CATAPULT
Connected Places

ZERO EMISSION FLIGHT INFRASTRUCTURE

Hydrogen Infrastructure Options for Airports

March 2023

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ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

EXECUTIVE SUMMARY

The goal of achieving net zero flying by 2050 represents a major challenge for technology and industry. The target has been set out in the Jet Zero Strategy, published by the UK Government in 2022.

At current rates, aviation is forecast to be one of the largest sources of greenhouse gas emissions by mid-century. Therefore, delivering against this objective will call for decarbonisation at scale and speed, requiring innovation at every level: from planes and fuels; to airports and infrastructure.

The Jet Zero Strategy sets out the important role that Zero Emission Flight (ZEF) can play in decarbonising the aviation sector. Airports and airfields will play a critical part in enabling the aims of ZEF. As a result, they urgently need to plan for the required infrastructure, which must evolve rapidly to meet the needs of future operations. Roll-out of this next-generation infrastructure will have to be managed with both maximum safety and minimum service disruption.

Liquid hydrogen has been identified by the FlyZero project as the most viable future fuel source for ZEF. In terms of implementation, the New Aviation Propulsion Knowledge and Innovation Network (NAPKIN) has suggested the entire UK regional fleet can be replaced with safe, certified, zero-carbon emission aircraft by 2040. The first hydrogen-fuelled service is expected to be operational in the UK as early as 2024. This timeframe highlights the need for an urgent change to fundamental infrastructure to enable and support hydrogen operations.

The Zero Emission Flight Infrastructure (ZEFI) programme has been commissioned by the Department for Transport (DfT) and brings together industry, regulators and academia to identify the viable infrastructure and the key requirements of enabling systems to facilitate implementation of ZEF in UK aviation. This report builds upon the infrastructure identified in the ZEFI Blueprint (1) to construct a model capable of identifying suitable infrastructure options for airports and airfields. The findings are by the Connected Places Catapult.

This report presents the results of the model, identifying suitable infrastructure for different sizes of airports and airfields — referred to as 'archetypes' — to support gaseous and liquid hydrogen-fuelled aircraft between 2030 and 2050. The scope of the project includes hydrogen-powered aviation only, and the model considers the arrival of hydrogen fuel at the airport or airfield, through to the connection to the aircraft. The airports considered are those with scheduled commercial flights, including handling Public Service Obligation (PSO) flights. The systems and technologies highlighted support hydrogen-fuelled conventional take-off and landing (CTOL) fixed-wing aircraft.

The model uses the infrastructure set out within the ZEFI system architecture, as shown in Figure 4.

A unique combination of infrastructure, from delivery to connection to the aircraft, is named an "operational pathway". Each infrastructure component is referred to as a "configuration point" and the model considers the respective capital expenditure (CAPEX), operational expenditure (OPEX), space requirements, power requirements, hydrogen flow rate, and, where applicable, water flow rate.

The model results present the three most relevant and feasible operational pathways for an airport archetype determined solely on total CAPEX and specific constraints. CAPEX may not be the only priority for all airports, so the highlighted pathways may not always be the most applicable option.

Within the model, the hydrogen estimates for each archetype are based on a peak day demand. This considers the transition from conventional aircraft fuel to hydrogen between 2030-2050, using 2019 peak day flight schedules. By 2050, the hydrogen demand for the largest airports (Archetype 5) in the UK is forecast to reach over 1.8 million kg per day per airport. The model suggests that gaseous hydrogen demand for aircraft will only be likely in the smaller airports (Archetypes 1 and 2), whereas Archetypes 3, 4 and 5 will likely use liquid hydrogen for more than 99% of their operations.

A summary of the model results is shown in Table 1 at the end of this section. The names of the pathways are used as identifiers, but do not include all the necessary configuration points. The numbers in brackets refer to the specific pathway, as recorded in the Appendix: List of Operational Pathways. The table in this Appendix includes all the possible operational pathways, as included in the model, as well as all the configuration points assumed for each operational pathway. All other assumptions included in the model can be found in the Appendix: Assumptions Log.

The operational pathways that are highlighted as most relevant and feasible identify some important key points, risks and recommendations. These are reviewed in this report and summarised below:

- Where hydrogen demand is low and delivery is viable, then direct gaseous or liquid refuelling will always be the optimal methodology.
- Where direct refuelling is not possible for liquid hydrogen, or as demand increases with airport size, then liquid tanker and liquid hydrant delivery become the optimal solution, giving the best combination of CAPEX and OPEX costs. However, if space is at a premium, then Liquid Tanker and Liquid Refueller pathways are optimal.
- Supplying hydrogen to the UK's largest airports will not be possible using tankers and will instead require a pipeline. The current cost data suggests a medium-pressure gaseous pipeline, on-site liquefaction, and hydrant delivery system is the preferred solution, based on CAPEX and OPEX.
- Out of all the hydrogen infrastructure, hydrogen storage often takes up the most space for a particular system. Whilst more energy-dense forms of storage, such as liquid hydrogen or high-pressure gaseous, can help to reduce the footprint, there is a trade-off between the number of days of hydrogen in reserve and the space requirement.
- Liquid hydrogen pipelines may be required for the biggest airports to move the liquefaction plant offsite, particularly if they are space constrained. There is a balance between pipe length and boil-off, therefore any offsite liquefaction will need to be close to the airport boundary (current technology is limited to roughly a few hundred metres).
- Onsite electrolysis is only feasible for the smallest airport archetypes. For larger airports, the space and power requirements for onsite electrolysis are likely to be too high.
- For Archetypes 1-4 the annual OPEX is nearly as high as the total CAPEX for many pathways, therefore airports should be aware that it is likely that the largest outgoings will be recurring OPEX costs.
- Further work should be done to identify impacts of inflation on OPEX costs for specific pathways, as well as minimising the risk of exchange rates on final CAPEX costs, particularly for Archetype 5.

As UK aviation transitions to a hydrogen future, it is understood that airports and airfields face a number of challenges and constraints, which will play a key role in implementation. As highlighted and explored in this report, the changes will not be limited solely to the refuelling infrastructure. Consideration must also be given to the implications of hydrogen operations on some of the wider enabling systems, such as billing and metering, safety management and emergency response. More information on this can be found in the Hydrogen Infrastructure Options for Airports: Supplementary Report.

This report signposts the aviation industry to where significant infrastructure change will be required and identifies what investment is necessary to facilitate Zero Emission Flight implementation in the UK. It sets out the options for airport and airfield operators to consider in their planning, alongside the critical importance of the wider enabling systems. Taken together, these steps will enable an effective transition to hydrogen operations, on the journey towards achieving Net Zero by 2050.

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Table 1: A summary of the operational pathways (with their reference number) in terms of CAPEX for each airport

Archetype	Med Pressure Gaseous		High Pressure Gaseous		Liquid	
	2030	2050	2030	2050	2030	2050
Archetype 1	Med Direct Refuelling Vehicle (41)		High Direct Refuelling Vehicle (42)		Liquid Direct Refuelling Vehicle (51)	
	Electrolyser and Med Refueller (37)		Liquid Tanker, Vaporiser and High Refueller (33)		Liquid Tanker and Liquid Refueller (35)	
	Low Tanker and Med Refueller (19)		Electrolyser and High Refueller (39)		Electrolyser, Liquefier and Liquid Refueller (43)	
Archetype 2	-	-	*8 x High Direct Refuelling Vehicle (42)		Liquid Direct Refuelling Vehicle (51)	
					Liquid Tanker and Liquid Refueller (35)	
					Liquid Tanker and Liquid Hydrant (36)	
Archetype 3	-	-	* 1 x High Direct Refuelling Vehicle (42)		Liquid Direct Refuelling (51)	Liquid Tanker and Liquid Refueller (35)
					Liquid Tanker and Liquid Refueller (35)	Liquid Tanker and Liquid Hydrant (36)
					Liquid Tanker and Liquid Hydrant (36)	Med Pipeline, Liquefier and Liquid Refueller (13)
Archetype 4	-	-	-	-	Liquid Tanker and Liquid Refueller (35)	
					Liquid Tanker and Liquid Hydrant (36)	
					Low Pipeline, Liquefier and Liquid Refueller (11)	Med Pipeline, Liquefier and Liquid Hydrant (14)
Archetype 5	-	-	-	-	Liquid Tanker and Liquid Refueller (35)	Med Pipeline, Liquefier and Liquid Refueller (13)
					Liquid Tanker and Liquid Hydrant (36)	High Pipeline, Liquefier and Liquid Refueller (15)
					Low Pipeline, Liquefier and Liquid Refueller (11)	Med Pipeline, Liquefier and Liquid Hydrant (14)

*** To meet the daily demand for the hydrogen of this type**

Table of Abbreviations

Abbreviation	Meaning
AIP	Aeronautical Informational Publication
BAU	Business as Usual
CAA	Civil Aviation Authority
CAPEX	Capital Expenditure
CTOL	Conventional Take Off and Landing
DfT	Department for Transport
EASA	European Aviation Safety Agency
FAA	Federal Aviation Administrator
GDP	Gross Domestic Product
IATA	International Air Transport Association
ICAO	International Civil Aviation Organisation
ISO	International Standards Organisation
LBD	Learning By Doing
LH2	Liquid Hydrogen
NAPKIN	New Aviation Propulsion Knowledge and Innovation Network
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
PA	Per Annum
PAX	Passengers transiting per year
PEM	Polymer Electrolyte Membrane
PPE	Personal Protective Equipment
PSO	Public Service Obligation
RABA	Regional and Business Airports
RFFS	Rescue and Fire Fighting Service
SAF	Sustainable Aviation Fuel
TRL	Technology Readiness Level
UPS	Uninterruptible Power Supply
ZEF	Zero Emission Flight
ZEFI	Zero Emission Flight Infrastructure

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BACKGROUND

Fundamental infrastructure changes are required to support the introduction of zero emission aircraft to meet the target of reaching net zero by 2050.

Fundamental infrastructure changes are required to support the introduction of zero emission aircraft to meet the target of reaching net zero by 2050. The Zero Emission Flight Infrastructure (ZEFI) programme, funded by the Department for Transport (DfT) and led by the Connected Places Catapult, seeks to support the UK Government's commitment to net zero by 2050 under the Ten Point Plan through facilitating Zero Emission Flight (ZEF) implementation in UK aviation.

The aviation industry could account for 39% of the UK's greenhouse gas emissions by 2050 (2), making clear the need for an accelerated transition to zero-carbon fuels. The New Aviation Propulsion Knowledge and Innovation Network (NAPKIN), a consortium including Heathrow Airport, Rolls Royce, GKN and others – has projected that the entire UK regional fleet can be replaced with safe, certified, zero-carbon emission aircraft by 2040. The first hydrogen-fuelled service is expected to be operational in the UK as early as 2024 (3). However, airports must have the necessary infrastructure to ensure the uptake of these aircraft, supported by sufficient zero emission fuel production capacity and regulatory frameworks. FlyZero suggested that slow progress towards Net Zero aviation could lead to restrictive measures to aviation, impacting the UK economy and moving us no closer to net zero targets (4).

Phase one of the ZEFI programme took place in 2021-22 (5). As part of phase one of this programme, a Blueprint document was created, alongside other reports and a roadmap. The Blueprint document presented infrastructure operational concepts required for battery-electric and hydrogen operations that airports and airfield operators should consider in their planning. This phase of the programme (ZEFI 2) will further prepare airports and airfields for zero emission flight by modelling suitable infrastructure options to support gaseous and liquid hydrogen-fuelled aircraft. ZEFI 2 builds on work carried out by FlyZero (6), looking at all available options for hydrogen infrastructure across a wide range of airport sizes. This year, our focus has been on hydrogen-powered aviation only. There are some limitations in the evidence for a clear way forward for airports and airfields. This report aims to address any gaps and limitations on the understanding of the infrastructure requirements for this technology, compared to the electrical systems to charge battery-powered aircraft. In addition, there has been a clear shift in industry thinking on the potential of hydrogen to provide Zero Emission Flight, but likely limitations to the extent to which battery aircraft can decarbonise commercial air transport.

INTRODUCTION

ZEFI 2 presents the viable infrastructure options for airport and airfield operators to consider as they look to deliver the significant infrastructure changes required to support the next evolution of UK aviation. This report presents the most relevant and feasible infrastructure options for different sized airports and airfields to implement when transitioning to and facilitating hydrogen-fuelled aircraft. These options consider energy demand, fuelling capabilities, space requirements and rough order of magnitude costs. This report also highlights key implementation requirements, including general requirements and those affecting the wider enabling systems for operators, government, regulators and the wider aviation ecosystem to consider.

