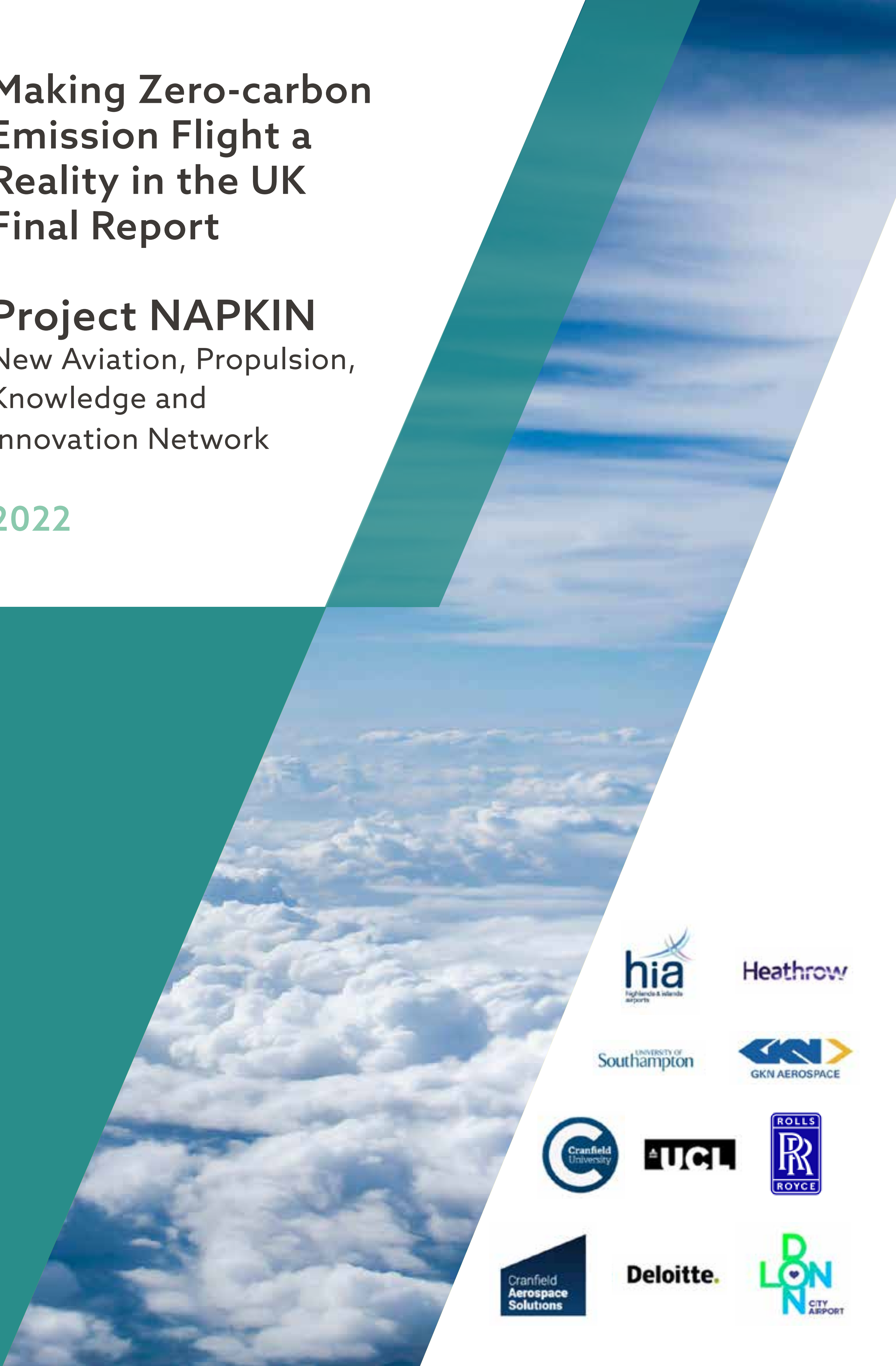
# Making Zero-carbon Emission Flight a Reality in the UK Final Report

## Project NAPKIN

New Aviation, Propulsion, Knowledge and Innovation Network

2022



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# Executive Summary

## What we have done

Within the scope of advancing zero-carbon emission regional connectivity, NAPKIN has explored the conditions necessary to enable the successful introduction of Zero-carbon Emission Flight (ZEF) in the UK for domestic air travel. A model of affordable domestic sustainable aviation has the potential to address climate and connectivity challenges together. We believe that regional and sub-regional hydrogen-powered flight presents an economic and environmental opportunity the UK must consider.

However, moving towards a zero-carbon aviation system requires transformative change and coordinated action. NAPKIN recognises that and takes a 'whole systems' approach – integrating Aircraft, Airlines, Airports, Airspace and Air Passengers (the so-called "five As" model).

Rolls-Royce, GKN Aerospace and Cranfield Aerospace Solutions developed a series of hydrogen fuelled aircraft concepts with capacities from 7 to 90 seats, both retrofit and clean sheet (the 'NAPKIN fleet'). The design process benefitted from the creation of hydrogen technology roadmaps aimed at identifying the key technological challenges the aerospace industry should focus on in the short term to unlock the zero-carbon opportunity afforded by the NAPKIN fleet.

Uptake of these concepts will depend on whether the right market conditions for airline profitability are in place. Within this report, NAPKIN sets out what these market conditions could look like, and the hydrogen required to serve the demand.

New ground infrastructure will be required at individual airport and national level to enable regional uptake. Different airport sizes will have different infrastructure and investment needs. This project presents what new infrastructure will be required to deliver hydrogen to airports and aircraft, as well as potential changes to airport operations, including a focus on noise performance.

Given the novelty of this technology, research on safety and new standards requires continued support and collaboration with the regulatory authorities. NAPKIN is the first project of this kind to explore the potential of zero-carbon air transport with the CAA – a key regulatory body for addressing the challenges ZEF will face. A solid regulatory framework will also give passengers confidence in it. NAPKIN has also conducted a series of surveys to understand the expectations and main concerns of passengers regarding hydrogen aircraft to inform industry efforts.

## What we have found

- Zero-carbon Emission Flight (ZEF) is possible from the middle of this decade on sub regional lifeline routes, on aircraft that range in size from 7 to 19 seats.
- Over the short-term horizon (3-5 years), the first hydrogen aircraft are likely to be retrofits which, while not providing the most efficient design, will provide the basis for the development of new, clean sheet aircraft by 2035.
- It is projected that it could be cost-effective to replace the entire UK regional fleet with safe, certified, zero-carbon emission aircraft by 2040, provided sufficient aircraft production capacity exists matched by sufficient fuel and infrastructure availability.
- Zero-carbon emission aircraft have the potential to significantly reduce UK domestic CO2 emissions and contribute to the UK Government target of net zero domestic aviation by 2040.
- Improvements to noise are conceivable on take-off assuming requirements are integrated from the early stage of design, particularly for larger aircraft.
- For the 'NAPKIN fleet' (the concepts developed in this project) operating cost is not expected to be a barrier to a zero-carbon UK domestic aviation system in the 2040s.
- While airport infrastructure will not prevent the uptake of zero-carbon aircraft in the short term, it is vitally important to be available by 2035 as the uptake grows. A lack of investment in the necessary infrastructure could directly inhibit the zero-carbon opportunity afforded by the NAPKIN fleet.
- From surveys conducted as part of this study, passengers show a willingness to take ZEF flights as long as they do not excessively impact the flight experience. For passengers, travel cost and flight time are likely to be the most decisive factors. One third of the passengers surveyed were willing either to pay more or have a longer flight.

## What we recommend

- Accelerating the production of green hydrogen should be a critical focus for policymakers and industry if the opportunity represented by NAPKIN is to be delivered.
- Similarly, production of Sustainable Aviation Fuel (SAF) needs to be accelerated to provide the air transport industry with a sustainable solution in the short-term while zero-carbon emission aircraft are being developed to offer a complementary solution.
- Continued support is required from the UK Government for aircraft technology

development through considered policy interventions and further investment to de-risk the economics of introducing zero-carbon emissions aircraft into fleets.

- The publication of the Jet Zero Strategy by the UK Government is a good step in demonstrating commitment. However, greater certainty on future fossil fuel and hydrogen prices, and the associated taxation regime, may be required to de-risk investment in ZEF.
- Government urgently needs to provide further clarity on how airports will fit within the wider UK Hydrogen Strategy. A lack of a national distribution infrastructure network will limit the potential for regional uptake, which could delay the introduction and scalability of zero-carbon emission flight.
- In addition, the UK Hydrogen Strategy should assess costs required for new airport infrastructure and potential operational impacts on capacity, including during the transition period when different aircraft types will operate.
- The development of a regulatory framework setting out the new safety procedures and standards that should govern hydrogen aircraft operations should be accelerated. This should be a short-term priority for policymakers and industry and would provide airports with the required support to start this transition.
- Government and the industry should start reskilling for such a significant change. This transformation will require knowledge that many of the industry partners and authorities do not currently have. This reskilling will take time and effort, which is why it is important to start now.

Table 1 summarises the characteristics and key insights for the 3 use cases developed under the NAPKIN project to study the potential of ZEF within the UK aviation network.

**Table 1: Summary of key characteristics and insights of NAPKIN Use Cases**

<table>
<tr><th>Use Case</th><th colspan="2">A</th><th>B1</th><th>B2</th><th>C</th></tr>
<tr><td>Title</td><td colspan="2">Small Gaseous Hydrogen Retrofit Aircraft by 2025</td><td colspan="2">Liquid Hydrogen Regional Aircraft by 2035</td><td>Domestic Aviation Market by 2040</td></tr>
<tr><td>Hydrogen Fleet</td><td colspan="2">7 and 19 Seat</td><td>7, 19, 40 and 50 Seat</td><td>7, 19, 40, 50 and 90 Seat</td><td>-</td></tr>
<tr><td>Estimated Forecast Year</td><td colspan="2">2025-2030</td><td>2035</td><td>2040</td><td>Turboprop</td></tr>
<tr><td colspan="6">Aircraft added to hydrogen fleet:</td></tr>
<tr><td>Seats</td><td colspan="2">7 and 19</td><td>40</td><td>50</td><td>90</td></tr>
<tr><td>Airframe Type</td><td colspan="2">Retrofit</td><td>Clean Sheet</td><td>Clean Sheet</td><td>Study Aircraft[1]</td></tr>
<tr><td>Retrofit Airframe</td><td colspan="2">Britten Norman Islander<br><br>DHC-6 Twin Otter</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Propulsion Technology</td><td colspan="2">Gaseous Hydrogen Fuel Cell</td><td>Liquid Hydrogen Fuel Cell</td><td>Liquid Hydrogen Gas Turbine</td><td>Liquid Hydrogen Gas Turbine</td></tr>
<tr><td>Entry into Service</td><td colspan="2">2025</td><td>2035</td><td>2035</td><td>2035</td></tr>
<tr><td>Example UK Domestic Route</td><td colspan="2">SYY – GLA</td><td>LCY - JER</td><td>LCY - DND</td><td>LHR - EDI</td></tr>
<tr><td colspan="6">Wider implications for:</td></tr>
<tr><td rowspan="2">Technology</td><td colspan="5">NAPKIN has developed viable technical aircraft based on technology assumptions broadly in line with those of the wider industry published views, including FlyZero.</td></tr>
<tr><td colspan="2">Retrofit aircraft, although not as efficient as new aircraft, will provide a good solution for small scale aircraft and a valuable learning opportunity for the development of clean sheet aircraft.<br><br>The NAPKIN fleet technology transitions from gas to liquid hydrogen around the 19-seater scale. Which is appropriate for the 19-seater aircraft will depend on the aircraft application.</td><td colspan="2">At the small regional scale, both fuel cell and gas turbine propulsion systems show potential – as highlighted by the two aircraft added in this use case.<br><br>While fuel cells are a novel technology for aerospace applications, they have the potential to provide zero CO2 and NOx emissions.<br><br>For gas turbines, although they have operated in an aerospace environment for more than 75 years, some changes are required to allow operation on pure hydrogen. Gas turbines have operated in an aerospace environment for more than 75 years and although some changes will be required to allow operation on hydrogen, the pedigree of this technology remains.</td><td>At the large regional scale, a liquid hydrogen gas turbine propulsion system aircraft has been included as this technology is similarly as scalable as current gas turbines.<br><br>Further work is required on the viability of fuel cell aircraft at this scale, which is the focus of several other programs, including GKN Aerospace's H2GEAR programme.</td></tr>
<tr><td rowspan="2">Operating Costs</td><td colspan="5">In the long run, the results indicate cheaper ownership costs for all H2 concept aircraft. For aircraft based on existing designs, an average 16% decrease in ownership costs are observed. For new clean sheet design aircraft, the marginally higher initial production and integration costs of these aircraft make them more comparable with the reference kerosene aircraft. These results do not account for the reduction in passenger capacity and hence earning power in comparison to the reference aircraft.</td></tr>
<tr><td>7-seater gaseous H2 aircraft<br><br>TCO (over 15 years): £640 -832/ FH[2]</td><td>19-seater gaseous H2 aircraft<br><br>TCO (over 15 years): £996-1,302/FH</td><td>40-seater liquid H2 aircraft<br><br>TCO (over 15 years): £2,477-3,065/FH</td><td>50-seater liquid H2 aircraft<br><br>TCO (over 15 years): £2,578-3,034/FH</td><td>90-seater liquid H2 aircraft<br><br>TCO (over 15 years): £5,901-7,581/FH</td></tr>
</table>

1 This study aircraft is loosely based on an Airbus A220-100, featuring a liquid hydrogen fuel storage and gas turbine propulsion system. It is not intended to be a retrofit design as it is unconstrained by spatial and structural integration limitations of an existing aircraft.

2 FH: Flight Hour

<table>
<tr><th>Use Case</th><th>A</th><th>B1</th><th>B2</th><th>C</th></tr>
<tr><td rowspan="2">Noise</td><td colspan="4">Noise performance of hydrogen aircraft is comparable with that expected for future conventional aircraft with significant potential of noise reduction in the proposed technologies. Airport noise could eventually benefit from the introduction of hydrogen concepts once their market share becomes significant (>10%) and their operation optimised.</td></tr>
<tr><td>The use of retrofit designs means there is negligible noise change due to minimal design and operational changes. Looking beyond 2025, clean sheet designs could offer significant noise reductions.</td><td colspan="2">All concepts present an overall noise benefit on a combined take-off-landing basis. While the take-off noise is reduced for all concepts, the approach noise increases for the concepts, primarily due to the greater approach weight. The potential noise gains are not fully realised as more flights are needed to account for the lower passenger capacity of H2 aircraft.</td><td>By 2040, NAPKIN hydrogen concepts will positively impact medium airports such as LCY due to reduced take-off noise. For larger airports such as Heathrow, this is found to be negligible due to the dominance of larger aircraft (not considered within NAPKIN's scope). This also holds for the entire UK aviation noise emissions.</td></tr>
<tr><td rowspan="2">$CO_2$ Emissions</td><td colspan="4">Significant reductions in UK domestic CO2 emissions using hydrogen aircraft will also require use of SAF with conventional aircraft at least during the transition period. The respective role of each technology will be driven by the economics and policy choices regarding green hydrogen production, airport infrastructure, the competitiveness of new hydrogen aircraft both economically and technologically, and their rate of penetration into airline fleets.</td></tr>
<tr><td>Limited impact on UK domestic CO2 due to the small scale of the market. However, in many ways, it offers the foundations for subsequent CO2 reductions.</td><td colspan="2">Potential to produce significant reductions in UK domestic CO2 under favourable hydrogen price and/or policy conditions if ambitious reductions in operating costs can be achieved.</td><td>By 2040, UK domestic CO2 levels could meet the UK Government year-2040 net zero ambition under favourable hydrogen prices, which provides a good policy opportunity.</td></tr>
<tr><td rowspan="2">Infrastructure and Operations</td><td colspan="4">Airport infrastructure will not be a barrier to the introduction of zero-carbon emission aircraft if the industry acts with a degree of urgency. The business case to invest in hydrogen infrastructure will differ for different-sized airports.<br><br>Aside from new airport infrastructure, a national infrastructure network to supply and distribute hydrogen will also need to be in place to allow regional uptake.</td></tr>
<tr><td>"Start small": Small scale operations will provide the opportunity to develop and gain knowledge on the new safety and operational procedures, regulation and standard definitions.<br><br>Intrusive hydrogen infrastructure will not be required, with road delivery being sufficient. Permanent storage will not be required for smaller airports initially.<br><br>Due to the small-scale of hydrogen operations and small size of hydrogen aircraft, turnaround times are not likely to increase.</td><td colspan="2">"Common refuelling infrastructure": At this point, ensuring most (if not all) airports across UK (and EU) have hydrogen infrastructure in place will be essential. Additionally, standardisation of the hydrogen infrastructure will be needed to ensure airports do not become the barriers for hydrogen uptake.<br><br>Further investment in hydrogen infrastructure, such as storage tanks, will be required for medium-size airports.<br><br>An increased number of hydrogen operations will require more sophisticated operations and trained personnel.</td><td>"Full-scale infrastructure roll-out": From 2040, larger airports such as Heathrow are likely to require a parallel hydrogen hydrant system and liquefaction on-site. This will create an energy demand that most airport networks do not currently have capacity to deliver.<br><br>The increased number of hydrogen operations and larger hydrogen aircraft are likely to increase turnaround times if existing procedures and technology are used. Opportunity to introduce automation into the refuelling process if technology is available.</td></tr>
</table>

<table>
<tr><th>Use Case</th><th>A</th><th>B1</th><th>B2</th><th>C</th></tr>
<tr><td rowspan="2">Economic Case</td><td colspan="4">Achieving a low cost per passenger-km will be key to build a successful economic case. For smaller designs, reducing maintenance and capital costs is most important, whilst for larger designs fuel and other per-passenger type costs increase in importance.</td></tr>
<tr><td>Niche market but could be increased with creation of new short-hop routes, enabled by lower operating costs. Examples include (i) exploring markets outside the UK and (ii) exploring new routes within the UK.<br><br>Not as sensitive to hydrogen prices as the larger aircraft but limiting increases in capital and maintenance costs is important.</td><td colspan="2">Commercial viability is sensitive to operating costs. If operating costs at the low end of those projected can be achieved, there is an economic case for this size of aircraft; however, operators who currently rely on larger conventional aircraft are likely to opt for larger designs.<br><br>Further investment and research on fuel cell and combustion related technologies is required to reduce uncertainty on the operating costs produced.</td><td>Can serve a large part of the UK domestic market (>80%) and up to 95% of the existing global regional market.<br><br>Level of uptake is more sensitive to hydrogen prices and level of Air Passenger Duty than for smaller designs.<br><br>Although international flights were not modelled in NAPKIN, the 90-seater has the range capability to serve short-haul international routes, which could increase its uptake.<br><br>One key uncertainty is if low-cost carriers will consider using the 90-seaters or will opt for larger short-haul aircraft. This will drive demand and the need for a robust distribution infrastructure.</td></tr>
<tr><td rowspan="2">Policy</td><td colspan="4">Of central importance is the UK green hydrogen production strategy – with clearly significant levels of demand from aviation. This is true irrespective of the specific role of ZEF and SAF as green hydrogen will be required in large volumes to support both. Government can play a critical role in the success of ZEF in three further main ways: (i) continued support for the aircraft technology development (ii) by considering clear and carefully defined policy interventions to de-risk the economics of introducing zero-carbon emission aircraft into fleets and (iii) provide a detailed attention to the airport level infrastructure requirements, including clarity on how airports fit with the wider hydrogen industrial strategy.</td></tr>
<tr><td>Upstream supply of green hydrogen is vitally important. As green hydrogen is required for the production of both SAF and used directly to power ZEF, continued expansion of supply should be a focus for both industry and Government.</td><td colspan="2">Operating cost is one key parameter for uptake of hydrogen aircraft. Government industrial strategy on hydrogen is critical and should target lowest possible production costs. Government will have various levers at its disposal to provide cost certainty to airlines, or to close any price premium above fossil kerosene, by creating price incentives or intervening through the taxation system.<br><br>Given the novelty of some of these technologies and their application to the aerospace industry, investment should focus on both fuel cell and combustion related technologies, an area in which the Government should play a critical role.</td><td>Further development of the UK hydrogen strategy, including how aviation will fit with demand coming from other sectors is of fundamental importance and a top priority area.</td></tr>
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# 1 Introduction to Project NAPKIN

The NAPKIN consortium formed in spring 2020 and commenced grant funded work in November 2020. The consortium features three airports/airport groups (Heathrow, London City, Highlands and Islands), three manufacturers (GKN Aerospace, Rolls-Royce, Cranfield Aerospace Solutions), three academic institutions (University College London, Cranfield University and the University of Southampton) and Deloitte.

NAPKIN evaluates each part of the future aviation system to model the impact of modified and original aircraft concepts on 'five As' 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.

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 flights.

While the focus for the consortium is the UK sub-regional and regional market (<100 pax), it is expected that the learnings can be applied across markets globally. It is also the shared view that hydrogen aircraft represent a credible solution to reach zero-carbon flight and are the natural complement to Sustainable Aviation Fuels.

# 2 Scenario Selection

In the early stages of the project, the consortium developed several zero-carbon emission aircraft designs based on a set of baselined performance characteristics relevant across a number of different technologies. As the project progressed, aircraft types and use cases were identified that represented both the scope of the Future Flight Challenge (regional and sub-regional) and the technologies that the consortium considered to be most likely to be exploited by the industry.

It is worth noting that the aircraft concepts presented in this report are based on predictions of the technology and architectures available in these time frames. As the development and integration knowledge for hydrogen propulsion builds, they have the potential to change and hence impact the designs of these aircraft concepts. Some of the technological developments needed are outlined within the NAPKIN Technology Roadmap.

## 2.1 Technology Selection

Below are the types of technologies considered at the beginning of the project and the reasons why some were discarded.

- **Battery-only concepts:** Whilst suitable for very small aircraft and some eVTOLs/ UAV applications, battery-only propulsion is not considered a practical solution for most conventional commercial operations due to energy density challenges and therefore was not included.
- **Hybrid (battery + conventional gas turbine):** This technology was excluded from the scope of the project as this is focussed on zero-carbon emissions at the point of use.
- **Sustainable Aviation Fuels:** SAF concepts were excluded from this study as the nature of the fuel as a drop-in solution means current aircraft and operational capability can be maintained. SAF is seen as a complementary solution to hydrogen and hence it is assumed to be accommodated within the fuel prices but CO2 savings from its usage are not included.
- **Hydrogen:** All the aircraft concepts used as a basis for the market analysis are powered by some form of hydrogen propulsion system, be that fuel cell or combustion. Hydrogen powered aircraft have the potential to achieve sub-regional and regional ranges as well as provide a zero-carbon emission solution. Both clean sheet and retrofit aircraft have been considered when developing the NAPKIN fleet. Designs beyond 9-19 seats, however, are unlikely to be a retrofit as they do not provide a particularly cost-effective or efficient solution. Smaller cases though provide a good opportunity to build technical and operational

experience to guide the development of the regulatory framework on which this aircraft will need to operate, while still offering a solution that is commercially viable.

## 2.2 Use Cases Selection

The report has been developed around three use cases. For each use case, specific aircraft types from all those developed by the Consortium were selected based on potential entry-into-service years, range, cost performance and commercial viability. Because the scope of the Future Flight Challenge is limited to the regional and sub-regional domestic UK network, the aircraft designs explored in NAPKIN range from 7 to 90 seat aircraft.

The rationale for presenting the NAPKIN findings through use cases is to provide a potential roadmap for the introduction of zero-carbon emission aircraft into the UK domestic network and its further implications for the different stakeholders, including airports, airlines and policymakers.

### 2.2.1 Use Case A: Small Gaseous Retrofit Aircraft Take-off by 2025-30

Small, gaseous hydrogen fuel cell powered aircraft operating short routes from small/regional airports represent the most likely first step towards widespread use of hydrogen in aviation. Nineteen seat aircraft were also considered and, as uses of these aircraft are generally similar to those for 7-9-seaters, this use case could be classed as 7-19 seat for the purpose of the analysis.

### 2.2.2 Use Case B: Liquid Hydrogen Regional Aircraft by 2035

Although retrofits of larger, existing aircraft were considered to achieve the 40-50 seat outcome, the technical and commercial viability of such solutions was considered questionable and therefore the focus was put on how a clean sheet aircraft of this size could perform if it were optimised around potential new propulsion systems. Both combustion and fuel cell aircraft of this size were modelled.

### 2.2.3 Use Case C: Domestic Aviation Market by 2040

By 2040 there is scope for a reasonable level of fleet penetration to have been achieved by larger regional hydrogen aircraft into the UK domestic aviation market. To represent this aircraft class, a liquid hydrogen gas turbine aircraft concept was produced. Large regional aircraft of this scale are currently used on some of the most popular domestic routes but also have the range capability to be used for short haul international flights, hence the range design requirement for this concept was not restricted to the needs of the UK market.

The performance and design characteristics of each of these aircraft are further explained in sections 6, 7 & 8 below.

# 3 Airline Behaviour Model

The core output of the NAPKIN project is to provide a blueprint for zero-carbon emissions services within the UK and what the conditions are to enable them. To model the competitiveness of the hydrogen technology within the current UK aviation network, the UCL airline behaviour model (ABM)[1] has been adjusted to the UK domestic context. Deloitte's role was to provide the current transport modelling figures into the UCL aviation behavioural model.

This is an optimisation model which simulates competing airline and passenger behaviour within UK domestic flight networks by assuming that each individual airline or alliance acts to try to maximise its own profit. The UK domestic aviation market is a complex market with competition both between airlines and between air and other modes. In the ABM, passenger demand for a given flight itinerary is modelled as a function of origin-destination demand (e.g., London-Edinburgh), mode choice given characteristics of ground alternatives, and the characteristics of both that itinerary and any competing ones (e.g., time, fare, number of stops, flight frequency, airline and airports used). To attempt to maximise their profits, airlines can change itinerary fares, flight frequency and the type of aircraft they use on each route. They are also subject to constraints including airport capacity and runway length, available fleet, and aircraft range. Airlines can respond to both the actions of competitor airlines and those of passengers, so the model is solved iteratively, with repeated rounds of optimisation until system equilibrium is reached across all airlines. If new designs of aircraft are made available as an option for airlines to use in the ABM, the level of profit-optimal uptake of those designs can be assessed.

The ABM is used to simulate profit-optimal market uptake of the aircraft designs assessed in Use Cases A, B and C presented below. Because the version of the ABM used here simulates only UK domestic operations, it is not used for projections which include an international component (e.g., analysis of hydrogen infrastructure requirements). The methodology and assumptions used for the model, as well as validation outcomes and model outcomes assessing individual aircraft designs, are described in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes".

1 Doyme, K., Dray, L., O'Sullivan, A., & Schäfer, A. (2019). Simulating Airline Behavior: Application for the Australian Domestic Market. Transportation Research Record, 2673(2), 104–112; Dray, L., Doyme, K. and Schäfer A.W., 2020. Airline Profit Maximisation, Cost Pass-through, and Scarcity Rents in Capacity-constrained Aviation Systems. Journal of Transport Economics and Policy, 54(4), 244-266.

# 4 Operating Cost Modelling

One of the key inputs for the ABM is the operating cost of the various aircraft concept designs (Figure 1). Given the ABM is looking at the solution that maximises profits for airlines, the cost of operating these new aircraft is one of the most influential parameters and so consistency on how these are calculated across the different aircraft concepts is essential.

Based on the technical specifications of the various aircraft concept designs, an ownership and operating cost model was developed by Cranfield University and used across all aircraft concepts. This model calculates the total cost of ownership (TCO), which includes the purchase price and the costs of operating the asset. Three stages were identified within the cost estimation framework:

- aircraft cost estimation model
- maintenance cost model
- operating cost model.

In the first stage, the total cost to design and manufacture the aircraft was estimated. With added profit for the manufacturer or seller, this returned the total purchase price of an aircraft. In the second stage, maintenance costs were estimated. This included two key factors: the conventional airframe maintenance and then, based on the lifecycle analysis of fuel cells, battery and fuel tank, the propulsion system maintenance cost for the hydrogen fuelled system. For the hydrogen combustion systems, the gas turbines were assumed to have an equivalent maintenance cost burden as existing kerosene gas turbines, with an additional factor added to account for the fuel system and tank. The final stage involved computing the operating cost of the aircraft based on fixed and variable direct costs. Operating costs include any expenses that are required to utilise the aircraft commercially.

The uncertainty around the future operating conditions of these concept aircraft, as well as having few (if any) existing aircraft upon which to base these assumptions, posed several challenges. Consequently, it was necessary to set and agree key assumptions amongst the consortium for parameters relevant to the model. Additionally, a Monte Carlo simulation was developed with defined distributions to account for uncertainty.

To view the full methodology on how the ownership and operating cost model was developed refer to the accompanying technical report “Ownership and Operating Cost Model”.

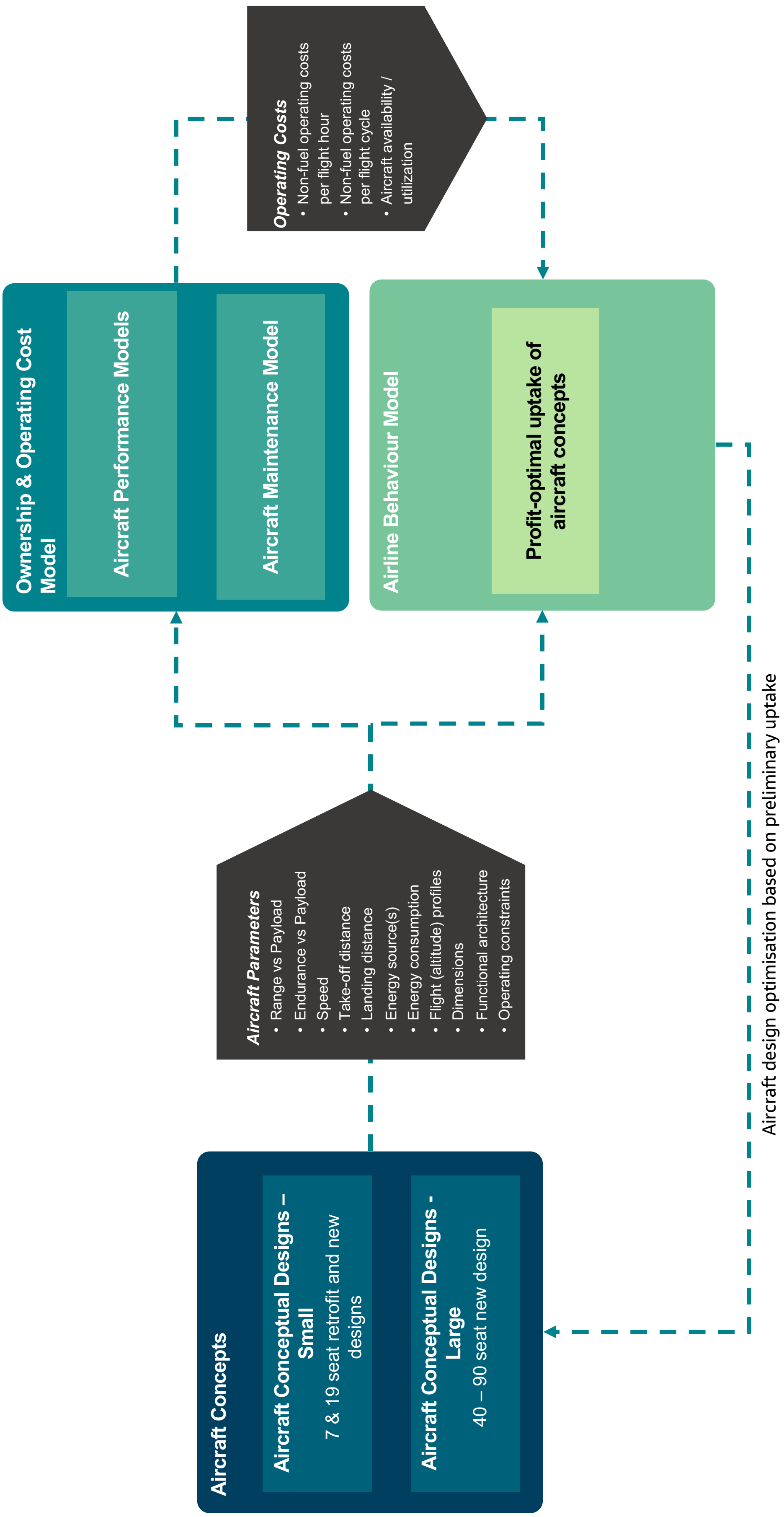



Figure 1: Flow of data

# 5 Hydrogen Demand

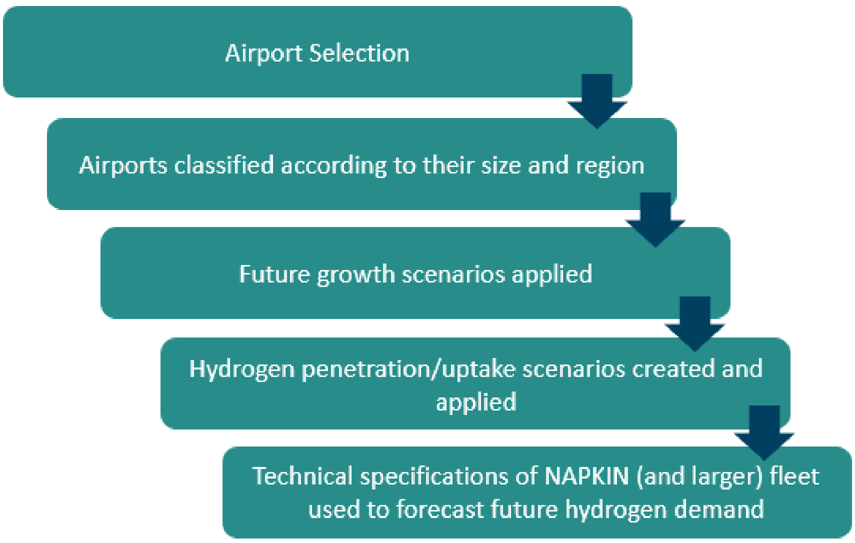
At a fundamental level, an understanding of the level of hydrogen supply required to support hydrogen air transport over varying timescales will assist with the planning and phasing of hydrogen production facilities in the UK, as well as help support efficient development of related supply and delivery infrastructure.

As is the case with traditional aviation fuel, demand for hydrogen fuel will vary both at the airport and regional level. Given that future demand for hydrogen will come not only from aviation but also from other major industries as well as domestic use, determining aviation's contribution to the overall demand landscape will assist in planning hydrogen production capacity and transportation at a regional level.

## 5.1 Methodology

The methodology used for forecasting future hydrogen demand is summarised in Figure 2 and explained below.

**Figure 2: Process used to forecast future hydrogen supply at UK airports**




Initially, 25 UK airports were selected covering a range of sizes and geographies. Collectively, these airports accounted for 95.6% of all UK passengers in 2019. Airports were then classified by size according to their annual passenger numbers in 2019 and UK region (see Table 2).

**Table 2: Airport classification table**

| Airport Name | Airport Code | Size | Region |
|---|---|---|---|
| **Heathrow Airport** | LHR* | Very Large | South-East |
| **Gatwick Airport** | LGW | Very Large | South-East |
| **Manchester Airport** | MAN | Large | North-West |
| **London Stansted Airport** | STN | Large | South-East |
| **Luton Airport** | LTN | Large | South-East |
| **Birmingham Airport** | BHX | Large | Midlands |
| **Edinburgh Airport** | EDI | Large | Scotland- South and East |
| **London City Airport** | LCY* | Medium | South-East |
| **Bristol Airport** | BRS | Medium | West and Wales |
| **Liverpool John Lennon Airport** | LPL | Medium | North-West |
| **East Midlands Airport** | EMA | Medium | Midlands |
| **Newcastle International Airport** | NCL | Medium | North-East and East |
| **Glasgow Airport** | GLA | Medium | Scotland- South and East |
| **Aberdeen Airport** | ABZ | Medium | Scotland- South and East |
| **Southampton Airport** | SOU | Small | South-East |
| **Cardiff Airport** | CWL | Small | West and Wales |
| **Jersey Airport** | JER | Small | Channel Islands |
| **Belfast International Airport** | BFS | Small | Northern Ireland |
| **Oxford Airport** | OXF | Very Small | South-East |
| **Bournemouth Airport** | BOH | Very Small | South-East |
| **Isle of Man Airport** | IOM | Very Small | North-West |
| **Norwich Airport** | NWI | Very Small | North-East and East |
| **Humberside Airport** | HUY | Very Small | North-East and East |
| **Inverness Airport** | INV* | Very Small | Scotland-North and Islands |
| **Kirkwall Airport** | KOI | Very Small | Scotland-North and Islands |

*Airports chosen for the use cases

Three growth scenarios were then adopted and applied to each airport (against a baseline of 2019 movements) to forecast future growth on annual movements[1]. These were adapted from EUROCONTROL's most recent forecasts (October 2021[2]) for UK air travel and extrapolated out to 2050 (see Table 3).

