburg-Heathrow
	70-100	Short to medium haul; pan European	Cross continent	Liquid hydrogen (combustion)	Zero carbon / GHG	Heathrow-Madrid Heathrow-Reykjavik Gatwick-Menorca London City-Rome

GHG – Greenhouse Gas emissions

Airports

One of the key challenges for airports is understanding how their physical infrastructure will need to be adapted, and over what time horizon, to accommodate zero carbon emission flights. Key issues relate to changes to refuelling processes and supporting infrastructure, as well as safety considerations around the safe storage and handling of hydrogen alongside traditional kerosene aircraft.

Encouragingly, early indications from this work suggest that, at least initially, the level of adjustment needed to accommodate new aircraft types should not be overly intrusive. Until new ZEF aircraft are adopted in significant numbers, a model based on road (or river, or rail) delivery will not differ markedly from existing refuelling processes.

It could be assumed that given a 25-year average operational life of an aircraft, an introduction into fleets at a rate of 4% per year for like-for-like aircraft would occur on average. There's no existing evidence to suggest initial acquisitions would be more rapid, although this warrants further investigation with the consortium's advisory board[1].

Based on the profile of the aircraft studied by the consortium to date, initial analysis suggests local airstrips and airports that offer a high volume of regional services represent a logical initial focus for achieving significant scale of ZEF operations. Until larger narrowbody ZEF aircraft become available the above renewal rate will have limited impact on larger UK airports, and these aircraft are not currently expected until after 2035. We use a simple illustration to model the impact from 2030 to 2035:

In a sample of Heathrow 2019 data (drawn from four randomly selected months) aircraft with 120 or fewer seats represented 2.7% or 12,750 flights. Using this baseline figure, not accounting for any growth in air traffic, at a rate of 4% introduction of up to 120 seat ZEF from 2030, this would equate to about 500 flights in 2030, climbing to around 2,500 per annum by 2035. From the case studies below, it is possible to see that one liquid hydrogen delivery by truck per day at Heathrow would be sufficient to support ZEF flights, at least until 2035.

From a London City perspective, domestic services made up roughly 20% of its entire flight schedule in 2019. As illustrated below, with the necessary infrastructure in place, two deliveries of hydrogen per day would be required to facilitate its entire domestic schedule becoming ZEF. The modelling has assumed delivery of hydrogen by road but some airports, given their specific geography, and in the case of London City proximity to the River Thames, may be able to develop alternative solutions.

[1] NAPKIN Advisory Board consists of: AGS Airports Ltd, British Airways/International Airlines Group, Easyjet, Ferrovial, Jacobs, Manston Airport (representative), NATS, Loganair, UK Power Network Services.

Case studies –
introducing the ATR-72-600 LH2 concept aircraft into London City

Further analysis, validated by airlines, will help to inform future capital investment programmes for airports. Optimising solutions to enable turnaround times comparable to current performance will very likely be required in order to achieve viable operating costs. This should be done alongside an assessment of the size and location of storage facilities and delivery solutions that, over time, eliminate the need for transportation of liquid hydrogen by road.

Case study 1 would likely generate few challenges for London City, nor any airport. However, with case study 2, the potential to require around 8,700kg (approximately 123,000 litres) of liquid hydrogen on site daily, combined with the airport's location, may require investigation of alternatives to road delivery, with permanent storage solutions on site.

The final report will also compare the full suite of NAPKIN scenarios across the three airports with commentary on the implications for the future of hydrogen production, use and distribution in the UK and identify possible solutions for the consortium airports. This will include consideration of alternative configurations of both off-site and on-site production, delivery (including by road, rail, river and pipeline) and storage.

A central question remains the level of production and supply of green hydrogen in the UK required to fulfil demand. This remains a key, and as yet unresolved, issue for policy makers to consider.

1: LCY to Dundee only

Number of flights per year: 572 (2019 data)

Range of aircraft: 1366km

Tank Mass & Reserve Tank Mass: 698kg (mission) + 177kg (reserve) = 875kg

Annual Amount of Liquid Hydrogen Required: 213,320kg (equivalent to 2,999,282 litres)

Daily Delivery of Hydrogen per day (by truck): 1 truck, carrying 1000kg of LH_2

2: LCY to 2019 Domestic Destinations (EDI, GLA, JER, DND, ABZ, BHD, EXT, IOM, MAN)

Number of flights per year: 9,726 (2019/2020 data)

Range of aircraft: 1366km

Tank Mass & Reserve Tank Mass: 698kg (mission) + 177kg (reserve) = 875kg

Annual Amount of Liquid Hydrogen Required: 3,168,832kg (equivalent to 44,553,779 litres)

Daily Delivery of Hydrogen per day (by truck): 2 trucks, each truck carrying 4,500kg LH_2

Airspace

The impact of the introduction of ZEF on airspace management is a critical aspect, representing one of the potential barriers to adoption given that airspace changes take many years to design, consult on, and implement.