The findings of this report have informed an updated ZEFI roadmap of the expected availability of the capabilities with reduced uncertainty as development of technology matures. ZEFI 2 has also undertaken work on standards development and conducted demonstrations of ZEF infrastructure operations. In the longer term, Connected Places Catapult hopes that a network of "Living Labs" will be created for trials of necessary processes, techniques, infrastructure, technologies and systems.

ZEFI 2 is supported by a wide range of industry experts. Our thanks go to the project partners Jacobs, Costain, KPMG, the University of Strathclyde and Edinburgh Systems, for contributing to this report and the complementary "Hydrogen Infrastructure Options for Airports: Supplementary Report" report. We would also like to thank the range of aviation professionals, original equipment manufacturers (OEMs) and airports whose input has enabled us to provide more useful and robust findings.

This report addresses the technical requirements for hydrogen infrastructure to support ZEF, including the processes and systems affected by the transition to ZEF operations. The main findings have come from the ZEFI 2 model, which was created to present an indication of the CAPEX, OPEX, space requirements and energy requirements for a range of hydrogen systems. In this report, we display these outputs for five different airport archetypes which have been defined based on their scale and type of operations.

SPECIFICALLY, THIS REPORT PRESENTS:

- The ZEFI 2 model methodology, outlining the model development and its application.
- Archetype definitions and hydrogen demand per archetype between 2030 and 2050.
- Results of the model for five airport and airfield archetypes, demonstrating the most viable operational pathways considering relative constraints and challenges.
- Implementation requirements for ZEFI including general requirements and those affecting airport enabling systems.
- A summary of general findings of the Hydrogen System Architecture work package.
- Further information on sensitivity testing and future costs.
- Our conclusions of the model and future development.
- A log of all assumptions made during this report: (Assumptions Log)

PROGRAMME SCOPE

The scope of ZEFI 2 considers the arrival of hydrogen fuel at the airport or airfield, through to the connection to the aircraft. The supply chain outside the physical site boundary is out of scope; it is assumed that hydrogen production will take place outside of the physical airport boundary, except for on-site electrolysis. The airports considered in the scope for this project are those with scheduled commercial flights, including those with Public Service Obligation (PSO) flights. All assumptions made, including on the scope of this project, can be found in the Assumptions Log.

ZEFI focuses on the systems and technology for hydrogen-fuelled conventional take-off and landing (CTOL) fixed-wing aircraft utilised for commercial passenger and freight services. Electric battery aircraft, including electrical vertical take-off and landing (eVTOL) aircraft, are out of scope for ZEFI 2.

Although it is anticipated a share of these aircraft will be fuelled by hydrogen, they will be predominantly battery-electric powered and it is currently unclear how they will fit within the airport landscape. There is work as part of the Future Flight Challenge that is addressing this area (7).

WHY HYDROGEN?

Green hydrogen is hydrogen that is created by “splitting water into hydrogen and oxygen using renewable electricity” (8). FlyZero concluded that green liquid hydrogen is the most viable fuel source for the ZEF transition, as it will be able to power large aircraft using fuel cell, gas turbine and hybrid systems. It is also forecast to become cheaper and greener than Sustainable Aviation Fuel (SAF) due to carbon pricing and production inefficiencies of SAF. The projected costs for each fuel type from the FlyZero work are shown in Figure 1. These forecasts suggest that green liquid hydrogen is likely to become the cheapest fuel capable of decarbonising aviation by the mid-2030s (4). It is also notable that the cost of kerosene is assumed to remain constant over the next 50 years.

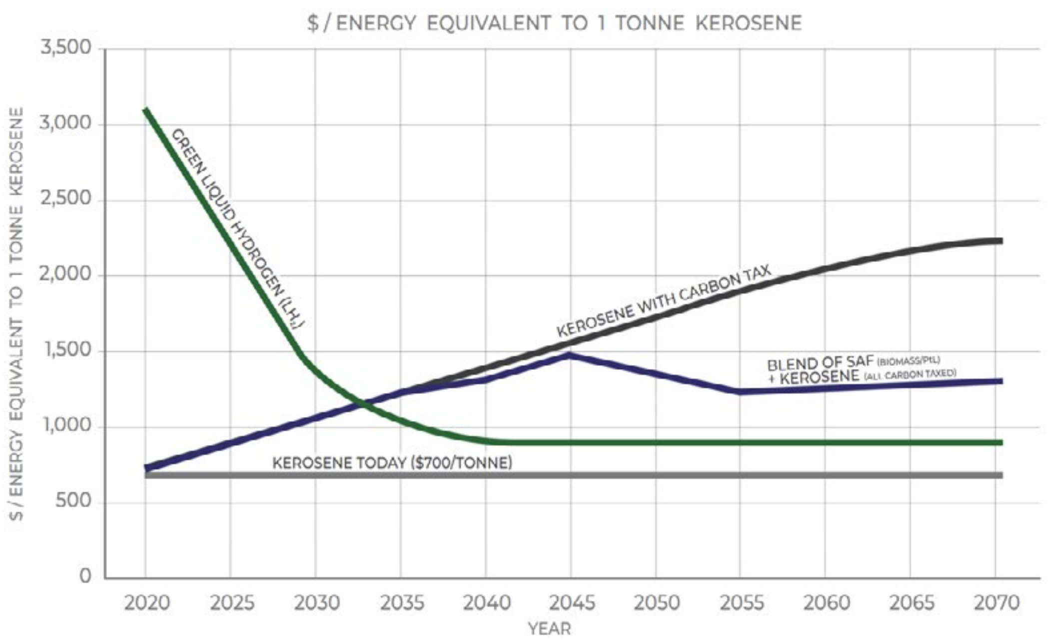

Figure 1: FlyZero fuel forecast comparison (2)

Bloomberg New Energy Finance states that the fall of renewable energy prices, reducing cost of electrolysers and their increasing efficiency will increase the commercial viability of green hydrogen production. Figure 2 shows that green hydrogen could be produced for $0.70 to $1.60/kg in most parts of the world before 2050 (9).

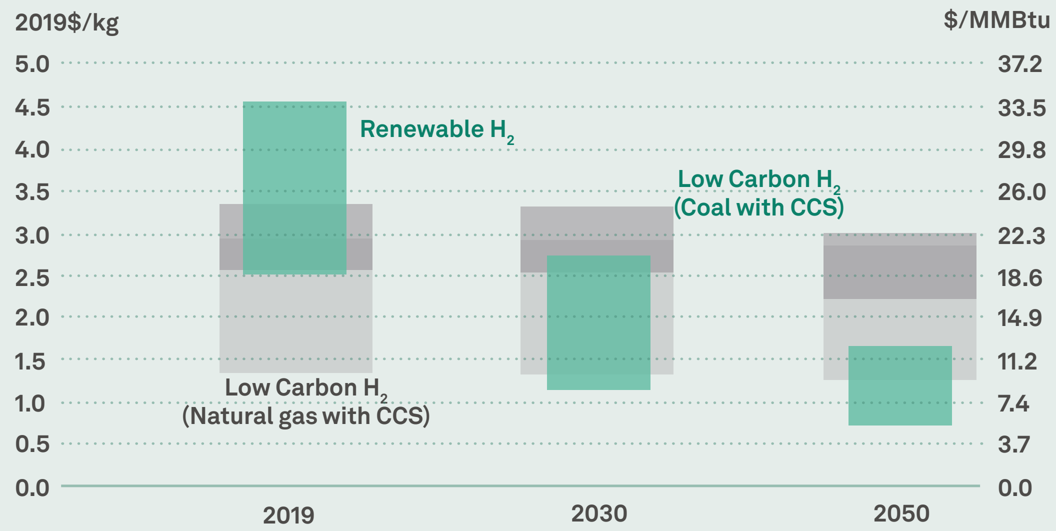

Figure 2: Forecast of the global range of levelized cost of hydrogen production for large projects through 2050 (9).

The transition to Net Zero will be a major change for airports and will result in mixed aircraft and fuel types, affecting operations and infrastructure requirements. As an example, the Government’s Jet Zero Strategy (10) outlines multiple measures which will be required to reach net zero aviation by 2050, including system efficiencies, zero emission flight, SAF and markets and removals. SAFs are drop-in fuels that are likely to be introduced in incrementally higher blends, meaning little-to-no airport infrastructure changes will be required.

The Future Systems Schematic in the ZEFI Blueprint (1) visualises possible systems at future airports. These environments will contain a wide range of other aircraft and ground handling technologies, some of which will have a synergy with hydrogen operations (e.g. ground support equipment, backup power and heating), whereas others will conflict with hydrogen operations (e.g. concurrent use of hydrocarbon fuels). Whilst these are out of scope for this report, ZEF infrastructure should be able to operate in parallel with these broader system applications.

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METHODOLOGY

ZEFI 2 has created a model of relevant and applicable infrastructure for airport and airfield hydrogen operations, including capturing energy demand, fuelling capabilities, space requirements and rough order of magnitude costs. The results from the model are presented in this report.

APPROACH

The model considers constraints on the different airports and airfields, viability of technologies and their system integration, and wider supporting infrastructure. The ZEFI Blueprint, completed as part of the first phase of ZEFI, sets out further details of the infrastructure, subsystems and components.

The ZEFI 2 hydrogen system architecture has been updated from the ZEFI Blueprint following detailed analysis of the feasibility of specific infrastructure and its integration into the architecture. The system architecture is shown in Figure 4. It displays the project scope, including all the potential infrastructure options through each stage of hydrogen operations, from delivery or production on-site, through to the supply of fuel to the aircraft. The architecture demonstrates the viable options to supply gaseous and liquid hydrogen to an aircraft.

For the purpose of this report, each item of infrastructure included in the architecture has been labelled as a configuration point, which combine to create an operational pathway. These configuration points are denoted as a singular block in the system architecture. An operational pathway is defined as an individual or unique "route" through the architecture. An example of both of these is shown in Figure 3.

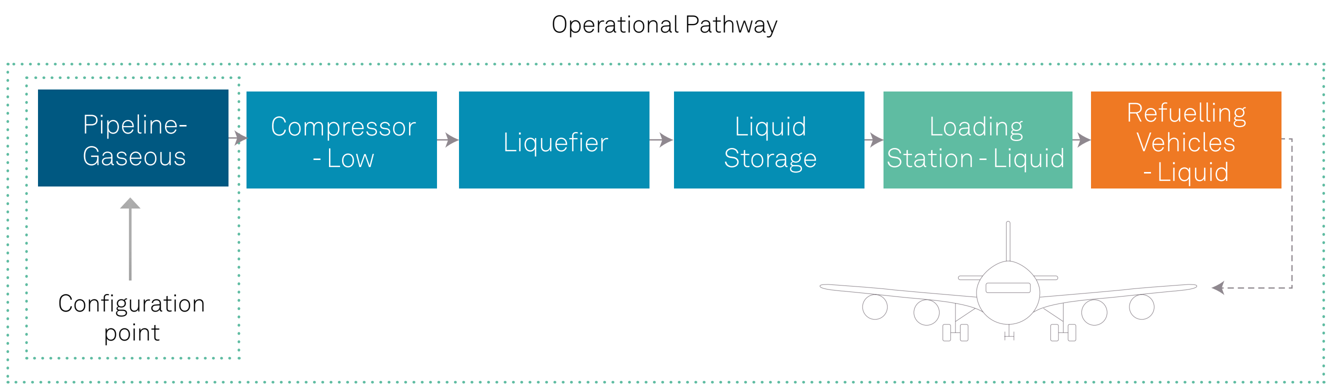

Figure 3: Example operational pathway and configuration point from the ZEFI model

OPERATIONAL PATHWAYS

The model aims to identify the relevant and feasible operational pathways for a particular airport based on its specific requirements. The viable infrastructure and operational pathways have been informed by desktop research, industry engagement and validation through our project partners. The viable operational pathways are set out in Appendix: List of Operational Pathways.

This document presents the results of the model for five different types of airports, or "archetypes". We have chosen to define "archetypes" rather than use specific airport examples to enable us to describe the broadest range of characteristics representing airports in the UK. The archetype definitions have been informed through a review of the UK's airports, which are set out in the Appendix: Airport Table. This table also highlights the proximity to expected hydrogen supply projects, as well as ports, rail stations and major roads. This may help airports decide which of the pathways may be more appropriate, due to their proximity to these services.