**Table 3: EUROCONTROL's forecasts**

| | |
|---|---|
| **High Growth** | 1.8% AAGR |
| **Baseline (Medium) Growth** | 0.4 % AAGR |
| **Low Growth** | -0.4% AAGR |

For each airport category (i.e., Very Large, Large, etc) three scenarios were generated reflecting hypothetical future outcomes of hydrogen aircraft uptake at each airport from 2025 to 2050. These were reflected as a percentage of hydrogen movements relative to overall movements, delineated by aircraft size.

**Table 4: 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. Underlying considerations include:<br>• Airlines always buy hydrogen aircraft alternatives when available.<br>• Like-for-like aircraft replacement regarding seating capacity.<br>• Rapid fleet turnover for small airports to reflect the impact of airline choices at these airports.<br>• Neither refuelling infrastructure nor regulation is a blocker for hydrogen adoption. |
| **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 was likely to be more expensive, it was considered airlines would choose SAF aircraft instead of zero-carbon emission aircraft. |

1 All movements were accounted for, i.e., scheduled and non-scheduled.
2 https://www.eurocontrol.int/sites/default/files/2021-10/eurocontrol-7-year-forecast-2021-2027.pdf

| Scenario | Description |
|---|---|
| **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. The lower hydrogen penetration rates could be due to higher operating costs than expected, government interventions not having the right effect, limited and/or uncoordinated refuelling infrastructure in place or limitations on hydrogen production among others. |

In the final step, technical specifications of the NAPKIN fleet were used to forecast future hydrogen demand at each of the 25 airports studied. However, because the NAPKIN project focuses on the UK network only, to explore the full-scale implications of hydrogen operations for airports, hydrogen demand coming from the larger FlyZero[3] concept aircraft[4] (i.e., short-haul and midsize aircraft) operating on international routes was also accounted for.

The specified fuel burn rate (kg/km) of the different concept aircraft was combined with an assumed average sector distance of 75% of the aircraft maximum range to estimate the quantity of hydrogen required for each departing flight.

Chapters 5.2 and 5.3 present the hydrogen demand at an airport and regional level respectively. Additionally, the use cases presented in sections 6.3, 7.4 and 8.4 explore the implications of hydrogen operations for the following three airports: Inverness (Use Case A), London City (Use Case B) and Heathrow (Use Case C). For the use cases, the actual 2019 flight schedule, average sector distance and annual movement growth projections were used.

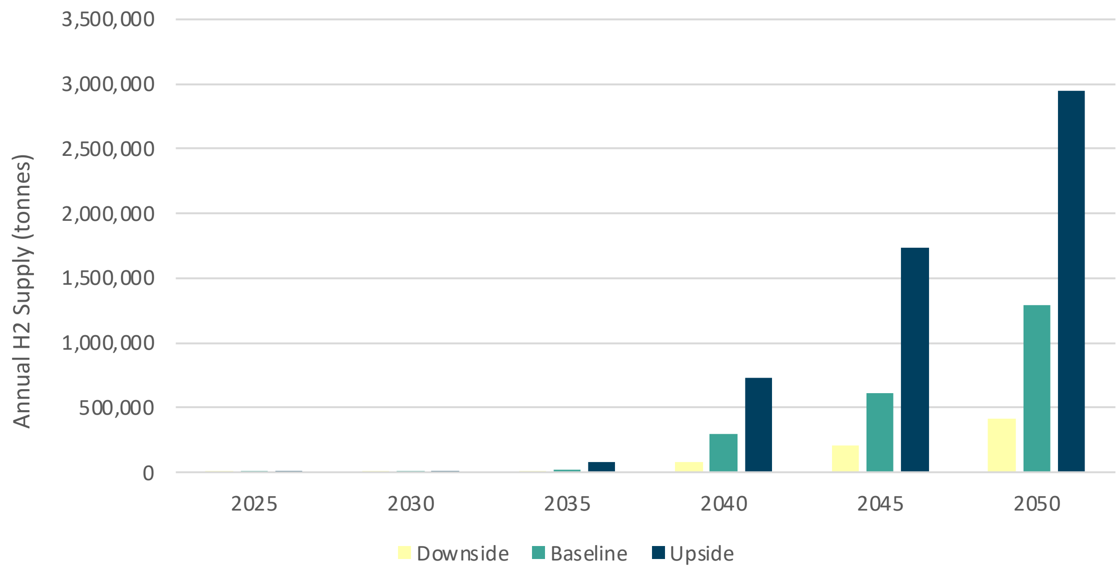
Also, it should be noted that the hydrogen demand analysis conducted below assumes that each of the NAPKIN fleet aircraft are available from their EIS year, whereas the later case studies analyse a particular selection of aircraft.

## 5.2 Airport Demand

Figure 3 shows the overall hydrogen demand (incorporating both gaseous and liquid hydrogen) required for the 25 airports included in the study up to 2050. Until the introduction of liquid hydrogen aircraft in 2035, demand is universally derived from GH2 for small commuter (7-19 seat) class aircraft. From 2035 onwards, overall demand increases significantly, with liquid hydrogen representing the overwhelming share of overall demand. Figures are shown for the three hypothetical scenarios described in Table 4.

3 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-ALL-REP-0003-FlyZero-Executive-Summary.pdf
4 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

**Figure 3: Hydrogen Supply (annual, tonnes) for UK airports to 2050**




Under the balanced 'baseline scenario', annual hydrogen demand at the UK airports studied grows from a low base of nearly 550 tonnes per year in 2025, to just under 22,000 tonnes per year by 2035. By 2040, total hydrogen supply grows to just over 300,000 tonnes annually, and then rises rapidly to 610,000 tonnes by 2045. By 2050, the baseline scenario forecasts that annual hydrogen demand will reach nearly 1.3 million tonnes.

By comparison, the more optimistic 'upside' scenario sees overall hydrogen demand rise from just under 1,400 tonnes per year in 2025, rising rapidly to just under 3 million tonnes per year by 2050. The more pessimistic, 'downside scenario' shows far more modest growth, with annual demand reaching just under 420,000 tonnes by 2050.

To put these figures into context, the British Energy Security Strategy[5] doubled the UK target of low carbon hydrogen production to up to 10GW, providing approximately 88TWh[6],[7] annually by 2030, a target recently confirmed by the Jet Zero Strategy[8]. Although it is unknown how much of this supply will be available for aviation, this production could meet the demand coming from UK air transport until 2050 under the 'baseline' scenario (Figure 4), if it were made available to the sector.

Demand for green hydrogen, however, is anticipated to start as early as 2025. 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

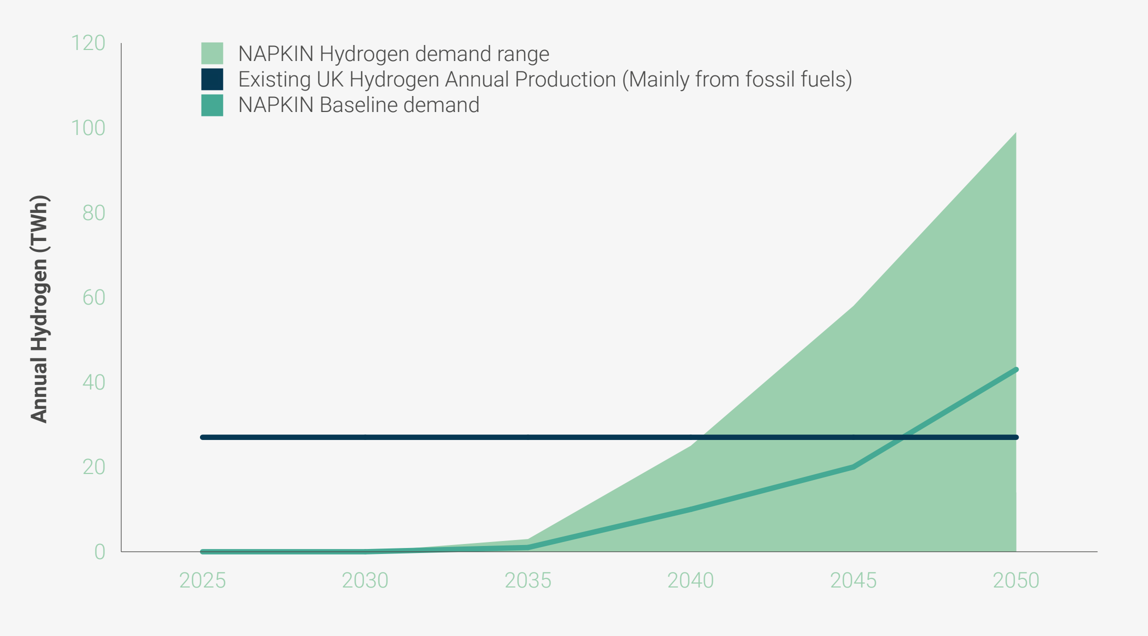
5 https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy
6 Assumption: 8,765 hours full-load of electrolyser operation and an efficiency ratio of 100%
7 2.6 million tonnes
8 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1091834/jet-zero-strategy.pdf

and other studies are to be met. In this regard, other countries within the EU have 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[9]. The new German Government however, recently announced its intention to double this target up to 10GW of green hydrogen electrolyser capacity by 2030[10].

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[11]. So, 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.

**Figure 4: Comparison between NAPKIN forecast hydrogen demand with UK current hydrogen production**

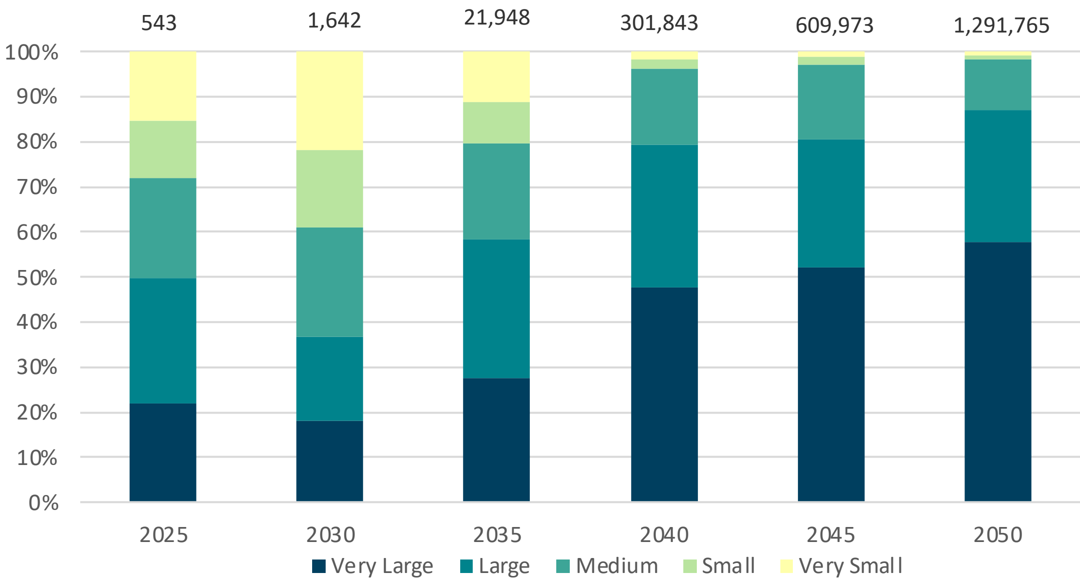



Looking at how the demand for hydrogen will develop, under both the 'baseline' and 'upside' scenarios, growth in demand across the UK occurs largely from 2030 onwards. In these early years of hydrogen adoption, demand is anticipated to be focused on much smaller regional airports (classified here as 'small' or 'very small') (see Figure 5). This reflects the nature of the smaller (7-to-19-seater), shorter-range hydrogen aircraft which are expected to enter the market first and operate at these airports.

9 https://www.bmwk.de/Redaktion/EN/Publikationen/Energie/the-national-hydrogen-strategy.pdf?__blob=publicationFile&v=6
10 https://fuelcellsworks.com/news/germany-to-double-2030-hydrogen-production-target-to-10gw/
11 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

More pronounced growth in demand is anticipated to occur from 2035 onwards, driven by the entry into service of the NAPKIN 40, 50 and 90 seaters and then the narrowbody (180 seats[12]) and, later, in 2040, midsize (279 seats[13]) aircraft. Here, overall demand is driven by the operation of these larger aircraft at 'very large' (>40m passengers; LHR and LGW) and 'large' (10-39m annual passengers, MAN, STN, LTN, BHX, and EDI) airports. In the baseline scenario, these airports collectively account for about 80% of overall hydrogen demand by 2045, and nearly 87% by 2050. In the upside scenario, they account for 83% and 85% of demand by 2045 and 2050, respectively (Figure 5). This indicates the need to establish a clear hydrogen strategy for the UK, for these scenarios to become possible.

**Figure 5: Share of annual hydrogen demand by airport size and total annual hydrogen demand (annual, tonnes) under the Baseline scenario**




## 5.3 Regional Demand

As well as questions around the production and supply of hydrogen at a national level, it is also important to consider how the pattern of demand will vary regionally. It seems likely that sites of hydrogen production will be established ahead of demand from aviation, will vary in scale, and may be situated some distance away from airport (as is the case with kerosene). This has important supply chain implications in terms of regional supply capacity and transportation.

As shown in Table 2, the 25 UK airports in the study were grouped into one of nine UK regions. Figure 6 and Figure 7 show how hydrogen supply develops up to 2050 under the baseline scenario for each region. Airports in the South-East account for

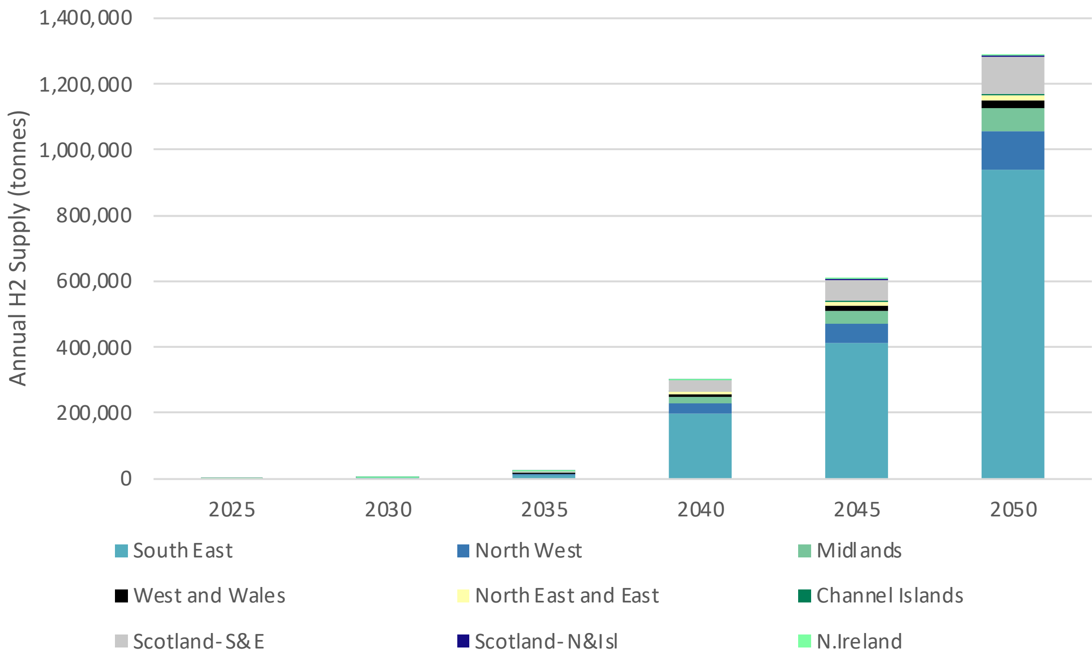
12 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

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

the vast majority of overall supply, accounting for just under 200,000 tonnes in 2040, rising to 414,000 tonnes in 2045, and 940,000 tonnes by 2050. By comparison, airports in the North-West account for 31,000, 57,000 and 115,136 tonnes over the same timeframe. Collectively, airports in England, Wales, Northern Ireland and the Channel Islands will account for 1.29 million tonnes of liquid hydrogen by 2050 under the baseline scenario.

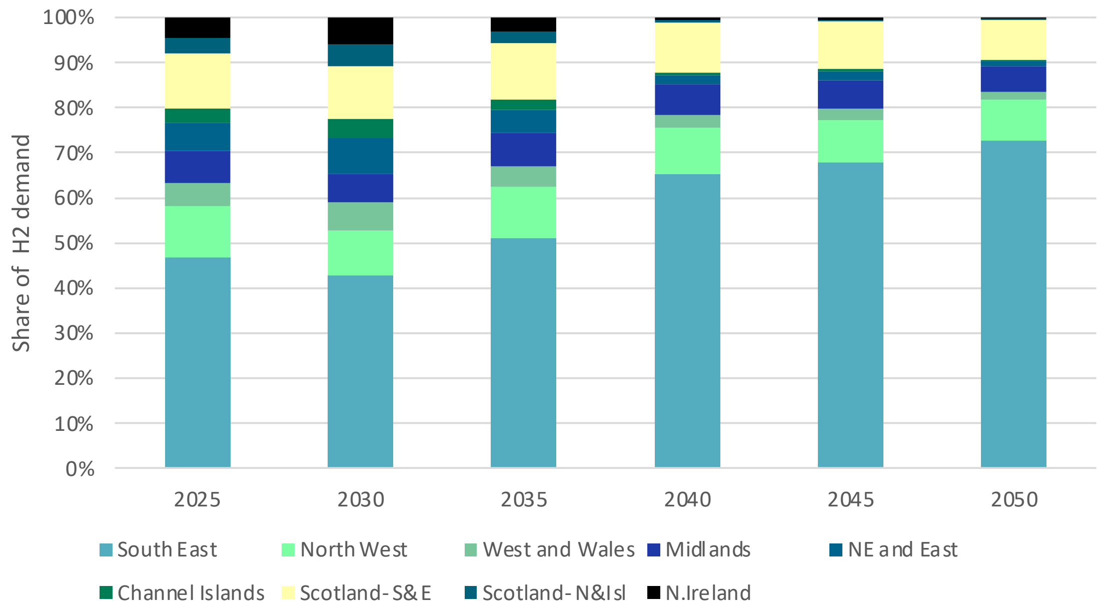
Hydrogen supply for airports in Scotland grows from just under 35,000 tonnes in 2040, to 66,000 tonnes in 2045, and 116,000 tonnes annually by 2050. The significant majority of this demand is derived by the larger airports located in the South (EDI and GLA) and East (ABZ). By comparison, the two airports located in the North and Islands of Scotland (INV and KOI) account for just over 1,000 tonnes of hydrogen per year in 2040 and 2045, and 2,025 tonnes by 2050.

**Figure 6: Regional supply of hydrogen (annual, tonnes) up to 2050 - Baseline scenario**




Given that the South-East has a higher concentration of large airports than elsewhere, it is unsurprising to find that the South-East accounts for the majority of overall demand up to 2050. However, in the early phases of adoption, demand from outside of the South-East plays a greater role than in later years. As can be seen in Figure 7, in 2025 (baseline scenario) airports in the South-East account for less than half (46%) of overall demand, just over 42% by 2030, and just over 50% by 2035. By 2050, demand from the South-East rises significantly to over 70% of the total UK demand from aviation.

**Figure 7: Share of hydrogen supply (annual, tonnes) by region up to 2050 - Baseline scenario**




In the earlier years of adoption, there is a greater role for smaller and medium sized airports where the first hydrogen aircraft will likely operate. For example, in 2025, airports in South and East Scotland (EDI, GLA and ABZ) account for 12.4% of total demand, while the Midlands (BHX and EMA) account for 7.0%. Equally, airports in the North-East and East (NCL, NWI and HUY) account for 6.1% in 2025, while the West and Wales (BRS and CWL) accounts for 5.3%. By 2050, the role of these regions drops to 1.2% and 1.7% of total hydrogen supply, respectively. By this time, the larger hydrogen aircraft (100 seats plus) have entered service, operating to and from the much larger airports (notably LHR and LGW) located in the South-East.

The findings raise some important questions about the UK's production and delivery supply chain. In the early years of adoption, the geographical demand for hydrogen will be evenly spread out across the UK. With the scale of hydrogen production still likely to be limited around 2025-2030, it poses the question as to whether existing planned production facilities will be sufficient to meet regional demand. In the longer term, from 2045 onwards there is a notable shift in demand towards the South-East, both proportionally and in overall terms. It is not clear if there will be sufficient production capacity in the South-East to fulfil this demand. If not, then it poses questions as to where the hydrogen would be sourced from and, perhaps more importantly, the most efficient and economical way of transporting it to where it will be consumed. This is an important question given the scale of demand and the costs associated with transporting liquid hydrogen.

## 5.4 Implications for Airport Hydrogen Infrastructure and Operations

Hydrogen powered aircraft will require new airport infrastructure and change to current operations. The scale and nature of these changes will vary for different types and size of airport, as well as the rate of hydrogen aircraft uptake into the market.

Results from the NAPKIN project indicate that there are likely to be two key phases in terms of infrastructural and operational impacts.

### 5.4.1 Early Years (2025-2040)

In the initial phase of adoption, hydrogen demand at UK airports will predominantly come from commuter (7-9 seat) and small regional (19 seat) aircraft on short sectors, operating from smaller regional airports like Inverness, Southampton, or Jersey.

Given the relatively small amounts of hydrogen needed at this stage, delivery by road is likely to be the most cost-effective solution for most airports. As is the case with kerosene, road transportation of hydrogen will not require intrusive infrastructure for the airport, avoiding the need for significant upfront capital investment.

Table 5, Table 6 and Table 7 show the number of tankers (4,500kg each) that would be required on a peak day for airports of different sizes in the UK in the upside, baseline and downside scenario respectively up to 2035, and the NAPKIN view on when permanent storage or piping would be required.

There is not a single answer as to how many daily trucks airports will be able to handle as capacity of the surface access and airside roads, as well as space available to park the tankers, differs between airports. However, to provide commentary around when airports are likely to need permanent storage, it has been considered that anything above 10 daily tankers would require a large area to park and manoeuvre. Anything above 30 tankers a day would require an area that most airports do not have and the alternative, which would be unload the tankers into a permanent storage when they arrive, would take too long. So, at this point, and given the volumes involved, piping the hydrogen in, and storing it has been considered to be the most suitable solution.

**Table 5: Peak number of daily hydrogen tanker requirements for UK airports – Upside Scenario**

| Airport (annual pax) | 2025 | 2030 | 2035 |
|---|---|---|---|
| Very Large (>40m) | 0.1[14] | 0.3 | 4.0 |
| Large (10-39.9m) | 0.1 | 0.4 | 3.0 |
| Medium (3-9.9m) | 0.1 | 0.2 | 2.0 |
| Small (1-2.9m) | <0.1 | 0.2 | 1.0 |
| Very Small (<1m) | <0.1 | 0.3 | 2.0 |

**Table 6: Peak number of daily hydrogen tanker requirements for UK airports – Baseline Scenario**

| Airport (annual pax) | 2025 | 2030 | 2035 |
|---|---|---|---|
| Very Large (>40m) | <0.1 | <0.1 | 2.0 |
| Large (10-39.9m) | <0.1 | <0.1 | 1.0 |
| Medium (3-9.9m) | <0.1 | 0.1 | 0.6 |
| Small (1-2.9m) | <0.1 | <0.1 | 0.6 |
| Very Small (<1m) | <0.1 | 0.1 | 0.4 |

**Table 7: Peak number of daily hydrogen tanker requirements for UK airports – Downside Scenario**

| Airport (annual pax) | 2025 | 2030 | 2035 |
|---|---|---|---|
| Very Large (>40m) | <0.1 | 0.1 | 0.2 |
| Large (10-39.9m) | <0.1 | <0.1 | 0.1 |
| Medium (3-9.9m) | <0.1 | <0.1 | 0.1 |
| Small (1-2.9m) | <0.1 | <0.1 | 0.1 |
| Very Small (<1m) | <0.1 | <0.1 | 0.1 |

14 Decimal numbers represent the option for airports to have hydrogen delivered every few days

Green = Tanker delivery and storage sufficient (the case for all scenarios in this phase);

Light Blue = Need for permanent storage;

Dark Blue = Need for permanent storage and pipeline delivery

In all three scenarios, the number of tankers required remains fairly low for all airports until at least 2035. This reflects the smaller aircraft operating in this early phase of adoption and the modest uptake at this time. In this case, the delivery and storage of hydrogen on-site in tankers is likely to be suitable for the majority (if not all) airports (shaded in green).

While hydrogen demand for smaller airports may be modest in overall terms, it will be important to consider specific geographical factors that may present challenges at certain sites. For example, at airports located in the Channel Islands, Scottish Islands, or in other smaller islands, hydrogen delivery will be required by sea and road, which may add additional supply chain and logistical complexities.

Hydrogen delivery by road would bring gaseous or liquid hydrogen to the airport using road tankers. However, a critical unknown planning consideration here relates to the volume of liquid hydrogen that could be transported in a single road tanker, and the size of the vehicles employed. Unlike kerosene and other petroleum-based products, liquid hydrogen and other cryogenic liquids are not widely transported in large volumes by road in the UK. Consequently, there is no existing fleet of such vehicles upon which to base assumptions.

In the US, the major chemicals producer Air Products indicate that liquid hydrogen can be transported in semi-trailers containing between 12,000-17,000 US gallons[15]. This volume equates to around 45,420 to 64,350 litres, or 3,230 to 4,576 kg of liquid hydrogen. Reasoning that it would be preferable to operate a smaller fleet of larger vehicles able to transport higher quantities of hydrogen (as opposed to a larger fleet of smaller vehicles that would need to make more frequent visits), we assume that liquid hydrogen road tankers will have a maximum capacity of 4,500kg (63,270 litres). It is worth noting here that the recent FlyZero report on hydrogen infrastructure and operations assumed a much smaller tanker size of 20,000 or 40,000 litres (1,420 or 2,840kg)[16].

Equally, there are other important aspects to consider for airports with tunnels as part of their surface access road network (for example, at LHR, MAN, or LTN). As tunnels present higher fire safety risks than open roads, the European Agreement concerning the International Carriage of Dangerous Goods by Road (ADR) assigns to each regulated tunnel a particular category, A to E, A being the least restrictive

15 Air Products, 2014. Safety Gram 9, Liquid Hydrogen. www.airproducts.com/company/sustainability/safetygrams
16 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf

and E being the most[17]. Any CAT E tunnel in the vicinity of an airport is likely to pose logistical challenges for the delivery of hydrogen to the airport.

From an operational perspective, the impact of hydrogen on aircraft turnaround times and airport capacity has been identified as a key operational factor that will need further investigation. The FlyZero report[18] suggests that turnaround times for regional and narrowbody aircraft could increase by 5 to 15 minutes depending on whether simultaneous activities will be allowed and refuelling of narrowbodies is conducted with two hoses instead of one. In the short-term, however, given the small scale of operations in the early phase of adoption, refuelling challenges associated with this new type of operation should be manageable for airports if sufficient advanced planning is conducted. Additionally, airports could consider remote refuelling operations, where aircraft would be taken away from the gate for refuelling and then return for leading. This would potentially add to the turnaround time but could be considered as an intermediate step over the next few years.

Therefore, while airport infrastructure will not be a significant challenge in the short-term, the key issue will come from the regulatory perspective. When it comes to safety requirements for hydrogen operations at airports, there is still a high level of uncertainty on critical aspects such as safety radius around hydrogen storage tanks and whether parallel refuelling will be permitted. This issue especially will be pivotal in determining the operational impacts of new hydrogen aircraft at airports.

Another key issue regional airports will need to consider as first movers will be the lack of the right expertise not only within their organisation but at a government and regulatory level[19]. For airports, hydrogen operations will require new ground handling capabilities that most of them do not currently possess. Reskilling for such a significant change will require a continuous process of recruitment, training, and certification. Initially, airports will need to collaborate with the relevant institutions to acquire appropriate personnel while gradually upskilling existing staff. For airports, however, bringing in new people is a relatively quick and straightforward process. Public institutions, however, tend to move slower. Governments, as policymakers, will be responsible for laying out a solid policy framework to support airports, airlines and other stakeholders within the supply chain on this transition towards hydrogen operations, and therefore, any imbalance between the different party's timelines could be a barrier for the uptake of this new technology.

Another challenge that some airports will face in the early years will be the lack of common infrastructure across UK airports. This will require careful planning when developing schedules and slot allocations at airports to ensure hydrogen aircraft will be able to be refuelled when needed. The largest challenge will come if

17 https://unece.org/adr-2021-files
18 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf
19 FFC Project NAPKIN - CAA Key Regulatory Considerations Workshop Note

hydrogen aircraft get diverted to airports with no hydrogen infrastructure in place. To overcome this issue, round-trip fuel planning may be required for operations between very small airfields as these may have performance limitations in place which could mean they are unsuitable for hydrogen powered aircraft[20]. At larger airports, initially this will probably create longer delays but it will be rapidly overcome once all airports start to develop their own hydrogen infrastructure in coming years.

KEY TAKEAWAY

IN THE EARLY YEARS, INTRUSIVE HYDROGEN INFRASTRUCTURE WILL NOT BE REQUIRED, WITH REGIONAL AIRPORTS LEADING THE TRANSITION TO HYDROGEN AVIATION. DEVELOPING NEW SAFETY PROCEDURES AND PROVIDING COMMON HYDROGEN INFRASTRUCTURE ACROSS UK AIRPORTS ARE LIKELY TO BE THE KEY CHALLENGES TO OVERCOME.

### 5.4.2 Longer Term (2040+)

From 2040 onwards, the introduction of larger narrowbody and midsize aircraft sees demand increase significantly, especially at the larger airports such as Heathrow, Manchester, or Stansted. At this point, hydrogen delivery by road tankers may no longer be feasible and permanent storage solutions and pipeline distribution are likely to be required.

**Table 8: Peak number of daily hydrogen tanker requirements for UK airports – Upside Scenario**

| Airport (annual pax) | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| **Very Large (>40m)** | 0.1 | 0.3 | 4.0 | 70.0 | 144.0 | 334.0 |
| **Large (10-39.9m)** | 0.1 | 0.4 | 3.0 | 16.0 | 33.0 | 81.0 |
| **Medium (3-9.9m)** | 0.1 | 0.2 | 2.0 | 14.0 | 22.0 | 29.0 |
| **Small (1-2.9m)** | <0.1 | 0.2 | 1.0 | 5.0 | 7.0 | 13.0 |
| **Very Small (<1m)** | <0.1 | 0.3 | 2.0 | 2.0 | 4.0 | 5.0 |

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**Table 9: Peak number of daily hydrogen tanker requirements for UK airports – Baseline Scenario**

| Airport (annual pax) | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| **Very Large (>40m)** | <0.1 | <0.1 | 2.0 | 29.0 | 64.0 | 158.0 |
| **Large (10-39.9m)** | <0.1 | <0.1 | 1.0 | 12.0 | 17.0 | 40.0 |
| **Medium (3-9.9m)** | <0.1 | 0.1 | 0.6 | 6.0 | 10.0 | 14.0 |
| **Small (1-2.9m)** | <0.1 | <0.1 | 0.6 | 1.0 | 2.0 | 2.0 |
| **Very Small (<1m)** | <0.1 | 0.1 | 0.4 | 1.0 | 1.0 | 2.0 |

**Table 10: Peak number of daily hydrogen tanker requirements for UK airports – Downside Scenario**

| Airport (annual pax) | 2025 | 2030 | 2035 | 2040 | 2045 | 2050 |
|---|---|---|---|---|---|---|
| **Very Large (>40m)** | <0.1 | 0.1 | 0.2 | 16.0 | 36.0 | 68.0 |
| **Large (10-39.9m)** | <0.1 | <0.1 | 0.1 | 3.0 | 7.0 | 24.0 |
| **Medium (3-9.9m)** | <0.1 | <0.1 | 0.1 | 2.0 | 6.0 | 6.0 |
| **Small (1-2.9m)** | <0.1 | <0.1 | 0.1 | 1.0 | 1.0 | 1.0 |
| **Very Small (<1m)** | <0.1 | <0.1 | 0.1 | 0.1 | 0.3 | 0.6 |

Green = Tanker delivery and storage sufficient (the case for all scenarios in this phase);

Light Blue = Need for permanent storage;

Dark Blue = Need for permanent storage and pipeline delivery

In the baseline scenario, Table 9 shows that by 2040, airports like Manchester, Birmingham and Edinburgh could require up to 12 tankers a day, with Heathrow and Gatwick each requiring 29 tankers per day on average across the two airports (see 8.4 for specific figures for Heathrow airport). In the upside scenario, this could increase to 16 and 70 tankers daily for large and very large airports, respectively (Table 8).

While it is difficult to anticipate or quantify an individual airport's capacity (and tolerance) to accommodate tanker deliveries, from 2040 onwards it seems likely that more permanent storage solutions would be needed (shaded in light blue in Table 8, Table 9 and Table 10). Beyond 2040, the level of anticipated demand (at least in the baseline and upside scenarios) would likely require both permanent storage and alternative pipeline delivery (shaded in dark blue in Table 8, Table 9 and Table 10). In the downside scenario, permanent storage and pipeline delivery is not anticipated at very large airports until 2045, and may not be required at smaller airports at all before 2050 (see Table 10).

If storage tanks were needed, their size would depend on the airport demand for hydrogen but, as with conventional jet fuels, additional hydrogen stock would be needed to account for any potential disruption with the supply chain. In any case, the location of the storage tank fuel farm would need to be carefully planned. Storage fuel farms located landside would require multiple control post crossings, adding pressure to the security system at the airport. However, those located airside would need to allow delivery trucks airside.

The preference would be to locate the storage tank fuel farm outside the airport's security perimeter to avoid delivery trucks being subject to detailed security clearance, potentially creating congestion issues. In this case, an offloading facility located outside the airport's boundary connected to the storage tank farm by a short pipe is likely to be the less intrusive solution for most airports. In this regard, ZeroAvia and Shell, with the support of the Zero Emission Flight Infrastructure (ZEFI) project, demonstrated a landside-to-airside hydrogen airport pipeline at Cotswold Airport in the UK[21]. The hydrogen pipeline was 100-meter-long and was demonstrated alongside an electrolyser and mobile refueler.

Regarding permanent delivery options, dedicated pipelines would likely be required to transport gaseous hydrogen to the airport or a facility nearby. Transporting liquid hydrogen by pipeline for anything but a very short distance is prohibitively difficult due to the need to keep the liquid hydrogen cryogenically cooled to reduce boil-off. Consequently, given that the majority of the larger hydrogen aircraft will require liquid hydrogen at point of use, this scenario would require liquefaction facilities located on-site or very close by, before being transferred by pipe to the storage tanks.

Securing the necessary space to locate these facilities (i.e., liquefaction plant and storage tanks) will be a key challenge for many airports. While the specific footprint of this infrastructure will depend on the demand at each airport, the additional space needed at many large airports is expected to pose significant master planning challenges, as many are already space constrained. Liquefaction is also highly energy intensive. For example, by 2050 hub airports such as Heathrow could require almost 500MW for liquefaction with significant impact on the power distribution network. One possible opportunity for airports with highly seasonal traffic; if the

21 https://www.zeroavia.com/shell-collaboration

supply and liquefaction process was continuous (24/7), the surplus of hydrogen production during off-peak periods could be used for other purposes such as to power ground support equipment or terminal or building heating.

While it has been suggested that it could be possible to re-purpose existing natural gas pipelines for transporting gaseous hydrogen (for example, Project Union[22] aims at developing 2,000km of hydrogen pipelines by 2030 by re-purposing 25% of the current gas network) there are a number of challenges such an approach would face. Namely, existing pipe networks would need to be upgraded and fitted with additional sensors to reduce and control leaks and aid leak detection (gaseous hydrogen molecules are extremely small and the gas is highly buoyant). This would require accessing the existing subterranean pipe networks, which would almost certainly be highly disruptive and costly (for example, needing to divert underground utilities or disruption to airport pavement surfaces during installation).

The possibility of hydrogen production at some airports is another area that has received attention. However, space limitations and the high energy demand needed to support electrolysis and liquefaction make this prospect extremely unlikely before 2050. Liquefaction and electrolysis would demand between 3.0 and 4.0 GW by 2050 for larger airports. For context, the UK installed nuclear capacity in 2020 was ca. 9 GW[23]. The complexity of implementing the required scale of transmission grid network would also substantially undermine the feasibility of hydrogen production at the airport.

From an operational perspective, based on existing refuelling technology and processes it is likely that refuelling times would increase for larger aircraft even if two hoses were used[24], potentially leading to reductions in route profitability, especially in the regional and narrowbody space. Also, these hoses are likely to be heavy which will make manual handling challenging and potentially riskier than existing refuelling practices. Automation of the refuelling process would create an opportunity to speed up the turnaround time as well as reduce the risks associated with hydrogen aircraft refuelling. However, this is not expected to be a feasible short-term solution as the technology it still at a very early stage of development and would inevitably require thorough testing and safety assessments before implementation. In addition, to ensure compatibility of technologies between different aircraft manufacturers and refuelling infrastructure, standardisation of connectors is required, which does not yet exist.

22 https://www.nationalgrid.com/stories/journey-to-net-zero-stories/making-plans-hydrogen-backbone-across-britain
23 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/789655/Nuclear_electricity_in_the_UK.pdf
24 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf

The largest aircraft from the NAPKIN fleet is the 90-seater aircraft. For this aircraft size, refuelling times would likely stay within the existing requirements[25]. However, if larger hydrogen aircraft such as the narrowbody and midsize aircraft proposed by FlyZero[26] were developed, further research on how to speed up and potentially automate the refuelling process will be key.