The aircraft concepts so far produced for NAPKIN have predominately based on existing airframes, and assume performance characteristics broadly consistent, meaning that they would be capable of operating in UK airspace as it exists today.

However, UK airspace is being modernised. This sets up important considerations for manufacturers, airports and policy makers, and will be included as a key focus for the design of novel, 'clean sheet' concept aircraft through the remainder of the project.

The process is expected to conclude towards the end of the decade, around the time that the first services from larger airports are viable. In order for any associated new requirements to be factored into airspace design and consultation, they need to be built into the process within the next few years.

Where economic viability of zero carbon emissions aircraft may be proven to rely on (or even be optimised by) operational changes, such as speed, take off angle, or cruise altitude, it is imperative to determine the extent to which airspace design could take account of these requirements to help accelerate their adoption.

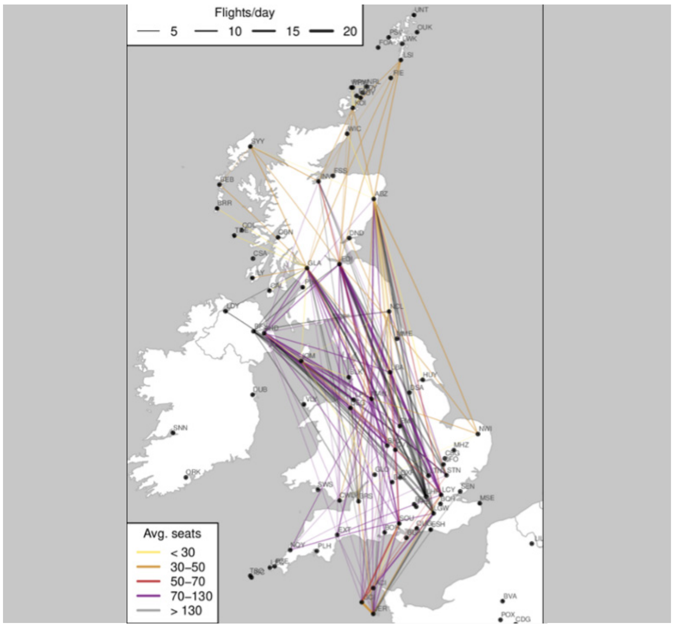
At an airport close to capacity, like Heathrow, any new aircraft requirements could have significant system-wide effects. For instance, the 'time-based separation' approach used to optimise arrivals and departures may need to be modified to optimise use of airspace in favour of new ZEF, without a detrimental impact on existing aircraft.

For London City and Heathrow, and other airports close to major centres of population, any trade-offs between noise and carbon emissions reductions will be essential to set out and will represent a complicating factor. NAPKIN is exploring noise impacts to help inform its final phase of work on new aircraft concepts.

Airlines

Potential Routes
There are routes in the UK, for example between the mainland and the Scottish islands, that depend on air connectivity. The map below shows the UK domestic scheduled flight network in 2015. Examples of aviation-dependent routes include those between the Orkney and Shetland Islands and Outer Hebrides, routes to and from the Channel Islands and the Isles of Scilly, and connections between Northern Ireland and the rest of the UK.

Common to these routes is limited potential for ground connectivity, suggesting an ongoing need for continued air service.



UK domestic scheduled flight network, 2015

Both the Islander (9 seats) and Twin Otter (19 seats) could operate these routes. Given the specific nature of lifeline routes, the consortium believes, based on the current flight frequency, that 24 reconfigured aircraft would be required and that lifeline routes could be entirely zero emissions during the second half of the 2020s, given the right package of policy support to accelerate manufacturing – also building the potential for the UK to capture export markets. Policy support to underpin operating costs may also be required as the market becomes established. This will be explored in full in the final report.

The ATR 72-600 based concept offers significant regional connectivity potential across the UK. Its capacity of 48 lends itself to replicating regional routes like Derry to Stansted, Southampton to the Channel Islands, as well as replacing the existing PSO route between Dundee and London City Airport by the end of the decade.

And given the range of the ATR 72-600 concept, it could, for example, operate on one of London City's busiest routes, to Edinburgh. Currently it is served by an Embraer E190 with a 98-seat capacity. However, with a significant proportion of business traffic, and with the potential for a zero-carbon version of the aircraft to enter operation by 2030, commercial models could be explored that make the route economically viable. The consortium is presently analysing the results of surveys looking at whether passengers would be willing to pay more for zero-carbon aircraft, and if their availability would affect their decisions about whether or not to fly and which airport to fly from.

A key goal for the consortium has been to demonstrate the scalability of zero emission aviation in the UK. Existing routes have been studied for purposes of illustration, but given the range and performance of the aircraft, it is feasible for new zero-carbon routes to be considered, subject to supply and airport infrastructure considerations. Similarly, new business models on existing routes might become possible, for example providing higher frequency services with smaller zero-carbon aircraft.