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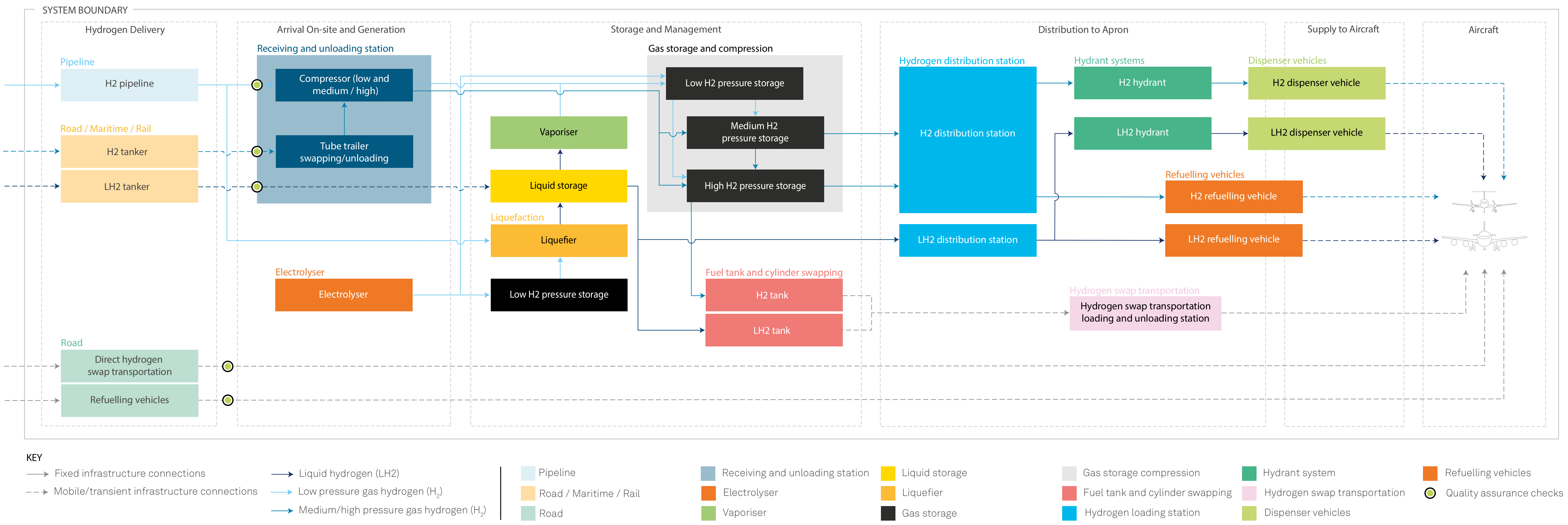
Figure 4: ZEFI System Architecture



The ZEFI 2 model gives a high-level understanding of the hydrogen infrastructure options and demonstrates the capabilities of the model for future years. It has been built to include the ability to tailor the model to the individual needs of an airport or airfield should this be required in the future.

If an airport or airfield would like to use the model, they can contact Connected Places Catapult directly to find out more information.

Having identified viable infrastructure and operational pathways, capital expenditure (CAPEX), operational expenditure (OPEX), space requirements, power requirements, hydrogen flow rate, and, where applicable, water flow rate data was collected for each configuration point. The data collected covered a baseline, lower and upper scenarios, to capture the uncertainty associated with specific infrastructure components, mainly caused by their current low Technology Readiness Levels (TRLs). CAPEX and OPEX are presented using only 2022 GBP annual cost estimates, with no attempt to forecast changes in costs up to 2050, while other parameters were forecast to 2030. Any advancements expected beyond 2030 have been captured in five-year increments up to 2050.

The "baseline CAPEX" for each configuration point represents a central cost estimate for obtaining the technology alone (exceptions are detailed in the Appendix: Assumptions Log). These costs have not been adjusted for transport, labour, design and other installation costs required to deploy each archetype fully. Therefore, "CAPEX" has been uplifted to reflect installation costs and optimism bias (see assumptions log for further details). These costs should not be interpreted as true final costs, despite these adjustments. CAPEX calculations also do not include the cost of grid reinforcement, which is expected to be required for ZEFI implementation. The final cost will be highly dependent on currently unknown elements, which will only be better defined once site requirements are better understood. The costs presented in this report are based on the knowledge and data available at the time of writing, however it is highly likely that the actual costs will be higher than stated here once unique project requirements for individual airports are better defined.

OPEX is estimated either as a specific figure for each infrastructure item or as a percentage of the CAPEX. This includes the costs of electricity and for the electrolyser, the cost of hydrogen fuel. More details on the hydrogen fuel cost can be found in the assumptions log. These are presented here as one-year and ten-year totals. OPEX is not adjusted for optimism bias, which is instead considered through sensitivity testing. The sensitivity tests look at how one- and ten-year OPEX estimates would be expected to change if global and domestic economic variables change. These variables will be represented by adjusting forecast exchange rates and inflation rates.

The model uses the data for each of the infrastructure components and scales it based on the hydrogen demand of the archetype. The assumptions made for the model are stated in the assumptions log in Appendix: Assumptions Log and were kept consistent across all archetypes. The model can determine the top pathways based on CAPEX, OPEX, space or power requirements. For this report, **the selected pathways were determined solely on total CAPEX**, with the three most appropriate pathways highlighted for each archetype. We understand that CAPEX may not be the top priority for all airports, and therefore the highlighted pathways may not be the best option. This may be because individual airports will need to tailor their infrastructure choices based on their needs and constraints, such as space available or OPEX. It is hoped that in future ZEFI phases, airports will be able to use our model to identify the most suitable operational pathway, by sorting the model outputs based on the factor which is most important to them. We are considering the best means of developing the model and enabling airports to benefit from it in future.

AIRPORT ARCHETYPES

ZEFI 2 defined five generic airport archetypes. The five airport archetypes are shown in Table 2. These should be used for guidance only, and not all criteria have to be satisfied. It is up to the airport to choose which archetype they identify with most and verify their own specific constraints and requirements. These archetypes give a rough indication of pax (passengers arriving and departing per year).

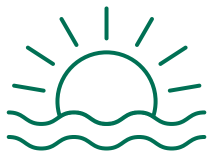
Archetype		Descriptor	Pax (approx.)	Other Defining Factors
1		Small or Island Airports	< 150,000	• Small or island airport and airfields, including those from Regional and Business Airports Group (RABA) Trade Body • The only airport for an entire island or community • The primary or only way of accessing the location it serves, potentially receiving Public Service Obligation Flights (PSOs)
2		Regional and Business Airports (RABA)	< 2 million	• All RABA airports, except those that fit into Archetype 1 (island airports) and Archetype 3 (regional and short-haul operations)
3		Regional and Short-haul Operations	2-5 million	• Larger-scale operation RABA airports, i.e. those that do not fit into Archetype 1 or 2
4		International with Predominantly Medium-haul Operations	5-20 million pax	• Up to approximately 200,000 aircraft movements a year
5		Long-haul Operation Airports	> 30 million pax	• International focus with intercontinental flights • Approximately > 200,000 aircraft movements a year

Table 2: The five generic airport archetypes and their guide definitions

1. The Regional and Business Airports Group (RABA) Group is a trade body that "provides a collective voice for UK airports with less than 3 million passengers per annum" (30)

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Airports who are members of the Regional and Business Airports Group (RABA) Group[1] are likely to be split across three archetypes; they do not necessarily all fit Archetype 2. It should be noted that RABA were not involved in this project; the use of their name and Trade Body is for reference purposes only.

The results for each archetype are presented in the Model Results section, with the most viable operational pathways highlighted accordingly. Constraints and challenges facing each archetype in the transition to hydrogen are also considered.

HYDROGEN DEMAND

The hydrogen demand for each archetype is based on a peak day demand, calculated using the University of Strathclyde's AIRISE model (11). This model looks at the transition of conventional fuel aircraft to hydrogen between 2030-2050, to forecast the hydrogen requirements. These calculations were based on 2019 peak day schedules for each archetype and a forecast growth percentage. This growth percentage was based on 2017 DfT forecasts alongside GDP data to provide a more realistic view of aviation growth given recent events since the last DfT forecast. Table 3 sets out the forecast for the daily hydrogen demand between 2030 and 2050 per archetype.

	2030	2035	2040	2045	2050
Archetype	Gaseous (kg)	Gaseous (kg)	Gaseous (kg)	Gaseous (kg)	Gaseous (kg)
1	5,580	5,650	5,650	5,700	5,750
2	4,990	4,800	4,800	4,910	5,100
3	567	573	573	578	583
4	-	-	-	-	-
5	-	-	-	-	-
Archetype	Liquid (kg)	Liquid (kg)	Liquid (kg)	Liquid (kg)	Liquid (kg)
1	-	-	-	-	-
2	17,470	35,460	35,500	36,260	37,720
3	15,180	69,990	211,900	213,900	216,100
4	44,760	122,100	218,600	220,700	224,600
5	63,350	490,700	1,616,500	1,617,400	1,821,200

Table 3: Daily hydrogen demand per Airport by Archetype

For Archetypes 3-5 it has been assumed that any gaseous hydrogen will be high pressure. For Archetypes 1 and 2, the infrastructure requirements to support medium pressure gaseous (350 bar), high pressure gaseous (700 bar) and liquid hydrogen have been output for completeness, although liquid hydrogen has not been forecast in Table 3.

2. C refers to the code letter given to an aircraft as set out in the ICAO Aerodrome Reference Code (25).

Within the ZEFI model it has been assumed that all Small code C aircraft[2] and larger will exclusively use liquid hydrogen, whilst those aircraft smaller than this, primarily used for shorter regional routes, will use gaseous hydrogen. However, there are smaller aircraft concept projects such as H2 Fly's HEAVEN (12) and Project Fresson (13) which are making developments in the use of liquid hydrogen to fuel smaller aircraft. Options for both forms of hydrogen for these smaller aircraft have been included to account for this where possible.

Figure 5 shows the flow of information from flight schedule data to the ZEFI model outputs. Flight schedule data was fed into the AIRISE Model to give a daily hydrogen demand profile. This was then fed into the ZEFI model which used the configuration point parameter data to provide the model outputs for each of the Operational Pathways (CAPEX, OPEX, space requirements and power requirements).

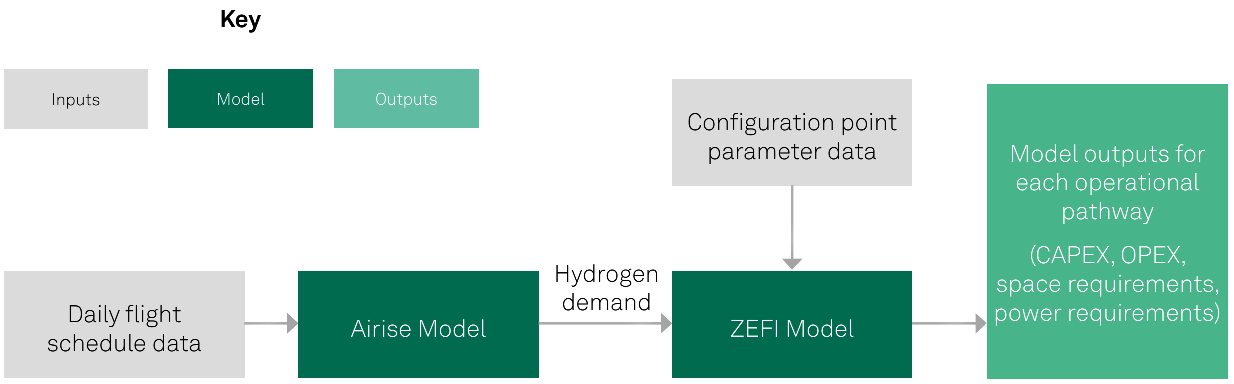


Figure 5: Data flow through the ZEFI model to provide outputs for each of the five airport archetypes

It should be noted that the peak gaseous hydrogen demand of any of the five archetypes is approximately 5,800kg kg per day in Archetype 1 in 2050. However, this is only approximately a 200kg increase from 2030. This shows the expected rapid rise in demand over the coming years, especially for the smaller, remote and regional airports. Archetypes 1, 2 and 3 demonstrate a minimal increase in demand up to 2050, suggesting that most of their hydrogen operations will be ready before 2030. It also highlights this as a key area where early benefits can be realised through ZEFI delivery and operation for local and regional flights using gaseous and fuel cell aircraft. Archetypes 2 and 3 are forecast to require a smaller gaseous hydrogen supply in comparison to Archetype 1 due to the growing integration of liquid hydrogen fuelled aircraft into their operations.

Unsurprisingly, Archetype 5 drives the largest liquid hydrogen demand, totalling approximately 1.8 million kg per airport within this archetype per day. For context, this is more than eight times the current global hydrogen production (14). This will set a challenge for ZEFI delivery, especially as the daily demand is expected to increase from approximately 63,000kg a day in 2030. There are also significant rises in liquid hydrogen demand in Archetypes 3 and 4, each forecasting over 200,000 kg per day by 2040. Rapid demand scaling combined with new technologies presents a unique challenge for airport operators in forecasting and planning.