KEY TAKEAWAY

FROM 2040 A MAJOR OVERHAUL OF THE EXISTING INFRASTRUCTURE WILL BE REQUIRED AT LARGE AIRPORTS TO INTRODUCE PARALLEL FUEL SYSTEMS AND LIQUEFACTION ON SITE. TO MAINTAIN TURNAROUND TIMES AND SAFETY WITHIN EXISTING STANDARDS, THE REFUELLING PROCESS WILL NEED TO BE PARTIALLY OR FULLY AUTOMATED.

## 5.5 Airport Regulatory Framework

While the full-scale roll out of hydrogen infrastructure will pose significant planning and logistical challenges, airports will also need to raise substantial finance for such infrastructure. The ownership model of an airport will be important for financing models.

Airports can either be regulated or non-regulated assets and private or publicly-owned. Internationally, most large-infrastructure projects are publicly funded – as international major airports remain predominantly state-owned, and the risks associated to the scale and complexity of major airport infrastructure have favoured this approach. In the UK, however, most airports are privately owned and operated and, in the case of Heathrow, fully regulated by the CAA. While state-owned airports generally have greater flexibility for developing new infrastructure, there are also some issues associated to public funded projects. Significant changes in the political scene can impact willingness of Government to prioritise airport investments over other commitments. In addition, public funding of large-scale infrastructure should demonstrate its economic and social benefit as not only the users will pay but all taxpayers.

25 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf
26 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-AIN-REP-0007-FlyZero-Zero-Carbon-Emission-Aircraft-Concepts.pdf

There are different funding models airports can adopt depending on their ownership and regulatory status. This funding model will dictate which steps airports will need to take to secure the capital to fund the future hydrogen infrastructure. The use cases presented in the following sections explore in more detail some of these funding models.

# 6 Case Study A: Small Gaseous Retrofit Aircraft Take-off – 2025-30

## 6.1 NAPKIN 7 seat Gaseous Fuel Cell Aircraft

This aircraft concept, developed by Cranfield Aerospace Solutions Ltd (CAeS) is based on a retrofit of an existing 9 seat aircraft, the Britten Norman Islander. The retrofit includes the removal of the conventional piston engines and any related systems. These are then replaced with hydrogen fuel cell systems (HFCS) and electrical propulsion units (EPUs) packaged in the nacelles, high pressure tanks mounted under-wing storing gaseous hydrogen, and heat exchangers integrated into the nacelles for the thermal management of the HFCS.

**Figure 8: NAPKIN 7-seater GH2 retrofit aircraft**

Conventional Islander aircraft are in service today in the UK around the Orkneys, Shetland Islands and Scilly Isles and used globally for short journeys particularly in coastal, island and remote areas where they often provide life-line services to local communities.

To serve these routes and to be able to take off and land at unconventional airfields (e.g., grass, beach, very short), the Islander has superior Short Take Off & Landing (STOL) capabilities, and these have been maintained with the conversion to hydrogen fuel cell electric propulsion.

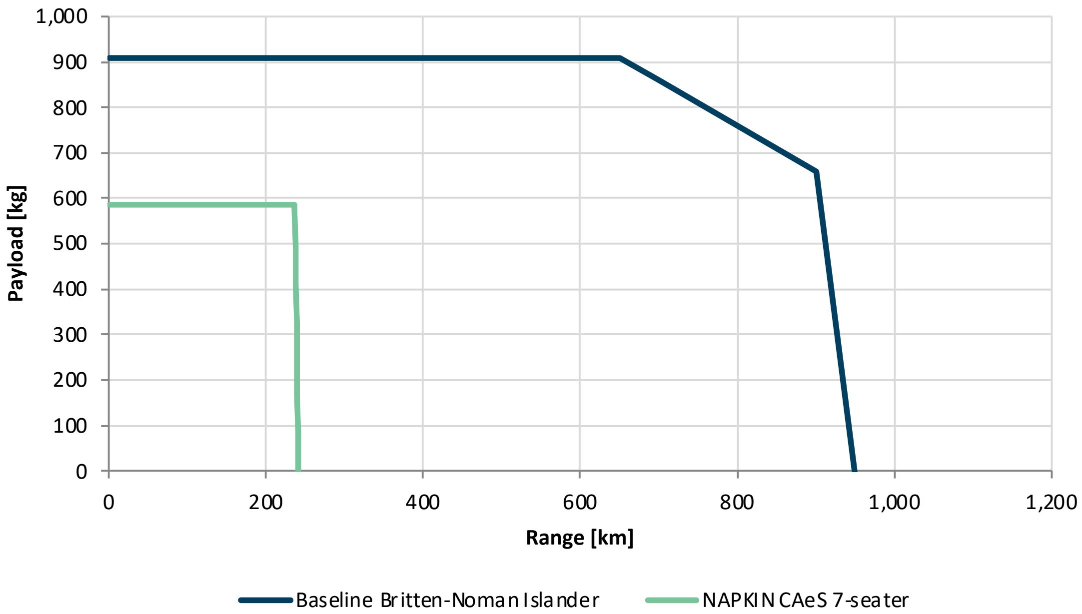
The technology assumed for this concept is based on gaseous hydrogen as for this size of aircraft, the small amount of hydrogen required means that the heavy, high-pressure tanks can be incorporated while maintaining acceptable payload and therefore commercial viability. The increased complexity of liquid hydrogen is not required for this size aircraft, nor would liquid hydrogen be likely to be available at remote airfields in the near future.

The wing-mounted fuel tank assemblies provide advantage in replacing inertia relief previously provided by the gasoline stored in the wings outboard of the nacelles. However, they also result in increased drag and therefore the installed power has been increased to maintain the take-off and climb airfield performance of the conventional aircraft.

**Table 11: Key performance characteristics of the NAPKIN 7-seater aircraft**

| | |
|---|---|
| **Range (Max passenger)**[1] | 200-230 km (108 – 125 nm) |
| **Payload** | 585 kg |
| **Cruise Speed** | 125 kts (TAS) |
| **Take-off Weight** | 2,994 kg |
| **Landing Weight** | 2,975 kg |

**Figure 9: Payload-Range diagram of the NAPKIN 7-seater aircraft and the baseline aircraft, Britten-Norman Islander**




1 With 45 minutes reserve

### 6.1.1 Operational Costs

Given the current similar market of both the 7-seater described above and the 19-seater gaseous hydrogen fuel cell-powered aircraft described in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes" (G2 Concept), both have been analysed. These two aircraft are based on two existing reference aircraft designs, the BN2B-26 and DHC-6-400, respectively. Table 12 shows the key operating costs of the concept aircraft and how they compare with the reference aircraft.

The Total Cost of Ownership (TCO) per flight hour (FH) reflects the overall costs of owning and operating the aircraft per flight hour. As can be seen in Table 12, the concept aircraft were found to perform competitively as a zero-carbon alternative to reference aircraft.

A full description of the methodology is provided in the accompanying technical report "Ownership and Operating Cost Model".

**Table 12: Total Cost of Ownership per Flight Hour of the 7- and 19 seat NAPKIN aircraft (shaded in green) and their reference aircraft (shaded in grey)**

**NAPKIN Aircraft** **Reference aircraft**

| | 7-seater | 19-seater | BN2B-26 | DHC-6-400 |
|---|---|---|---|---|
| **Number of seats** | 7 | 19 | 9 | 19 |
| **Range (km)** | 230 | 290 | 700 | 750 |
| **TCO/FH (£/FH)** | 640 - 832 | 996 – 1,302 | 880 | 1,503 |
| **£/Seat FH** | 91 - 119 | 52 - 68 | 97 | 79 |

As can be seen in Figure 10 and Figure 11 below, in terms of production costs, manufacturing is the largest share, followed by airframe engineering and design costs. New propulsion and fuel systems account for 21% of the production cost for the 7-seater, and 23% for the 19-seater H2 aircraft (Figure 11). As both concepts are based on an existing design, less effort is considered on the full airframe engineering and design aspect.

**Figure 10: Breakdown of the production cost of the 7-seater**

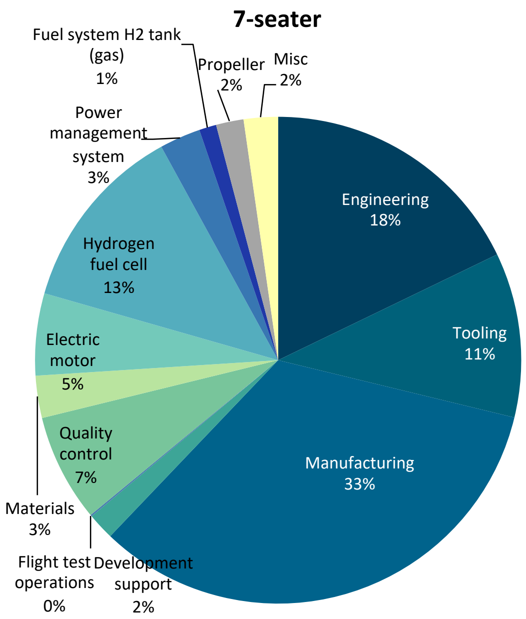



**Figure 11: Breakdown of the production cost of the 19-seater**

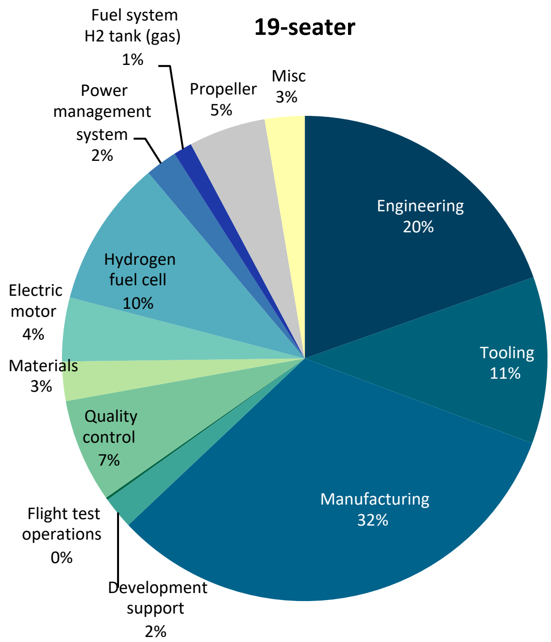



Figure 12 and Figure 13 present the cost breakdown of total cost of ownership (TCO) of the 7- and 19-seater NAPKIN aircraft respectively. In both cases, crew costs have the biggest share followed by maintenance and airport related charges. Overall concept aircraft figures show competitive values to reference aircraft, shown in Figure 14 and Figure 15. For both concepts, the share of fuel accounts for around 7% of total costs, compared with 20% for the (kerosene fuelled) reference aircraft. While the share of maintenance costs for the H2 concepts are slightly higher than for the equivalent reference aircraft, in absolute terms, total maintenance costs for the concept aircraft are lower than the reference aircraft.

**Figure 12: Breakdown of total cost of ownership of the 7-seater**

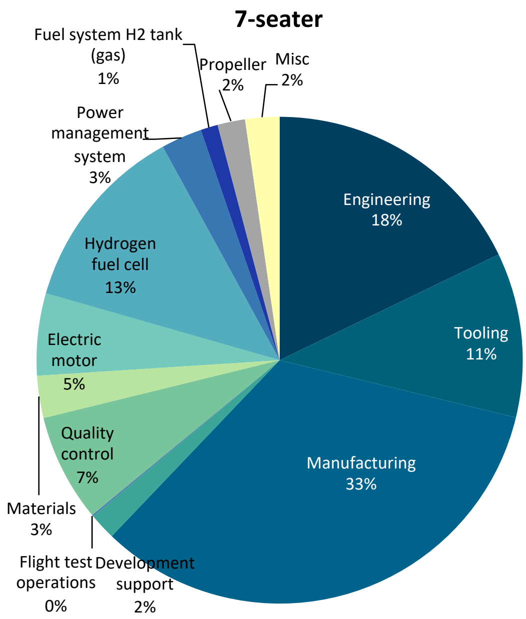



**Figure 13: Breakdown of total cost of ownership of the 19-seater**

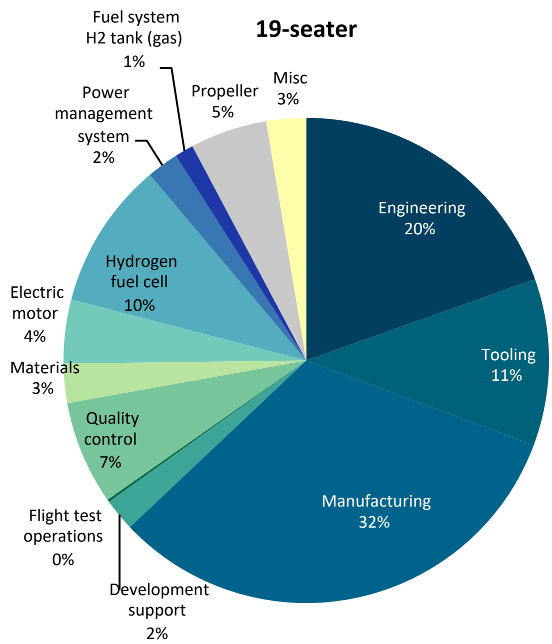



**Figure 14: Breakdown of total cost of ownership of the Britten-Norman BN-2B-26 Islander**

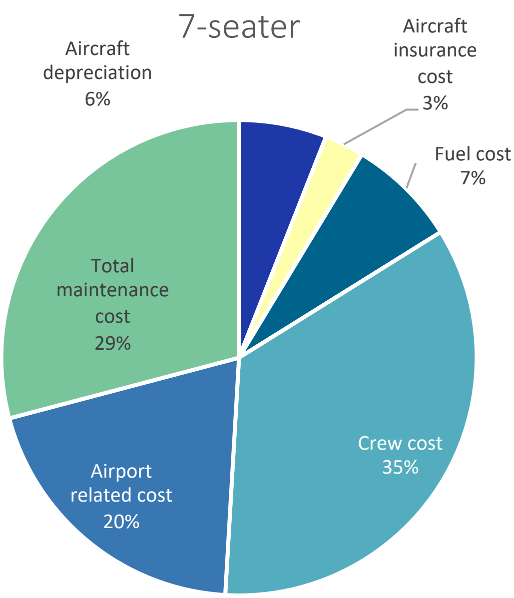
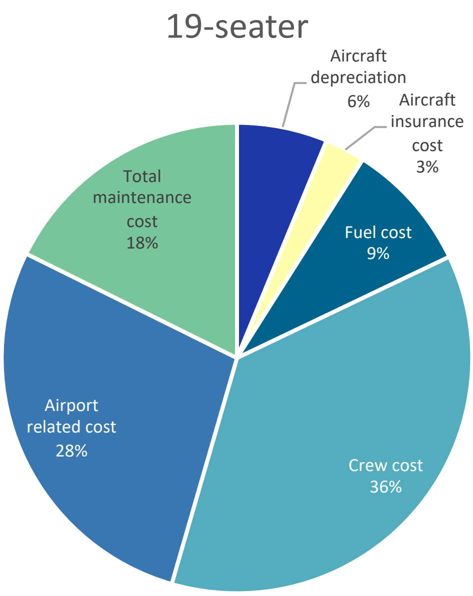



**Figure 15: Breakdown of total cost of ownership of the Twin Otter**



### 6.1.2 Noise Performance

The noise of the 7-seater NAPKIN aircraft is dominated by propeller tone sources. The propeller geometry remains unchanged relative to the reference aircraft, the Britten-Norman Islander, resulting in higher loading of blades and increase in power to accommodate a slight increase in thrust requirement during take-off. The tip Mach number of 0.823 equals that of the reference aircraft, considered relatively high, so the design could benefit significantly by a reduction in tip speed.

During operation, the need for increased thrust leads to an increase in instantaneous maximum sound pressure level () of 1.4dBA relative to the baseline aircraft. Despite this, there is still significant margin to ICAO Chapter 10 levels and the time averaged sound exposure level (SEL) remains relatively unchanged at low altitudes, with a small increase observed at higher altitudes due to increase in levels of the lower frequency harmonics, which are less affected by atmospheric attenuation.

As a conclusion, due to the small design and operational changes between the 7-seater aircraft concept and the baseline aircraft, there is little change in overall noise impact, subject to the variation in expected flight numbers.

The complete set of results as well as the methodology followed to assess the noise performance of the 7-seater concept aircraft (Concept A) are presented in the technical report "An assessment of the noise impact of zero-emission regional hydrogen aircraft and their operation".

## 6.2 UK Domestic Market

The market for 9-19 seater aircraft in the current UK domestic aviation system is relatively specialised. Typically, they are used on short routes to, from and between islands or other remote regions. Smaller aircraft usually have higher operating cost per passenger than larger aircraft, and commuter-sized aircraft below 20 seats are relatively difficult to operate profitably; many of the UK routes where they operate are supported by Public Service Obligations (PSOs) which give additional funding to airlines to provide service to remote communities on the condition that a minimum flight frequency is supplied. Although they have high per-passenger costs, small aircraft have low per-flight costs, which makes them suitable for routes with a minimum flight frequency where load factor may sometimes be low. Additionally, many of the airports where 9- and 19-seater aircraft currently operate have short runways, making them impossible to fly to with larger aircraft that do not have STOL capabilities. Most routes are also fully exempt from Air Passenger Duty (APD), as are aircraft with Maximum Take-Off Mass (MTOM) below 5.7 tonnes. Because typical flights in this size class are short, fuel costs are a relatively small fraction of operating costs. However, the conventional Britten-Norman Islander aircraft in operation on current UK 9-seater routes use aviation gasoline, which can be several times the price of kerosene on a per-kg basis.

The potential market for 7-9 and 19-seater hydrogen aircraft depends on where these aircraft can be operated cost-effectively. Because of the small number of passengers they can carry, they are likely to have higher per-passenger costs than larger aircraft even if hydrogen prices become very low. As such, their use within a near-future UK domestic system is likely to be on routes similar to those where 9- and 19-seater aircraft are already operated. For 2025, using UK and US government estimates, the effective price of fossil Jet A could be around £0.5-1.2/kg once carbon price is factored in, and that of aviation gasoline is likely to remain high (around £2.1/kg)[2]. Gaseous hydrogen prices on an energy-equivalent basis to kerosene may be around £0.7-1.6/kg kerosene equivalent[3], and the 7- and 19-seater hydrogen aircraft designs discussed above are significantly more energy-efficient than their currently operating conventional alternatives, which also acts to reduce fuel costs. As such, fuel costs for hydrogen aircraft are likely to be well below those of aviation gasoline aircraft and may be at a similar level or below those of kerosene aircraft. Any additional reduction in non-fuel operating costs below those of comparable kerosene aircraft will strengthen the case for hydrogen aircraft adoption.

To assess potential markets for these aircraft, both the 7-seater design described above, and a gaseous hydrogen fuel cell-powered 19-seater design (Concept G2) described in the accompanying technical report “UK Domestic Market Modelling – Methodology and Additional Outcomes” were added as options into a UK version of UCL’s Airline Behaviour Model (see Chapter 3 Airline Behaviour Model). For these model runs, outcomes across a range of Jet A (+ carbon price) and hydrogen prices appropriate to the time period around 2025 were assessed. Only UK domestic flights are modelled. The year-2023 reduction in domestic APD[4] is included, but changes to other demand drivers were not modelled due to uncertainty in how UK domestic demand may develop[5]. Airlines are given the option of adopting the 7- and 19-seater gaseous hydrogen designs with operating and cost characteristics discussed above. They are also given the option of adopting additional conventional aircraft. For the other use cases, both the case where hydrogen aircraft are eligible for APD (if operating on an eligible route) and the case where they are not were considered. At present, HMRC regulations on APD eligibility exclude both aircraft which are not fuelled by kerosene and those which have MTOM below 5.7 tonnes[6], suggesting the no-APD case is much more likely for at least the 7-seater. As such, only the APD-

2 See discussion of fuel price ranges used in the accompanying technical report “UK Domestic Market Modelling – Methodology and Additional Outcomes”. Note that ‘central’ fuel prices reflect central-case projections for kerosene, carbon and hydrogen prices rather than being exactly half-way between upper and lower case prices.
3 See discussion of fuel price ranges used in the accompanying technical report “‘UK Domestic Market Modelling – Methodology and Additional Outcomes”.
4 HM Treasury, 2021. Autumn budget and spending review 2021: documents. https://www.gov.uk/government/publications/autumn-budget-and-spending-review-2021-documents.
5 See discussion in the accompanying technical report “‘UK Domestic Market Modelling – Methodology and Additional Outcomes”. Note that this assumption applies only to domestic aviation; for projections of international demand, growth projections are significantly more robust.
6 HMRC, 2022. Air passenger duty for plane operators. https://www.gov.uk/guidance/air-passenger-duty-for-plane-operators

exempt situation for this use case was considered.

**Figure 16: 7- and 19-seater gaseous hydrogen aircraft uptake (flights) in the UK domestic aviation system under Year-2025 Use Case A conditions across a range of kerosene and hydrogen prices.**

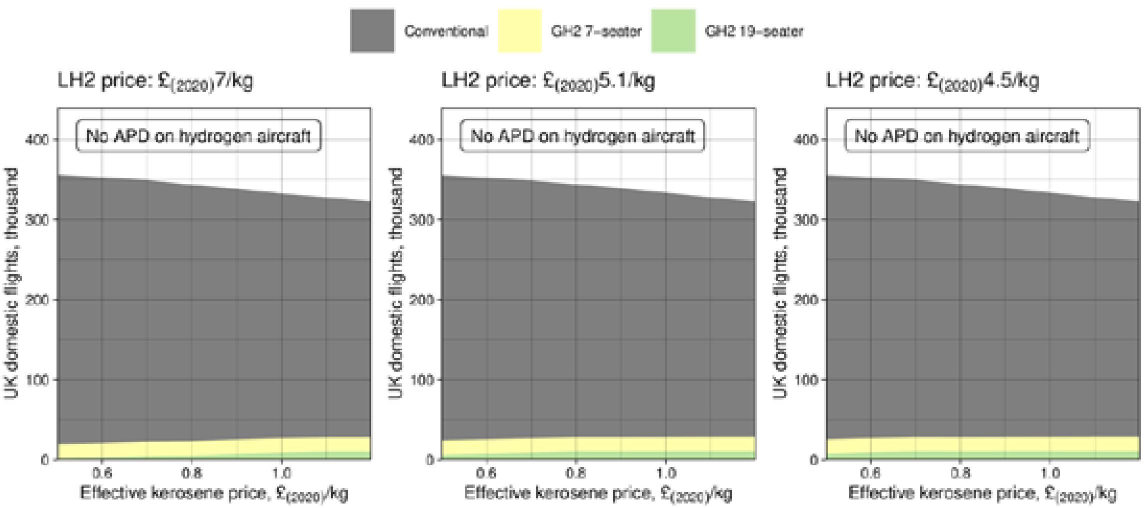



Figure 16 shows whole-system number of flights by all aircraft and by individual models of hydrogen aircraft across different hydrogen and kerosene prices. These outcomes represent a profit-optimal equilibrium state after all necessary fleet turnover has taken place. For comparability with other use cases, liquid hydrogen price is shown; the corresponding gaseous hydrogen price range is £2.0 – 4.5/kg (£0.7-1.6/kg kerosene equivalent). Under these conditions, uptake of hydrogen aircraft is relatively small (under the most favourable conditions, 9% of flights and 1% of passengers). Uptake of the 7-seater hydrogen aircraft has only limited dependence on fuel prices, and is highly concentrated on network regions involving remote and island regions, as discussed below[7]. Uptake of the 19-seater hydrogen aircraft is more dependent on fuel price and is projected to be close to zero where hydrogen price is at the upper end of the range modelled and Jet A price is at the lower end of the range modelled.

7 Note that these outcomes are somewhat dependent on fuel cell maintenance costs, which are uncertain. Sensitivity runs assessing 7- and 19-seater aircraft at different values for maintenance and capital costs are included in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes".

### 6.2.1 Route Network

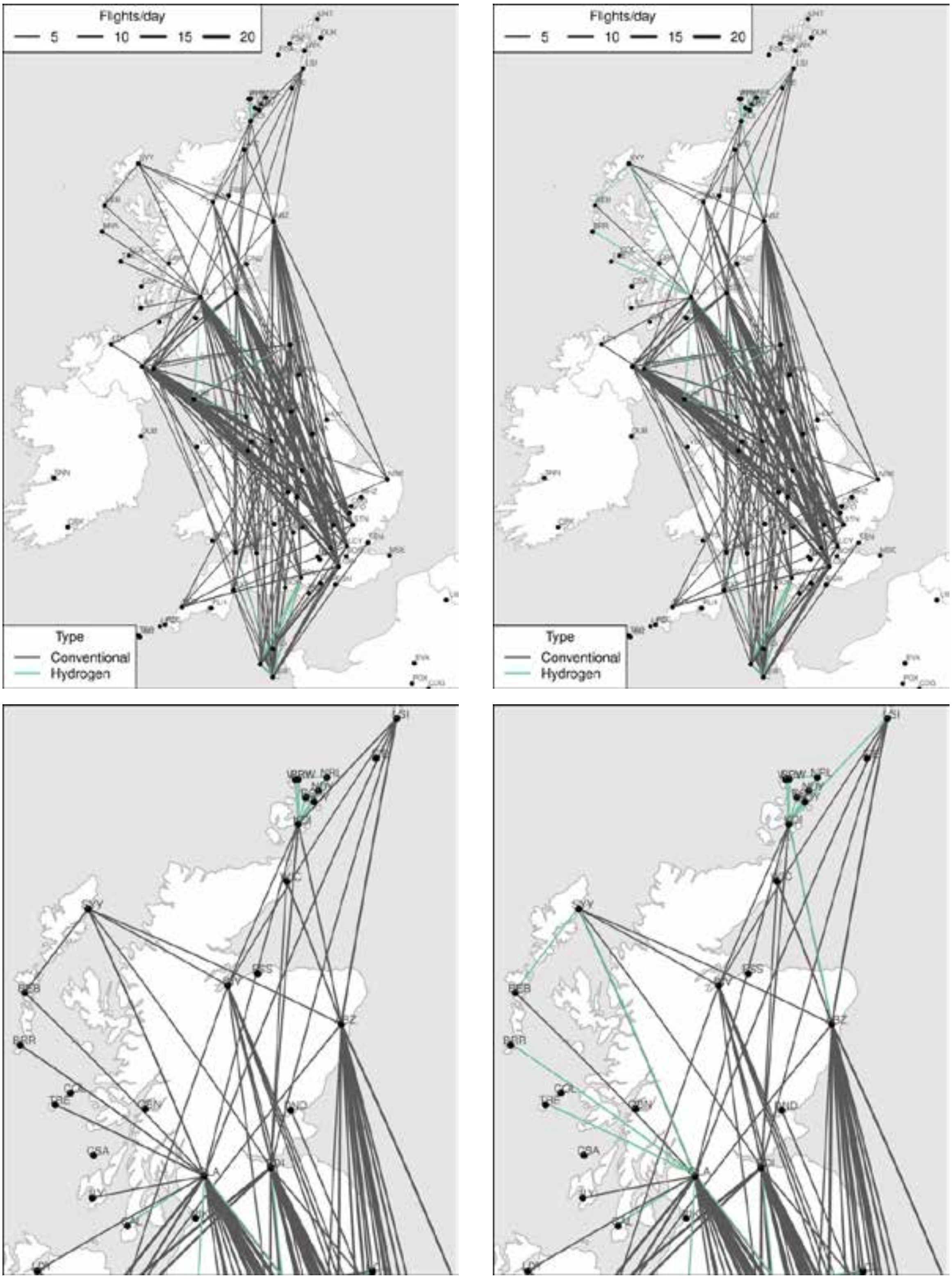
Three types of uptakes for hydrogen aircraft are seen in these simulations. First, routes which are currently operated using aviation gasoline see some uptake of 7-seater hydrogen aircraft across the whole range of fuel costs modelled[8], reflecting the high operating costs associated with existing aircraft on these routes. These routes are mainly ultra-short haul routes between Scottish Islands (e.g., intra-Orkneys). Second, some additional uptake of both the 7- and 19-seater designs is seen on routes between the Channel Islands where small aircraft are currently operated. Thirdly, where hydrogen prices are on the low end of the 2025 range modelled and kerosene prices on the high end, some use is seen on other Scottish inter-island routes, other short-distance regional routes (including to and from the Isle of Man) and between the Channel Islands and Southampton[9]. Cornwall-Scilly Isles routes were not modelled due to lack of representation in schedule data, but these routes are another likely use case. In general, use of the 19- rather than the 7-seater is seen on routes that have sufficient demand to support a slightly larger aircraft, have lower (or no) PSO-type flight frequency requirements, and that are above the maximum range of the 7-seater. Example flight networks at different levels of hydrogen price are shown in Figure 17 below, including additional detail on Scottish routes. As discussed in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes", the baseline route network used is that operated in 2015; notably, some routes (e.g., ABZ-SYY) which have ceased operation since then may be cost-effective to operate with hydrogen aircraft, suggesting that use of hydrogen aircraft under favourable fuel cost conditions may be one way of improving the viability of previously-abandoned regional routes.

8 This is similar to the conclusions of ELICA, 2020. Economic Feasibility Study for a 19 PAX Hybrid-Electric Commuter Aircraft. https://www.rolls-royce.com/~/media/Files/R/Rolls-Royce/documents/innovation/elica-d2-1-economic-feasibility-study-for-a-19-pax-hybrid-electric-commuter-aircraft.pdf

9 This use is dependent on small hydrogen aircraft being APD-exempt as routes between the Channel Islands and mainland UK are not in themselves APD-exempt, i.e., the lack of APD gives small hydrogen aircraft a small cost advantage when competing against slightly larger aircraft for which APD is charged.

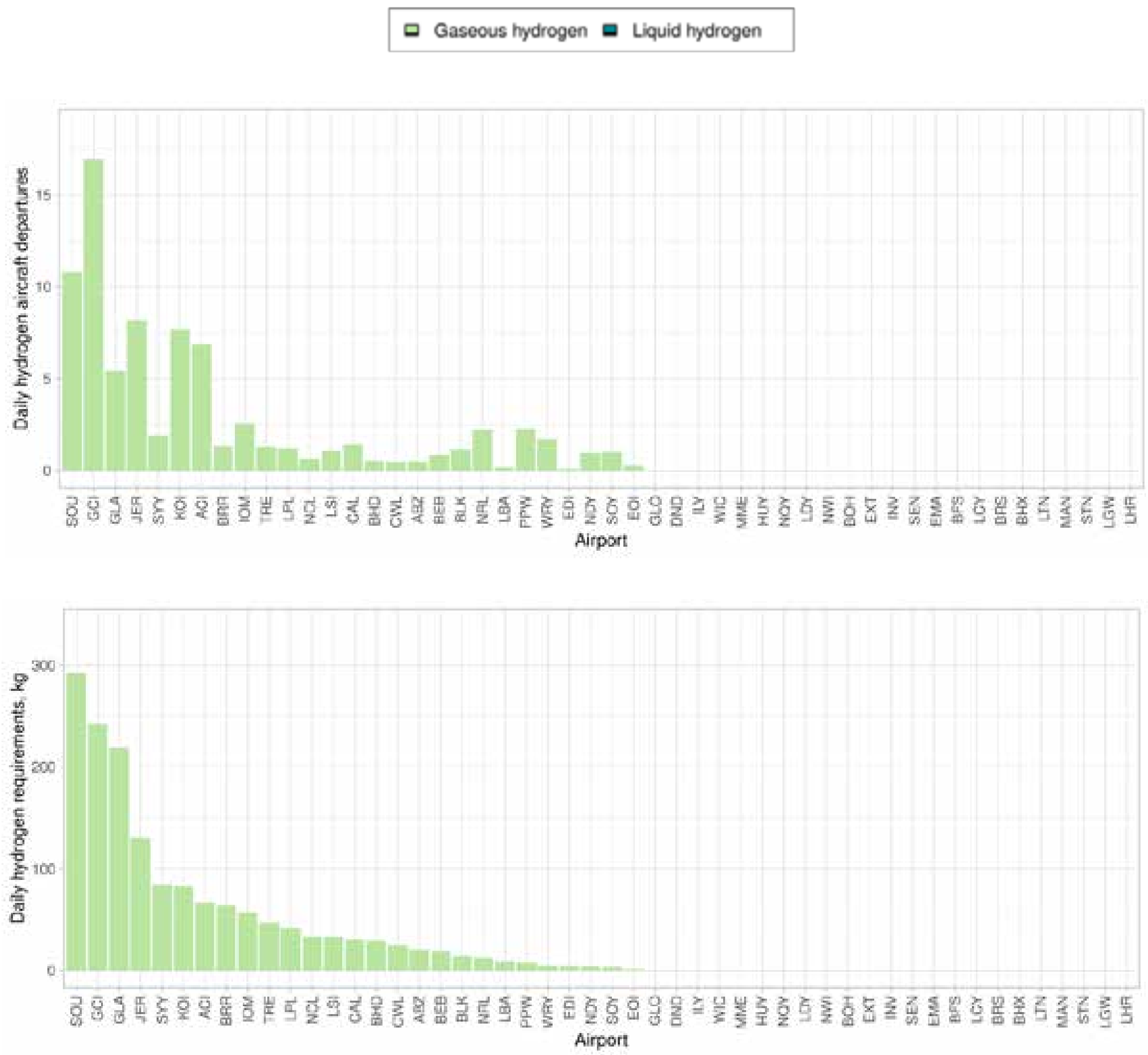
**Figure 17: Projected flight networks for Use Case A at central kerosene prices and lower and upper values of hydrogen price for 2025.**

GH2: £4.5/kg (LH2: £7/kg) GH2: £2/kg (LH2: £4.5/kg)



These limited networks imply relatively small initial requirements for aircraft and infrastructure for domestic routes. Figure 18 shows airport-level numbers of hydrogen aircraft flights and airport hydrogen requirements for domestic flights. The bars in Figure 18 show outcomes at central fuel prices of £0.8/kg Jet A including carbon and £2.5/kg gaseous hydrogen. The implied UK domestic fleets in these simulations across the different fuel prices simulated are around 7-8 7-seaters (i.e., a similar number to the current UK Islander fleet) and around 0-5 19-seaters. In practice, these would be supplemented by demand related to other UK PSO-type routes (not all of which are modelled here), other world regions, and potentially additional use cases.

**Figure 18: Airport-level number of hydrogen aircraft flights and amount of hydrogen required, at central fuel prices modelled for Use Case A (Jet A + carbon: £0.8/kg; gaseous hydrogen: £2.5/kg; liquid hydrogen: £5.0/kg). Note that only domestic demand is modelled.**



Under the 2025 conditions modelled here, domestic flight demand for hydrogen aircraft and infrastructure is relatively small and is concentrated on use by small regional carriers at a limited number of airports. This largely reflects specialised current usage for 7-9- and 19-seater aircraft in general, i.e., even at very low hydrogen price, replacing one flight with a 70-seater aircraft with ten flights with a 7-seater aircraft will typically not be feasible from a cost, capacity or noise perspective. Impacts on airline profit and average fares are projected to be small in all cases. The commercial case for these aircraft could be strengthened by examining additional use cases within or outside the UK domestic system, further reducing capital and maintenance costs, or applying additional incentives for adoption. However, even a small network can serve as a useful test case to increase the visibility of hydrogen aircraft and assess their operational requirements in practice.

Because uptake is limited to a small selection of routes, the direct impact on UK domestic aviation CO2 of 7- and 19-seater hydrogen aircraft is also likely to be small (around 0.2-1.1% decrease, or 2-12 kt CO2 per annum in these simulations compared to simulations with the same fuel price conditions but no hydrogen aircraft). However, they will still have longer-term indirect impacts on CO2, helping to increase passenger acceptance of hydrogen aircraft through safe use in practice and through the long-term impact of learning on technology, infrastructure, and operational considerations.

## 6.3 Use Case A Airport: Inverness Airport

As mentioned in Section 5.2 Airport Demand, regional airports are expected to lead the transition towards hydrogen aviation in initial years due to the nature of their point-to-point and short-range operations. For this use case, Inverness Airport has been chosen to investigate early-challenges related to infrastructure, operations and commercial impacts. Rather than just looking at the 2025-adjacent timeframe used in the market simulations above, this section considers airport-level outcomes up to 2050, including larger aircraft and international operations.