In the final report the consortium will look to demonstrate how a small narrowbody aircraft could be powered by hydrogen and operate on core UK domestic aviation trunk routes into the nation's hub airport, Heathrow.

Early Operational Cost Insight

Research to date has focussed on regional routes flown by the Islander and DHC-6 to model the likely operational costs of these new aircraft types. Using example routes between Kirkwall (KOI) to North Ronaldsay (NRL) and Glasgow (GLA) to Campbeltown (CAL). The model considered multiple factors, including the cost to convert aircraft to Hydrogen operations, sector length, passenger numbers, fuel burn, aeronautical charges (including landing fees and en route ATC charges) and likely maintenance costs.

While modelling of the operating costs of larger aircraft concepts is ongoing, early results suggest that the higher passenger numbers on larger aircraft may help drive further cost advantages over equivalent kerosene aircraft, and compared with smaller aircraft types.

Consistent with current technologies, early indications from the model show that the operational costs of new aircraft types will be closely linked to the number of passengers and payload capacity of the aircraft. Where accommodating liquid hydrogen fuel tanks (which have to be located in the fuselage, rather than the wings) requires removal of seating rows, this will pose a challenge for operators from an operating costs perspective. This also likely drives towards the design of novel aircraft concepts in favour of retrofitting existing airframes for improve commercial performance.

With the aircraft concepts being presented, there are opportunities to achieve lower operational costs due to the nature of the novel propulsion systems being assessed. However, further analysis is needed to understand the real impact on "cost per passenger mile" for these aircraft, a key metric for operators, which is a priority for the project. This issue remains a key source of uncertainty, and one area where Government may have an important role to play in supporting early adopters of these new aircraft types when they first enter the market such as through tax incentives.

In the final report, similar case studies will be presented for a service between London City and Rotterdam using a hydrogen aircraft based on an ATR-72-600, and a service between Heathrow and destinations in Scotland and Northern Ireland using an A220-sized hydrogen aircraft, boosting trade connections with major global markets.

Summary

Challenges
As the whole industry responds to the catastrophic impacts of COVID-19, the consortium has identified several challenges which it will explore further in the next phase of the work:

• *Cost:* Given the emerging technologies involved, the associated costs right across the aviation supply chain are likely to be significant.

• *Scalability:* While the consortium believes the technology is available for commercial zero emission flights in the UK this decade, they are likely to be on a limited number of routes, representing a fraction of the 320,000 domestic aviation flights in the UK in 2018. UK domestic aviation accounts for around 1.7 Mt CO2, and the concepts explored so far typically address under 10% of this total. The CO2 benefits at different stages of aviation system evolution will be explored, and barriers to more rapid progress set out.

• *Aircraft Performance:* NAPKIN has been informed by hydrogen performance on existing certified aircraft with concepts for new aircraft currently being assessed. These should perform better as they can be designed to mitigate the adverse effects of the technology (namely fuel storage). However, the performance of initial converted aircraft will enable the emergence of ZEF, with new aircraft coming to market later on to enable a more expansive, commercially-viable ZEF regional aviation system to be adopted. The indicative timescale for delivering a new aircraft from concept to commercial operation is 10-15 years.

• *Commercial viability:* The cost to airlines of acquiring new aircraft is significant, particularly aircraft with significantly lower seating capacity. Airlines may also be reluctant to invest in aircraft that are significantly different to their existing fleet. At the same time, passengers may have preferences for some aspects of the new technologies (lower emissions) and against other aspects (potentially lowered luggage capacity) which will affect demand for their use. There is a challenge to industry and the Government around introducing measures which will accelerate the provision of Zero Emission Flight.

Next Phase of Work
In the final report, the consortium will include insight in the following areas:

• Consideration of the performance of zero emission 9, 19, 40-70 and 100+ seat aircraft on core domestic trunk routes, including to and from Heathrow

• Indicative noise performance of the aircraft

• Aircraft turnaround performance

• Operational cost insights

• Safety and Maintenance insights

• Hydrogen storage, refuelling options with indicative performance indicators at the three consortium airports

• The overall carbon profile of a zero-emission aviation network relative to other transport modes

• Insights into how airlines may adopt and use zero emission aircraft across their networks, the resulting hydrogen and fleet requirements and emissions impact, and how this varies by the characteristics of the zero emission aircraft (range, size, required runway length etc).

• Consumer insights from passenger surveys on consumer willingness to pay for zero carbon emissions flight and the other aspects of zero emission flight that may influence their travel decisions and maximise uptake.

• An indicative 2040 net zero domestic aviation routemap, outlining how it can complement journeys on road and rail.

• Policy recommendations that the consortium believe will accelerate the introduction of zero emission flight in the UK through this decade and next.

UCL
GKN
Heathrow
University of Southampton
Deloitte.
hia highlands & islands airports
Cranfield University
Rolls Royce
Cranfield Aerospace Solutions
London City Airport