Based on Table 3, Table 4 below displays the percentage of the total hydrogen demand for each archetype. Please note, these figures do not include kerosene, SAF or other alternative fuels.

	2030		2035		2040		2045		2050	
Archetype	% Gas	% L	% Gas	% L	% Gas	% L	% Gas	% L	% Gas	% L
1	100%	0%	100%	0%	100%	0%	100%	0%	100%	0%
2	22%	78%	12%	88%	12%	88%	12%	88%	12%	88%
3	4%	96%	1%	99%	<1%	100%	<1%	100%	<1%	100%
4	<1%	100%	<1%	100%	<1%	100%	<1%	100%	<1%	100%
5	<1%	100%	<1%	100%	<1%	100%	<1%	100%	<1%	100%

Table 4: Demand share of gaseous and liquid hydrogen per Airport and Airfield Archetype

The results demonstrate the forecasted reliance on gaseous hydrogen for Archetypes 1 and 2. Archetypes 3, 4 and 5 are likely to have almost exclusive liquid hydrogen operations to support small C aircraft and above, as they come into service.

ARCHETYPE COST ESTIMATES

The cost estimates displayed in the tables in the Model Results section are based on current cost estimates presented in 2022 prices for the baseline scenario. The outputs presented are annual demand estimates for the years 2030 and 2050, however costs are still based on current 2022 estimates; any difference in costs for the 2 years is solely down to different hydrogen demand levels.

Costs have not been adjusted to reflect decreasing technology prices, which may occur as technologies become more developed; they represent the CAPEX and OPEX required if the infrastructure were to be built today. The impact of technological development on future costs is addressed separately in the Future Costs section. A waterfall chart showing how the final CAPEX values have been reached has been included as an appendix.

Additionally, the ten-year OPEX cost is based on the total OPEX over the period 2023-2032. Costs over this period have been discounted, using an annual discount rate of 3.5%, in line with treasury green book guidance, to reflect the preference for current vs f
uture consumption.

Full details of all the assumptions made on the costs can be found in the Assumptions Log.

FUTURE COSTS

The costs presented for each archetype are based on 2022 estimates of hydrogen refuelling infrastructure component costs. However, as this technology develops, costs can be expected to drop as firms are able to take advantage of improved economies of scale, human capital and investment.

There are, however, significant uncertainties in forecasting future costs for hydrogen technologies. Future costs will be highly dependent on the level of domestic and international demand, as well as geopolitics and government policy, amongst other factors. Due to this uncertainty, we have not attempted to model future costs. Instead, the Learning By Doing (LBD) curves, shown in Figure 6, have been calculated. The LBD curves assume certain conditions are met, such as ZEFI achieving a 2.5% uptake within UK airports by 2030 and a 75% uptake by 2050. LBD curves assume that an industry has a Learning Rate (LR) which defines how the industry increases its expertise and therefore reduces costs as time progresses. Research from Costain suggested that the LR for relevant industries is between 5-20% Per Annum (PA). Based on the technologies used for ZEFI, a LR of 10% was chosen for all technologies, except compressors which was assigned a LR of 5% due to the more developed nature of this technology.

These LBD costs suggest that most ZEFI technology, which is still relatively novel, could see cost reductions of up to 55% from today's costs. Hydrogen compressors, a more developed technology, could see more intense cost reductions of up to 98% if the above LBD conditions are met. As an example, for Archetype 5 airports, the lowest cost pathway that can meet the 2050 demand (medium pressure gaseous pipeline and liquefier to liquid refueller) is estimated to cost £8.1b CAPEX and £2.7b PA in OPEX. If this technology reduces in-line with the ZEFI technology LBD curve, costs will reduce to £3.6b CAPEX and £1.2b OPEX PA by 2050.

It is important to note that LBD curves are not a perfect approach to estimating future costs. Research has shown that whilst learning curves can be a reasonable estimator of future technology prices, they also tend to underestimate future costs in some cases (15).

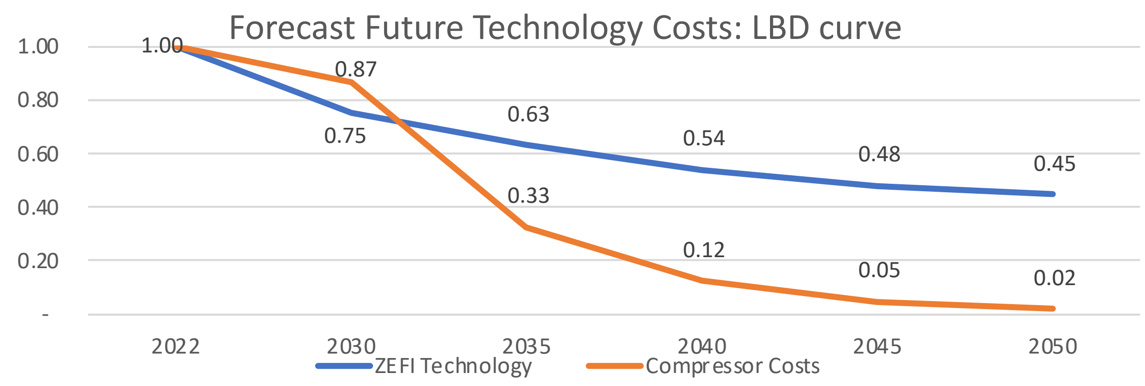


Figure 6: Forecast changes to ZEFI technology costs

SENSITIVITY TESTING

The uncertainty of the cost estimates has been addressed within the CAPEX estimates by applying an optimism bias uplift. This is not an appropriate methodology for OPEX; instead, the sensitivity of OPEX costs have been addressed by adjusting both the forecast level of inflation and exchange rates.

EXCHANGE RATES

Exchange rates have been calculated using the standard deviation of GBP to USD and EUR exchange rates for the last 28 years. An upper and lower bound of ±1.96 standard deviations has been performed to produce a 95% exchange rate confidence interval. This was calculated as -0.18 and +0.33 for GBP to USD and -0.19 and +0.35 for GBP to EUR.

The results of this analysis found that CAPEX is more exposed, and therefore more sensitive to, fluctuations in the exchange rate compared to OPEX. The CAPEX impact ranges from -121% to +39%, vs -0.9% to + 5.5% for OPEX. This is expected as far more CAPEX components were based on overseas costs, with no domestic costs available. The majority of OPEX costs will also be based on domestic labour and energy. Labour costs are not as sensitive to changes in exchange rates compared to material costs, as a higher percentage of materials may need to be imported. By 2050, the implementation of renewable energy to meet 2050 net zero targets should also result in domestic energy prices which are less sensitive to exchange rates fluctuations. The key findings are outlined below and a table with all exchange rate cost impacts is provided as an appendix.

The pathways which are least sensitive to changes in exchange rates were direct refuelling vehicle pathways (only for Archetypes 1, 2 and 3) and liquid tanker with liquid refuelling pathways (for all archetypes), with a CAPEX impact range of -0.2% to +0.3%. These pathways see minimal exposure as the technology required is already available in the UK in GBP prices and requires few imports. Pathways 51 and 35 were identified as the least expensive options for many archetypes. Their lack of sensitivity exchanges rates may act as another incentive to adopt these pathways.

Liquid Hydrant (for Archetypes 2 and 4 only) and medium/high pressure gaseous refueller (just for Archetype 1) pathways are somewhat more exposed to changes in exchange rates, with a CAPEX impact range of -6% to +111%. This is because the hydrant and gaseous refuellers are presumed to be imported, with a lack of domestic options available. Cost analysis found gaseous refuellers to be sub-optimal compared to liquid refuellers and their increased sensitivity to exchange rates strengthens this argument. However liquid hydrant delivery is identified as the optimal whole life cost option for Archetypes 2, 3 and 4. Whilst liquid hydrant delivery is more sensitive to exchange rates than other options for these archetypes, the level of sensitivity is not large enough to change the pathway rankings. However, it does suggest some advantage from producing this technology domestically.

For Archetypes 1-4, pathways 33, 43, 11, 14 and 13 are particularly sensitive to changes in exchange rates, with a CAPEX impact of -21% to +38.5%, however the high initial costs of these solutions suggest these pathways are already sub-optimal.

All optimal solutions for Archetype 5 are subject to high degrees of exchange rate sensitivity. In 2030 pathway 36, which is the optimal solution in terms of whole life cost, sees a possible exchange rate impact of -16% to +30%. The CAPEX required to satisfy Archetype 5 demand levels is much larger than other archetypes, and therefore the size of the exchange rate impact has also increased.

In 2050, all Archetype 5 pathways (13, 14 and 15) are based on pipelines and are subject to high level of CAPEX exchange rate sensitivity, from -21% to 39%. Pathway 15 has the lowest CAPEX (£8.1b). If the maximum exchange rate impacts were realised for this pathway, then costs could reduce by up to £1.7b or increase by up to £3.1b. This is a significant amount and given the historic weakening of the pound since 2016, there is a higher risk of increasing costs. If a pipeline pathway is eventually chosen for this archetype, the government and aviation industry should work together to provide a domestic production solution to reduce the exposure to this risk.

INFLATION

For simplicity, the core OPEX estimates assume that inflation within the aviation construction industry will not deviate from general inflation experienced by the wider economy. However, the UK construction sector is particularly sensitive to fluctuation in energy prices due to its reliance on energy-intensive materials, labour and skills shortages and scarcity of materials (16). These combined impacts mean that the recent inflation has led to higher price rises for UK construction than the rest of the economy. Historically, construction price rises have usually been higher than general inflation, including over the past two years of higher inflation (14). Therefore, future costs could be higher than expected unless the cost of inflation is accounted for.

There are opportunities for new technologies such as digital twins, modular construction, renewable energy and robotics to reduce the cost of construction, which could result in deflation, but overall, the inflation is more likely to result in increased costs.

To provide indicative cost impacts, different annual ZEFI cost inflation rates were applied to the ten-year OPEX estimates from 2022 over the years 2023-2032. Table 5 outlines the average impact of inflation over the period. For example, if ZEFI OPEX inflation was 2.5% higher than general inflation every year, then overall ten-year OPEX costs would be 11.3% higher compared to without inflation.

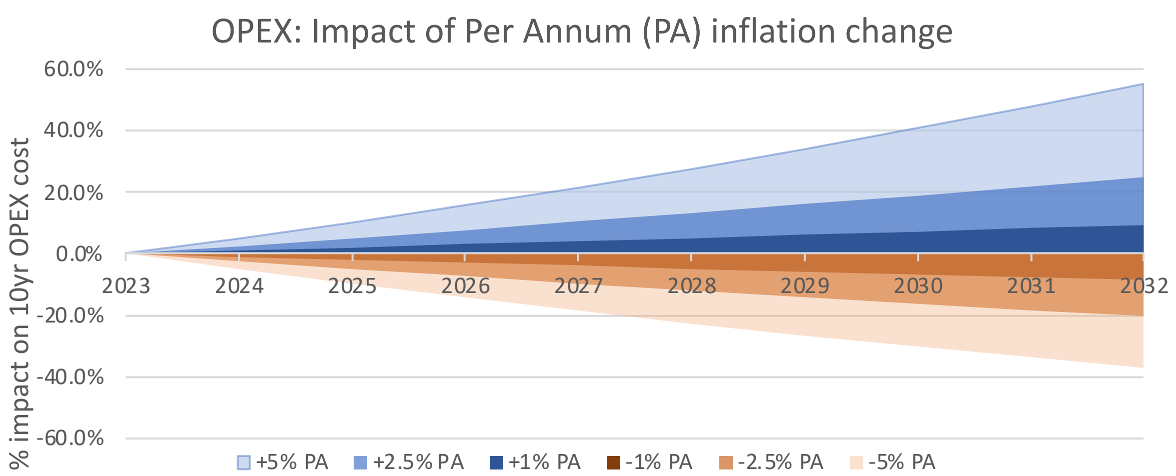
Table 4: Average impact of additional inflation or deflation on OPEX costs

Annual inflation deviation per annum (PA)	Average impact on 10yr OPEX costs
-5% PA	-18.6%
-2.5% PA	-9.9%
-1% PA	-4.1%
+1% PA	4.3%
+2.5% PA	11.3%
+5% PA	24.1%

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

The graph in Figure 7 shows the impact of inflation over the ten-year time period; as inflation is cumulative, the impact on costs increases with each year. Assessing the likely level of inflation for ZEFI OPEX costs was not within the scope of this project, however sustained inflation of ±5% of general inflation is historically uncommon, therefore inflation within the ±2.5% margin is more reasonable. We recommend that further research into the main drivers of ZEFI OPEX cost inflation is performed in order to gain a better understanding of the likely inflation risk. This should be done by consultants with experience in inflation calculations, as an understanding of key labour, materials, fuel and OPEX costs would be needed.