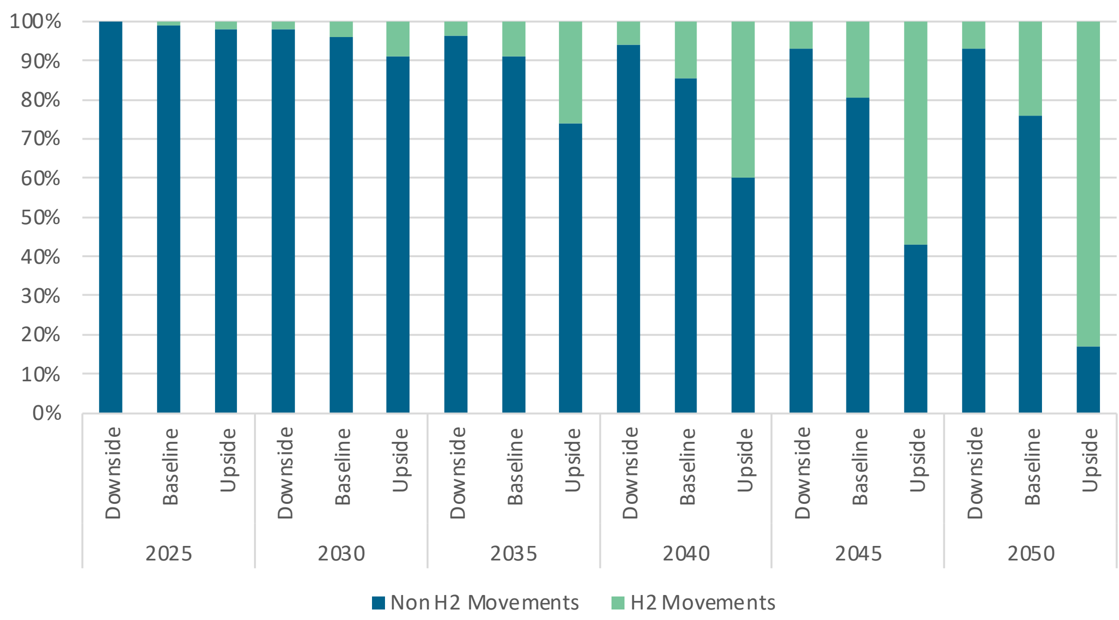
### 6.3.1 Hydrogen Demand

The fleet mix at Inverness Airport is dominated by regional aircraft (60%) and narrow bodies (40%). The domestic market dominates the total traffic demand, with 90% of the movements. Looking at the range of the routes being operated from Inverness Airport, most of the routes, if not all, have the potential to switch to hydrogen.

Only four airlines operate year-round from Inverness airport: easyJet (53%), Loganair (20%), British Airways (15%) and KLM (10%). Holiday charter flights are operated by TUI and JetsGo. This means a shift towards hydrogen aircraft from only one or two of these airlines will have a significant impact for the airport operation. To reflect this potential situation, the upside scenario considers that by 2050, more than 80% of the total airport movements will be hydrogen. This translates to just over 44,000 hydrogen movements (scheduled and non-scheduled) and 61 million litres of hydrogen per year. The downside and baseline scenarios consider a more conservative fleet turnover, with an overall hydrogen fleet penetration of 7% and 24% respectively which reduces the annual hydrogen demand to 5 and 18 million litres respectively.

Hydrogen demand at Inverness Airport is expected to start small and scale up. The first zero-carbon emission aircraft are expected to take off from regional airports between 2025 and 2030. Considering this is less than five years away, uncertainty around safety, operational issues and policy regulation will need to be worked through by airports, preferably with policymakers. These initial small-scale hydrogen operations, however, will provide the perfect opportunity to gain knowledge about key issues and provide initial answers to them.

**Figure 19: Split between H2 and Non H2 movements at Inverness Airport**




## 6.3.2 Hydrogen Infrastructure

The potential hydrogen demand for Inverness airport, based on current aircraft types, indicates that a major overhaul of existing infrastructure is not essential before 2050. Even for the upside scenario, only three trucks per day would be required to meet the daily demand, and therefore it is unlikely that surface access would be an issue for deliveries into Inverness Airport.

**Table 13: Summary of H2 demand and infrastructure requirements for Inverness Airport**

| | 2035 | | | 2040 | | | 2045 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Downside | Baseline | Upside | Downside | Baseline | Upside | Downside | Baseline | Upside | Downside | Baseline | Upside |
| **H2 Peak Day Demand (thousand litres)** | 2 | 9 | 26 | 10 | 25 | 70 | 13 | 37 | 109 | 15 | 50 | 175 |
| **H2 Storage (thousand litres)** | 4 | 17 | 49 | 20 | 48 | 133 | 26 | 71 | 208 | 28 | 96 | 334 |
| **H2 Truck Deliveries per day** | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 1 | 2 | 1 | 1 | 3 |
| **Bowsers** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Space (sqm)** | 20 | 90 | 250 | 100 | 250 | 700 | 135 | 370 | 1,100 | 145 | 500 | 1,750 |
| **Preferred Airport Delivery Method** | Truck Delivery | | | | | | | | | | | |
| **Preferred Aircraft Delivery Method** | Bowser | | | | | | | | | | | |

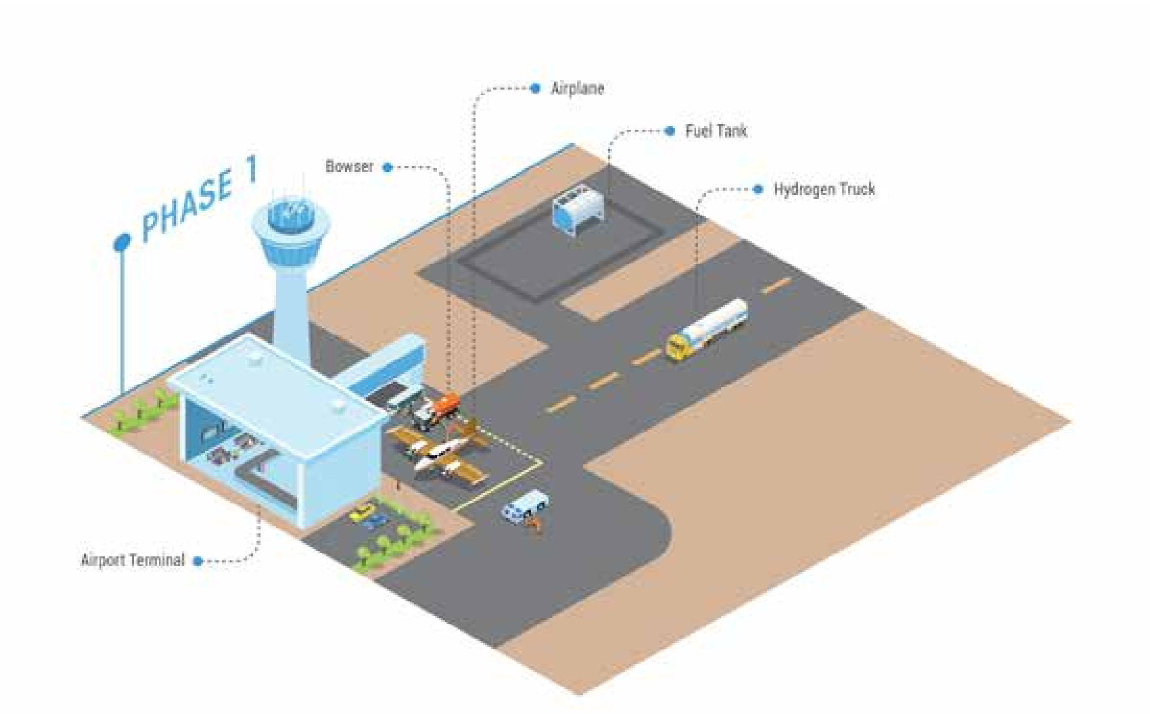
Given pipeline delivery is not expected to be required at Inverness Airport before 2050, supporting infrastructure requirements will be driven by the hydrogen fuel farm only. It could be that given the low demand levels, in the short-term, hydrogen storage facilities would not be required and instead, hydrogen would be supplied to aircraft directly.

In the longer run, storage facilities will be needed. By 2050, these facilities would need a footprint of land ranging between 145m2 to 1,750m2. Although the masterplan is currently not showing any space allocated for hydrogen operations, given the airport footprint, finding a suitable space for storage facilities should be possible.

Fuel at Inverness Airport is currently being delivered using bowsers as given its airfield size and demand, a hydrant solution is not required. The forecasted hydrogen demand indicates that a bowser solution would still be feasible to deliver hydrogen to aircraft up to 2050 as only one 20,000 litre bowser would be required.

Given the potential hydrogen demand, liquefaction at Inverness airport is not essential and therefore, a significant increase in energy demand is not predicted before 2050. The current electrical supply for Inverness is at full capacity so any substantial additional energy supply requirements would require an upgrade to the local substation, and these would need to be discussed with the energy provider

(SSE) to understand its feasibility. However, based on the outcomes of this project, this is not likely to be needed.




While the airport infrastructure will not be a barrier for the uptake of zero-carbon emission aircraft, the hydrogen supply and delivery networks need to be planned and agreed in advance.

Scotland, and especially the Highlands, has the potential and ambition[10] to become a leader on green hydrogen production given its high offshore and onshore wind potential. Hydrogen is already being produced in the Highlands and Islands region and a number of projects to increase its production are in early planning, most of them targeting early 2030s as the initial years of production[11]. However, first hydrogen aircraft are expected to arrive between 2025 and 2030, thus, accelerating the production of green hydrogen will be a critical focus for policymakers and industry across UK-EU if the estimated timelines under NAPKIN and other studies are to be met.

Additionally, most of the hydrogen currently produced in the Highlands is not being used locally but sold to other regions of the UK due to the lack of distribution infrastructure in the Highlands, which increases the distribution costs. Therefore, even if the Highlands were to produce enough green hydrogen for all the potential users within the region, including Inverness Airport, a distribution infrastructure needs to be planned and developed to enable regional uptake. The need for new distribution

10 https://www.gov.scot/binaries/content/documents/govscot/publications/speech-statement/2020/12/scottish-government-hydrogen-policy-statement/documents/scottish-government-hydrogen-policy-statement/scottish-government-hydrogen-policy-statement/govscot%3Adocument/scottish-government-hydrogen-policy-statement.pdf

11 https://forum.all-energy.co.uk/wp-content/uploads/2021/03/Joanne-Allday-North-of-Scotland-Hydrogen-Programme-for-AllEnergy_Mar-2021.pdf

infrastructure capable of supporting all forms of energy, including hydrogen, has already been included in the latest draft National Planning Framework (NPF4) issued by the Scottish Government[12]. It will be key that this delivery infrastructure is available soon to enable the uptake of zero-carbon emission aircraft.

### 6.3.3 Operations

While hydrogen demand at Inverness is not likely to require very intrusive infrastructure developments, changes to current operations will need to happen. If the introduction of hydrogen operations occurs in a phased manner, as the downside and baseline scenarios estimate, there is an opportunity to leverage the learning from these early years to help implement the larger operational strategy improvements required as the number of hydrogen flights increases.

As previously highlighted, a key issue for regional airports as the first movers will be the lack of expertise within their organisations. This is also the case within the government and authorities in charge of developing the policy framework, which is needed to guide and support these airports with their transition towards zero-carbon services.

At Inverness Airport, the delivery of the hydrogen is likely to be carried out by a third party. The airport team would therefore need a certain level of training to understand the security and safety implications of the use of hydrogen on the airfield, as well as a sufficient level of understanding of the hydrogen delivery, storage and transfer process to allow the airport to audit any contractors' operation. The airport will need to ensure appropriate training on new safety procedures is in place for any hydrogen refuelling contractors.

In terms of impact on the airport capacity, the overall airport load factor in 2019 was around 80%, which suggests there is some spare capacity. A sight capacity loss due to either increased turnaround times or lower seating capacity on certain routes would therefore not largely impact the overall airport's capacity.

### 6.3.4 Cost Implications and Commercial Opportunities

Highlands and Islands Airports Limited (HIAL) is a private limited company wholly owned by the Scottish Ministers and responsible for the management and operation of 11 regional airports including Inverness. HIAL's mission is to create social benefit and economic prosperity by building Scotland's sustainable regional airport group of the future. This is reinforced by their vision to become a 'net-zero-carbon regional airport group'. In 2020, HIAL invested over £27 million to the benefit of customers, passengers and communities. HIAL have embraced innovation and change and pushed ahead with ambitious plans to develop a test environment for low carbon aircraft in the Highlands and Islands. HIAL already own 2 regional aircraft which

12 https://www.gov.scot/publications/scotland-2045-fourth-national-planning-framework-draft/documents/

Loganair operates on Public Service Obligation (PSO) routes, from Glasgow to Campbeltown, Tiree and Barra.  As HIAL seeks to retain and even expand an integrated air service network that properly supports and encourages the economic development of the region, and augments service provision on lifeline routes, they recognise they must explore safe, but also different operating models to decarbonise operations and enable greener air service

HIAL recognise that the infrastructure to support sustainable aviation will not be realised without new initiatives and support from government, and will work closely with the Scottish Government and others to achieve this. Indeed, HIAL is already working with employees, key partners and their communities to realise their vision to become a net zero-carbon regional airport group.

# 7 Case Study B: Liquid Hydrogen Regional Aircraft by 2035

## 7.1 B1: NAPKIN 40-seater Fuel Cell Aircraft

This aircraft concept, developed by GKN Aerospace in support of the H2GEAR programme, is not based on retrofitting an aircraft already available in the market. Instead, a preliminary aircraft design activity has been undertaken to produce a concept aircraft which is best able to take advantage of a 1MW fuel cell system powering electric fans, fuelled by cryogenically stored liquid hydrogen.

The design of this concept was based on data from existing sub-regional aircraft and an extension of some of the 19 seat concept aircraft. The fuselage cross-section has been maintained with a 2+2 seat arrangement but lengthened to accommodate additional rows of seats. The aircraft and its propulsion system are sized to be compliant with existing CS25 regulations, including one engine inoperative climb requirements, range and field performance. The entire hydrogen system would be contained in unpressurised safe zones in the rear of the fuselage, with no hydrogen conveyance paths placed around the passenger cabin. This is thanks to only electrical power being distributed between these safe zones and the propulsors.

An initial configuration with a low wing and rear fuselage mounted fan propulsors was proposed. Whilst this showed benefits from a noise perspective, it posed a number of aircraft design challenges, especially around maintaining the position of the centre of gravity (CG). As such, the configuration was changed to a high wing with wing mounted fan nacelles as shown in Figure 20.

**Figure 20: NAPKIN 40+ seat fuel cell aircraft**

The 40-passenger aircraft concept is an early example of an integrated platform with liquid hydrogen fuel storage, fuel cells, electrical power distribution and innovative low pressure ratio ducted fans driven by cryogenically cooled electric motors. The integration of these technologies has been pursued with top level aims of zero emissions, reduced noise footprint, short turnaround time and competitive operating costs. Whilst the fuel cell aircraft achieves zero-carbon and NOx emissions, water vapour is still emitted which can lead to the creation of contrails. Further atmospheric science research is urgently required to understand how the characteristics of the water vapour exhaust influences the formation of contrails and their subsequent impact on global warming. Potential mitigations include specific control of the exhaust and avoidance of critical atmosphere zones.

The use of low-pressure ratio ducted fans driven by electric motors creates a significant opportunity to further reduce both take-off and approach noise levels but may require higher fidelity noise assessments (relative to those available within NAPKIN) to fully identify the benefits. All the notional platforms have features that simplify the turnaround operation within the limits for LH2 fuel as accepted by all the NAPKIN Use Cases.

A particular area of uncertainty concerns the regular maintenance of the fuel cell stacks. The development of aerospace standard fuel cells is still in its infancy and therefore stack performance data over an extended number of cycles is, at best, speculative. The GKN-40 is assumed to operate with one-third of the fuel cell stacks being replaced in a phased programme. This delivers a full stack complement with only minor deviations from a constant mid-life performance level. Each individual stack is assumed to have a life of 10,000 flight hours in alignment with the recommendations from FlyZero. An assumed annual utilisation of ~3000 hours implies that one-third of the stacks are exchanged each year. Since the additional 1/3 of the total stacks required will be part of the initial purchase price, there should only be a regular charge for stack inspection and refurbishment.

The GKN-40 platform has also considered how the aircraft might fit into an operational environment. Taxi speeds and field performance are all competitive and the entire design has accounted for the most obvious CS-25 requirements including one engine inoperative (OEI) operations. The rear part of the fuselage is maintained as two non-pressurised zones for the fuel cell stacks and hydrogen storage tanks. An additional refinement is that all hydrogen routes are restricted within the fuel safe zones. The cryogenic cooling of the motor and other components is enabled by a closed loop gaseous helium system.

The GKN-40 Use Case represents a single time point in the development of integration knowledge for hydrogen fuel cell electric propulsion. The technology roadmaps in NAPKIN indicate the potential for improvements in aircraft performance, range, noise and cost reduction. GKN are also optimistic for the development of larger aircraft that will obviously impact the market penetration for fuel cell aircraft operations.

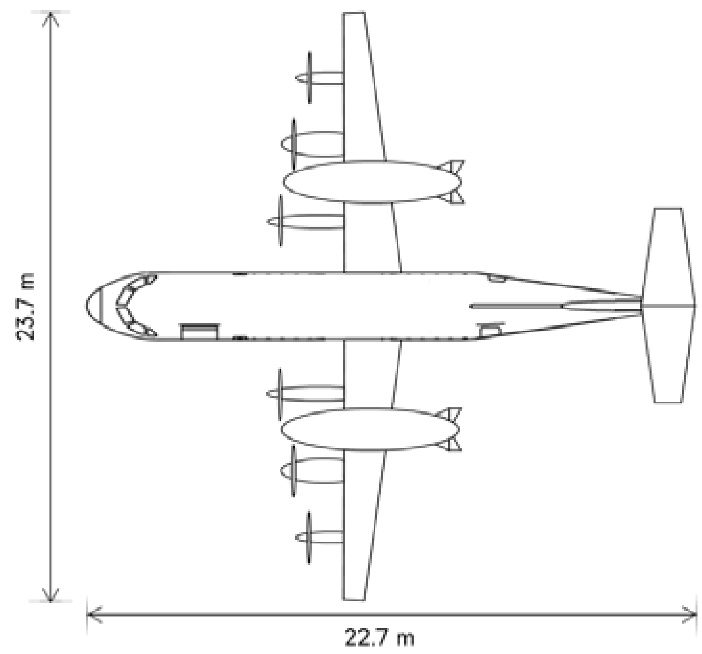
**Table 14: Key performance characteristics of the NAPKIN 40-seater aircraft**

| | |
|---|---|
| **Range (Max passenger)**[1] | 1,506 km (813 nm) |
| **Payload** | 4,082 kg |
| **Cruise Speed** | 354 kts (TAS) |
| **Take-off Weight** | 19,055 kg |
| **Landing Weight** | 18,900 kg |

## 7.2 B2: NAPKIN 50-seater Gas Turbine Aircraft

This aircraft concept, developed by Rolls-Royce, is a clean sheet design driven by the requirement to achieve a 600 nm design mission with a 50-passenger payload. Additionally, the aircraft take-off and landing performance was constrained by the London City operating requirements.

**Figure 21: NAPKIN 50 seat gas turbine aircraft**




As with other hydrogen fuelled aircraft concepts, the low volumetric energy density of hydrogen presents fuel storage challenges. For efficient storage of the cryogenic liquid hydrogen, the tank surface area to volume ratio needs to be low which drives towards a spherical or cylindrical tank shape with a low length to diameter ratio.

1 With 5% trip fuel, 100 NM diversion and 20 minutes hold.

Often the tank is incorporated in the aft fuselage, similar to other concepts discussed in this report. An alternative approach is taken for this concept where fuel is stored in external tanks on the wings. This allows the fuselage layout to remain largely unchanged from the baseline and helps to provide bending moment relief in the wings but does introduce significant extra drag.

For the propulsion system, the aircraft incorporates a pair of hydrogen combusting turboprops which are electro-mechanically linked to two additional propellers on each wing. The distributed propulsion effect caused by this enables improved take-off performance to achieve the required London City capability.

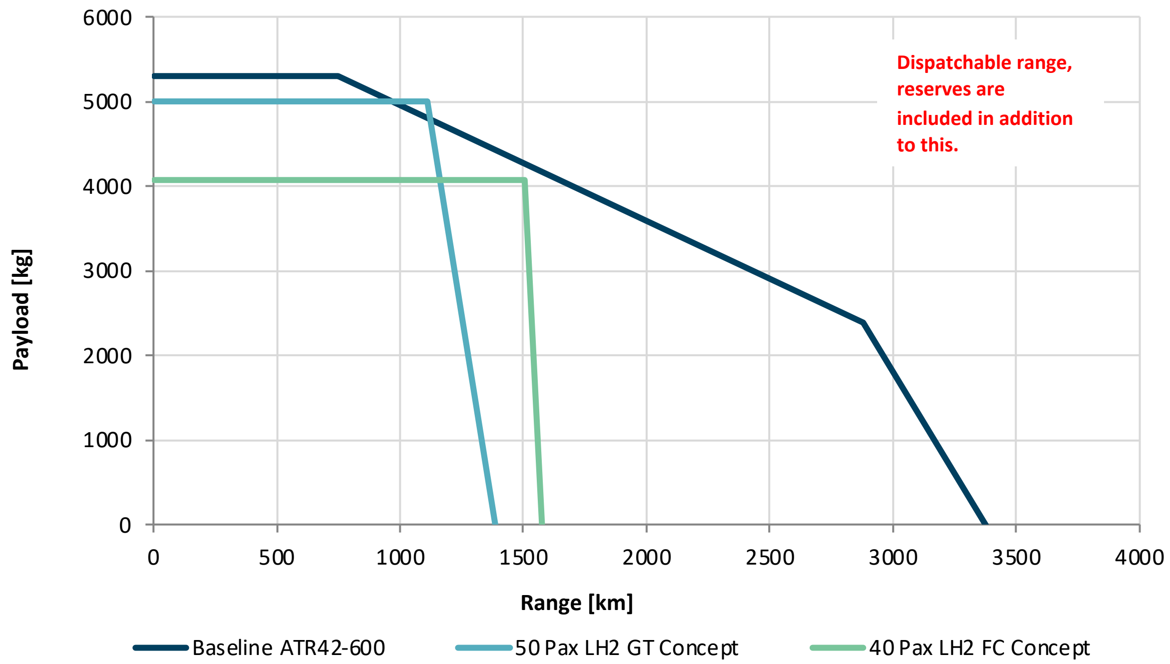
The combination of these design choices produces an aircraft capable of meeting all the design requirements while still retaining a payload mass fraction of 31%, similar to the existing ATR42, which is a strong indicator of the potential economic performance of the aircraft during operation.

**Table 15: Key performance characteristics of the NAPKIN 50 seat aircraft**

| | |
|---|---|
| **Range[2] (Max passenger)** | 1,111 km (600 nm) |
| **Payload** | 5,000 kg |
| **Cruise Speed** | 300 kts (TAS) |
| **Take-off Weight** | 16,000 kg |
| **Landing Weight** | 16,000 kg |

2 Reserves included in addition to this: 14CFR 121.641 Flag Operations with 100 NM Diversion

Figure 22: Payload Range Diagram of the Use Case B aircraft concepts




## 7.3 Operational Costs

In this use case, the ATR72-600 was used as the reference aircraft for the design, but the ATR42-600 aircraft is also included as a benchmark to compare operational performance based on an aircraft with a similar number of seats. Table 16 below shows how the economics of the 40- and 50-seat concepts compare with the reference aircraft. Details of the parameters and methodology used are presented in the technical report "Ownership and Operating Cost Model". Accepting the uncertainty inherent in such novel designs and the cost estimation methodology, the conclusion is that either concept would exhibit operating costs consistent with existing kerosene fuelled aircraft of similar size.

**Table 16: Key operating costs of the 40- and 50 seat NAPKIN aircraft (shaded in green) and their reference aircraft (shaded in grey)**

NAPKIN Aircraft | Reference aircraft

| | 40-seater | 50-seater | ATR42-600 | ATR72-600 |
|---|---|---|---|---|
| Number of seats | 40 | 50 | 48 | 78 |
| Range (km) | 1,506 | 1,111 | 1,259 | 1,404 |
| TCO/FH (£/FH) | 2,477 – 3,065 | 2,578 – 3,034 | 2,954 | 3,840 |
| £/Seat FH | 62 - 77 | 51 - 61 | 62 | 49 |

In terms of production cost, engineering and manufacturing costs have the biggest share, followed by propulsion and tooling costs. New propulsion and fuel systems account for a third (33%) of the production cost for 40-seater, and 23% for 50-seater H2 aircraft (Figure 23 and Figure 24). In addition to passenger capacity, other key differences between the 40- and 50-seater aircraft include the propulsion systems and design approach. The 40-seater hydrogen concept utilises a new design propulsion system (H2GEAR) fed through electricity generated by fuel cells, whereas the 50-seater aircraft utilises turboprop engines burning hydrogen.

**Figure 23: Breakdown of operating costs for the 40-seater**

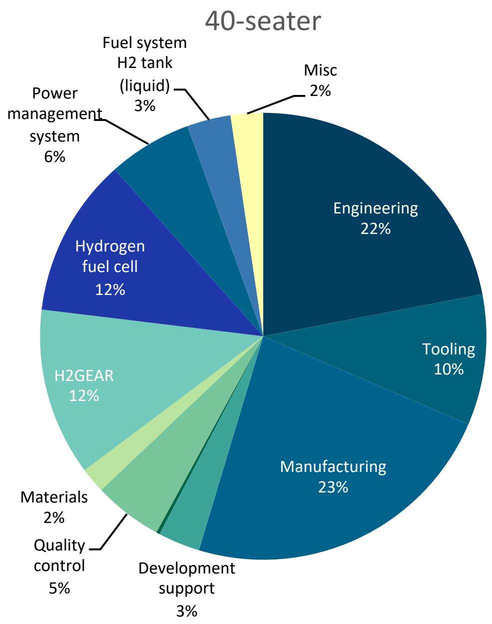
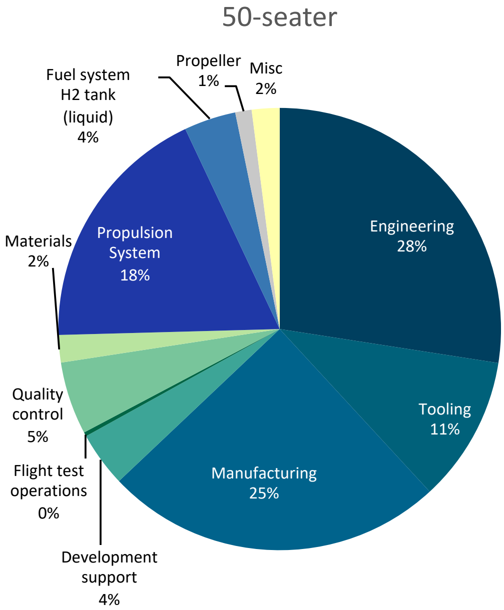



**Figure 24: Breakdown of operating costs for the 50-seater**



Similarly, Figure 25, Figure 26 and Figure 27 present the cost breakdown of total cost of ownership for both concept aircraft and reference aircraft respectively. In both cases, the share of total maintenance costs increases when compared to the reference, baseline aircraft. Overall, the concept aircraft are comparable with the reference aircraft, as the share of fuel costs drops to 19% and 21% for 40- and 50-seater hydrogen aircraft, respectively, compared with 26% for the reference aircraft.

**Figure 25: Breakdown of the total costs of ownership for the 40-seater**

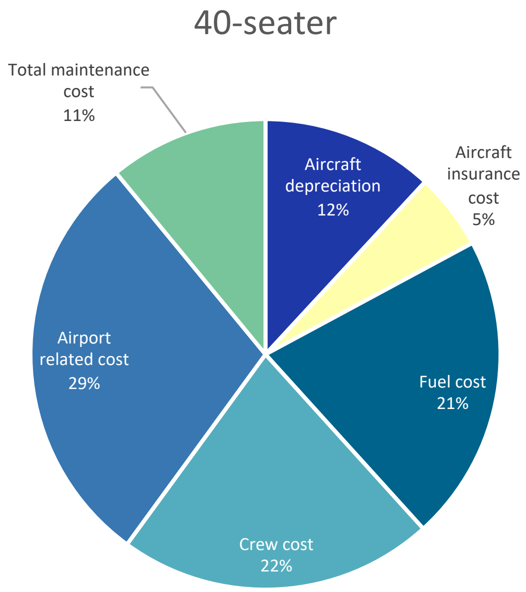



**Figure 26: Breakdown of the total costs of ownership for the 50-seater**

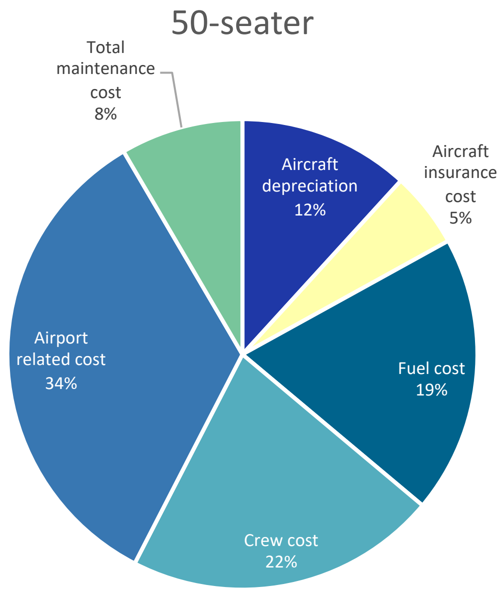
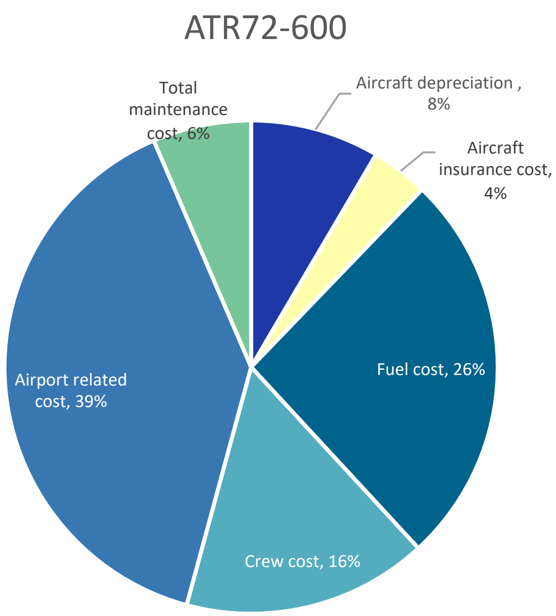



**Figure 27: Breakdown of the total costs of ownership for the ATR72-600**



## 7.4 Noise Performance

The ATR42-600 was chosen as the reference aircraft for the noise performance analysis. In terms of Noise-Power-Distance (NPD) curves, the ATR42 is indistinguishable from the ATR72 in the ANP noise database, meaning that an appropriate reduced power setting must be used as the reference point for the calculations. Results show that the concept would be certified under the Chapter 14 of the ICAO Annex 16.

### 7.4.1 Noise Performance – GKN 40 concept (use case B)

The fan configuration of the GKN-40 aircraft was modelled as a propeller with the following modifications: the directivity was changed from the dipole like directivity of a typical open propeller, to a directivity pattern similar to that of a turbofan. Two dominant lobes, one in the forward arc and one in the rear arc, represent the emission of the fan source in the forward arc, and the fan and jet combination in the rear respectively. The purpose of the specific directivity pattern is to capture the blockage effects due to the duct.

Corrections to account for reflections of main wing and horizontal tailplane reflections, and reductions in blockage effects have been added.

It is important to note that the only source modelled is the fan rotational self-noise. Effects and sources due to acoustic coupling with the duct, turbulence (including boundary layer) ingestion, stator/strut interaction are not taken into account at this stage as detailed design of the ducted fan geometry would be required.

Typically, ducted fan configurations lend themselves to the implementation of acoustic liners for further noise abatement. However, due to lack of knowledge of the dimensions of the ducts, benefits due to liners are not implemented.

The number of blades and fan geometry was not specified, therefore the parameters of the 40-seat high-wing, wing mounted propeller configuration were used. Essentially, assuming that the ducted fan has 5 blades. Data on stator number, geometry and position was not available at this stage of the design process.

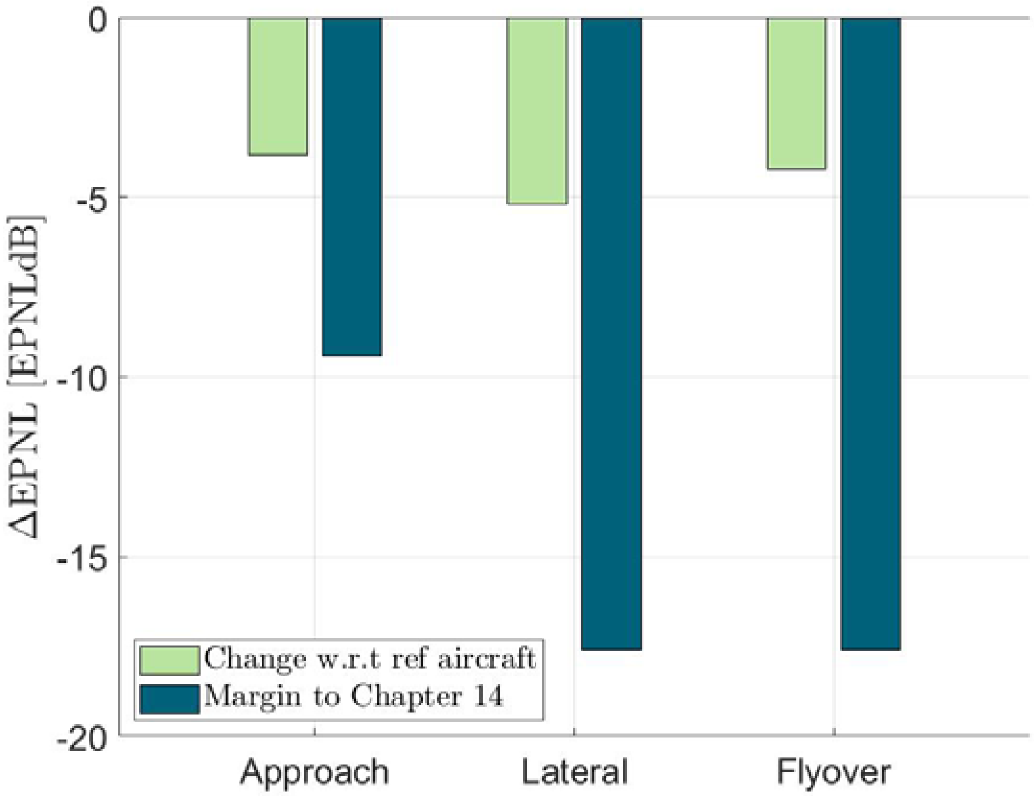
Operation of such a fan at the rotational values specified would mean a significantly reduced tip Mach number of approximately 0.45 and, therefore, per unit thrust an improved design relative to the ATR reference aircraft.

Overall, the concept leverages the position of the fan, and its preferential directivity to reduce maximum SPL and SEL noise levels relative to the ATR42-600.

The cumulative (arithmetic sum of levels at the three certification points) change in noise level relative to the current generation baseline aircraft is −13.2 EPNdB. The largest benefit is achieved at the lateral certification point with a reduction of −4.2 EPNdB. Modifications to the airframe and propulsion system allows for reductions at approach to also be achieved.

For the full methodology and results, refer to the technical report "An assessment of the noise impact of zero-emission regional hydrogen aircraft and their operation".

**Figure 28: GKN 40 seat margins to noise limits set by Chapter 14 and changes in levels relative to baseline aircraft.**




## 7.4.2 Noise Performance – RR50 concept (use case B)

A complete analysis has not been undertaken due to time constraints. However, the distributed nature of the propulsion system could be leveraged to benefit noise performance in a number of ways including:

- An increase in flow area and subsequent reduction in pressure ratio of the individual propulsors would be beneficial as would a careful consideration of blade number.
- Reduction in the pressure ratio could also allow for a reduction in tip speed for a given propeller diameter.

Preliminary analysis indicates that (without considering technological improvements) there is potential to achieve a cumulative margin of up to 16dB relative to Chapter 14. However, there is the risk of new noise sources arising from the positioning of the wing mounted fuel tanks.

## 7.5 UK Domestic Market

For the market analysis of Use Case B, both the Use Case B1 and B2 aircraft are simulated together. Regional aircraft such as the ATR-42, ATR-72 and Dash-8 have a much wider current set of use cases in the UK domestic market than 9- and 19-seater aircraft. For example, in 2015 FlyBe, then the second largest domestic carrier by passenger numbers, based its whole fleet around this aircraft size class. Typically, these aircraft are used on routes to and from smaller regional airports, as well as from airports with short runways that cannot be used by larger designs. Because they are used for longer routes than 9- and 19-seaters, and because they carry more passengers per flight, the proportion of operating cost attributable to fuel is higher. Most routes that they are operated on are not PSO routes and therefore are not APD-exempt.

The market outlook for all hydrogen aircraft designs is likely to change between 2025 and 2035. This is because hydrogen prices are projected to decrease substantially over this time period as work towards ambitious European and US hydrogen price targets continues[3]. At the same time, UK and EU ETS carbon prices are projected to rise as caps for both schemes decrease over time. By 2035, Jet A prices including carbon could be in the range £0.6-2.2/kg, whilst liquid hydrogen could be £0.8-2.1/kg kerosene equivalent (£0.4-1.6/kg kerosene equivalent for gaseous hydrogen)[4]. Hydrogen aircraft can offer a fuel cost saving over conventional aircraft of the same size and fuel efficiency over a large part of these ranges. For 40- and 50-seat aircraft, in turn, fuel cost savings are larger relative to total operating cost than for 7-9- and 19-seaters. The operating cost analysis shown above indicates that some savings may also be possible in non-fuel costs for these designs. The general level of uncertainty associated with each element of the cost estimation analysis means that only indicative results can be produced for use case B aircraft.

As with Use Case A, the 40- and 50-seat designs were introduced into the UK-adapted Airline Behaviour Model (ABM) to assess the potential extent of uptake across a range of 2035-appropriate conditions. The 7- and 19-seater designs included in Use Case A were also included and, as before, airlines were also given the option of also adding additional conventional aircraft to their fleet.

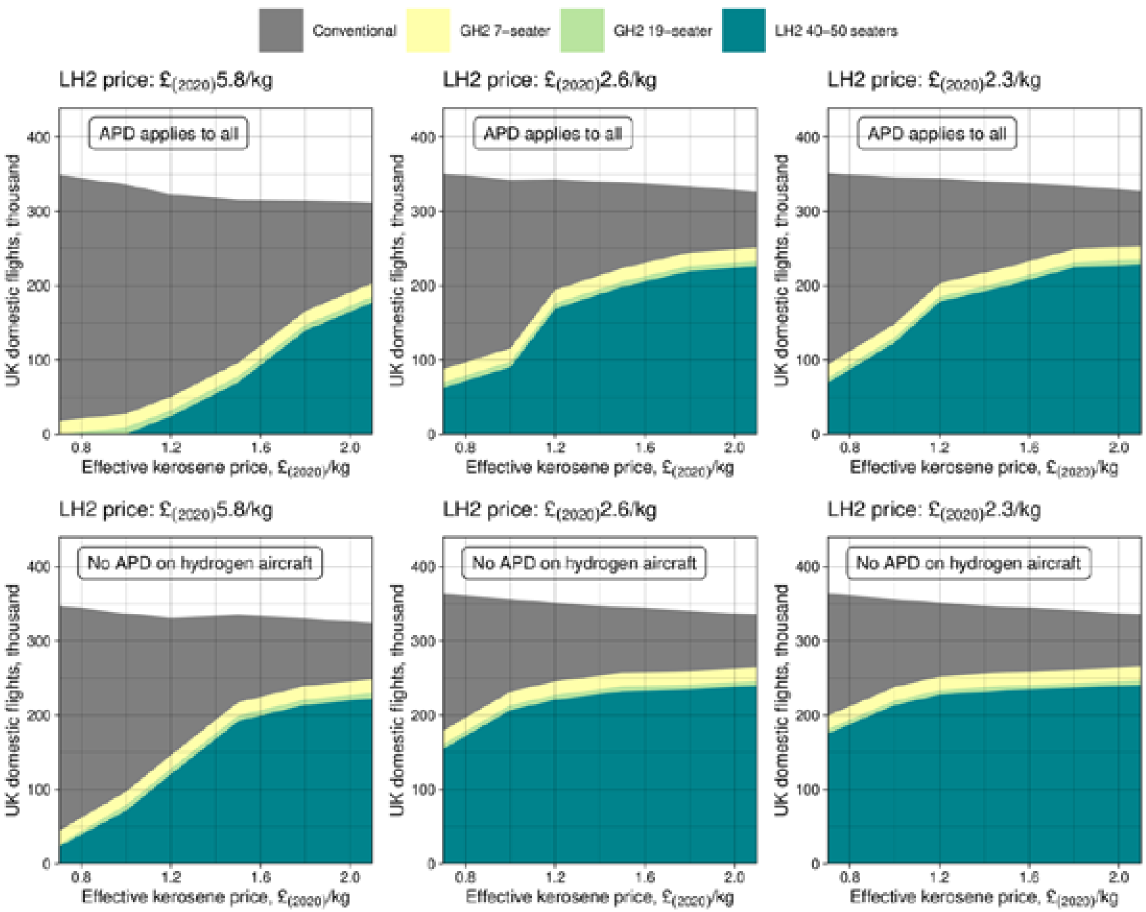
The uncertainties in the operating cost model suggest that differentiation between the individual aircraft types of use case B may be subjective at this stage. Figure 29 illustrates the results from the ABM and illustrates the powerful impact of hydrogen price on the uptake of hydrogen aircraft independent of propulsion mechanism. Because most regional-sized aircraft operate on routes that are not APD-exempt,

3 E.g. the U.S. Department of Energy is targeting $1/kg for gaseous green hydrogen before this date; https://www.energy.gov/eere/fuelcells/hydrogen-shot.
4 See the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes" for more detail on how these fuel price ranges are derived.

two cases are included for APD in Use Case B: one where hydrogen aircraft are exempt, and one where they are not.

Providing the hydrogen fuel price reduces below £2.6/kg the use case B aircraft could capture around three quarters of all UK domestic flights under most kerosene price conditions modelled, independent of the application of APD.

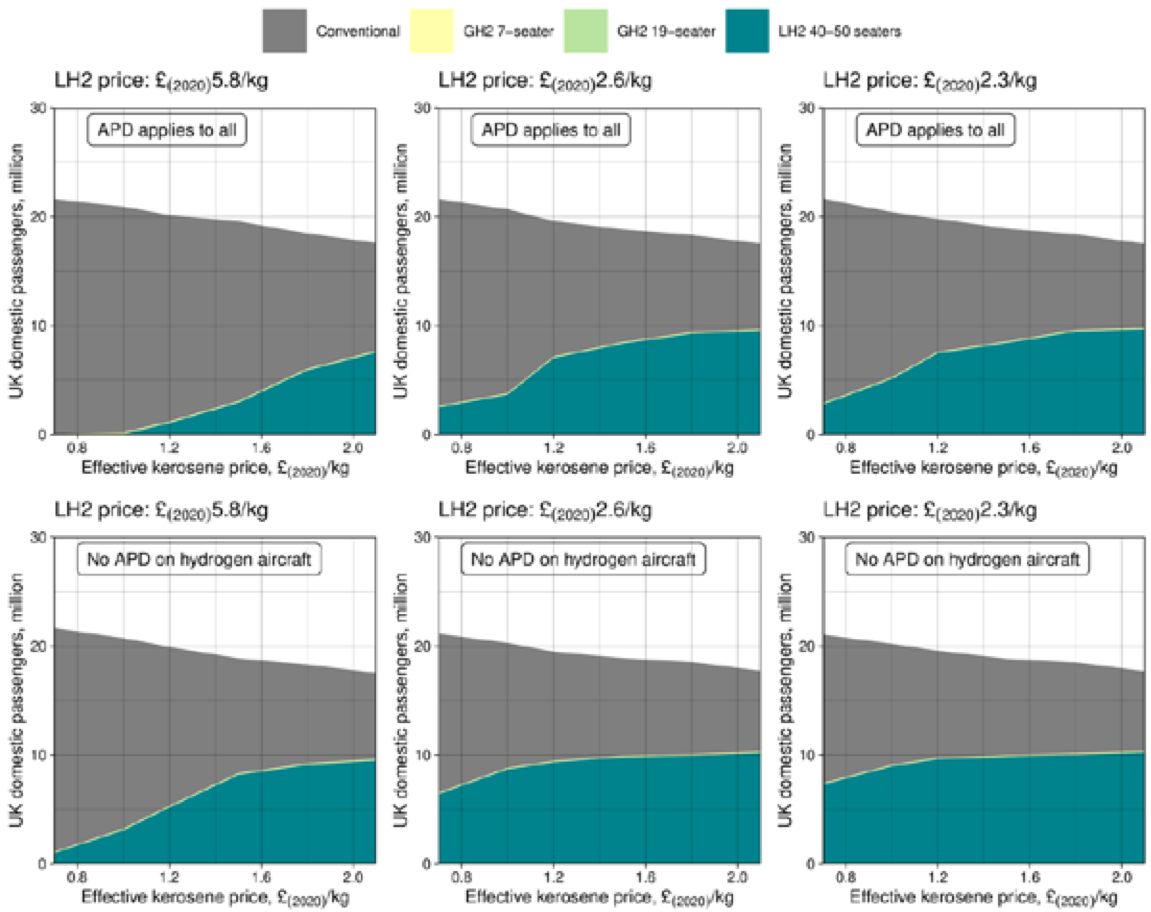
**Figure 29: 7- and 19-seater gaseous hydrogen, and 40-50-seater liquid hydrogen aircraft projected number of flights in the UK domestic aviation system under Year-2035 Use Case B conditions across a range of kerosene and hydrogen prices.**




Projected uptake in terms of number of flights is shown in Figure 29, and passengers in Figure 30. Note that these simulations examine what the profit-optimal solution for airlines would be after all necessary fleet turnover has taken place – i.e., for an EIS date in 2035, higher levels of uptake would require some time for fleet turnover to occur.

Accepting that some high load factor routes would continue to be operated by legacy kerosene aircraft rather than the concepts in this use case, as hydrogen price continues to decrease it is estimated that ~50% of all UK domestic passengers would be carried on hydrogen fuelled aircraft. This level of capacity would require significant investment in ramping up production rate of the use case B aircraft to meet the demand and would be expected to echo world-wide demand for UK based products.

**Figure 30: 7- and 19-seater gaseous hydrogen, and 40- and 50-seater liquid hydrogen aircraft projected number of passengers in the UK domestic aviation system under Year-2035 Use Case B conditions across a range of kerosene and hydrogen prices.**




As shown in Figure 29 and Figure 30, uptake of the use case B designs is much more sensitive to fuel prices than the 7- and 19-seater designs. If kerosene prices are at the bottom end of those considered, hydrogen prices close to the top end, and hydrogen aircraft are subject to APD, then uptake may be zero. At the upper end of kerosene prices, lower end of hydrogen prices, and where APD is not charged on hydrogen aircraft, there is the potential for approximately three-quarters of UK domestic flights to use these aircraft types.

This outcome takes no account of the development of a larger hydrogen aircraft, for example, those in use case C. At the high end of kerosene prices, a ceiling for uptake is apparent; substituting further flights beyond this amount would require use of 40 and 50-seater aircraft by airlines that normally use only aircraft above 100 seats; additional use at airports that have capacity constraints; and use on high-volume routes which would require very high flight frequency to serve with use case B aircraft.

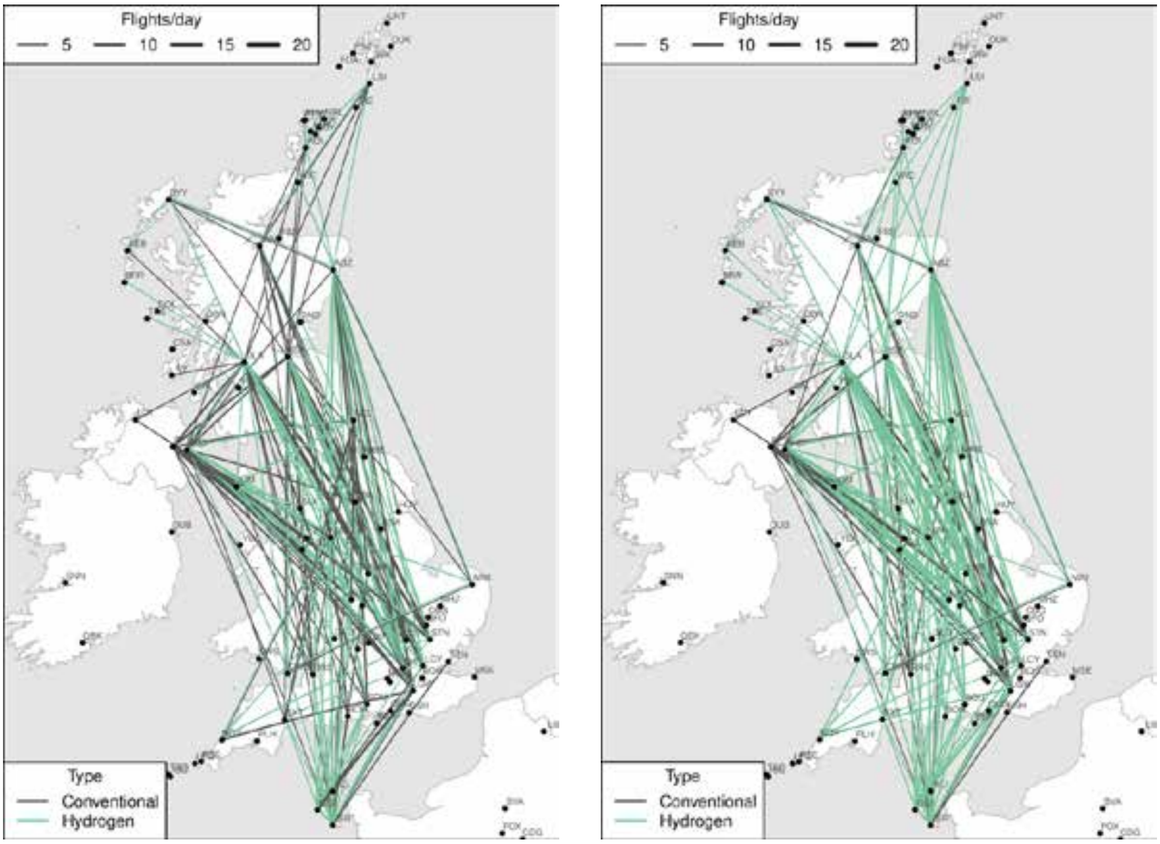
### 7.5.1 Route Network

Uses for the intermediate-sized aircraft in Use Case B are potentially much wider than for the 7- and 19-seater aircraft modelled in Use Case A. Some typical route networks at different levels of hydrogen price, assuming hydrogen aircraft are not APD-eligible, are shown in Figure 31. Although the 7- and 19-seater aircraft are included, their networks and use types remain similar to those in Use Case A.

**Figure 31: Projected flight networks for Use Case B at central (£1.3/kg) kerosene + carbon prices and lower and upper values of hydrogen price for 2035 (hydrogen aircraft assumed not APD-eligible).**

LH2: £5.8/kg (GH2: £4.5/kg)

LH2: £2.3/kg (GH2: £1.0/kg)



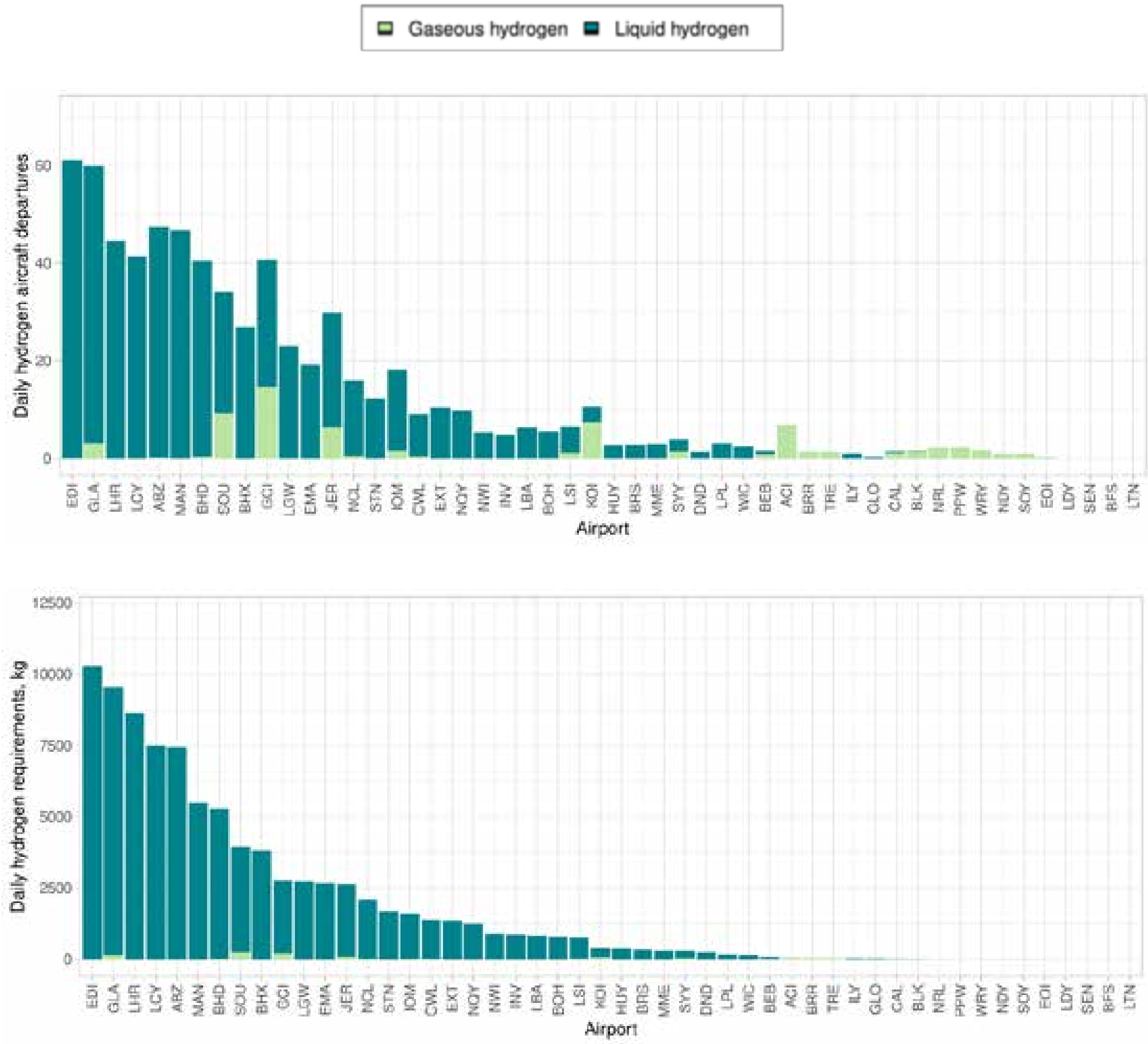

The networks identify three types of routes for the use case B aircraft. Uptake varies depending on hydrogen price and the types of conventional aircraft that are typically used on current routes. First, use case B aircraft are used on routes to and from remote regions (for example, Aberdeen-Shetland Islands or Jersey-London City). These routes can be taken up at relatively high hydrogen prices provided that hydrogen aircraft are not APD-eligible. Second, they can be used for flights to, from or between regional airports (e.g., Newquay-London Gatwick). Many of these flights are taken up by hydrogen aircraft as hydrogen price decreases. Third, the simulations project some use at lower hydrogen prices to supplement flight frequency on competitive London-Scotland and London-Northern Ireland routes alongside larger conventional aircraft, provided sufficient airport capacity is available to support this (either currently unused capacity, or reductions in numbers of larger aircraft on domestic flights in combination with increased fares). Use at capacity-constrained airports, most notably Heathrow, is zero at higher hydrogen prices/lower kerosene prices. However, because year-2035 kerosene prices are projected to be substantially above year-2025 once carbon price is factored in[5], operating from Heathrow would become cost-competitive.

For Use Case B, hydrogen demand requirements will be significantly higher than in Use Case A, although the level of uncertainty is also significantly higher. Figure 32 shows airport-level simulated numbers of UK domestic hydrogen aircraft flights and the corresponding airport domestic flight hydrogen requirements. The bars in Figure 32 show outcomes at central fuel prices of £1.3/kg Jet A including carbon price, and £2.6/kg liquid hydrogen.

The demand for GH2 is clearly very low and is driven by the use case A aircraft operating primarily on very short routes. This does not imply that there is no demand and for communities which rely on small, short-runway capable aircraft the provision would be essential. The GH2 fuelled aircraft from Use Case A will remain operating from a number of airports, some of which will therefore require infrastructure to support both gaseous and liquid hydrogen.

5 The calculations here assume fossil kerosene. By 2035, there is the potential for SAF blends of 2-20% in UK departing flight fuel (DfT, 2021; Sustainable aviation fuels mandate consultation. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005382/sustainable-aviation-fuels-mandate-consultation-on-reducing-the-greenhouse-gas-emissions-of-aviation-fuels-in-the-uk.pdf). SAF is currently exempt from the UK ETS, but SAF prices are currently twice or more those of fossil kerosene. As such, SAF blending is likely to result in similar kerosene price ranges, but substantial decreases in SAF price could result in kerosene prices towards the low end of those simulated.

**Figure 32: Airport-level number of hydrogen aircraft flights and amount of hydrogen required, at central fuel prices modelled for Use Case B (Jet A+carbon: £1.3/kg; gaseous hydrogen: £1.3/kg; liquid hydrogen: £2.6/kg). Note that only domestic demand is modelled.**




The uptake modelling for Use Case B suggests that there is a commercial case for the liquid hydrogen designs in the 40-50 seat range under year-2035 projected fuel price conditions, provided projected operating cost characteristics can be achieved. A key condition for large-scale uptake of these aircraft is for LH2 prices to be around or below effective Jet A prices, including carbon price, on an energy-equivalent basis. This level of uptake can also be influenced by the level of APD charges applied to these hydrogen-based concepts, predominantly at low kerosene prices.

These outcomes are already supported by policy in the form of carbon prices and potentially APD exemption. For example, the projected Jet A price range excluding carbon price would be £0.4-1/kg, a range which leads to limited projected uptake unless hydrogen prices are very low (Figure 31).

A further consideration is that uncertainties are particularly high around the operating costs for these technologies, which may affect the uptake of use case B aircraft. Given these uncertainties and their potentially large impact on zero-carbon emissions targets, additional research into aviation-specific hydrogen fuelled aircraft designs, the associated technologies and their likely operating costs is urgently needed.

The range of potential reduction in UK domestic CO2 in these simulations is large. At the low end, if the SAF blend in kerosene remains low, UK domestic CO2 declines little when compared to simulations with the same fuel price but no hydrogen aircraft (minimum 0.2% reduction or around 2.5 ktCO2 per annum). At the high end of uptake, a 51% reduction in UK domestic CO2 compared to simulations with the same fuel price but without hydrogen aircraft (reductions up to around 0.5 Mt CO2 per annum) is possible.

It is also important to note that these use case B results are based on the assumption that a larger regional aircraft has not entered the market. Outcomes including a larger regional aircraft are explored within use case C (Section 8).

## 7.6 Airport Implications: London City Airport

In the short- to medium-term, larger hydrogen-powered aircraft are expected to land at medium-size airports. To identify which infrastructure will be needed to support these aircraft and level of hydrogen operations, London City Airport has been chosen as the use case B airport. As with Use Case A, airport implications are explored over the time range to 2050 and include both domestic and international operations and all NAPKIN fleet (including the 90-seater described in the Use Case C).

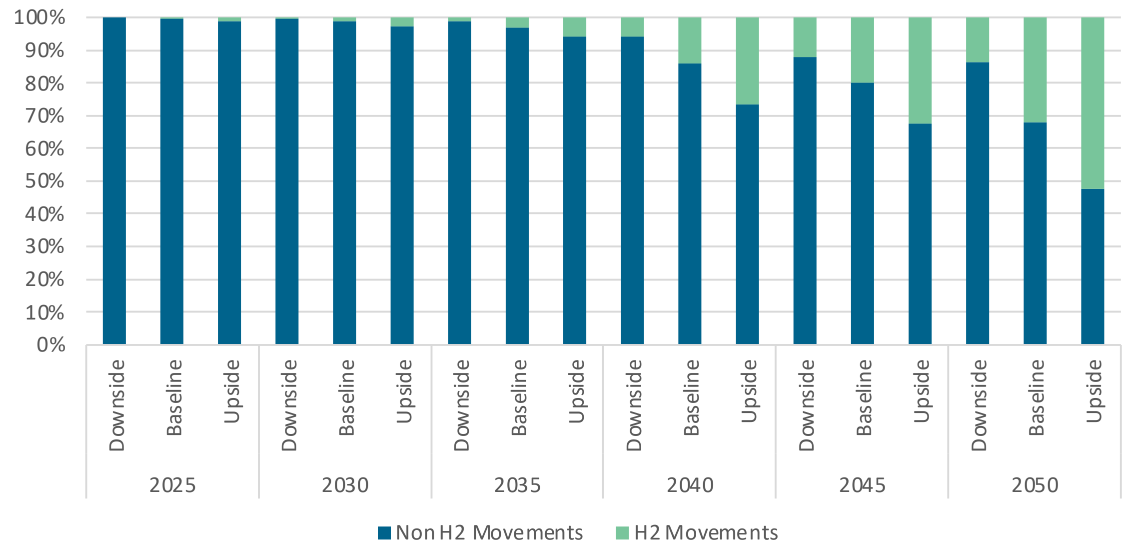
Medium-size airports in the UK have quite a diverse fleet, which will lead to different infrastructure requirements over time. For London City, most of the movements are operated using the 98-seater Embraer 190 aircraft, which offers a high similarity with the 90 seat NAPKIN aircraft (see Section 8.2NAPKIN 90 Seat Gas Turbine Aircraft).

### 7.6.1 Hydrogen Demand

Hydrogen demand at London City commences in 2030, growing to represent around 30% of the total number of movements by 2050 for the NAPKIN 'baseline' scenario. This translates into almost 60,000 annual hydrogen movements or 82 daily departures. Given most of the movements at LCY are operated with Embraer's 190 and results from Use Case C project a high adoption of the 90-seater alongside the use case B aircraft (for the 90-seater results see Case Study C: Domestic Aviation Market by 2040 below), it is expected that the regional fleet represented in NAPKIN will largely dominate future movements at LCY.

In the upside scenario, the total number of hydrogen operations by 2050 increases up to 53%, which represents just under 95,000 annual movements or 130 daily departures.

**Figure 33: Split between H2 and Non H2 movements at London City Airport**



### 7.6.2 Hydrogen Infrastructure

Hydrogen demand levels and frequency of deliveries expected until 2050 suggest a transition towards a more intrusive infrastructure is not likely to be required at London City Airport.

**Table 17: Summary of hydrogen demand and infrastructure requirements for London City Airport**

| | 2035 | | | 2040 | | | 2045 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Downside | Baseline | Upside | Downside | Baseline | Upside | Downside | Baseline | Upside | Downside | Baseline | Upside |
| **H2 Peak Day Demand (million litres)** | 0.01 | 0.04 | 0.08 | 0.1 | 0.2 | 0.4 | 0.2 | 0.3 | 0.6 | 0.3 | 0.6 | 1.0 |
| **H2 Storage (million litres)** | 0.01 | 0.08 | 0.15 | 0.18 | 0.42 | 0.79 | 0.39 | 0.66 | 1.07 | 0.48 | 1.15 | 1.88 |
| **H2 Truck Deliveries per day** | 1 | 1 | 2 | 2 | 4 | 7 | 4 | 6 | 9 | 4 | 10 | 16 |
| **Bowsers** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 1 | 2 | 3 |
| **Space (sqm)** | 50 | 410 | 750 | 900 | 2,100 | 3,900 | 2,000 | 3,200 | 5,200 | 2,500 | 5,600 | 9,200 |
| **Preferred Airport Delivery Method** | Truck / River Delivery | | | | | | | | | | | |
| **Preferred Aircraft Delivery Method** | Bowser | | | | | | | | | | | |

By 2050, the baseline scenario estimates that 10 trucks per day could be required to deliver the daily hydrogen demand. While this frequency seems feasible, given the central location of the airport, additional pressure to the already constrained access roads should be avoided if possible.

In this regard, the river Thames provides an opportunity to deliver the hydrogen by barge. Should the airport opt for this solution, there are some operational challenges the airport should account for. First, bespoke hydrogen tanker barges would need to be procured. The process to transfer the hydrogen into the storage facilities should also need to be further investigated. However, to decrease the complexity of the process, storage facilities should preferably be located near the river, either at the King George V dock or at the apron. Given the limited apron space of the airport, the dock would probably be the most suitable option both operationally and commercially.

Given pipeline delivery is not expected to be required at London City Airport before 2050, the space requirements will come from the storage facilities only. At London City, by 2050 an area ranging between 2,500m2 to 9,200m2 would be required. In terms of scale, this represents 45% of the London City Airport's Code C stand capacity in the latest Master Plan. But, given the airport's location in the Royal Docks, potentially offsite locations could be assessed.


The forecasted fuel demand is expected to exceed the capacity of the existing fuel facility in 2026 and so, the airport has already signalled that new infrastructure will be required. At this point, it is therefore essential to ensure any future infrastructure is future-proof and able to support all new fuel types.

Fuel at London City Airport is currently being delivered using bowsers as given its airfield size, a hydrant solution is not required. The forecasted hydrogen demand indicates that a bowser solution would still be feasible to deliver hydrogen to aircraft up to 2050. The 'baseline' scenario projects that two 20,000l bowsers will be required by 2050.

If the hydrogen fuel farm was to be located landside, one operational factor to consider will be whether to provide an airside dispensary area to avoid bowsers doing multiple landside-airside crossings (this solution would require an underground pipe connecting both sites) or to provide a dedicated 'road' between the fuel farm and the stands (this solution would require a Vehicle Control Post). It should be noted that a bridge between the King George V dock and the East Apron is planned within the

City Airport Development Programme (CADP)[6], which could be a suitable solution if the latter layout is adopted.

For London City, as liquefaction is not envisaged to be required before 2050, additional energy demand will primarily come from the storage tanks and is expected not to be a significant challenge for the airports' network capacity.

### 7.6.3 Operations

At London City, impact on the operations is not expected to be significant until late-2030s. Until then, given the low number of hydrogen movements expected, bespoke operations and procedures would not disrupt the normal operation of the airport.

From 2040, however, normal operations will need to be reassessed. Refuelling at London City takes on average 9 minutes with overall fueller engagement closer to 20 minutes[7]. The FlyZero study indicates that the refuelling process of a hydrogen regional aircraft could range between 3 to 19 minutes depending on the fill time speed and the diameter of the refuelling hoses[8]. Smaller hoses provide handling advantages due to its reduced weight but increases refuelling times.

If refuelling times remain similar to existing and if parallel refuelling is feasible, which is still uncertain, an increase in turnaround times is not expected. However, if either of these two conditions were not met, impact on turnaround times is likely. An increase in turnaround time could impact the airport capacity as more slots would be needed to accommodate the same demand.

Similarly, the NAPKIN 90-seater aircraft provides a slightly smaller payload than the E-190 currently operating at LCY (90 seats vs 98 seats).

Notwithstanding these two issues, the average 2019 airport load factor was around 70%, which suggests there is still some spare capacity, especially on those routes served by the 50-75 seats aircraft. Therefore, there is the potential for airlines to operate hydrogen aircraft in off-peaks and on those routes where loads are not expected to be very high without impacting the overall airport capacity.

### 7.6.4 London City Airport Noise Assessment

A more detailed noise assessment has been conducted for London City Airport as the fleet mix of this airport is expected to be able to be largely replaced by the NAPKIN aircraft. Because the expected entry into service date of the NAPKIN 90-seater aircraft presented below is 2035 (see Chapter 8Case Study C: Domestic Aviation Market by 2040), for this noise study the 90-seater has also been included.

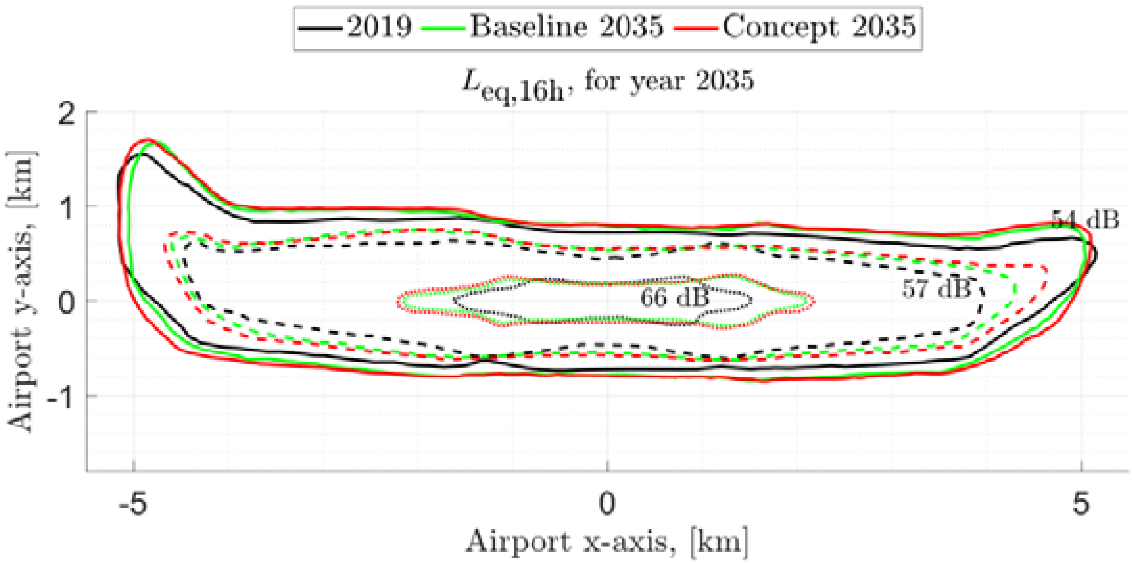
6 https://downloads.ctfassets.net/ggj4kbqgcch2/4auw6GSrzHWwMJkfIxRBF2/c1ac4a3870e9caf2b53a8c53f8052a58/p01-100_LCY_MP.pdf
7 Source: London City Airport direct communication
8 https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf

The noise assessment has been performed at two moments in time, 2035 and 2040, using predicted operations and fleet compositions. Details regarding the set-up of the case study may be found in the technical report "An assessment of the noise impact of zero-emission regional hydrogen aircraft and their operation".

In order to assess the impact of introducing the concept aircraft to the fleet, the predictions for 2035 have been performed twice: once for a baseline scenario, where no concepts are introduced but the overall traffic growth still takes place, and once for the scenario where hydrogen concepts have been introduced. The presented contours are based on the requirements of appraisal module 5[9] and comprise the 54 dB, 57 dB and 66 dB. The 57 dB and 66 dB contours were chosen as they represent the first and second tier works eligibility boundaries respectively, for the case of the City Airport Development Programme (CADP). The 54 dB is predicted for information purposes as it is of interest to LCY and third parties as a result of the CADP 1 planning enquiry[10].

Figure 34 shows the predicted contours for the year 2035. As expected, the 2035 baseline contours (green line) extend beyond that of 2019, influenced by the expected fleet growth. When the concepts are introduced, a small increase in the area of the contours is observed. This is primarily due to the operations of the large regional concepts being almost double of those of the current generation aircraft, without gaining a significant advantage on the aircraft noise performance.

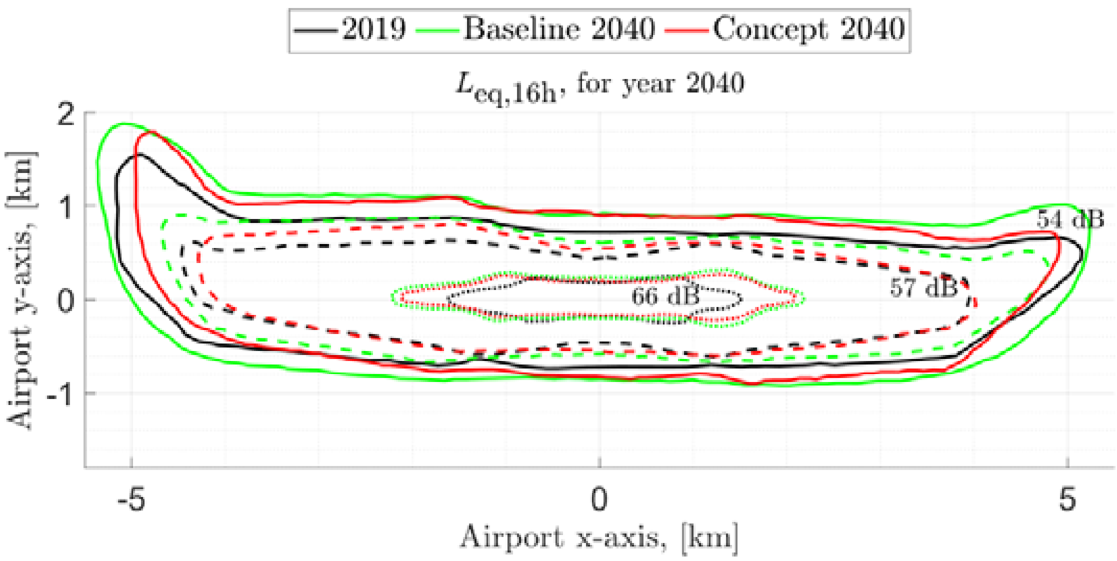
**Figure 34: Contour calculation for 2035. Results are compared to the published contours for LCY in 2019 and a baseline calculation for year 2035 assuming no hydrogen aircraft introduction. Line types indicate different contour levels**




9 Jacobs. 5. Noise: National Assessment, Prepared for the Airports Commission. 2014
10 London City Airport. City Airport Development Programme (CADP1), Condition 56: Sustainability and Biodiversity Strategy. 2017.

In 2040, the hydrogen concept penetration rates become substantial. The 90-seat aircraft concept is represented by 1,115 movements over a three-month (quarter) period, whereas the Embraer 190 (representing current generation aircraft) by 11,542, which is below the 2019 baseline movements. Additionally, ATR72-600 movements have been completely phased out with the Dash 8 representing the current generation of large regional aircraft with 2,455 movements, whilst the 40- and 50 seat concept aircraft combine for 670 operations.

**Figure 35: Contour calculation for 2040. Results are compared to the published contours for LCY in 2019 and a baseline calculation for year 2040 assuming no hydrogen aircraft introduction. Line types indicate different contour levels.**




The effect is visible in Figure 35, where the introduction of the hydrogen concept aircraft, quieter at take-off, means that the contour areas are reduced relative to a continuous growth scenario with current generation aircraft. The significant difference between the predicted certification levels (resulting from the NPDs) for the concept and those of the Embraer 190, means that noise reduction at source dominates the fleet effects, as an increase in number of movements due to the difference in passenger capabilities is minimal (concept aircraft is 90- seat whereas E190 is 100 seat single class, or 96 seat dual class).