Figure 7: Cumulative impact of additional inflation or deflation on OPEX costs



ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

MODEL RESULTS

This section presents the results of the model for the five airport archetypes. All the results are given for a generic example airport that represents each archetype.

This includes the three most appropriate pathways for gaseous or liquid hydrogen operations, dependent on forecasted demand shown in Table 3 and Table 4. To account for disruptions, the daily hydrogen demand is oversized by 10%.

The operational pathways have been identified by the model in terms of decreasing CAPEX, i.e. the lowest CAPEX option ranks highest. The CAPEX costs presented in the tables below represent the baseline scenario. OPEX, space requirement and energy demand have also been included in the results. The full range of "low", "base" and "upper" CAPEX and OPEX scenarios for the highlighted operational pathways are shown as an appendix.

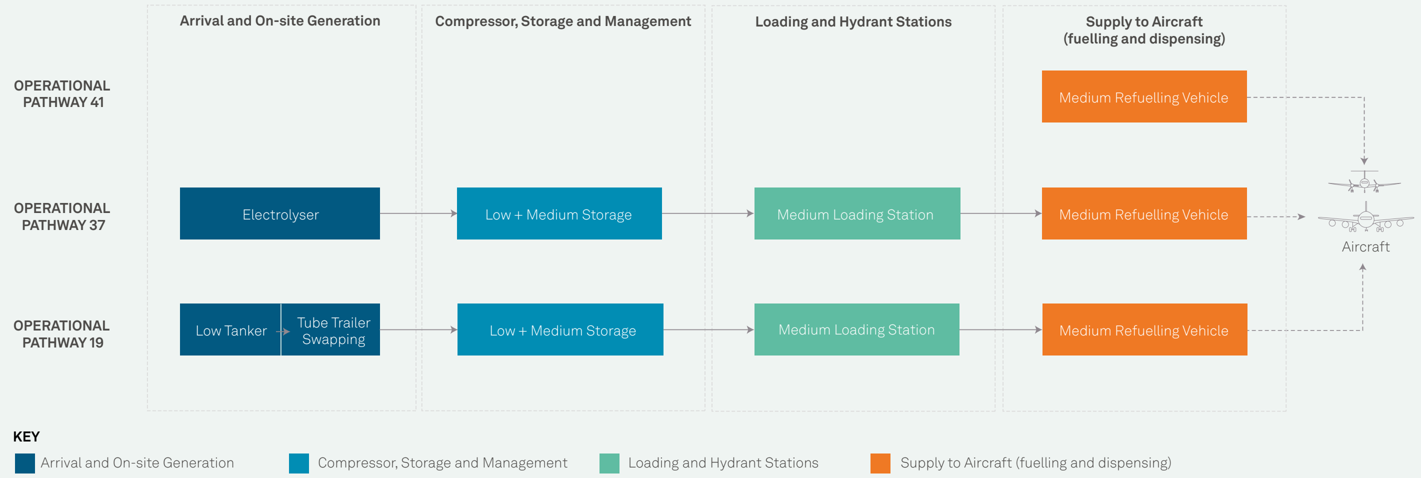
The names of the pathways are identifiers and do not include all the configuration points needed for the entire pathway. The numbers in the brackets refer to the number of the operational pathway, as recorded in the Appendix: List of Operational Pathways. The table in this Appendix includes all the possible operational pathways, as included in the model, as well as all the configuration points assumed for each operational pathway.

For any operational pathways that include a pipeline, the model has assumed a pipeline length of 25km. Any pipelines longer than this will have associated increases in the values stated, including for CAPEX and OPEX. Conversely, any pipelines shorter than this may have lower associated costs. A full list of assumptions can be found in the Appendix: Assumptions Log.

ARCHETYPE 1: SMALL OR ISLAND AIRPORTS

The following section sets out the most viable operational pathways for Archetype 1 – Small or Island Airports and Airfields.

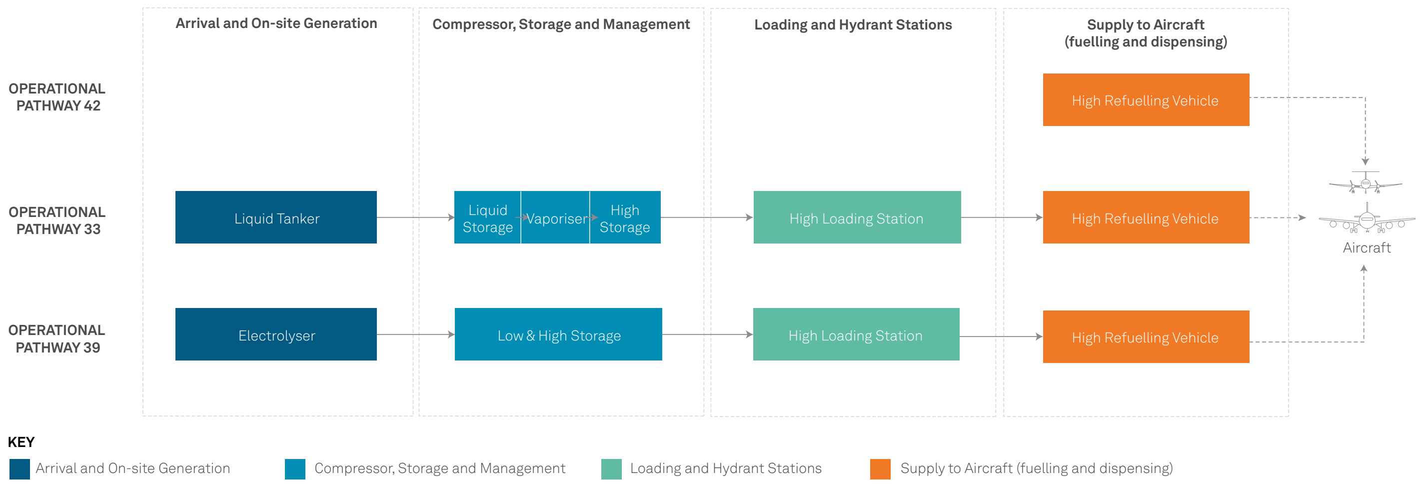
Our assumption that only small C code aircraft and above will be powered by liquid hydrogen, means that Archetype 1 has 100% of its operations as gaseous hydrogen in both 2030 and 2050. However, many aircraft concepts at this size have also been designed to utilise liquid hydrogen. As a result, the model outputs for Archetype 1 include the top ranked operational pathways for medium and high-pressure gaseous hydrogen, as well as nominal liquid hydrogen pathways.



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Medium Pressure Direct Refuelling Vehicle (41)	2030	£13.5m	£3.0m	£27.5m	-	-
	2050	£13.5m	£3.0m	£27.5m	-	-
Electrolyser and Medium Pressure Refueller (37)	2030	£34.5m	£13.5m	£1154.0m	6,000	325,000
	2050	£35.5m	£13.5m	£118.0m	6,000	375,000
Low Pressure Tanker and Medium Pressure Refueller (19)	2030	£40.0m	£7.5m	£64.5m	7,000	105,000
	2050	£37.5m	£7.5m	£65.5m	7,000	105,000

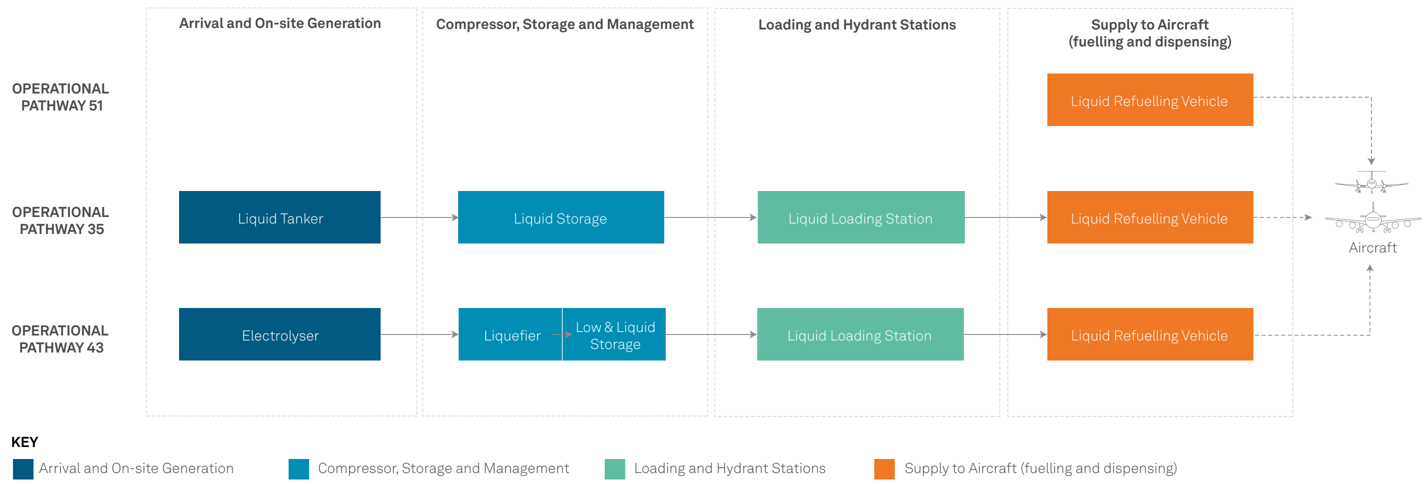
Table 6: Top operational pathways in terms of CAPEX for medium-pressure hydrogen for 2030 and 2050 for Archetype 1

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
High Pressure Direct Refuelling Vehicle (42)	2030	£15.0m	£3.5m	£31.0m	-	-
	2050	£16.5m	£4.0m	£34.5m	-	-
Liquid Tanker and Vaporiser to High Pressure Refueller (33)	2030	£22.5m	£8.0m	£68.0m	500	105,000
	2050	£23.0m	£6.5m	£57.5m	500	80,000
Electrolyser and High Pressure Refueller (39)	2030	£39.0m	£14.0m	£121.0m	6,000	365,000
	2050	£40.5m	£14.5m	£124.5m	6,000	375,000

Table 7: Top operational pathways in terms of CAPEX for high-pressure hydrogen for 2030 and 2050 for Archetype 1



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Direct Liquid Refuelling (51)	2030	£3.5m	£1.0m	£7.5m	-	-
	2050	£3.5m	£1.0m	£7.5m	-	-
Liquid Tanker and Liquid Refueller (35)	2030	£11.5m	£10.5m	£90.5m	600	175,000
	2050	£11.5m	£7.0m	£59.5m	400	100,000
Electrolyser and Liquefier to Liquid Refueller (43)	2030	£50.0m	£18.0m	£155.5m	6,000	455,000
	2050	£52.0m	£17.0m	£149.0m	6,500	440,000

Table 8: Top operational pathways in terms of CAPEX for liquid hydrogen for 2030 and 2050 for Archetype 1

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

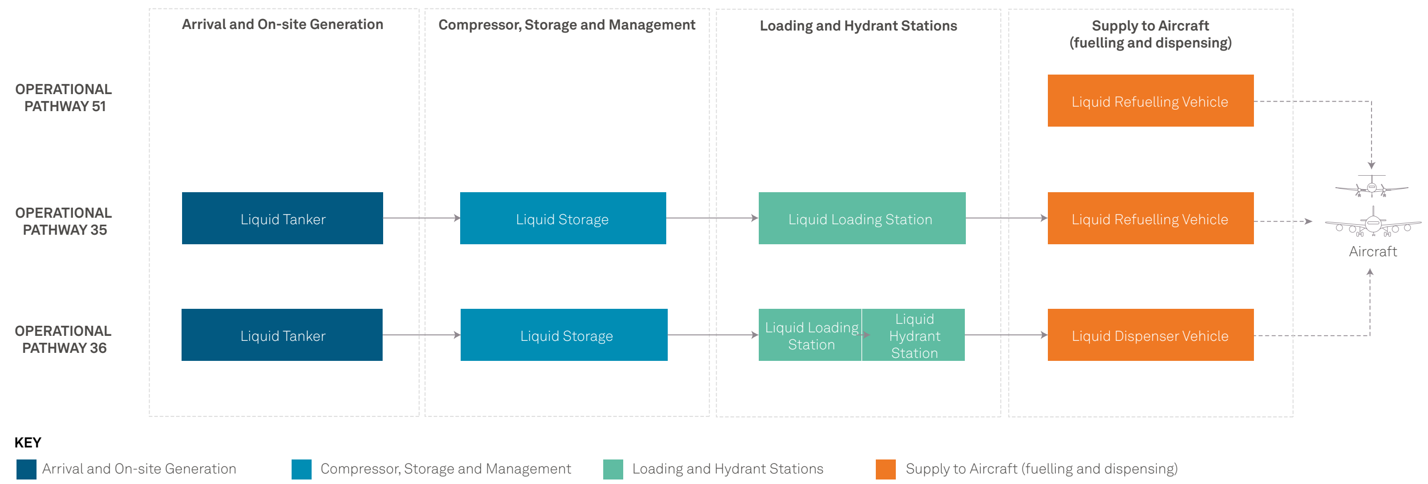
The results of the model for Archetype 1 present the following conclusions:

- Direct refuelling vehicles (pathway 41) has been identified as the top pathway in terms of CAPEX for medium pressure hydrogen for 2030 and 2050 scenarios, both with a CAPEX of £13.3m. Based on current estimates, medium-pressure hydrogen would require the same number of vehicles as high-pressure hydrogen, but each vehicle is cheaper, resulting in lower costs. Whilst pathways 33 and 39 would result in reduced refuelling vehicle costs, this saving is offset by storage costs, with additional costs for the pathway 39 electrolyser. However, airports may prefer to shoulder the burden of storage costs to guarantee that a supply of hydrogen is always available.
- Direct refuelling vehicles (pathway 42) has also been identified as the top pathway in terms of CAPEX for high pressure hydrogen for 2030 and 2050 scenarios, with a CAPEX of £14.9m in 2030 and £16.6m in 2050. As with medium-pressure hydrogen, adding additional elements will increase the CAPEX and OPEX required. Note that tanker deliveries have been capped at 144 per day so the model will not highlight a pathway which requires more deliveries than this.
- Direct liquid refuelling vehicles (pathway 51) has been identified as the top pathway in terms of CAPEX for liquid hydrogen for 2030 and 2050, both with a CAPEX of £3.5m. Liquid hydrogen significantly reduces the number of vehicles required to transport hydrogen, which produces substantial savings. Each additional requirement drives up CAPEX and OPEX costs, therefore adding the electrolyser technology to pathway 43 pushes up both CAPEX and OPEX costs. Removing the requirement to store the hydrogen significantly reduces the OPEX.
- Electrolysers (pathway 37 and 39) have been identified as a viable option for medium-pressure and high-pressure hydrogen pathways. It has also been identified as a viable option for liquid hydrogen systems (pathway 43). It is notable that these are the only scenarios in which the model selects a pathway that includes an on-site electrolyser, highlighting Archetype 1 as the best use case for this infrastructure.
- It is notable in Table 6 that the CAPEX of a low-pressure tanker with a medium pressure refuelling vehicle (operational pathway 19) is less in 2050 (£37.6m) than 2030 (£39.9m). This is a result of expected efficiency gains in tanker capacity over time, therefore requiring fewer tankers in 2050 compared with 2030. For Archetype 1 there is less than 200kg increase in hydrogen demand between 2030 and 2050, so the cost savings from technological improvements will be noticeable.
- Overall, given the low levels of hydrogen demand, direct liquid refuelling represents the best delivery method in terms of CAPEX, if this is logistically viable given airport geography.

ARCHETYPE 2: REGIONAL AND BUSINESS AIRPORTS

The following section sets out the most viable operational pathways for Archetype 2 - Regional and Business Airports

Based on our assumptions, aircraft at Archetype 2 airports will predominantly utilise liquid hydrogen, with only a small percentage of gaseous hydrogen required in both 2030 and 2050. Results for Archetype 2 include the top-ranked operational pathways for liquid hydrogen. Gaseous hydrogen results are excluded due to the ability to meet demand through supplementary hydrogen tanker deliveries, noted in each scenario.



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Direct Liquid Refuelling (51)*	2030	£21.5m	£5.5m	£45.5m	-	-
	2050	£31.0m	£8.0m	£67.0m	-	-
Liquid Tanker and Liquid Refueller (35)*	2030	£31.0m	£31.5m	£272.5m	2000	550,000
	2050	£43.0m	£37.0m	£318.0m	3000	660,000
Liquid Tanker and Liquid Hydrant (36)*	2030	£36.5m	£30.0m	£256.5m	3000	550,000
	2050	£47.5m	£35.0m	£301.0m	4000	660,000

***With eight direct high pressure gaseous refuellers to meet the daily demand.**

Table 9: Top operational pathways in terms of CAPEX for liquid hydrogen for 2030 and 2050 for Archetype 2

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

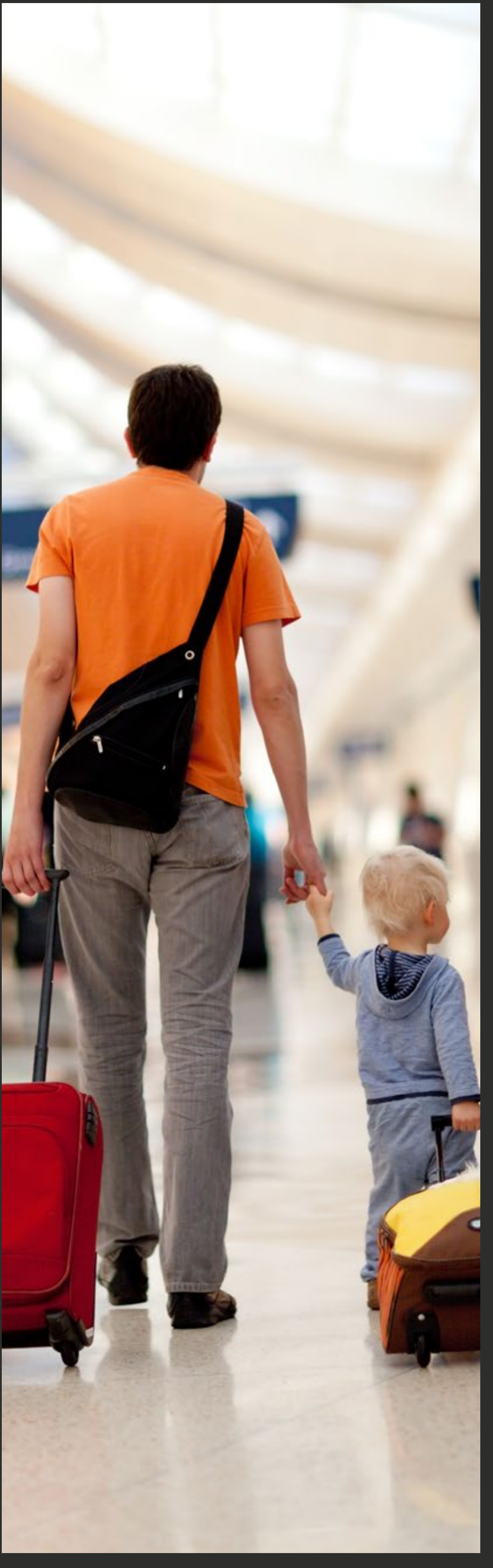
sults of the model across 2030 and 2050 scenarios
t the following conclusions:

ct liquid refuelling vehicles (pathway
has been identified as the top pathway
erms of CAPEX for liquid hydrogen for
0 and 2050 scenarios, with a CAPEX
21.5m and £30.9m, respectively.
hetype 2 sees increases in CAPEX
OPEX requirements compared to
hetype 1 due to the increased volume
ydrogen required, which is now
vered in both liquid and gaseous
n. In 2050, 88% of the hydrogen
uirements are delivered in liquid form,
liquid hydrogen represents just 57%
he total CAPEX as gaseous hydrogen
uires more transportation vehicles per
f fuel.

id Tankers with liquid refuelling
cles and hydrants (operational
hways 35 and 36) were identified as
other most viable pathways for liquid
rogen. Both pathways include liquid
rogen delivery via tanker and liquid
age but differ in distribution method.
hway 35 utilises refuelling vehicles,
ereas pathway 36 utilises liquid hydrant
ems and dispenser vehicles. The
ease in costs for these pathways
pared to pathway 51 is primarily driven
he tanker cost, with the decrease in
site refuelling vehicle costs now equally
et by storage costs.

nments under Table 9 refer to
plementary gaseous hydrogen tanker
plies, stating the need for a further
t gaseous tankers per day in 2030 and
0 scenarios to meet the daily gaseous
rogen demand.

rall, the forecast hydrogen demand
ls mean that Archetype 2 is still able
e supplied by direct liquid refuelling,
ch represents the ideal delivery
hod in terms of CAPEX. If this is
stically unviable, the current data
gests that pathway 36 should be
sued over pathway 35, as lower OPEX
ts will quickly recoup the higher CAPEX
ts. If space is at a premium, then
hway 35 may represent the
t pathway.



CONSTRAINTS AND CHALLENGES FOR A HYDROGEN TRANSITION – ARCHETYPES 1 & 2

Archetypes 1 and 2 cover the smaller airports with regional flights within the UK. These airports are likely to be early adopters of hydrogen, utilising small aircraft (below 20 seats) that are expected to enter into service first. Both gaseous and liquid hydrogen are likely to be used in these aircraft. Their key challenges are regulation and the logistics of delivering hydrogen to the site.

Smaller airports and airfields will likely have space for electrolysis on or near the site. This archetype is interested in building economies of scale by providing hydrogen to other local community users, and these relationships must develop further. Other users have not been accounted for in these models, and operators may wish to look at the next largest archetype results if they expect greater demand.

Logistics

Most challenges for smaller airports relate to their locations. They include:

- **Power Connections** – many airports of this size are served by one or two 33kV electricity connections, which will not support electrolysis.
- **Road infrastructure** – road connections are often limited, and journeys may include a ferry. Managing the safe delivery of hydrogen may prove to be a challenge.
- **Staffing** – There are challenges around encouraging specialists to relocate (e.g. for maintenance) and how to retrain the existing workforce in new operations, including fuelling, hydrogen safety and fire training.
- **Supporting island airports** – it is unclear how current minimal "forecourt" style pumped fuel operations on islands will be replaced for any liquid hydrogen demand. Operators may need more substantial infrastructure on the islands for storage and monitoring, compared to current aviation fuel infrastructure.
- **Costs** – Airport geography is likely to have significant impacts on costs, for example the optimal direct refuelling pathway identified for Archetype 1 and 2 costs will be much larger if an airport is remote or on an island.

Regulation

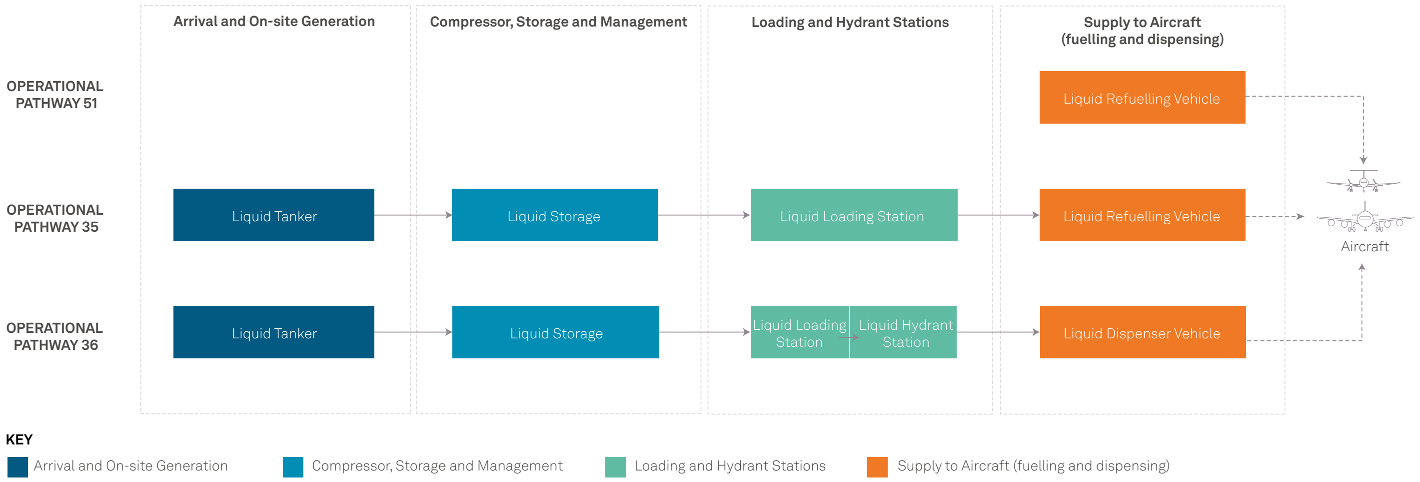
As many of these smaller airports will be early adopters of hydrogen flight, they may have to install infrastructure before regulations and guidance are finalised. This can be achieved by gaining approval for a safety case or specific trials with regulators such as CAA and HSE. There is therefore a risk that these airports will have to make changes down the line as regulation learns from these early trials and standards change. Specific gaps include safety zones and separation distances around hydrogen operations. For this reason, early ZEFI may need to be modular and flexible in its design to mitigate the risk of rework once regulation and guidance are in place. The ZEFI Standards Advisory Group is also aiming to mitigate some of these risks. For more information, please see the ZEFI website.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

ARCHETYPE 3: REGIONAL AND SHORT-HAUL OPERATIONS

The following section sets out the most viable operational pathways for Archetype 3 – Regional and Short-haul Operation Airports and Airfields.