The impact of the concepts is measurable by 2040 at LCY, as small single aisle narrowbody aircraft represent the majority of movements and represent the larger class of aircraft operating at the airport.

### 7.6.5 Cost Implications and Commercial Opportunities

While hydrogen infrastructure developments at London City Airport are not expected to be highly intrusive, a significant investment will still be required. However, new commercial opportunities could arise for the airport as well.

London City is well positioned to be part of a hydrogen hub given the urban context, the types and operational needs of local stakeholders, including businesses (Excel, Tate and Lyle), local council buildings, Greater London Authority, and the university, as well as housing. This provides the airport with opportunities for collaboration and potential partnership on shared facilities and supply.

With companies around the world making commitments to ESG reporting, it is possible that an early market for ZEF could be business travel. With the highest share of business travel in the UK, and with the potential to facilitate ZEF at scale across the UK between 2035 and 2040, London City could become the focal point for zero emission business trips to and from the capital.

This new infrastructure, however, will require capital investment from airport ownership. The drivers behind the business case for investment would not only be the reduction of emissions, in line with the airport Sustainability Roadmap, but to support current operator's fleet development in coming years.

In this regard, to support airlines on this transition to cleaner and quieter aircraft, the airport could consider incentivisation through reduced airport charges and partnerships agreements with operator of zero-carbon emission aircraft in the assessed periods.

# 8 Case Study C: Domestic Aviation Market by 2040

## 8.1 Overview

This case study is an analysis of the UK domestic aviation market in 2040. Each of the concepts in the NAPKIN fleet have been included, spanning 7, 19, 40, 50 and 90 seat aircraft. In this time period, it is expected that there will have been several years since each aircraft type's EIS so there has been time for aircraft manufacture, infrastructure development and operational understanding.

## 8.2 NAPKIN 90 Seat Gas Turbine Aircraft

For this case study, a large regional, 90-seat liquid-hydrogen-fuelled combustion aircraft has been included. An aircraft of this size is likely to have a similar 2035 EIS date to the 40 and 50 seat regional concepts included but a 2040 case study was chosen to demonstrate the impact on the market once there has been enough time for a reasonable level of fleet penetration to have been achieved.

The 90-seat concept is a study aircraft: it is loosely based on an Airbus A220-100, featuring a liquid hydrogen fuel storage and gas turbine propulsion system to produce a representative aircraft. It is not intended to be a retrofit design as it is unconstrained by spatial and structural integration limitations of an existing aircraft.

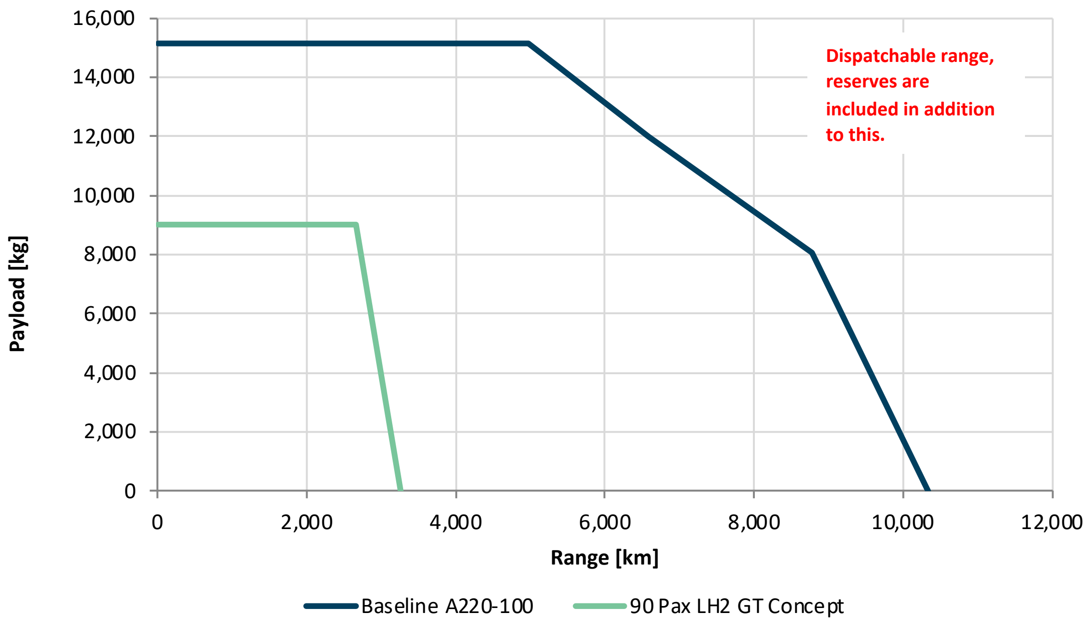
This design incorporates an aft mounted liquid hydrogen tank. As with other concepts with fuselage tanks, this creates a direct trade-off between payload and maximum range due to the limitations of the fuselage volume. For this concept a 90-passenger payload and 1,400nm range at maximum payload was selected as this was able to address 95% of the existing global regional market. For an aircraft of this size, it was important to consider the requirements of the global market as similar aircraft frequently operate both domestic and short haul international routes.

The propulsion system for this concept consists of two liquid hydrogen fuelled turbofans which provide a similar level of performance in operation to existing large regional jets. Therefore, the cruise speed for this aircraft is substantially higher than the previously discussed turboprop, ducted fan and propeller designs which has a potential impact on its uptake in the domestic market.

**Table 18: Key performance characteristics of the NAPKIN 90 seat aircraft**

| | |
|---|---|
| **Range (Max passenger)** | 2,654 km (1,433 nm) |
| **Payload** | 9,000 kg |
| **Cruise Speed** | 230m/s / 447 kts |
| **Take-off Weight** | 48,300 kg |
| **Landing Weight** | 46,500 kg |

**Figure 36: Payload Range diagram for the NAPKIN 90-seater**




## 8.2.1 Operational Costs

As the NAPKIN 90-seater aircraft concept is based on the A220-100, this aircraft was also used as the reference aircraft for the cost assessment.

Table 19 below shows the operating costs of the larger 90-seater concept, and how these compare with the reference aircraft. Details of the parameters and methodology used, including the assumed hydrogen and kerosene prices, are presented in the technical report "Ownership and Operating Cost Model".

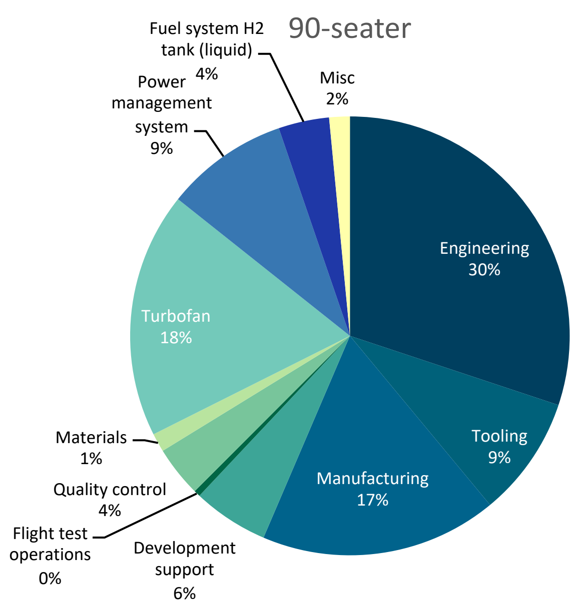
**Table 19: Key operating costs of the 90 seat NAPKIN aircraft (shaded in green) and the reference aircraft (shaded in grey)**

NAPKIN Aircraft | Reference aircraft

| | 90-seater | A220-100 |
|---|---|---|
| Number of seats | 90 | 120 |
| Range (km) | 2,654 | 6,390 |
| TCO/FH (£/FH) | 5,901 – 7,581 | 7,492 |
| £/Seat FH | 65 – 84 | 96 |

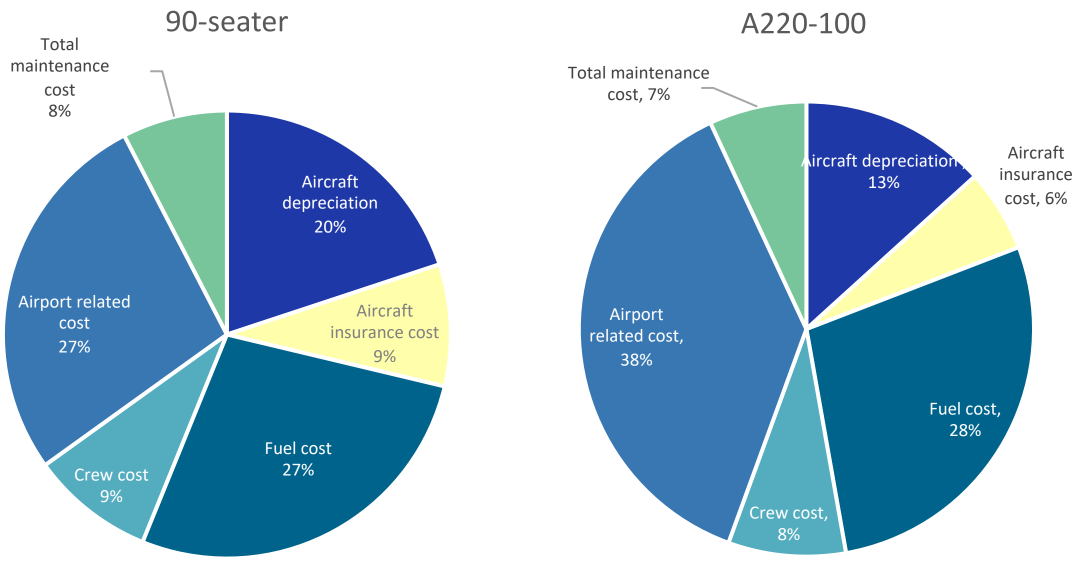
As with the smaller concepts, engineering costs represent the biggest share of production costs, followed by propulsion and manufacturing costs. New propulsion and fuel systems account for 31% of the production cost for 90-seater H2 aircraft (Figure 37). The cost of the propulsion system is considerably higher than for the 50-seat aircraft, based on the size and the power of the engines which are directly fed with hydrogen.

**Figure 37: Breakdown of the operating costs of the 90-seater**




Similarly, Figure 38 presents the cost breakdown of total cost of ownership of both the 90-seater and A220-100. As the purchase price of concept aircraft is higher, the depreciation of the aircraft increases along with the insurance costs. As was also the case with the 7- and 19-seater concepts, while the share of maintenance costs for the 90-seater hydrogen concept aircraft (8%) are marginally higher than the equivalent kerosene aircraft (7%), the overall maintenance costs of the hydrogen aircraft in absolute terms remain lower than the reference A220-100 aircraft.

**Figure 38: Breakdown of the total cost of ownership of the 90-seater (left) and the A220-100 (right)**




## 8.2.2 Noise Performance

Due to limited data on propulsion system design and operating characteristics, the design and operation of the hydrogen gas turbine was assumed to closely resemble that of the Pratt & Whitney PW1500G engines present on the original A220-100 aircraft. It is worth highlighting this assumption may not hold true, as design for hydrogen combustion may result in variations of parameters and additional noise sources.

For the NPD calculations, the reference aircraft was the A320neo, a significantly larger single aisle aircraft (MTOW = 79t compared to 48.2t of the concept), as no NPD data is available for the A220-100.

The dominant noise source used to model the LH2 turbofan engine are the fan and jet following the source breakdown of a conventional turbofan engine. The directivity of aircraft is chosen to be similar to that of a conventional modern high-bypass-ratio (HBPR) turbofan engine.

The take-off maximum Sound Pressure Levels (SPL) of the 90-seat concept is equivalent to the noise generated by the larger A320neo at an operational weight significantly below MTOW. Specifically, the power setting on the A320neo required to match the noise of the concept would equate to an operational weight of approximately 63t (identical to the MTOW of the A220-100), or 16t below MTOW. This gives a lateral certification value of 81.2 EPNdB (Effective Perceived Noise

Levels (EPNL) in decibels is a measure of the relative noisiness of an individual aircraft pass-by event) relative to 86.1 EPNLdB of the A320neo and a flyover value of 76.5 EPNLdB relative to the 81.3 EPNLdB of the A320neo. Approach levels are reduced by approximately 3 dBA relative to the A320. A summary of the certification point levels may be seen in Table 20.

**Table 20: Certification point levels for the 90-seat concept (shaded in green) compared to 3 current generation single aisle narrowbody aircraft (shaded in grey)**

NAPKIN Aircraft — Reference aircraft

| | 90-Seat Concept | A220-100 | A320neo | Embraer E190-E2 |
|---|---|---|---|---|
| **Approach** | 90.5 | 91.5 | 92.4 | 91.4 |
| **Lateral** | 81.2 | 86.6 | 86.1 | 85.4 |
| **Flyover** | 76.5 | 80.2 | 81.3 | 78.7 |

## 8.3 UK Domestic Market

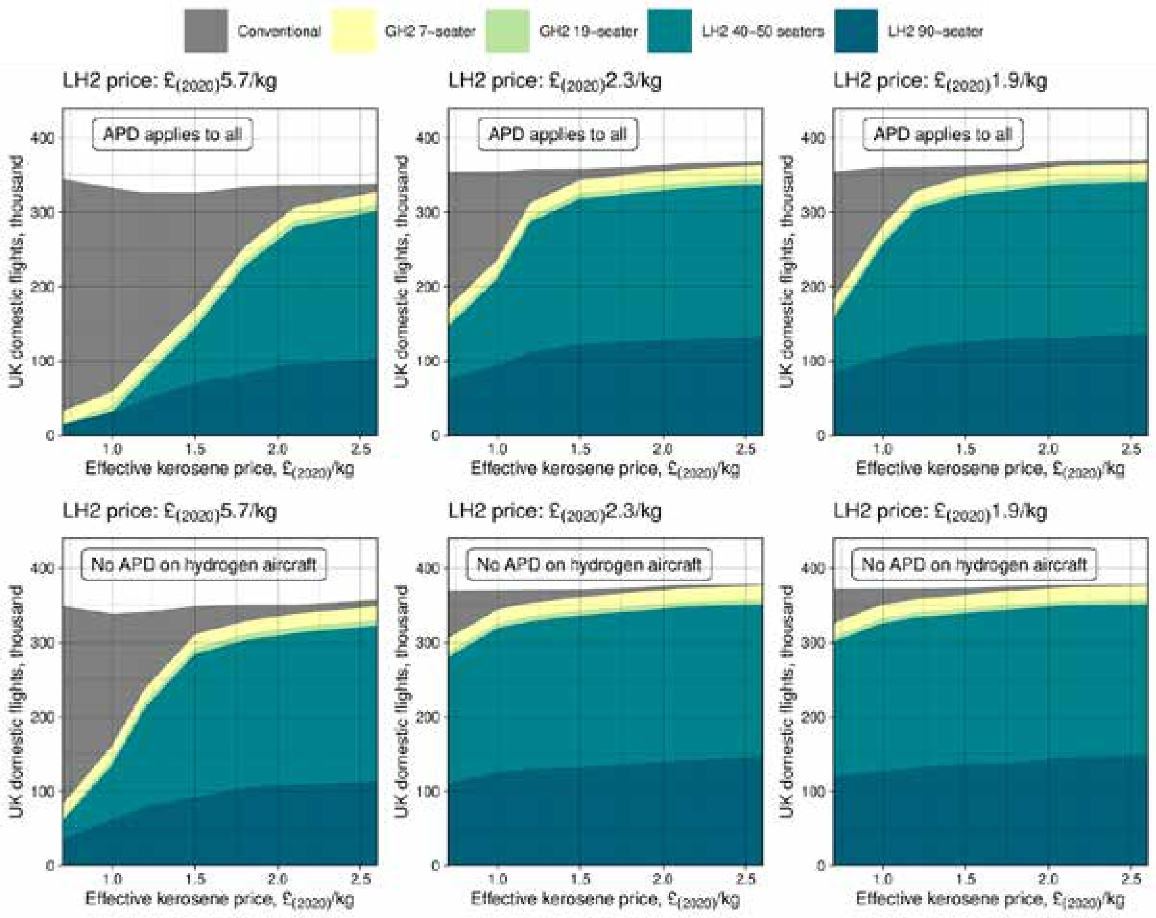
Most UK domestic flights are currently operated by a mix of smaller turboprop aircraft with lower cruise speed (e.g., ATR-72; on lower-demand routes) and small to large narrowbody turbofan aircraft with higher cruise speed (e.g., Airbus A320; on higher-demand routes). The 90-seater design discussed above reflects a combination of aircraft characteristics that is different to most current typical in-use aircraft. The closest conventional aircraft in terms of operating characteristics are small narrowbodies such as the Airbus A220 and Embraer E195; however, these have more seats. Similarly, the Dash-8 and ATR-72 turboprop aircraft in current UK operation have similar numbers of seats but lower cruise speed, leading to longer scheduled flight times[1].

Compared to the 7-50 seat aircraft examined in Use Cases A and B, the 90-seater is a more feasible replacement for narrowbody aircraft currently in operation on busy, competitive route groups such as London-Scotland or London-Northern Ireland. Several factors apply here, though we should beware of drawing too clear-cut conclusions in relation to such an aircraft in the absence of competition from a 165-pax narrowbody; although this section will give an indication of the potential of larger aircraft against mid-size regional turboprop aircraft. First, aircraft with more seats generally have lower per-passenger costs, allowing more competitive fares to be charged. Second, many routes in these groups are to or from airports that have capacity constraints, incentivising the use of larger aircraft. Finally, low-cost carriers

1 See discussion of flight times and cruise speed in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes".

operate on these routes. Low-cost carriers tend to have homogeneous fleets using a single narrowbody aircraft type or variants on a single narrowbody aircraft type, allowing them to reduce training and maintenance costs, and their point-to-point networks and infrastructure are structured around this type of fleet. A typical low-cost carrier would be unlikely to consider a 40- or 50 seat aircraft. There is the possibility that they might consider a 90-seat aircraft; however, it is most likely that they would wait for 150-seat hydrogen aircraft similar to the types that they already use to become available before investing. For this use case, therefore, two variants are considered: Use Case C1, where low-cost carriers do consider purchasing 90-seat hydrogen aircraft if by doing so they can increase their profits; and Use Case C2, where they do not. A further factor affecting uptake of this size class is that substituting one flight with 180 seats for two flights with 90 seats effectively doubles flight frequency, making journeys on such a route more attractive for passengers and potentially allowing airlines to charge higher fares for increased convenience. As such, if capacity exists to support such a change, airlines may still be able to increase profits by adopting aircraft in this size category even if per-passenger costs are higher than for larger aircraft.

**Figure 39: 7- and 19-seater gaseous hydrogen, and 40-50-seater and 90-seater liquid hydrogen aircraft projected profit-optimal number of flights in the UK domestic aviation system under Year-2040 Use Case C1 conditions across a range of kerosene and hydrogen prices. These simulations assume LCCs would consider adoption.**



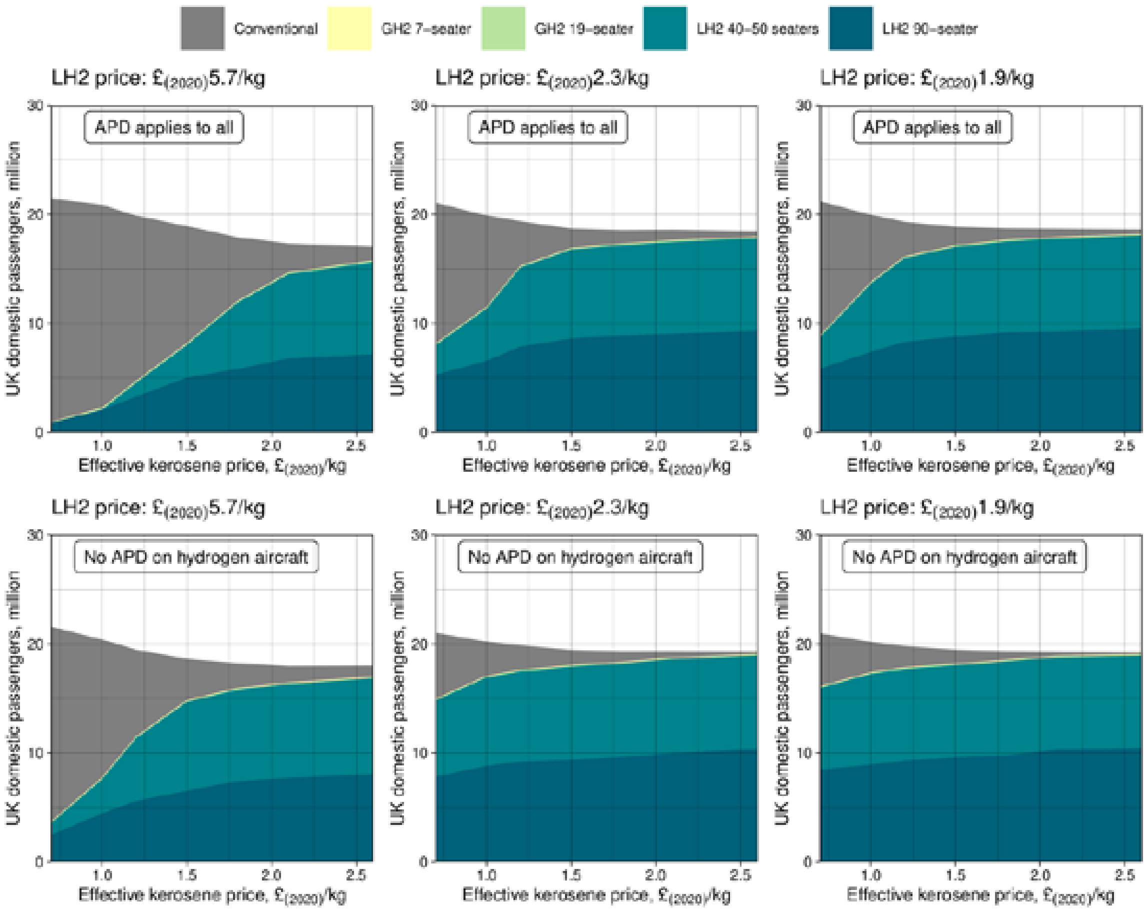
As for Use Cases A and B, a range of hydrogen aircraft designs in different size classes are made available to airlines in the UCL Airline Behaviour Model. This includes the 7- and 19-seater designs from Use Case A, the 40-and 50-seater designs from Use Case B, and the 90-seater design described above. Airlines can choose to adopt these aircraft if by doing so they can increase their profits[2]. They also have the option of adopting additional conventional aircraft of the types they already operate. The Airline Behaviour Model simulates equilibrium outcomes after all necessary fleet turnover has taken place, so outcomes are not representative of potential use at aircraft EIS dates but would require some time for fleet turnover. For this use case, outcomes are simulated across a range of hydrogen and effective kerosene price (including carbon price) appropriate for the 2035-2040 period. As discussed in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes", effective kerosene prices are considered between £0.7-2.6/kg; liquid hydrogen prices between £1.9-5.6/kg (£0.7-2.0/kg kerosene equivalent); and gaseous hydrogen prices between £0.8-4.5/kg (£0.3-1.6/kg kerosene equivalent). Figure 39 shows uptake in terms of flights by aircraft type across these price ranges. Figure 40 shows corresponding outcomes in terms of passenger numbers. These simulations project roughly similar levels of uptake for the 40/50 and 90-seater designs in terms of passenger numbers. For a larger geographic region, the 90-seater would be expected to have much higher uptake due to its longer range. Uptake for the 7 and 19-seater designs remain similar to those in Use Case B.

As with Use Case B, the range of potential hydrogen aircraft uptake with different fuel prices is very large. At the low end of kerosene price and upper end of hydrogen price, and if hydrogen aircraft are APD-eligible, cost-optimal uptake of hydrogen aircraft may be minimal (~2% of UK domestic flights). However, uptake of the 90-seater generally tails off less than that of the smaller regional aircraft at high hydrogen price. This reflects the frequency effect discussed above, i.e., that airlines can use the added convenience of increased flight frequency to offset per-passenger increased operating costs if this is consistent with capacity constraints – but this outcome is of relatively high uncertainty as additional models of conventional aircraft not considered here could still outcompete the 90-seater at high hydrogen prices. At the upper end of kerosene price and lower end of hydrogen price, profit-optimal solutions project that the hydrogen aircraft considered in NAPKIN could serve over 98% of UK domestic flights. In this case, the smaller typical aircraft size reduces the number of domestic passengers at congested airports (for example, domestic passengers at Heathrow decrease in the model by around 30% between the highest and lowest hydrogen uptake cases).

2 See methodology and validation discussion in the accompanying technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes". Note that this modelling excludes the impact on uptake of passenger attitudes to green aviation; a sensitivity case exploring this using a region-region based version of the airline behaviour model and passenger survey data is also included in the technical report.

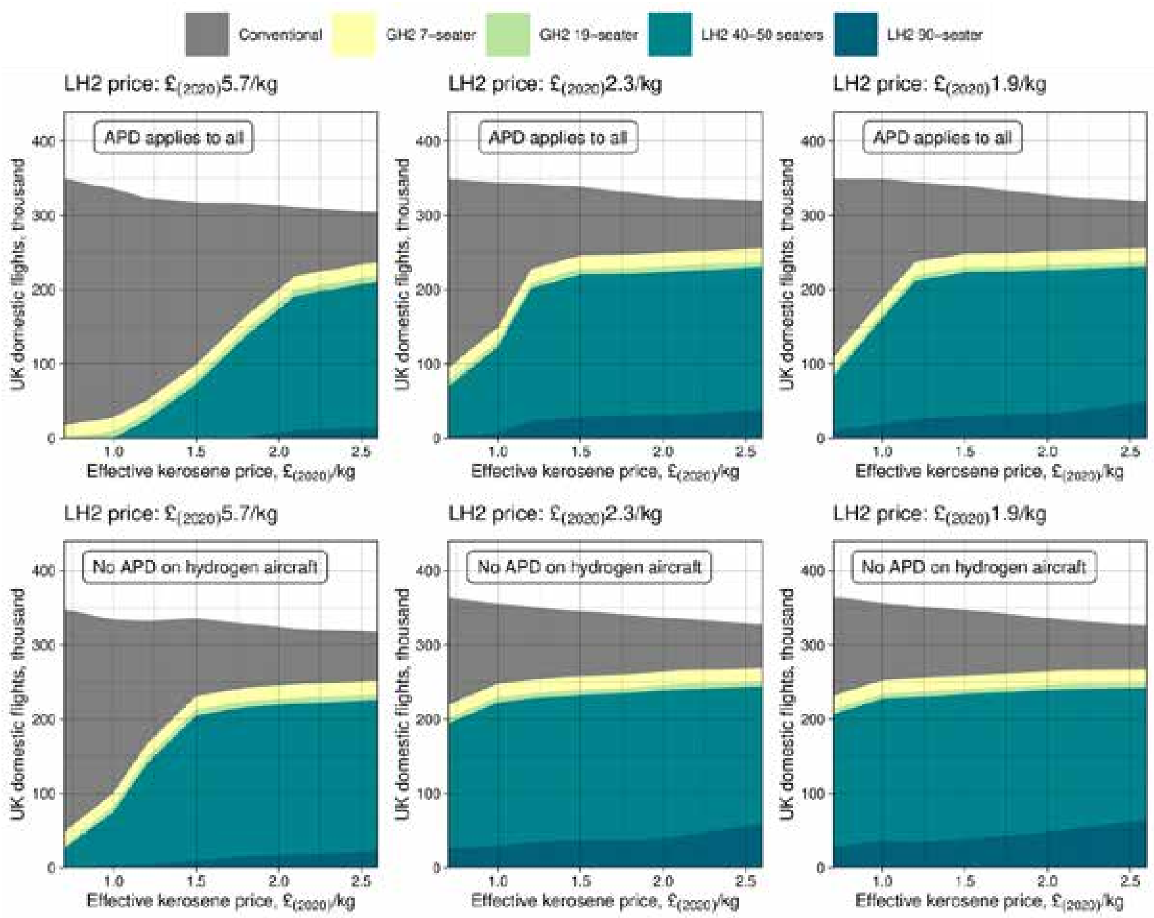
As with Use Case B, these outcomes assume a lack of larger hydrogen aircraft designs and represent a profit optimum which requires time for fleet turnover to achieve in practice. However, they do indicate that, even if only sub-100 seat designs are available, operating cost may not be a barrier to a UK domestic hydrogen aviation system in the 2040s, provided that targets for reducing green hydrogen price can be achieved.

**Figure 40: 7- and 19-seater gaseous hydrogen, and 40-50-seater and 90-seater liquid hydrogen aircraft, projected number of passengers in the UK domestic aviation system under Year-2040 Use Case C1 conditions across a range of kerosene and hydrogen prices. These simulations assume LCCs would consider adoption.**




One key uncertainty with the 90-seater design is whether low-cost carriers, who typically operate only larger aircraft and homogeneous fleets, would consider it. Given the potential availability of larger hydrogen designs around or shortly after the 90-seater EIS, airlines may also choose to wait for these larger aircraft. Technology Roadmap Figure 41 shows outcomes for Use Case C2, in which low-cost carriers are assumed not to consider 90-seater adoption. In this case, use of the 90-seater is considerably lower; LCCs continue to operate narrowbody conventional aircraft but lose market share to other operators at high kerosene prices. However, this drop in uptake would likely be offset by adoption of a larger hydrogen aircraft design (outside the size scope of NAPKIN), if one were available.

**Figure 41: 7- and 19-seater gaseous hydrogen, and 40-50-seater and 90-seater liquid hydrogen aircraft, projected number of flights in the UK domestic aviation system under Year-2040 Use Case C2 conditions across a range of kerosene and hydrogen prices. These simulations assume LCCs would not consider adoption.**




## 8.3.1 Route Network

The projected route networks in Use Case C1 cover essentially all types and distances of UK domestic flight routes. Figure 42 shows sample route networks for £1.5/kg effective kerosene price and LH2 prices between £1.9-5.7/kg (£0.7-2.0/kg kerosene equivalent). Due to the high baseline kerosene price at this time point, uptake is significant across the full range of hydrogen prices. As hydrogen price decreases, these routes are served by fewer conventional narrowbody aircraft and more hydrogen regional aircraft.

**Figure 42: Projected flight networks for Use Case C at central (£1.5/kg) kerosene + carbon prices and lower and upper values of hydrogen price for 2040 (hydrogen aircraft assumed not APD-eligible).**

LH2: £5.7/kg (GH2: £4.5/kg) LH2: £1.9/kg (GH2: £0.8/kg)

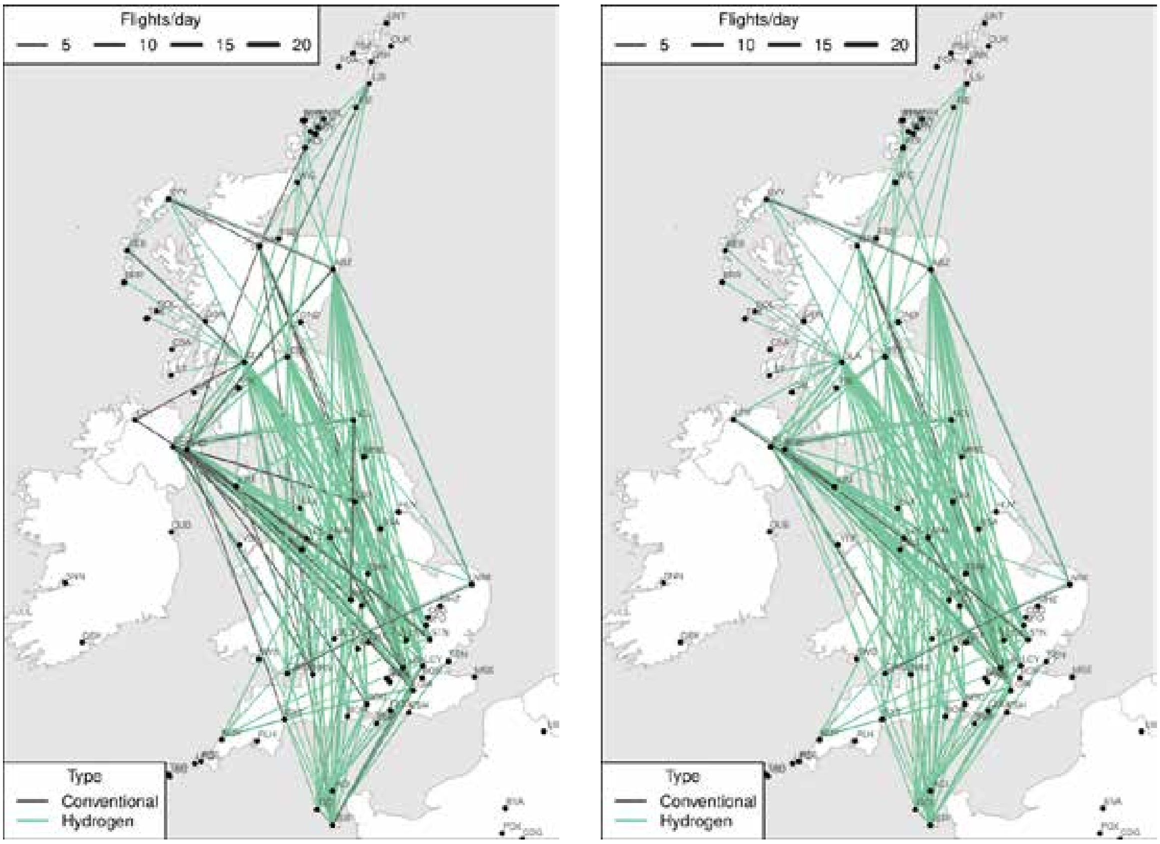
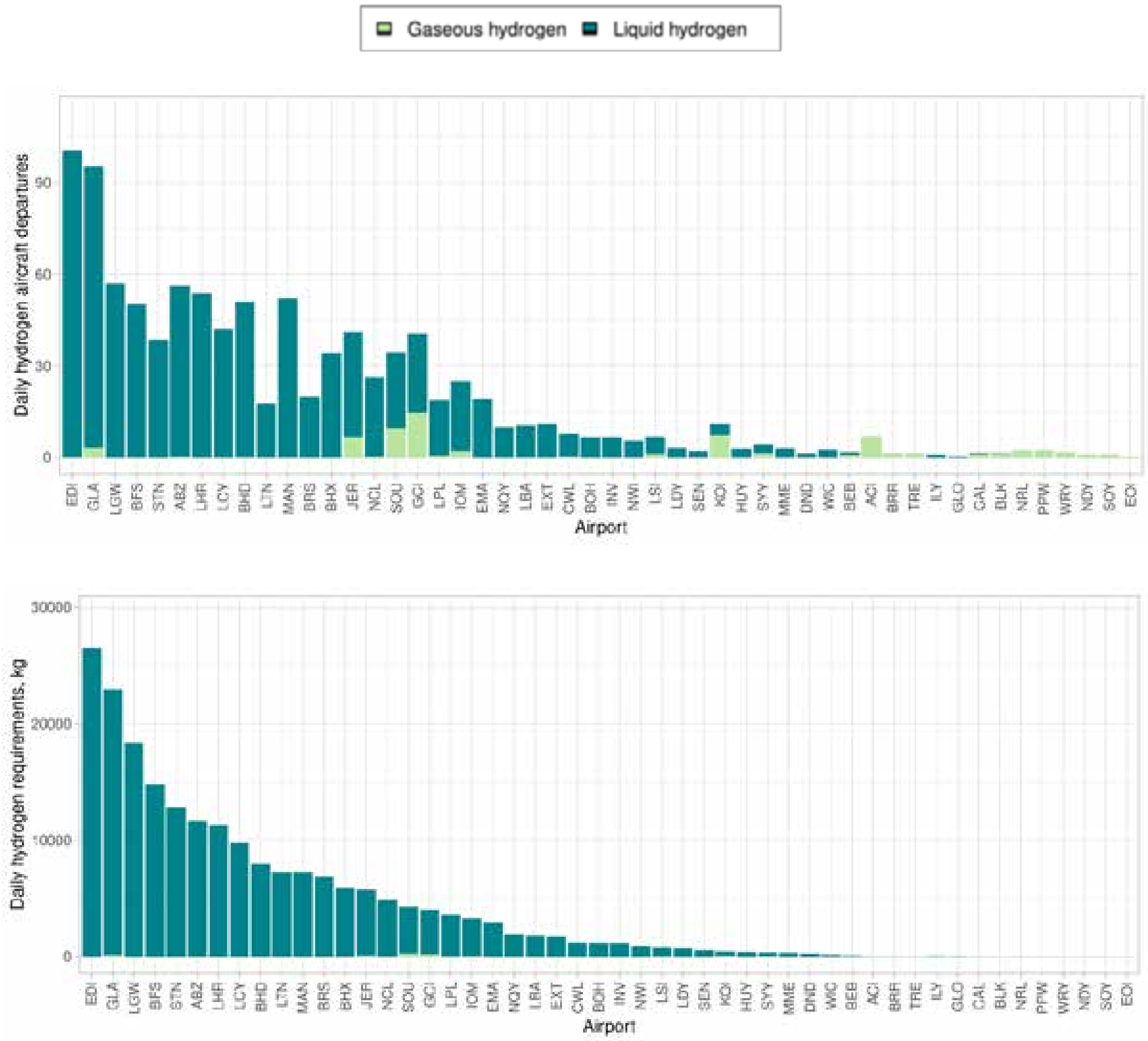



Figure 43 shows projected number of domestic UK flights and domestic flight hydrogen requirements by airport for the central fuel price simulations in Use Case C1. At these values, the fuel cost savings offered by hydrogen aircraft are significant and both the smaller and larger regional hydrogen designs are widely used across most airports. However, as with the previous use case, airport-level uncertainty ranges are large. These outcomes are also strongly influenced by the projected high fuel efficiency and low operating cost of the 40- 50-seater designs on UK domestic routes, which leads to significant 40- 50-seater use even where capacity constraints apply. However, if demand for international flights is also considered (as discussed in Section: Hydrogen Demand), the more constrained range of the smaller regional designs means that the majority of these flights operable with hydrogen aircraft would use 90-seater or larger designs. Implied fleets for domestic flights by aircraft size in these simulations are 7-8 (7-seaters); 0-4 (19-seaters); 0-104 (40- 50-seaters); and 8-81 (90-seaters), with the availability of the 90-seater somewhat reducing the number of smaller regional aircraft required compared to Use Case B.

**Figure 43: Airport-level number of hydrogen aircraft flights and amount of hydrogen required, for central fuel prices modelled in Use Case C (Jet A + carbon: £1.5/kg; gaseous hydrogen: 1.2/kg; liquid hydrogen: £2.3/kg). Central bars are stacked rather than overlaid. Note that only domestic demand is modelled. These simulations assume LCCs would consider adoption.**




The uptake modelling for Use Case C suggests that there is a commercial case for both the 40- 50-seater and 90-seater liquid hydrogen designs modelled under year 2035-40 projected fuel price conditions. These outcomes are dependent on whether low-cost carriers would consider the 90-seater, on projected high fuel efficiency and low maintenance costs for the smaller regional designs, and more generally on a range of technical developments which are presently uncertain. The range of outcomes across different fuel prices modelled is very wide and includes post-fleet turnover projected profit-optimal uptake between 10-99% of UK domestic flights. As for Use Case B, required conditions for large-scale uptake are LH2 prices to be around or below effective Jet A prices (including carbon price on an energy-equivalent basis), the absence of a larger liquid hydrogen aircraft, and preferably an exemption from APD.

The range of potential reduction in UK domestic CO2 in these simulations is large (7-99% reduction compared with model runs with the same fuel prices but no hydrogen aircraft, or between 90kt – 1 MtCO2 reduction per year), reflecting uncertainty in uptake. At the low end of uptake, if the SAF blend in kerosene remains low, UK domestic CO2 remains similar to base year values. At the high end of uptake, UK domestic CO2 is close to the UK government year-2040 net zero ambition (down to around 7 kt CO2 even in the case that no SAF is used) although the fleet turnover required may delay the practical achievability of full fleet replacement with 2035-EIS aircraft until after 2040. However, these outcomes do demonstrate in principle that operating cost is not necessarily a barrier to achieving net zero domestic UK aviation CO2 with hydrogen aircraft. If carbon prices follow the upper end of UK government projections and targets for green hydrogen price are achieved, these aircraft will likely be cost-competitive with conventional aircraft. The main barriers in this case may be fleet turnover and production line capacity. These barriers are easier to overcome if 40+ seat models of hydrogen aircraft are available at earlier dates, i.e., can potentially be addressed with R&D support aimed at accelerating technology development. Conversely, uptake may be much lower if hydrogen designs are subject to APD, or if significantly more fuel-efficient designs of small conventional aircraft become available.

The outcomes shown here cover only UK domestic demand and only aircraft below 100 seats. For large airports in particular, domestic flights are often only a small fraction of operations and international flights with larger hydrogen aircraft are likely to increase in importance after 2035. These considerations are discussed below in the Heathrow case study for Use Case C.

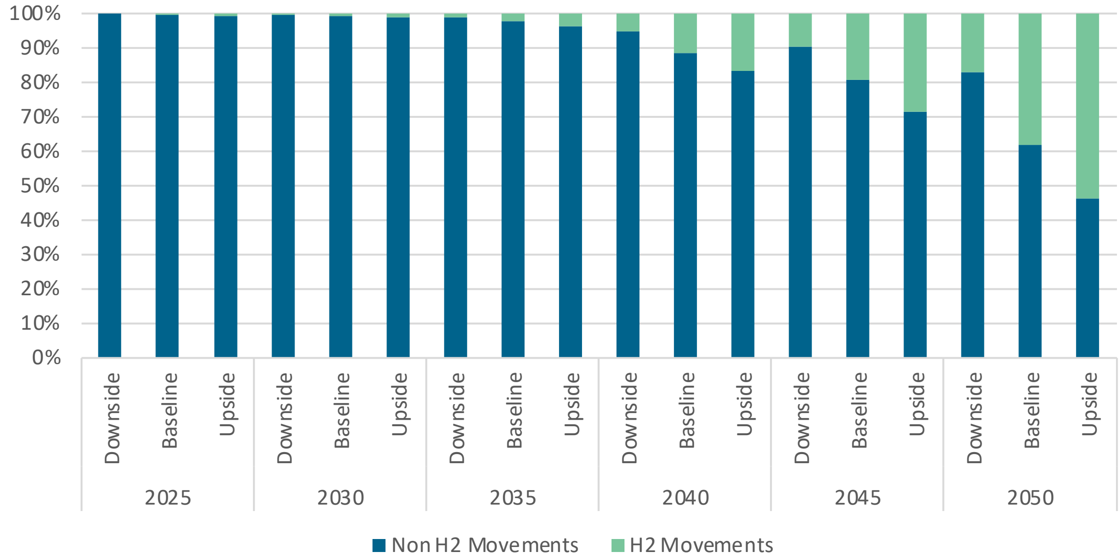
## 8.4 Use Case C Airport: Heathrow Airport

The focus of this use case was to identify the long-term and large-scale infrastructure and operational challenges airports will have to prepare and plan for. Heathrow, the largest airport in the UK, has been chosen.

### 8.4.1 Hydrogen Demand

Hydrogen demand at Heathrow is expected to start being significant from 2040, at which point hydrogen movements could represent between 5% to 20% of the total movements. Of these, only around 3% would be operated by the NAPKIN fleet due to its regional focus. By 2050, hydrogen movements could represent between 20% to 54%, with the baseline scenario projecting around 40% of all movements being hydrogen. This translates into almost 300,000 hydrogen movements. The remaining 60% of movements are likely to be fuelled by a mix of SAF and kerosene. The ratio between each, however, will be strongly influenced by policy and market changes, such as how the proposed UK SAF blending mandate is set in the coming years.

**Figure 44: Split between H2 and Non H2 movements at Heathrow Airport**



## 8.4.2 Hydrogen Infrastructure

Hydrogen demand levels and frequency of deliveries expected by 2045 suggest a transition towards a more intrusive infrastructure is likely to be required at Heathrow. To be ready by then, however, the airport should forward plan for this infrastructure.

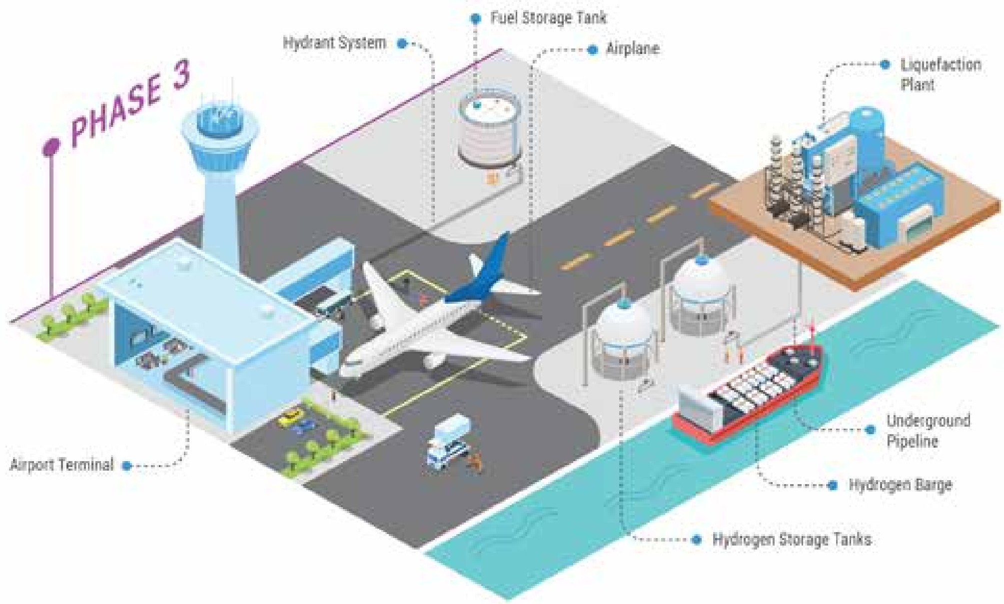
**Table 21: Summary of H2 demand and infrastructure requirements for Heathrow Airport**

| | 2035 | | | 2040 | | | 2045 | | | 2050 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Downside | Baseline | Upside | Downside | Baseline | Upside | Downside | Baseline | Upside | Downside | Baseline | Upside |
| **H2 Peak Day Demand (million litres)** | 0.02 | 0.12 | 0.28 | 1.4 | 3.6 | 6.6 | 3.4 | 7.8 | 12.7 | 6.6 | 18.7 | 27.2 |
| **H2 Storage (million litres)** | 0.04 | 0.3 | 0.6 | 2.8 | 7.1 | 13.0 | 6.7 | 15.6 | 25.3 | 13.3 | 37.2 | 54.2 |
| **H2 Truck Deliveries per day** | 1 | 2 | 5 | 23 | 57 | 104 | 54 | 123 | 200 | 105 | 294 | 428 |
| **Bowsers** | 0 | 0 | 1 | 3 | 9 | 16 | 8 | 19 | 31 | 16 | 45 | 66 |
| **Space (sqm)** | 200 | 1,200 | 2,800 | 14,200 | 31,000 | 53,800 | 29,500 | 60,000 | 93,600 | 51,300 | 127,500 | 174,200 |
| **Liquefaction Power (MW)** | 1 | 3 | 7 | 38 | 95 | 174 | 89 | 207 | 337 | 176 | 496 | 721 |
| **Preferred Airport Delivery Method** | Truck Delivery | | | Gaseous Pipeline | | | | | | | | |
| **Preferred Aircraft Delivery Method** | Bowser | | | Bowser | | Bowser/ hydrant | Bowser | Bowser/ hydrant | hydrant | Bowser/ hydrant | hydrant | |

By 2040, the baseline scenario projects that 57 trucks per day could be required, assuming a 4,500kg hydrogen truck. At daytime, between 5am and 11pm, when road traffic is high, the main tunnel leading to the Central Terminal Area (CTA) is category E, meaning vehicles transporting dangerous goods, including liquid hydrogen, are not allowed through the tunnel. This restriction is likely to lead to significant challenges to the delivery of hydrogen to the airport by road, as there is no alternative access route to the CTA.

Assuming hydrogen deliveries would need to be conducted at night-time (11pm to 5am) this would translate to 9-10 trucks per hour. Although there is no simple answer as to when the frequency of deliveries would become impractical, as an initial assessment it could be considered that one truck every 5-6 minutes would be unfeasible. Therefore, by the early 2040s, delivery of hydrogen by gas pipeline would be the most suitable solution for Heathrow.

To transform the gaseous hydrogen into liquid hydrogen, a liquefaction plant will be required. This will increase the footprint of land required up to 31,000m2 by 2040 and 127,500m2 by 2050 (for reference, the area of the existing fuel farm is around 15,000m2).




Large airports, such as Heathrow, should also plan for resiliency. Splitting the hydrogen infrastructure between two or more sites would provide levels of resilience in case one of the locations is unable to provide hydrogen as well as potentially reducing the length of underground pipe.

Fuel at Heathrow is delivered to aircraft via a hydrant system due to the airfield size and high demand. By 2045, assuming a 20,000l refuelling bowser, around 20 bowsers would be required to cope with the peak hour demand. These figures suggest that from 2045, a hydrant system should be in place to avoid congestion on the internal airport road network and at the refuelling point. In anticipation, ground and stand works should begin to take account of this change to make retrofit more cost-effective later. Providing dual fuel stands across the airfield at early dates will also bring higher levels of resilience and operational flexibility.

In terms of energy requirements, the electrical High Voltage network currently has a capacity of around 72MVA split across various locations of the airport site with some spare capacity at some locations, with pre-pandemic plans to increase the network capacity to around 132 MVA by the year 2050. This took account of the current operational infrastructure and allowed for an expanded airport operation with the introduction of a 3rd runway, associated buildings and increased electrical vehicle charging (at around 20 – 25MVA). It did not account for hydrogen-powered or electric aircraft.

Modelled requirements for liquefaction or production of hydrogen on-site via electrolysis far exceed the original electrical capacity strategies planned for by mid-2040. Therefore, early engagement with the National Grid and other parties regarding ZEF is imperative to ensure the cost and logistical implications for the solutions that may be needed are fully understood.

### 8.4.3 Operations

Initially, until the mid-2030s, given the small scale of hydrogen operations expected, the operational impact at Heathrow will be limited. However, there is an opportunity to leverage the learning from small scale hydrogen operations and use it in later years, as ZEF use increases.

One of the key operational impacts from hydrogen aircraft operations is potentially increased turnaround times and consequent impact on airport capacity. Given aircraft operating at Heathrow are primarily narrow and widebody, turnaround times are likely to increase unless boarding during refuelling is feasible and automation is introduced in the process. The extent to which the airport capacity would be impacted will depend on its daily demand profile.

Turnround operations could also be impacted if an exclusion zone around the aircraft, larger than the current one, is required during refuelling. It would mean turnaround operations on adjacent stands could not happen in parallel. Further investigation and real-life demonstrations will need to be performed to assess the size of the exclusion zone to safely conduct refuelling, as highlighted during the discussions with the CAA.

Given narrowbody and widebody aircraft make up most movements (and aircraft stands) at Heathrow, the 5-10m longer and 2-5m wider design of the LH2 medium-range and long-range aircraft in FlyZero[3] would pose significant challenges for operations as Heathrow does not currently have this level of buffer space on the stands.

Another factor at Heathrow will be the type and level of new ground handling capabilities required to scale hydrogen operations. Success will rely on having skilled personnel in place, so specific training and certification for ground crews will need to be available. Where significant training is required, specialist hydrogen crew could be considered, separate to Jet A1 refuelling teams. While this would limit the amount of training and certification required, and therefore costs, it could also limit the operational flexibility of ground handling.

From an airport noise perspective, for large airports such as Heathrow, the size of aircraft considered in NAPKIN make a small contribution to the overall airport noise – such that little or no difference in noise would be discernible.

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

### 8.4.4 Cost Implications and Commercials Opportunities

While introduction of hydrogen aircraft will have commercial implications and require major investment at Heathrow, it will also bring new opportunities. A consortium of fuel producers currently maintains and operates the fuel system, with Heathrow's role to identify space in the masterplan and commercial arrangements for use of that space. While truck deliveries and on-site storage of hydrogen are likely to suffice initially (i.e., to around 2040), post 2040 a new underground distribution system is likely to be needed, requiring a significant capital investment.

The funding model of an airport dictates the steps needed to take to secure the capital to fund future infrastructure. Heathrow is regulated by the CAA following a Regulated Asset Base (RAB) model in which a price cap is applied. Under this model, new capital expenditure is added to the RAB, if approved by the CAA, and the airport can earn a return on those additional assets. Accordingly, Heathrow will need to seek approval for future required expenditure on hydrogen infrastructure in order to add these assets to the RAB.

# 9 Technology Roadmap

Throughout the project, the aerospace manufacturers have been considering the technology factors which will enable the aircraft concepts presented in previous sections of this report. At the outset of the project, the three organisations agreed a set of parameters which would be key to ensuring comparable aircraft concepts. A high, medium and low scenario was agreed for factors such as gravimetric efficiency of hydrogen storage, motor efficiency and fuel cell system efficiency.

Each manufacturer then worked independently to define their concept aircraft through three development “spirals”, receiving feedback from the consortium at each stage. This resulted in a range of different aircraft concepts, culminating in those shared in this report which, whilst different in a number of areas, also face many of the same technical challenges. An attempt has been made to summarise the key technology challenges facing the adoption of these aircraft concepts in the wider aviation ecosystem, as well as some of the specific aircraft technology challenges that the consortium suggest are worthy of further investment.

## 9.1 Key Themes

Four key themes have been identified by the manufacturers within the consortium as being applicable across the wider ecosystem. These are summarised as follows:

### 9.1.1 Hydrogen storage

Although the specific energy of hydrogen is very high (approximately three times kerosene) it has a much lower energy density (approximately a quarter of kerosene for liquid hydrogen) meaning that it requires more space to store. There are considerable activities ongoing around the development of both liquid and gaseous hydrogen onboard storage systems, with liquefying of hydrogen at low temperature and pressure (~20K, 5bar) currently expected to be the most viable solution for aircraft in the regional size class and above. However, there are other potential options such as high pressure compressed gas, cryo-compressed gas and chemical storage (including metal hydrides and LOHCs). All of these will have an impact on both aircraft design and the storage and transportation infrastructure required on the ground.

### 9.1.2 Hydrogen handling safety

Hydrogen has very different properties when compared to kerosene which will introduce significant changes to the safety regulations related to its storage, handling and use. It is currently used as a fuel in the space industry and a coolant in power generation so there is a wealth of experience in its handling which can be used to inform the safety regulations required for widespread uptake in aviation.

### 9.1.3 Certification and regulation

Currently there is a lack of aerospace certification and regulation requirements for hydrogen applications and limited cases where hydrogen products have been operated in an aviation environment, in comparison to decades of experience safely operating existing technologies such as gas turbines. As the required technology platforms such as fuel cells and hydrogen combustion are developed through both private and government funded programs, there will be concerted effort to ensure the same incumbent levels of reliability and safety are maintained. However, it is important to ensure a parallel development of clear certification and regulatory requirements is carried out so accurate guidance can be provided by the regulator on the operation of these new technologies.

### 9.1.4 Liquid hydrogen production

Liquid hydrogen (LH2) presents additional challenges in its production, handling and storage relative to high pressure gaseous hydrogen (HPGH). LH2 presents mass and volume advantages relative to HPGH for aircraft carriage; however, LH2 production, handling and storage requires additional energy and introduces complexities that are likely to make it more expensive per unit mass. This is particularly the case for locations where the usage of the hydrogen is limited. Therefore, it has been analysed in this project as to whether the disadvantages of HPGH carriage may need to be suffered for aircraft operating from small airfields in remote locations.

## 9.2 Specific technology considerations

### 9.2.1 Liquid hydrogen storage

The current Gravimetric Index (GI) of liquid hydrogen storage tanks (15-25%, 2025 TRL6) is below that which are required to enable the aircraft concepts presented to date due to high fixed mass required to contain cryogenic liquid hydrogen. There are not currently any aerospace certified, manufacturable tanks for LH2 available today, with challenges around the safety factors required, as well as the thermal and pressure cycles likely to be seen by a tank. Technology development is required to reduce the mass of these tanks to enable increased GI (30-70%, 2030 TRL6), whilst also being certifiable for use in aerospace applications with an appropriate life. This could be through material developments, insulation techniques and further test work to establish design allowables. This higher GI allows the aircraft manufacturer more flexibility in the integration of these tanks into the airframe, with a reduced impact on the aircraft centre of gravity.

### 9.2.2 Fuel cell system

The mass of current fuel cell systems is high compared with the amount of power they produce (defined as specific power, kW/kg), with the 2025 TRL6 specific power estimated at 1.0-1.5 kW/kg. The fuel cell system includes the fuel cell stack, as well as the balance of plant (supporting components and auxiliary systems), required to produce power from a fuel cell. At present the majority of these systems are not specifically designed for aerospace applications, meaning that they are not optimised for the aerospace power cycle, operation at altitude or the required safety standards. This results in them performing poorly with regards to specific power and volumetric power density. Further optimisation of the fuel cell stack and balance of plant is required to reduce the mass relative to the power produced and achieve a 2030 TRL6 specific power of between 1.5-2.0 kW/kg. This reduces the weight implication of a fuel cell power system on the aircraft, and ensures that the aircraft receives optimum performance from the fuel cells.

### 9.2.3 Hydrogen combustion

Although gas turbine technology has been operating in an aerospace environment and has been improved upon for more than 75 years, there are some changes required to allow current technologies to operate on pure hydrogen. Hydrogen has different combustion characteristics to kerosene. It burns cleaner, emitting less soot particles, but it also has a higher flame temperature which raises the risk of NOx emissions. Counteracting these emissions will require further research and investment in advanced combustion technologies. Nonetheless, the gas turbine in itself comes with significant pedigree and is a prime candidate to continue to power larger aircraft in the time window considered.

### 9.2.4 Thermal management

The mass of the system required to deal with the waste heat of a hydrogen fuel cell is too high (approx. equal to the mass of the total fuel cell stacks in 2025 TRL6 technology). Current fuel cell technology outputs a large quantity of heat at a low temperature. Therefore, the temperature difference ($\Delta T$) between the exhaust and the environment is low which necessitates a heavy heat exchanger with a large air intake, hence leading to additional aircraft-level drag. Various systems can be used to help further dissipate this waste heat, but this comes with a further weight or "parasitic power" consequence. Investment is required to reduce the mass and energy required to dissipate the waste heat expelled from the fuel cell stacks. Achieving a TMS mass of approximately half that of the total fuel cell stacks (a 50% mass reduction) would be a good target (2030 TRL6).

### 9.2.5 Power distribution efficiency

At an aircraft level, the energy transfer system architecture has a high mass and complexity, as well as increased importance for the safety and reliability of the aircraft. For electrified propulsion systems, an order of magnitude increase in aircraft power per passenger is seen, which requires transferring around the aircraft. The necessary systems have different power requirements, leading to complex conversion systems and associated wasted energy. The system is also required to be adequately protected against lightning, electromagnetic compatibility (EMC) and arcing at altitude. Additionally, the separation of the propulsion and power source in an electrical architecture, such as that offered by the fuel cell system, changes the definition of system failures and hence would require an update in the way the reliability of these power systems are assessed. A reduction in the mass and complexity of the energy transfer system architecture onboard the aircraft is required, whilst also confirming its reliability.

### 9.2.6 Motor specific power

The current state of the art motors (2025 TRL6 technology) have a specific power of 4-8kW/kg, with development centred around the requirements of the automotive industry. This results in a mass and volume higher than would be ideal for the aerospace industry. Additionally, they have not been optimised for the speed, torque and cycle requirements of an aircraft propeller without the additional need for a gearbox, adding extra weight and complexity. Further aerospace specific development is required for an 8-15 kW/kg aerospace certified motor (2030 TRL6 technology).

# 10 Safety of Hydrogen Operations

This section highlights the particular properties of hydrogen as a fuel in aviation and its implications when it comes to the safety of airport operations.

While this section focuses on safety implications for airports, the accompanying technical report "Safety of Hydrogen Operations" expands on the properties and hazards of hydrogen in its liquid and gaseous forms, including interviews held with the chief /deputy chief fire-fighting officers of the airport operators included in the consortium as well as with the London Fire Brigade. A short summary of these interviews is included at the end of this section.

## 10.1 Risk in the aviation supply chain

Hydrogen has many properties which distinguish it from conventional fuels that potentially render it more hazardous in terms of transportation and storage. However, some recent reports have concluded that with the correct procedures and infrastructure, hydrogen could be a fuel as safe as, and potentially safer than kerosene[1].

Some advantages of hydrogen versus kerosene are the higher rigidity of hydrogen tanks which will be less likely to rupture, the buoyancy of the gas dissipating quickly, and the smaller heat and intensity of a hydrogen-fuelled fire[2].

The most possible dangerous situations arising from the use of hydrogen are related to the failure of pipes, connections, or equipment and subsequent hydrogen release, as the gas forms an easily ignitable mixture with air[3]. Hydrogen's ability as a gas to seep through containment lines or tanks unlike air or other gases causes challenges in identifying leaks. However, the heat from a GH2 flame is much less intense that that produced by hydrocarbon-based fuels. This not only limits the damage caused by an accident but also permits fire and rescue forces much closer access to the heat source[4]. However, it should be noted that flames from hydrogen fires are invisible to the naked eye creating additional risk for fire and rescue personnel.

Because of the different properties of liquid and gaseous hydrogen, safety procedures at airports will need to be designed according to the type of aircraft expected to be operated. Small airports will receive mostly, if not only, GH2 aircraft while larger airports will most likely see LH2 aircraft only.

1 ACI. (2021). Sustainable Energy Sources for Aviation White Paper, ACI, Montreal.
2 Brewer (1983). An Assessment of the Safety of Hydrogen Fuelled Aircraft, Journal of Aircraft, Vol 20, No 11, pp935-939
3 Schmidtchen, U., Behrend, E., Pohl, H. W., & Rostek, N. (1997). Hydrogen Aircraft and Airport Safety. Renewable and Sustainable Energy Reviews, 1(4). https://doi.org/10.1016/S1364-0321(97)00007-5
4 Rondinelli, S., Sabatini, R., & Gardi, A. (2014). Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation. November. https://doi.org/10.13140/2.1.2658.9764

The type of risks airports will need to address are presented next.

## 10.2 Airport Risks

There will be risks relating to take-off and landing, taxiing, aircraft refuelling and ground operations and inadequacy of existing firefighting capabilities among others.

### 10.2.1 Aircraft take-off and landing

The likelihood of an aircraft crash is very low. However, it is more likely to happen on landing or take-off, and when it occurs the impacts are severe. For a hydrogen aircraft, there would be a possible risk of LH2 / GH2 leakage from ruptured fuel tanks and associated fuel supply lines to the engine which needs to be managed.

For concept designs that use GH2, as fuel tanks are located on the wing, risks to passengers and flight crew would therefore be much lower. For other concept designs where LH2 fuel tanks are located under the cabin in forward and rear baggage bays, there is an increased risk of leakage and therefore explosions and fires around the tank and fuel line rupture from damage to the fuselage caused by a crash. This could be especially an issue as the fuel tanks could be closer to the point of impact.

For larger regional aircraft concepts, the LH2 fuel tank is located at the rear of the passenger cabin, raising the risk of direct passenger exposure to LH2 leaks. The risk of rupture on landing, however, may be lower.

Crashworthiness of aircraft will vary across the different aircraft concept developed, and thus, new requirements for safety based on data from tests will need to be developed by the competent authorities (e.g., CAA).

### 10.2.2 Risks related to aircraft taxiing

There are two main risks on taxiing: a heavy landing caused by a collapse in the under-carriage and potential collisions with foreign objects and other aircraft.

In both cases the main risk would be a leak. In the case of a heavy landing, the leak would be significant, especially with those concept designs where the fuel tanks are positioned under the wing, as they may be ruptured at point of contact / impact. There is a lower risk of this occurring with the regional aircraft concepts. Collisions with foreign objects and other aircraft may lead to smaller leaks.

These risks will be mitigated by robust tank design sufficient to withstand significant impact in these situations.

### 10.2.3 Risks related to refuelling and ground operations (stationary at the stand)

There are risks around LH2 / GH2 leaks during the refuelling process due to the large temperature differences encountered when refuelling[5]. Incidents involving leaks could be the result of an operator error, mechanical failure, impact or thermal shock.

There is a risk that poor insulation or damage could cause pipes and fittings to freeze, leading to surface water or gas being released from a failure in the pressure release valve leading to possible ignition from gas clouds.

The severity of the incidents will be greater due to the risk of contact with kerosene, which means that there may be a safety case for requiring LH2 / GH2 aircraft to use dedicated stands (this is investigated further in the accompanying technical report "Safety of Hydrogen Operations"). Ignition sources should be avoided in regions where hydrogen may leak or collect[6].

Key areas for further research are the release and ignition of large volumes of LH2, accidental release issues outside refuelling environment and analysis of volume, storage facility location, and precautionary and mitigation methods in case of leaks[7].

### 10.2.4 Risks related to airport fire-fighting

Airport RFFS (Rescue and Fire-Fighting Service) standards, protocols, responses and tactics that exist today are based on the risks and behaviours associated with incidents involving kerosene. Incidents involving alternative fuels (LH2, GH2, Battery) will require the creation of new protocols and response tactics with respect to each alternative fuel.

As the technology and science around hydrogen flight matures, it is expected that ICAO and national aviation safety regulators would commence work on new standards and recommended practices on how hydrogen is sited, supplied, stored, distributed and managed on an airport estate and on new protocols for fire and rescue services to ensure that they have the resources and the procedures to be able to deal with incidents involving hydrogen-fuelled aircraft. To date, there is very little literature on the implications of hydrogen flight on airport fire and rescue standards. This contrasts with those standards that have already been developed for motor vehicles and public transport (e.g., buses).

5 Rondinelli, S., Sabatini, R., & Gardi, A. (2014). Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation. November. https://doi.org/10.13140/2.1.2658.9764
6 Benson, CM Ingram, JM Battersby, PA Mba, D Sethi, V Rolt, A. (2019). An analysis of civil aviation industry safety needs for the introduction of liquid hydrogen propulsion technology. ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, June 17–21, 2019, Phoenix, Arizona, USA.
7 Benson, CM Ingram, JM Battersby, PA Mba, D Sethi, V Rolt, A. (2019). An analysis of civil aviation industry safety needs for the introduction of liquid hydrogen propulsion technology. ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, June 17–21, 2019, Phoenix, Arizona, USA.

Fires involving hydrogen should not be approached without appropriate flame detection equipment due to the low visibility of hydrogen flames and it is recommended to allow hydrogen fires to burn under control until its flow can be halted[8]. Small hydrogen fires can be extinguished by dry chemical extinguishers or with carbon dioxide, nitrogen, and steam.

Because of its specific properties, suitable hydrogen detection systems and sensors would need to be used by fire-fighters. The low ignition energy for hydrogen makes stringent ignition source control, and leak control and monitoring, even more important than for kerosene type fuels[9].

### 10.2.5 Fire-fighting hydrogen incidents

The present practice of creating a rescue path by laying down a blanket of foam to cover the evacuation and allow occupants to escape will not become obsolete, but the physical properties of LH2 need to be considered[10].

Given the short time of hydrogen burn-off, the implications of a hydrogen-based flash fire need to be considered. Specifically, for those aircraft with the fuel tanks located above the wings, a hydrogen fire may be limited to the ruptured fuel tanks, rather than spilled fuel below the aircraft, which may require the design and deployment of more mast-mounted hoses and such to spray fire suppressant at the elevated level of the fire. The intense heat created by a hydrogen flash fire, and the prospect of flash burns to passengers and crew, means that ARFF responders will need to carry large quantities of the latest in burn treatments[11].

Because the heat radiated by a hydrogen flame represents about a tenth of that of a hydrocarbon fuelled flame, this reduces the extent of possible damage and allows fire- fighters closer access to the heat source. However, specialist training and equipment will be needed, as contact with any cryogenically cooled metals will likely result in injury[12].

8 Benson, CM Ingram, JM Battersby, PA Mba, D Sethi, V Rolt, A. (2019). An analysis of civil aviation industry safety needs for the introduction of liquid hydrogen propulsion technology. ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, June 17–21, 2019, Phoenix, Arizona, USA.
9 Benson, CM Ingram, JM Battersby, PA Mba, D Sethi, V Rolt, A. (2019). An analysis of civil aviation industry safety needs for the introduction of liquid hydrogen propulsion technology. ASME Turbo Expo 2019: Turbomachinery Technical Conference and Exposition, June 17–21, 2019, Phoenix, Arizona, USA.
10 Murrell, J. (2008). Firefighting When Airplanes Are Loaded With Hydrogen Fuel. Aviation Safety Journal (Brief).
11 Murrell, J. (2008). Firefighting When Airplanes Are Loaded With Hydrogen Fuel. Aviation Safety Journal (Brief).
12 Rondinelli, S., Sabatini, R., & Gardi, A. (2014). Challenges and Benefits offered by Liquid Hydrogen Fuels in Commercial Aviation. November. https://doi.org/10.13140/2.1.2658.9764

## 10.3 Key Insights from Interviews

From the interviews conducted, it appears that professionals in airport fire and rescue are at the very early stages in knowledge acquisition in terms of how the industry is preparing for hydrogen aviation.

The NAPKIN concept designs were presented to the interviewees with the general consensus was that the designs did not appear to be "show-stoppers" and that they were comfortable and confident that incidents involving hydrogen fuel could be managed.

In terms of resources, the consensus view was that current assets can be used to handle hydrogen incidents with the only significant differences most likely to be around tactics. Tactics will be based on the need for new training protocols and requirements which will be set eventually by the regulatory authority. It is also possible that the RFFS industry will be able to make use of virtual / augmented reality-based training platforms that can be used to prepare fire crews in understanding hydrogen and also in how to respond to fires and other incidents. Opportunities may exist for the UK to take a lead globally in fire and rescue training for hydrogen in aviation through the establishment of a national centre.

Professionals interviewed in this study were of the view that given their current understanding of the science, dedicated hydrogen aircraft stands would not be necessary.

# 11 Passenger Acceptability

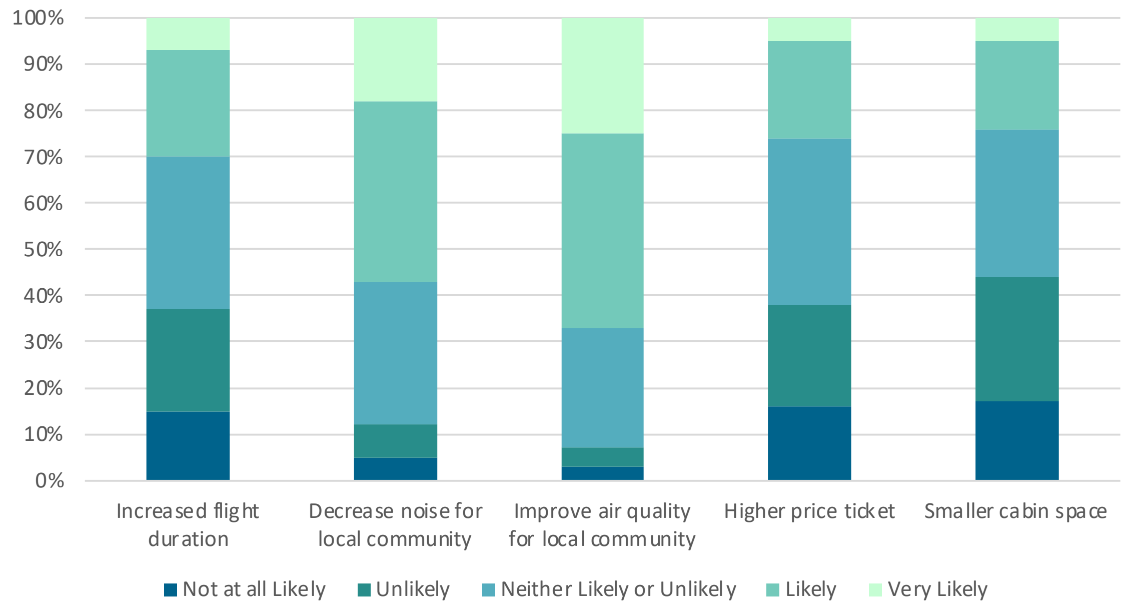
Passenger acceptability for zero-emission aircraft could be one of the key barriers for uptake of these aircraft. As part of NAPKIN, a multi-modal demand model was created which included the results from public surveys conducted across the UK, aiming to build initial insights on what factors could influence people's choice between conventional aircraft or zero-emission alternatives (electric and hydrogen). Market uptake sensitivity cases using the Airline Behaviour Model with this model are included in the separate technical report "UK Domestic Market Modelling – Methodology and Additional Outcomes".

The objectives of these surveys were to identify potential early adopters of zero-carbon emission aircraft and understand the trade-offs between conventional kerosene-based aircraft and new zero-emission aircraft. Four different surveys were conducted: two (1,471 and 2,000 responders) were conducted across the whole UK and two (414 responders and 208 responders) were focused on Londoners.

While this is just an initial attempt to examine public acceptance of zero-carbon emission aircraft and further research is needed, the surveys suggest that, although sustainability is a top issue for passengers, they are not keen to trade on changing flight experience and paying more. It also shows that zero-carbon emission flying will not be achieved with a single trade-off to customer experience – it may require broader compromises from passengers – so the aviation industry may need to focus in ensuring the overall experience of zero-carbon flying is not "net worse" than the current experience.

All surveys show that travel cost and flight time are likely to be the most decisive factors for aircraft choices (Figure 45).

**Figure 45: Results showing how likely would passengers be to accept specific changes to their flight experience in order to take a Zero-Carbon flight (if all other aspects of the flight experience were to remain the same) – UK-wide**




When considering all potential trade-offs together, a 2-3x longer flight duration seems as the least acceptable option for most of the responders (70- 80%). However, if the flight time increase is around 1.5x more, half of the responders would be happy to take the zero-carbon flight.