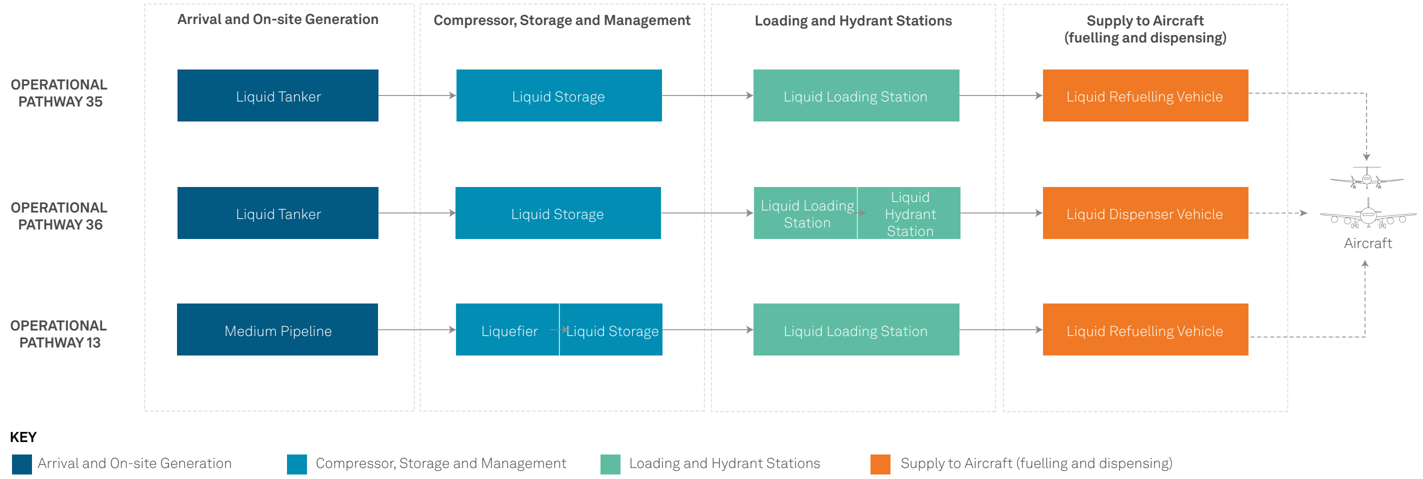
For Archetype 3, the top ranked operational pathways based on CAPEX for liquid hydrogen are shown. Liquid hydrogen reflects the vast majority of hydrogen volume in both the 2030 and 2050 scenario (96% and 99% respectively). The small gaseous demand in both cases can be met through supplementary hydrogen tanker deliveries, noted in each scenario.



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Direct Liquid Refuelling (51)*	2030	£8.5m	£2.0m	£19.0m	-	-
Liquid Tanker and Liquid Refueller (35)*	2030	£30.0m	£28.5m	£244.5m	1,700	480,000
Liquid Tanker and Liquid Hydrant (36)*	2030	£33.5m	£23.5m	£204.0m	3,600	480,000

***With one direct high pressure gaseous refueller to meet daily demand**

Table 10: Top operational pathways in terms of CAPEX for Liquid hydrogen for 2030 for Archetype 3



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Liquid Tanker and Liquid Refueller (35)*	2050	£141.0m	£187.0m	£1,607.5m	16,500	3,795,000
Liquid Tanker and Liquid Hydrant (36)*	2050	£149.5m	£182.0m	£1,567.0m	18,500	3,770,000
Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Liquid Refueller (13)*	2050	£969.5m	£321.5m	£2,766.5m	41,500	6,145,000

***With one direct high pressure gaseous refueller to meet daily demand**

Table 11: Top operational pathways in terms of CAPEX for liquid hydrogen for 2050 for Archetype 3

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

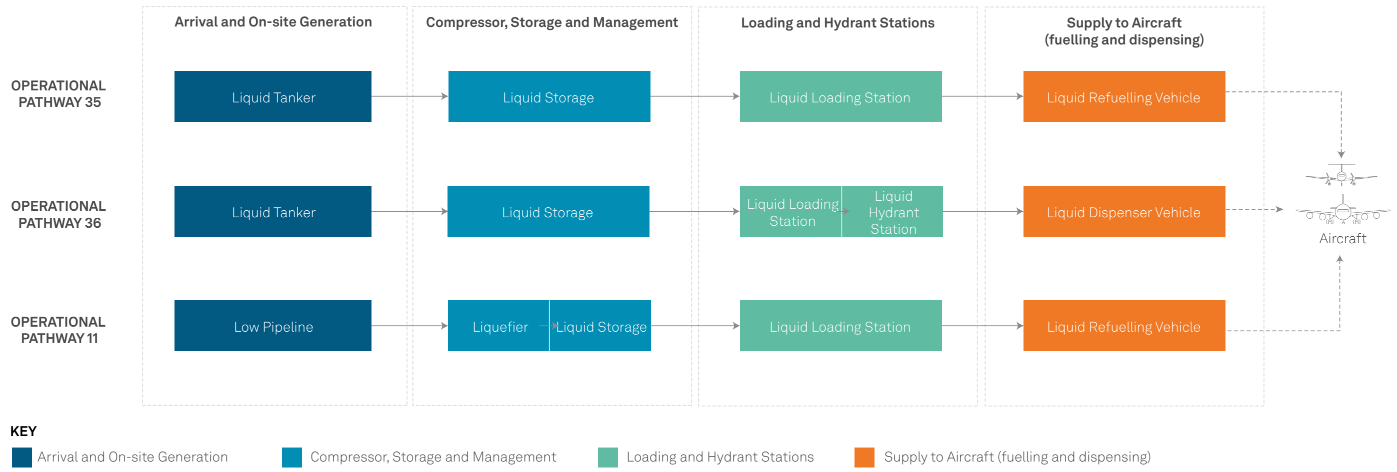
The results of the model across 2030 and 2050 scenarios present the following conclusions:

- In 2030, demand is lower and direct liquid refuelling vehicles (pathway 51) is the pathway with the lowest CAPEX (£8.7m) required to fulfil demand. However, direct liquid refuelling becomes unviable in 2050 as too many airside vehicles would be required to meet the demand. It is inevitable that some form of storage system is required for Archetype 3; airports will have to decide on the best time for installing storage.
- Liquid tanker and liquid refueller vehicle (pathway 35) has the second lowest CAPEX in 2030 (£30.2m), but becomes the top ranked pathway based on CAPEX for 2050, with a CAPEX of £140.9m.
- Operational pathway 36 is viable in 2030 and 2050 scenarios, with a slightly higher CAPEX than pathway 35. Both pathways include liquid hydrogen delivery via tanker and liquid storage but differ in distribution method. Pathway 35 utilises liquid refuelling vehicles, whereas pathway 36 utilises liquid hydrant systems and dispenser vehicles.
- The distribution method for pathway 36 has a lower OPEX than pathway 35 which would outweigh the higher CAPEX within 2 years for both the 2030 and 2050 scenario, indicating that this is the overall optimal pathway.
- Pathway 13 has the 3rd lowest CAPEX (£969.6m) in 2050, utilising medium pressure gaseous hydrogen delivery via pipeline, followed by liquefaction and distribution via liquid refuelling vehicles. Given the large cost differential and space required, it does not seem as financially or logistically viable as pathways 35 and 36.

ARCHETYPE 4: INTERNATIONAL WITH PREDOMINANTLY MEDIUM-HAUL OPERATIONS

The following section sets out the most viable operational pathways for Archetype 4 - International with Predominantly Medium-haul Operation Airports and Airfields.

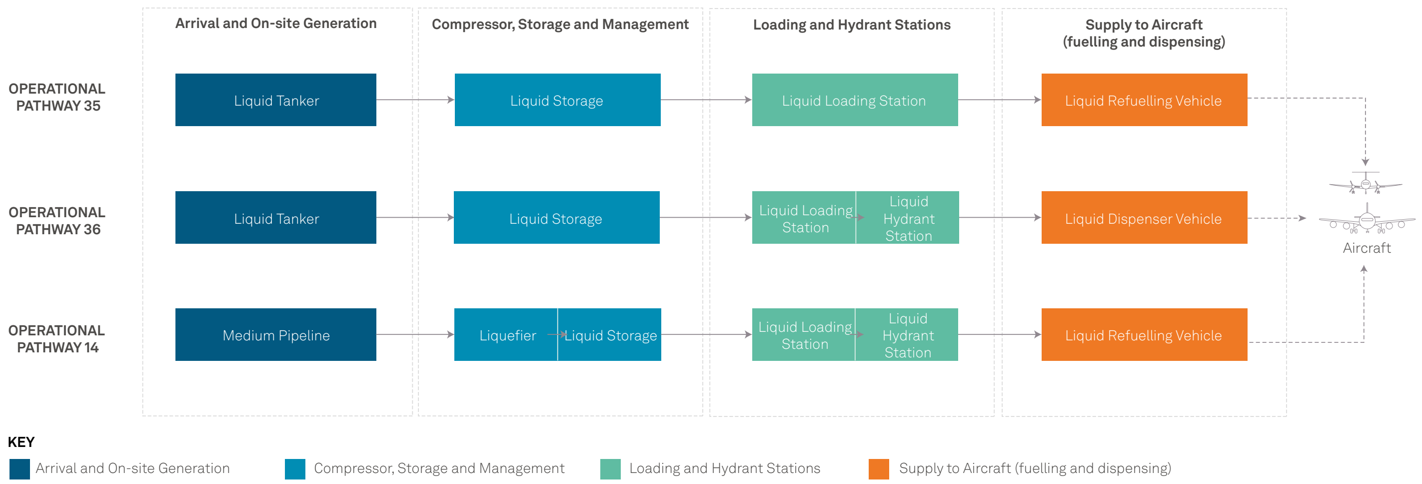
The results for Archetype 4 include the top ranked operational pathways based on CAPEX for liquid hydrogen for both 2030 and 2050. Gaseous hydrogen results are excluded as the demand is always expected to be <1%.



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Liquid Tanker and Liquid Refueller (35)	2030	£58.0m	£76.0m	£656.5m	5,000	1,410,000
Liquid Tanker and Liquid Hydrant (36)	2030	£60.0m	£68.0m	£586.5m	7,500	1,410,000
Low Pressure Gaseous Pipeline (7 bar) and Liquefier to Liquid Refueller (11)	2030	£247.0m	£104.5m	£899.5m	26,000	1,905,000

Table 12: Top operational pathways in terms of CAPEX for liquid hydrogen for 2030 for Archetype 4

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values)		Space required (m2)	Energy (kWh/day)
			1 yr	10 yrs		
Liquid Tanker and Liquid Refueller (35)	2050	£157.0m	£197.0m	£1,696.5m	17,000	3,920,000
Liquid Tanker and Liquid Hydrant (36)	2050	£161.5m	£189.0m	£1,626.5m	20,000	3,920,000
Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Hydrant (14)	2050	£1,016.5m	£329.0m	£2,830.5m	45,000	6,390,000

Table 13: Top operational pathways in terms of CAPEX for liquid hydrogen for 2050 for Archetype 4

The results of the model across 2030 and 2050 scenarios present the following conclusions:

- Liquid tanker and liquid refueller vehicle (pathway 35) has been identified as the top pathway in terms of CAPEX for liquid hydrogen in 2030 and 2050, with a CAPEX of £58.0m and £158.0m respectively. However, as with Archetype 3 Liquid Tanker and Liquid Hydrant (pathway 36) is the preferable option if space is available, as lower OPEX will result in a lower whole life cost.
- Pathways 11 and 14 in 2030 and 2050 scenarios respectively, represent the 3rd lowest CAPEX, including low and medium-pressure gaseous pipeline scenarios, however the CAPEX and OPEX is significantly higher than pathways 35 and 36, suggesting that this solution is not as viable.