Price has the most potential to sway passenger preference towards – or away from- zero-carbon emission flight, with 87% of passengers saying that a lower priced ticket is a potentially appealing benefit of zero-carbon flight but only 30% of the responders were willing to pay extra. These results reinforce the idea that, for mass uptake of zero-carbon emission aviation, reductions in hydrogen price will be required.

One of the surveys also asked about connectivity. Results show that availability of direct destinations could be a key factor as passengers consider zero-carbon emission flight, with only 34% of them willing to accept a decreased number of direct destinations. NAPKIN aircraft presented in this report have sufficient range capability to meet a significant majority of missions currently flown by aircraft in their size class and thus, connectivity should not be an issue from an aircraft point of view. To ensure good connectivity though, availability of hydrogen infrastructure in all airports and a network for hydrogen supply will also be required.

Finally, a smaller cabin space could also be a factor to consider when choosing between aircraft types, with only 20-30% of passengers keen to accept a reduced baggage allowance in favour of zero-carbon emission aircraft. Based on this, zero-carbon emission aircraft will need to be designed in such a way that the same (or a very similar) level of facilities and flight experience to that which is currently available can be provided.

Social benefits (i.e., improved air quality and reduced noise for the local community living around the airport) seem to have a higher impact for people to adopt this new technology. In this case, around 60% of passengers would accept flying with a zero-carbon emission aircraft with only around 10% unlikely to take the zero-carbon emission aircraft even if it provides benefits to the community. Although these passengers did not give reasons why they would not choose the zero-carbon emission alternative, it is plausible the reason will be uncertainty around safety. On this topic, the first survey, which also gave the option to choose electric aircraft, shows that battery-based electric aircraft are relatively more welcome than hydrogen aircraft. Advertising the safety of zero emission technology will therefore be essential to ensure uptake of this technology in the coming years.

Surveys also tested how far in the future passengers think the transition towards ZEF is. While passengers acknowledge that ZEF is on the horizon, it is not in people's minds for the immediate future (next 10-20 years) and around 10% of people think it will never happen in the UK.

Results also suggest that potential early adopters could be young people, females and those with previous carbon offset purchase experiences. Therefore, before zero-carbon emission aircraft are made available in large-scale operation, educating the public about the necessity, urgency and benefit of environmental protection to increase their environmental awareness will be important.

# 12 Policy Recommendations

## Current landscape

Currently, the status of zero-carbon emissions flight technology can be characterised by:

- A series of demonstration flights for small hydrogen fuel cell aircraft
    - Eg. Fresson Program with Cranfield Aerospace Solutions.
- Promising R&T moving towards manufacture of 19+ seat aircraft
    - Eg. H2GEAR with GKN on fuel cells
- Interest from airline operators, including placing advanced orders for concepts in development but also investing in technology programmes
    - Eg. Rolls-Royce and easyJet working towards a Pearl 15 turbofan engine demo
- Larger 'clean sheet' concepts, up to 200 seats, being developed
    - Eg. Airbus ZEROe and Embraer ENERGIA
- Collaborations between airframers and aero-engine providers being put in place as part of programmes such as Clean Aviation and in support to the above clean sheet designs
    - Eg. Rolls-Royce leading the CAVENDISH program in Clean Aviation
- Potential gaps exist on the energy, infrastructure and distribution requirements for fuel production and support for the atmospheric science research required to understand the impacts of emissions.

Given the current backdrop, Government policy is rightly focussed on aerospace technology R&D, mainly through funding for the Aerospace Technology Institute, and 'whole system' innovation to explore the other non-aircraft technologies and operational factors that will determine the success of ZEF. Project NAPKIN, funded through Innovate UK's Future Flight Challenge, falls in the latter category. The introduction of a ZEF delivery group within the Jet Zero Council is a promising move, though this has not yet met at the time of writing and is likely focussed, at least initially, on the question of trans-Atlantic zero-carbon flight. In support of these national efforts, there are also parallel ongoing activities in European programmes, such as Clean Aviation and Clean Hydrogen, which UK entities can participate in.

As confidence grows regarding the technology coming to market and its timelines, it is becoming apparent that the biggest risk to ZEF is that the wider aviation system is not prepared for its introduction – resulting in delay to the introduction of commercial services.

## UK "Jet Zero Strategy"

ZEF is a key strand of the Jet Zero Strategy. In its central 'high ambition' scenario ZEF delivers 27% of total aircraft movements by 2050 with up to 150 seat aircraft entering service in 2035, and 150-250 seat aircraft from 2040[1]. It's 'high ambition with breakthrough on zero-emissions aircraft' scenario sees these figures rise to 38% of all aircraft movements by 2050. This involves sub-150 seat aircraft entering service from 2030 with 150-250 seat aircraft from 2035 allied to early retirement of certain aircraft in 2040.

When consulting on the Jet Zero Strategy, the UK Department for Transport asked, "could ZEF connect regions of the UK by 2030, and could it deliver UK domestic services by 2040?"[2]

## Connecting regions by 2030

NAPKIN shows gaseous hydrogen 7-19 seat aircraft starting to enter service from 2025, likely powered by a fuel cell, serving short 'island hopping' and 'lifeline' services such as some of those in the Scottish Islands and the Southwest peninsula of England. These services will likely require or at least benefit from Government support to kickstart services. Subject to hydrogen costs, they will likely be economically rational for airline operators when renewing fleets when viewed over a whole-lifecycle cost basis, but an initial injection of support will help to de-risk these investments, considering future known unknowns – such as the degree of airline exposure to carbon costs and consumer expectations. These aircraft have the capability to fly routes such as those to, from and between Scottish islands and according to UCL's Airline Behaviour Model could compete on routes such as Jersey to Southampton.

By mid-2030's, NAPKIN believes that larger services serving 50 passengers or more could connect the regions of the UK, such as routes between London and Scotland depending on the evolution of underlying carbon price and policy developments on hydrogen and SAF. However, there is a key consideration for Government and industry to unpack:

From a technology point of view, retrofit is not likely to be a logical choice. Any hydrogen-based aircraft of 20 seats or above operating around 2030 would likely be retrofitted designs, or aircraft substantially based on existing airframes. Whilst they could enter service sooner than "clean sheet" concepts, which could come to

1 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1091866/jet-zero-strategy-analytical-annex.pdf
2 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1002716/jet-zero-consultation-a-consultation-on-our-strategy-for-net-zero-aviation.pdf

market from 2035, they will have significant performance limitations and therefore short-lived attraction. This potential of 5 years operating a domestic retrofit fleet could reduce the CO2 emissions for the small regional segment over this period but would likely displace the introduction of more capable and energy efficient clean sheet aircraft, which are likely to succeed more quickly in replacing conventional kerosene aircraft in the mid-2030s, given the likely limited funding for zero-carbon emission flight R&T. Furthermore, the life of a retrofit aircraft will face limitations due to the life of the airframe on which its built, especially for the commuter and regional markets where the average replacement rate is slow and the current airframes are old.

However, given the low level of penetration, the 7-19 seat retrofit aircraft would encounter limited or no barriers in the use of airspace or airports. As the NAPKIN retrofit concepts and infrastructure modelling demonstrate, the aircraft can perform in existing airspace and fuel requirements at airport level would be restricted potentially to a single truck delivery of gaseous or liquid hydrogen each day. Given the learning benefits, the NAPKIN technical advisory board has suggested that cargo-only operations, and low-volume passenger routes designed specifically to pilot commercial operations could both offer a valuable step forward in scaling up operating around the end of this decade. Depending on the evolution of underlying carbon price, policy developments and investor/consumer sentiment over the next ten years, the commercial case is likely challenging, and therefore represents a conscious 'jet zero' choice Government may wish to make.

### Domestic zero-carbon emission aviation by 2040

The NAPKIN proposed 2035 EIS date aligns with many industry commentators in suggesting it is the earliest date for the larger 90 seat and above liquid hydrogen-fuelled 'clean sheet' aircraft to enter into service. Towards 2040, this could climb through 'narrowbody' 150-250 passengers, to 'midsize' 300 passengers – aircraft which FlyZero[3] believes could connect any two destinations globally with one stop. Airline economics will govern the successful aircraft above 90 seats, which is beyond the scope of NAPKIN. However, NAPKIN's modelling clearly shows that in the UK market, 90-seater clean sheet regional liquid hydrogen aircraft capable of performing on existing short haul routes would compete well, with the potential to take on and challenge the smaller regional aircraft. This is because the ratio between operating costs and payload become more favourable as the aircraft scales, an effect which continues into the narrowbody space and not including the narrowbody segment is an important caveat to this study, which could have an impact on the conclusions drawn for the 90-seat aircraft especially.

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

UK domestic services are operated by regional carriers such as Loganair or international carriers, such as British Airways. The former operates a fleet entirely comprised of aircraft of 70 seats or fewer, the latter will predominantly utilise narrowbody aircraft from its international fleet. Often these aircraft will also complete at least one international segment on the same day. It is therefore difficult to separate UK domestic travel from international short-haul. Nonetheless, domestic aviation could be moving to zero-carbon emission by 2040 for regional operators, aided by the age of their fleet. For international airlines it will be an early 'work in progress' given the likely very recent introduction of zero-carbon narrowbody aircraft into the market at that time. Airport infrastructure preparedness is critical for these operators – as truck delivery to large airports like Heathrow will likely become too challenging for logistical and community reasons, and significant investment in new infrastructure will need to have come to fruition.

### Regulatory considerations

The success and scalability of this new technology will also depend on the timely development of a regulatory framework to support airport operators and airlines on this transition as well as build confidence for the flying public.

NAPKIN completed a CAA sandbox on the 20th of April. Some of the challenges identified, in which substantial investment on policy and industrial effort in the near-term will be required, include:

- **Fuel policy:** Existing fuel policy could be reviewed considering hydrogen powered aircraft tend to have reduced range performance compared to kerosene powered aircraft.
- **Aircraft refuelling:** Due to the different properties of hydrogen compared to kerosene, new refuelling procedures will need to be developed. However, there is lack of clarity on several technical aspects that will need to be further defined.
- **Crashworthiness of aircraft:** Crashworthiness of hydrogen aircraft will also need further investigation, with location of any pressurised fuel tank being a key parameter to determine the extent of damage.
- **Fire safety risks and emergency planning for accidents:** Fire safety risk will change. This will require consideration from RFFS and will influence the aerodrome emergency planning, which will require engagement with the local authorities.
- **Airworthiness certification:** The certification of novel propulsion technologies is following existing certification pathways. When a new technology is first applied to an aircraft for which a Type Certificate is applied, the vehicle for addressing the new technology is a Special Condition.

- **Changes to noise profiles:** While the performance on noise and carbon will rely on new technologies, their optimisation will also depend on the Airspace Modernisation Strategy and the option of compromising on noise reduction.
- **Government incentives:** CAA recognises that governments may have to incentivise the use of hydrogen fuels due to the sensitivity of airlines to fuel prices.

## Government focus

### Near-term

Government support, including continued R&D investment through the Aerospace Technology Institute, investment in European programmes through the Government Guarantee, and potentially targeted support to share risk on strategic routes, will build confidence for operators and investors and deliver substantial learning benefits for the subsequent generation of larger liquid hydrogen fuelled aircraft.

Underlying the success of the technology will be the provision of sufficiently available low or zero-carbon hydrogen. As such, the further development of a UK hydrogen strategy, including how aviation will fit with demand from other sectors, is of fundamental importance and a top priority issue. Given that green (or other zero-carbon) hydrogen will be required for Power to Liquid sustainable aviation fuels, its development should be seen as low risk. Other specific areas of research can be taken forward including further investigation of non-CO2 effects.

### Medium-term

The UK Department for Transport (DfT) Zero Emission Flight Infrastructure (ZEFI) programme anticipated that airport-level infrastructure questions require unpacking, with much of the specific fuelling and ground handling challenges not previously explored. Taken together, NAPKIN and FlyZero offer scenarios for future hydrogen demand. Albeit that the successful airport business models are uncertain, what is clear is that even under low scenarios put forward, considerable infrastructure investment needs to occur, involving storage and distribution and likely liquefaction. Electrolysis also needs to be considered – if not at the airport level – certainly within the overall energy system and factored into a suitable clean electricity plan as the world decarbonises. These questions require cross-Government co-ordination at least between HM Treasury, BEIS and DfT.

## Specific policy objectives and options

### Supply of green hydrogen

Green hydrogen is a key feedstock to underpin aviation's transition to net zero – whether use directly as a fuel in a gas turbine or fuel cell, or as one part of the feedstock requirement for Power to Liquid sustainable aviation fuel – also known as e-fuels. Consequently, Government leadership to develop the UK market is a key priority and a no-regrets activity given the existing and planned demand from other sectors, as outlined in the UK's Hydrogen Strategy4. Given 60 % of jet fuel is imported currently5, hydrogen produced domestically can benefit UK energy security and the issue should form a key consideration for the new hydrogen committee chaired by Baroness Brown6.

**Who pays?**

Aviation's path to net zero involves significant investment – in aircraft technology, fuels, operational efficiencies and more. The use of hydrogen in aircraft propulsion will ultimately involve significant, costly infrastructure investment at airport level as NAPKIN details. Whilst the finer detail will be hammered out at a later stage, it is clear that industry-Government co-operation will be necessary, with costs shared across the sector and with Government support. Neither airlines nor airports can shoulder the cost burden, but each can play a role, together with Airspace Navigation Service Providers (ANSPs) – with airports and ANSPs providing charging structures that benefit lower carbon flights. Government will have various options to help cut the cost premium – such as through tax incentives and exemptions.

**Public confidence**

NAPKIN does not identify any specific challenges with respect to public acceptability; however, providing targeted support to cargo-only services in the near-term could help provide a foundation for building public confidence in commercial services, as well as providing further learning opportunities.

**Overcoming payload constraints**

NAPKIN illustrates how clean-sheet aircraft below 100 seats can enter service and compete, aided by suitable incentives. The Airline Behaviour Model accounts for capacity constraints currently and consequently, where there are such constraints, the economic constraint of a smaller aircraft to replace a larger one is clearly apparent. Government could consider lifting movement caps for clean-propulsion aircraft to mitigate this deterrence.

4 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

5 https://www.gov.uk/government/statistics/petroleum-chapter-3-digest-of-united-kingdom-energy-statistics-dukes. (Table 3.3)

6 https://hydrogen-central.com/committee-uk-government-hydrogen-policy-pitfalls/

**Jet Zero – Driving rapid ZEF uptake**

The current policy focus on technology is welcome and necessary to progress the core aircraft technology. However, NAPKIN represents one of few aviation system-wide studies and these now need to feature much more in R&D funding programmes, as there are growing concerns that the barriers to technology adoption will be elsewhere in the system – such as at airport infrastructure level.

To hit the Jet Zero objective of ZEF services connecting regions of the UK by 2030, NAPKIN has highlighted that retrofit aircraft will be required. However, also that these do not appear to represent the economically rational choice for airlines. Consequently, Government could step in to support the difference in operating cost over appropriate timescales while providing more investment in the development of clean sheet aircraft technology. The factors governing operating costs will have a profound impact on the level and rate of uptake of these aircraft in the market.

There are few dissenting voices regarding the need to get aviation to zero-carbon. The main focus of debate regards the extent to which aviation can deliver on its promises and the alternative of demand management. Without commenting on the broader debate, when studying UK connectivity there is an important point to consider about the baseline assumptions. Surface transport is generally regarded to offer the lower carbon solution, but of today's airline operations 63% cross water. Today's road, rail and shipping operations on comparable routes rely heavily on fossil fuels and the carbon and cost impact to make them zero-carbon (e.g., new rail lines, electrification of existing rail lines) should be considered. The advantage of sub-regional air connectivity based on hydrogen is not about reaching parity with surface modes – it is about decarbonising UK transport in an efficient and effective way.

# 13 Further Work

This study has explored what are the conditions necessary to make zero-carbon emission UK domestic aviation possible. However, given the regional scope of the project and limited time, there are some areas in which further work is needed to gain a clearer understanding of the challenges and support needed by the industry for the introduction of ZEF services.

With that expectation, NAPKIN has prepared the following initial list of topics that need further investigation.

### Retrofit vs Clean sheet debate

As previously highlighted during this report, the question between going retrofit or waiting for clean sheet designs will need to be decided this decade.

From a technological point of view, retrofit designs could enter the market up to 5 years before the clean sheet designs, however, retrofits would come with significant performance limitations and an age-limit overhead. Given retrofit designs will require Government financial support to be economically viable for airlines, 5-years (or less) of retrofit operation is unlikely to provide a business case good enough for Governments.

From an emission savings point of view, this potential of 5 years operating a domestic retrofit fleet could reduce the CO2 emissions for the small regional segment over this period but would displace the introduction of more capable and energy efficient clean sheet aircraft, which could in turn, make a negative impact to overall CO2 emissions.

An alternative would be to use SAF-powered aircraft as a stepping-stone while the investment and research is focused on the development of clean sheet designs.

### Uncertainty on operating costs

One key area for further research is the operating costs of hydrogen aircraft. Whether the assumptions behind the operating costs analysis undertaken by NAPKIN are realistic or not will only become apparent once ground testing has taken place.

The key area for further research is the maintenance cost of the new hydrogen systems required for these aircraft (e.g., cryogenic hydrogen tanks and fuel systems) as well as maturing aerospace fuel cell and hydrogen combustion technologies.

Given operating costs are one of the main decision factors for airlines to decide whether or not to operate a certain route, research on fuel cell degradation in an aerospace environment, and subsequent impact on maintenance costs is essential to better understand the potential market for this technology.

### Uncertainty on technology development

As with any technology program, there is a level of uncertainty that the technologies proposed will be able to meet the necessary capability requirements. With the technology roadmap, we have aimed to outline the achievable levels, based on today's understanding, for key technologies such as the hydrogen storage, fuel cells and thermal management systems. However, continuing to improve these KPIs is dependent on carrying out the necessary further work to reduce the uncertainty levels.

### Identify the "Non-UK" potential routes and market for zero-carbon emission aircraft

The scope of NAPKIN was limited to UK services only. While this gives a useful picture of how and when the first ZEF could arrive, it is difficult, and potentially risky, when it comes to make commercial decisions.

The natural next step arising from this project is to replicate it at a European, and potentially worldwide scale, to understand the viability of zero-carbon emission aircraft in non-UK markets.

### Noise performance of larger zero-carbon emission aircraft

Under NAPKIN, a noise performance analysis of the NAPKIN fleet has been undertaken. However, due to time restrictions, a detailed analysis of the larger 90 seat aircraft has not been conducted. In addition, given operations at larger airports in the UK are dominated by narrowbody and widebody aircraft, additional noise performance analysis of these larger aircraft will need to be conducted. This is a clear area for further research, including to help focus technology investment and drive pace.

### Balance between carbon savings and economic benefit

The Airline Behaviour Model was developed on the basis of maximising airline profits. Within this framework, carbon pricing provides a lever to induce airlines to reduce environmental impact. However, other ways of maximising potential carbon or climate impact savings could be considered, for example considering the costs and constraints associated with other emissions sources and negative externalities, or minimising carbon emissions at a given level of airline profit. Accounting for both environmental and economic benefits of ZEF services is therefore an area that could be further explored.

### New airline operating models

Outputs of this project are based on existing airlines and networks. Airlines adding new routes to their networks, airlines going out of business and/or new airlines (potentially with new operating models/networks) entering the market have not been modelled, both of which may be important for ZEF uptake.

While we recognise this is a limitation of the study, the modelling can only be based on what we know today regarding airline networks and business models. Once more progress on zero-carbon emission aircraft and regulation is made, further modelling and analysis should be conducted to project future uptake of this new technology.

# 14 Conclusions

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. Notwithstanding the challenges and policy interventions identified within NAPKIN, this project has presented the technological, operational, infrastructure and commercial conditions needed to achieve net zero UK domestic aviation by 2040. The key insights, grouped in three themes, are presented below.

## Technology

Achieving net zero aviation by 2040 seems possible from a technology point of view. The first hydrogen aircraft could be retrofit which, while they are not as efficient as new aircraft and rely on suitable donor airframes, they nevertheless could provide a good basis for the development of new, larger clean sheet aircraft by 2035.

Between 2025-2030, 7 to 19 seat aircraft capable of flights around 200-300km have the potential to take off from small and regional airports. Mid-2030 is expected to be the period when regional (40 to 100 seat) hydrogen aircraft enter the market, with the potential to replace the entire UK regional fleet by 2040 under the correct conditions.

Both fuel cell and gas turbine technologies have shown potential to decarbonise the aviation sector. While fuel cells are a novel technology for aerospace applications, they have the potential to power zero CO2 and NOx emission aircraft, should their power density and thermal management system parameters continue to improve at system level. For gas turbine technology, although it has operated in an aerospace environment for more than 75 years, some changes are required to allow current technologies to operate on pure hydrogen and to optimise the engine. Further investigation in both technologies is of utmost importance if the timelines, and associated emission benefits proposed under NAPKIN, are to be achieved. Additionally, a key area of focus is around the tank and fuel system, as a true enabler to hydrogen aircraft, along with its integration on board the platform. Further considerations will also need to include hydrogen safety and the journey to certification.

NAPKIN concept aircraft provide an overall noise benefit compared with conventional aircraft. For retrofit aircraft, due to their minimal design and operational changes, the change in noise is negligible. The noise and carbon performance will also depend upon the Airspace Modernisation Strategy and the option of compromising on noise reduction.

## Infrastructure and Operations

New infrastructure to support hydrogen operations will be required at both airport and national level.

For small regional airports, infrastructure requirements will be relatively limited, with hydrogen (whether gaseous or liquid) largely delivered by truck and, at least in the initial years, these same trucks could also be used to directly supply the aircraft, avoiding the need for permanent storage at the airport.

For larger airports servicing longer distance aircraft, delivery of hydrogen from early 2040's will be done via dedicated gaseous pipelines. Gaseous hydrogen will need to be liquefied (either on site or nearby) at a liquefaction plant to then be transferred to the storage tanks.

From the storage tanks, the hydrogen will be distributed to the apron via either bowsers or a hydrant system. For small and medium-size airports, bowser vehicles are likely to be a suitable solution even for the long run, as is the current situation with kerosene refuelling trucks. However, hub airports will need a hydrant hydrogen system in place from early 2040's.

While airport infrastructure should not be a barrier for the uptake of zero-carbon emission aircraft in the short-term, R&D is still required on aviation-suitable hydrogen infrastructure, as some of this infrastructure still does not exist or is below TRL 8-9.

Equally important will be that the distribution infrastructure is available to enable regional uptake. Otherwise, a lack of immediate investment in the necessary upstream infrastructure will directly inhibit the zero-carbon opportunity afforded by the NAPKIN aircraft.

Early technology standardisation should be another key consideration in order to build confidence for operators in investment and implementation and, as with the introduction of any novel technology, new operational and safety procedures will need to be developed, alongside staff retraining and recruiting.

Overall, a significant effort is also required to ensure that green hydrogen becomes available in sufficient quantities to support the aviation sector and the birth of a larger hydrogen economy. Key to this will be a sufficient hydrolysis and low-carbon electricity production capability and distribution infrastructure. At present only about 3% of the world hydrogen is 'green' and the report has already highlighted challenges against the hydrogen volumes that will be needed against those in production. The policy required to enable this is addressed next.

## Policy

NAPKIN findings show that the cost of hydrogen relative to fossil kerosene will be a critical factor in achieving a net zero domestic aviation by 2040. Government industrial strategy on hydrogen is therefore critical and should target lowest possible green hydrogen production costs. To achieve this, the number and size of green hydrogen production plants should be increased so economies of scale can be achieved.

Production of green and low-carbon hydrogen is currently limited in the UK. The industry will need to work closely with Government and the energy sector to ensure enough supply around the country to propel zero emission flight. Given green hydrogen is required for the production of both SAF and used directly to power ZEF, continued expansion of supply is a no-regrets activity.

Additionally, more granular detail should be provided in regard to how much of the projected green hydrogen production will be made available for the aviation sector to show how aviation demand can co-exist with other sectors and how UK production can be ramped up further.

But it is difficult, and would be a mistake, to look only at the UK domestic travel given the relevance of the international market for UK airports. Cooperation and coordination between governments is vital to provide a common approach and measures towards the decarbonisation challenge and build confidence in the industry for investment on green hydrogen production, fleet renewal and hydrogen infrastructure among others.

# 15 Glossary

**Airline Behaviour Model (ABM)** – Optimisation model which simulates competing airline and passenger behaviour within UK domestic flight networks by assuming that each individual airline (or alliance) acts to try to maximise its own profit.

**Air Passenger Duty (APD)** – Excise duty charged on the carriage of passengers flying from a non-exempt UK or Isle of Man airport on an aircraft that has a take-off weight of more than 5.7 tonnes or more than 20 seats.

**Approach Noise** – Noise levels at the approach reference noise measurement point as defined by the appropriate Chapter of the ICAO Annex 16.

**'B' Checks** – 'Light' maintenance check performed approximately every 6-8 months.

**Baseline / Reference Aircraft** – Existing aircraft used to compare performance and design parameters of the comparable hydrogen aircraft.

**Battery Only Aircraft** – An aircraft that uses rechargeable batteries to store electrical energy and provide power to motors for propulsion.

**Clean Sheet Aircraft** – New aircraft design.

**Conventional Aircraft** – Existing jet fuel/gasoline-powered aircraft.

**CS25 Regulations** – Certification specifications for large aeroplanes from the European Union Aviation Safety Agency (EASA).

**Electrolysis** – Process of using electricity to split water into hydrogen and oxygen. This reaction takes place in a unit called an electrolyser. Electrolysis requires significant amounts of water and energy.

**Green Hydrogen** – Hydrogen produced using renewable electricity.

**Hydrogen Aircraft** – An aircraft that uses stored hydrogen to provide propulsion through either combustion or an electrochemical reaction within a fuel cell to power a motor.

**Hydrogen Fuel Cell** – A hydrogen fuel cell converts hydrogen as a fuel into electrical energy through an electrochemical reaction. Aside from the electricity produced, the only output from the cell is water.

**Hydrogen Gas Turbine** – A gas turbine that has been designed to run on hydrogen.

**Hydrogen Hub** – Region where multiple hydrogen users across various sectors such as transport, industrial or energy are co-located, minimising the cost of infrastructure and leveraging economies of scale in producing and delivering hydrogen to customers.

**Liquefaction** – Process to convert the gaseous hydrogen into a liquid form. It is a process that requires significant energy.

**Maximum Sound Pressure Level ()** – Maximum, A-weighted instantaneous sound level and has units of dB(A). While it is easily measured and understood by the public, it is less descriptive of the annoyance caused, since it omits the event duration.

**Cumulative (Multi-event) Noise** – Noise metrics used to assess the noise exposure of fleet operations around airports.  is globally the most commonly employed aircraft noise exposure metric with variations such as: I.  that represents exposure due to night events, II.  and  that describe 24-hour exposure by giving specific weighting to night and evening events. III. Finally, SEL (Sound Exposure Level) is similar to  but with a duration period . Thus, it is the one-second-long steady level containing equivalent total acoustic energy as the actual fluctuating noise.

**Noise-Power-Distance (NPD)** - Define, for steady straight flight at a reference speed in specified reference atmospheric conditions and in a specified flight configuration (power setting, airframe configuration), the received sound event levels, both maximum and time integrated, directly beneath the aircraft as a function of distance.

**Public Service Obligation Routes (PSO)** – Routes viewed as being necessary to provide essential connectivity to isolated regions (e.g., Scottish Islands) but which are unlikely to be profitable on a commercial basis and therefore are subsidised by governments.

**Retrofit Aircraft** – Aircraft design that includes modifications from an original aircraft design in order to incorporate improvements that did not exist, were available or used at the time or original manufacture. Such modifications are changes not covered by the original approved type certificate for the aircraft.

**Short Take Off & Landing (STOL)** – Ability of an aircraft to take-off and clear a 50-foot obstacle in a distance of 1,500 feet from the beginning of the take-off run. It must also be able to stop within 1,500 feet after crossing a 50-foot obstacle on landing.

**Sound pressure level (SPL)** - Measure of sound wave pressure strength relative to the reference sound pressure using a logarithmic scale.

**Study Aircraft** – A study aircraft is 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.

**Sustainable Aviation Fuels (SAF)** – Biofuel used to power aircraft that has similar properties to conventional jet fuel but with a smaller carbon footprint. Depending on the feedstock and technologies used to produce it, SAF can reduce life cycle GHG emissions substantially compared to conventional jet fuel.

**Take-off Noise** – Arithmetic sum (cumulative) of the noise levels at the lateral and flyover certification points as defined by the appropriate Chapter of the ICAO Annex 16. For aircraft that are certified under a single flyover measurement, that single flyover level defines take-off noise.

**Zero-carbon Emission Aircraft** – Aircraft that do not produce carbon emissions at the point of use.

**Zero-carbon Emission Flights (ZEF)** – Flights operated by zero-carbon emission aircraft.

# 16 Appendix: NAPKIN fleet in context

Figure 46 and Figure 47 show how much area in the US and South Asia the NAPKIN fleet could cover if taking Denver and Changi airports as reference points.

**Figure 46: Range of the NAPKIN fleet from Denver International Airport**

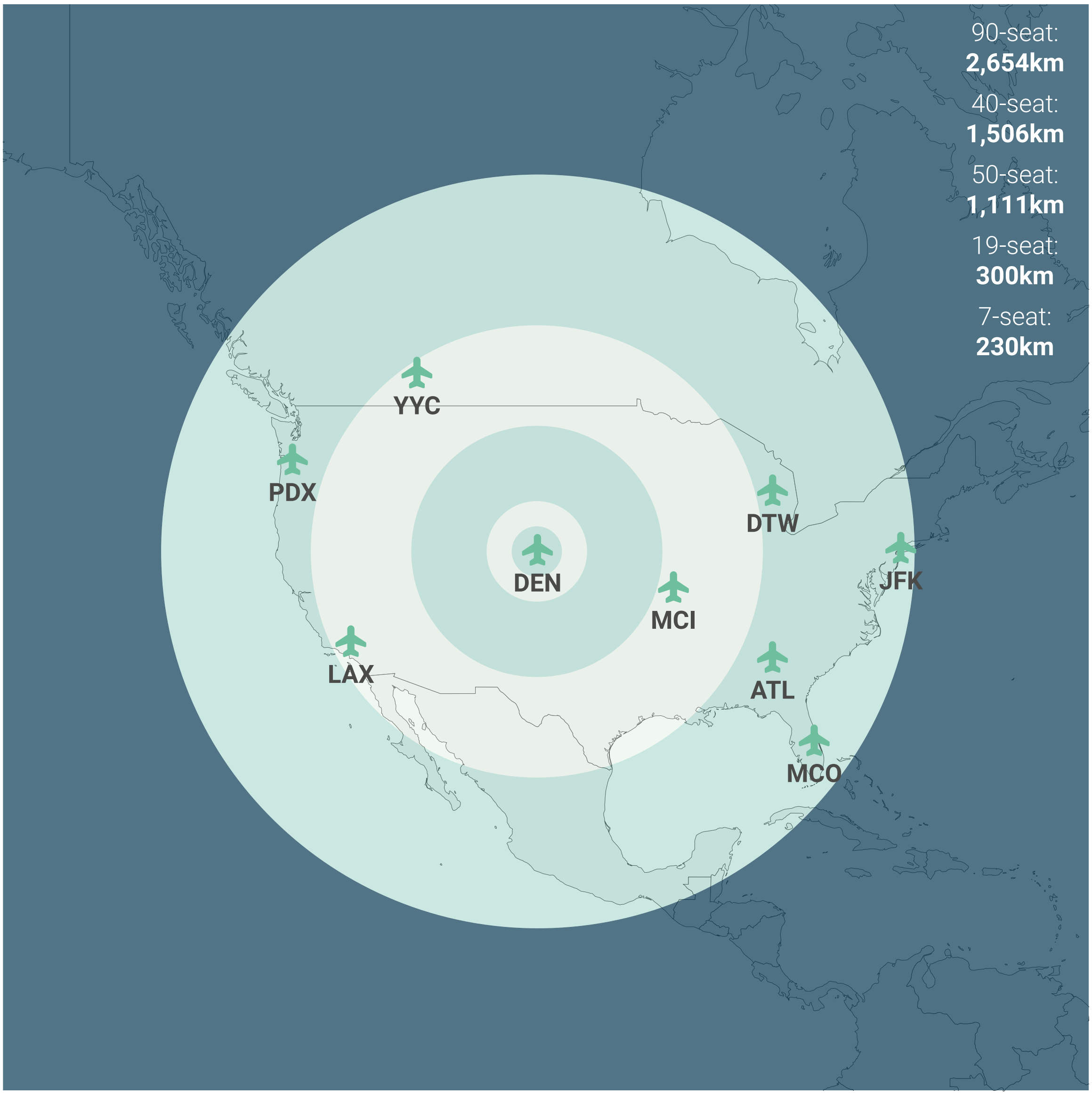
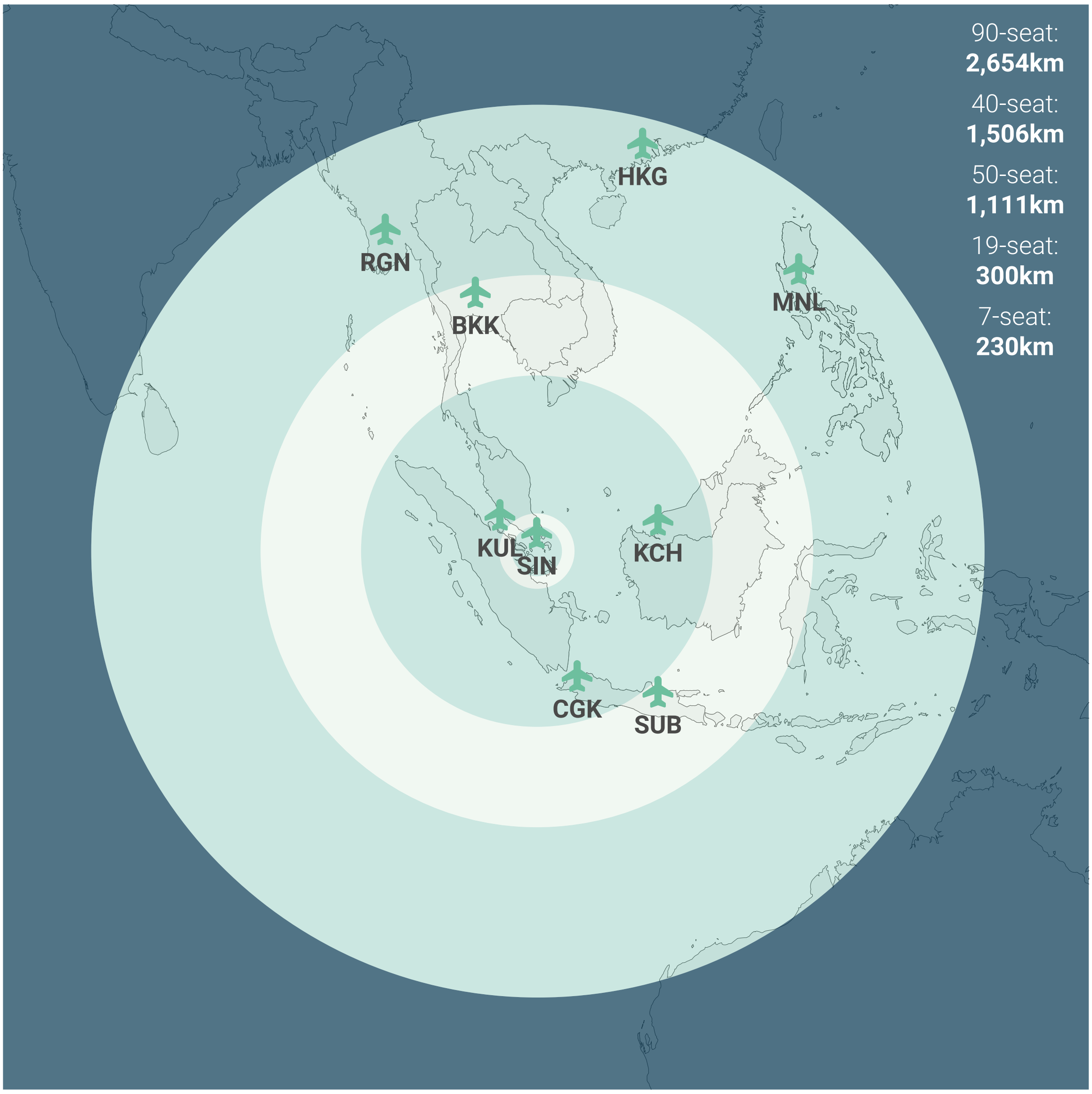


**Figure 47: Range of the NAPKIN fleet from Singapore Changi Airport**



# Contacts

**Cranfield University:** DarteC@cranfield.ac.uk

**Cranfield Aerospace Solutions Ltd:** enquires@cranfieldaerospace.com

**Deloitte:** UKDeloitteERandIIndustry@deloitte.co.uk

**GKN Aerospace:** Enquiries.GKNAerospace@GKNAerospace.com

**Heathrow Airport:** media_centre@heathrow.com

**Highlands and Islands Airports Limited:** info@hial.co.uk

**London City Airport:** media@londoncityairport.com

**Rolls-Royce plc:** Click to visit website

**University College London:** atslab@ucl.ac.uk

**University of Southampton:** S.M.Spearing@soton.ac.uk

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