CONSTRAINTS AND CHALLENGES FOR A HYDROGEN TRANSITION – ARCHETYPES 3 & 4

Archetypes 3 and 4 describe mid-size airports supporting predominantly regional, short-haul and freight operations. While these airports are keen to decarbonise, they do not have the same urgency to switch to hydrogen as others. They are likely to transition to SAF and remain kerosene-based for some time. Most see themselves as followers, looking to transition when they have enough demand to make substantial hydrogen operations viable, and they are unlikely to invest until a commitment is made by airlines.

These mid-size airports are generally based close to or within cities, resulting in challenges with significant space constraints, especially as their operations are already typically at capacity

Space Constraints

Space within the airports of these archetypes is minimal. There are opportunity costs associated with reallocating space for hydrogen operations, given the potential value of land for other commercial ventures. This restricts the opportunities available to introduce hydrogen easily and may need kerosene operations to be downscaled for hydrogen operations to be introduced.

Specific concerns are described below:

- A lack of space at stands where hydrants are used may cause overhangs onto airport roads and taxiways (especially if hydrogen aircraft are larger).
- Already busy airport roads may be unable to cope with the additional vehicle storage and movements required to service hydrogen flights.
- Airports have limited space available for hydrogen storage near existing operations.
- Large initial hydrogen safety distances will be required (also a reason for later adoption).
- The local road network may not accommodate substantial hydrogen tanker deliveries.

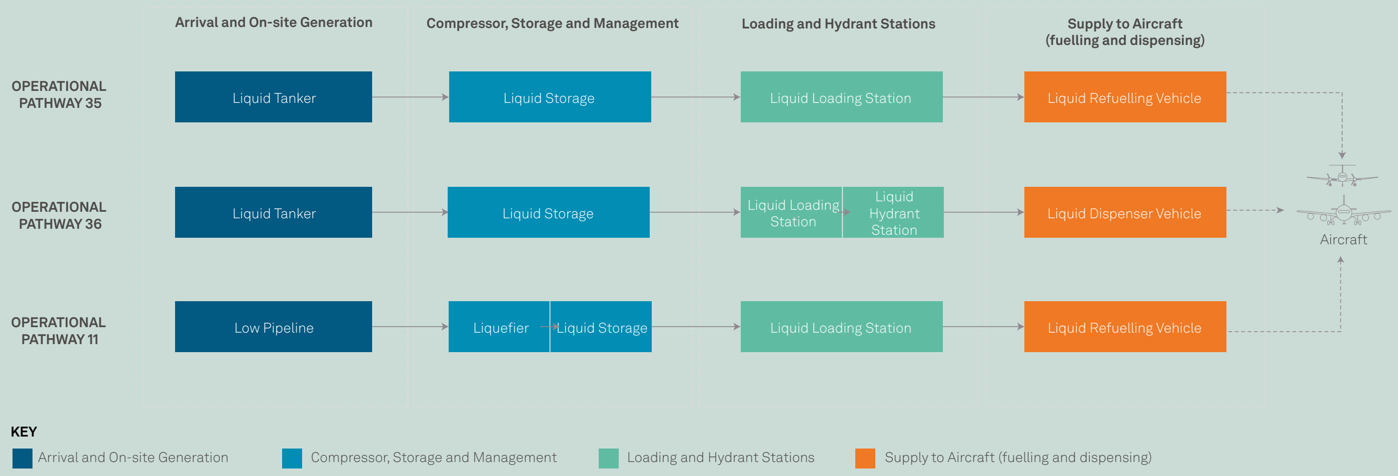
In these archetypes, airports may wish to consider whether fuel unloading from tanker deliveries should take place on landside facilities at or near the airport to reduce the number of vehicle movements through the security perimeter and to optimise land usage.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

ARCHETYPE 5: LONG-HAUL OPERATION AIRPORTS

The following section sets out the most viable operational pathways for Archetype 5 – Long haul Operation Airports and Airfields.

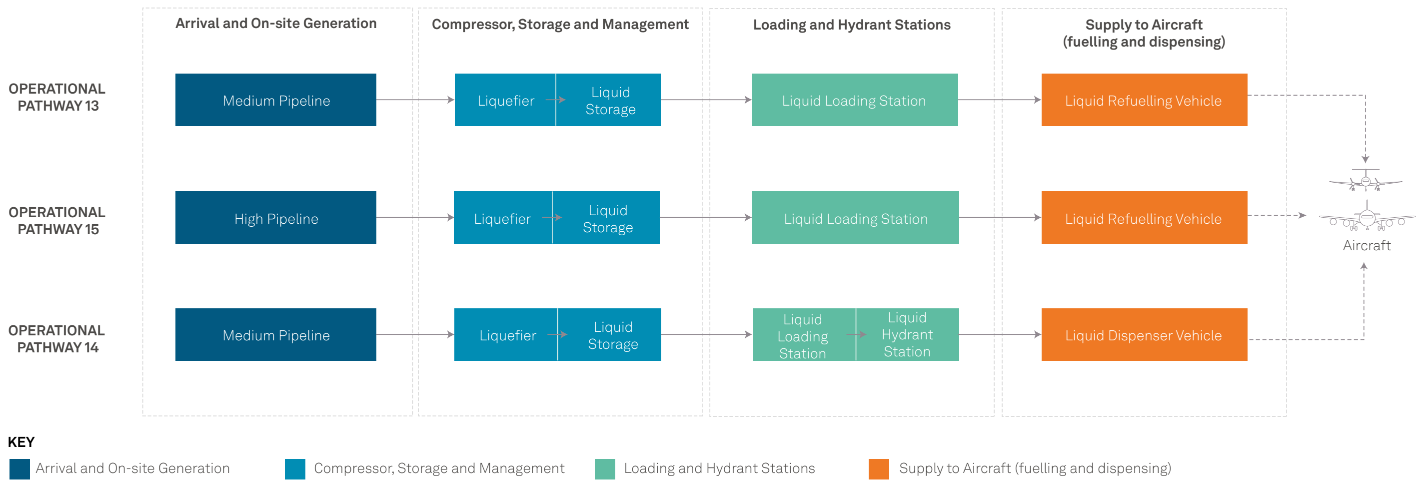
Results for Archetype 5 include the top operational pathways, ranked by CAPEX, for liquid hydrogen for both 2030 and 2050. Gaseous hydrogen results are excluded due to forecast results in Table 4 showing a 100% share of liquid hydrogen in 2030 and 2050.



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Liquid Tanker and Liquid Refueller (35)	2030	£128.08m	£120.0m	£1,034.5m	7,000	2,000,000
Liquid Tanker and Liquid Hydrant (36)	2030	£297.5m	£100.0m	£862.0m	13,000	2,000,000
Low Pressure Gaseous Pipeline (7 bar) and Liquefier to Liquid Refueller (11)	2030	£538.5m	£163.5m	£1,409.5m	28,500	2,695,000

Table 14: Top operational pathways in terms of CAPEX for liquid hydrogen for 2030 for Archetype 5

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS



Operational Pathway and demand forecast year		CAPEX ('22 values)	OPEX ('22 values) 1 yr	OPEX ('22 values) 10 yrs	Space required (m2)	Energy (kWh/day)
Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Liquid Refueller (13)	2050	£8,078.0m	£2,684.5m	£23,107.5m	201,500	51,795,000
High Pressure Gaseous Pipeline (80 bar) and Liquefier to Liquid Refueller (15)	2050	£8,100.5m	£2,684.5m	£23,108.5m	201,500	51,795,000
Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Hydrant (14)	2050	£8,246.5m	£2,664.5m	£22,935.5m	208,000	51,795,000

Table 15: Top operational pathways in terms of CAPEX for liquid hydrogen for 2050 for Archetype 5

The results of the model across 2030 and 2050 scenarios present the following conclusions:

- In 2030 pathways 35 and 36 are identified as the top liquid hydrogen pathways in terms of CAPEX (£127.8m and £297.5m respectively). For previous archetypes, hydrant systems have been cost competitive with refuellers, however the higher space requirements for Archetype 5 cause much higher hydrant costs due to longer pipeline distances and additional pits to service gates. The OPEX for pathway 36 is still lower, suggesting that in the long term this pathway is still optimal in terms of whole life costs.
- Low Pressure Gaseous Pipeline (7 bar) and Liquefier to Liquid Refueller (operational pathway 11) represents the 3rd lowest CAPEX for 2030, but requires significantly more space and CAPEX than pathway 35 and 36, suggesting this may not be optimal.
- In 2030 hydrogen demand requirements for Archetypes 4 and 5 are similar as the percentage take up of hydrogen aviation is forecast to be low. However, by 2050 Archetype 5 will be required to accommodate much higher levels of demand which can no longer be satisfied by tanker delivery methods, with pipelines now representing the only viable delivery option.
- The viable pathways in 2050 all include the liquefaction of gaseous hydrogen delivered through pipeline. The lowest CAPEX option is represented by a medium pressure pipeline with a liquefier and liquid refuelling vehicle (operational pathway 13) with a CAPEX of £8bn. This method is less expensive to build than the high-pressure option and has a similar OPEX.
- However, the optimal long-term solution is likely to be Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Hydrant (operational pathway 14), despite the higher initial CAPEX, as lower OPEX costs will result in a lower whole life cost.
- There is no supplementary gaseous hydrogen supply for this archetype, as aircraft that would use this type of hydrogen are not expected to operate at this archetype. If there were a small number that required this, the gaseous hydrogen could potentially be supplied from the boil-off from the extensive liquid supply.
- The current costs for 2050 are elevated due to being based on costs from 2022. Costs for this technology can be expected to decrease up to 2050, however this is not guaranteed. Efforts should be made to foster the production of this technology in the UK. This will speed up cost reductions and reduce exposure to fluctuations in costs from exchange rate changes and geopolitical issues.
- Our assumptions on power requirements for liquefaction for the largest airports in 2050 are significantly higher than the values quoted by FlyZero. The ZEFI model provides a figure of 2GW to power the liquefaction plant for the largest airports, whereas FlyZero gave a value of 650MW. This has been highlighted as a possible risk for airports and demonstrates the uncertainty in the predictions for these technologies. Further work and research will be needed to understand this better, ideally with trials and demonstrations.
- The energy consumption from the three highlighted operational pathways is roughly 52GWh per day. In comparison, the average daily UK energy consumption in 2021 was 800GWh (17). The predicted energy demand for a single large international hub airport therefore represents 6.5% of the UK's current energy demand. This is a significant figure, even without considering the energy for electrolysis, and demonstrates the vast quantities of energy which will be required to supply liquid hydrogen to airports. It should be noted that the scope of the model does not include getting hydrogen to the airport, therefore no assumptions have been made on how or where the hydrogen is produced.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

CONSTRAINTS AND CHALLENGES FOR A HYDROGEN TRANSITION – ARCHETYPE 5

Archetype 5 consists of the largest UK airports, including busy international terminals. They use substantial fuel volumes and require significant storage and operations space, given their size. They are likely to be involved in early hydrogen pilot programmes with flexible small-scale infrastructure; however, they will most likely transition once the options for scale are apparent. Their challenges are in supplying significant volumes of hydrogen to the site.

Hydrogen Supply

Similarly to medium-sized airports, pipelines are used for supply; however, these will require significant volumes of hydrogen and potentially dedicated off-site production. This may also require gigawatt grid connections for offsite electrolysis, or alternative sources with carbon capture technologies. Beyond initial deployment, road supply is unlikely except as a backup solution.

While larger airports are likely to have some space available for initial trials, run separately from existing infrastructure, they will quickly outgrow this. Hydrant distribution to the stands is expected to be the only viable solution for operations of significant scale. However, hydrant systems for liquid hydrogen are currently at very low TRL and come with long lead times for construction, leading to potential disruption to existing operations for their installation. These systems are specific to airports but can be informed by innovations that cut across several sectors, such as pipe insulation and boil-off recovery. However, any dispensing or connection systems will be aviation specific

CONSTRAINTS AND CHALLENGES FOR A HYDROGEN TRANSITION – ALL ARCHETYPES

As part of the investigation into the wider systems considerations for airports, constraints and blockers were explored through engagement with a range of airports and industry stakeholders. Generally, the importance of ZEF is well understood, but many airports still have considerable concerns which need to be addressed.

Specific constraints and challenges for each archetype are described in the Model Results sections. However, some general challenges which are common to all archetypes are:

- **Demonstrating the business case for hydrogen -** This is not clear for airports. More work is required to provide specific modelling for individual airports to help drive the business case forward as early as possible and ensure inclusion in masterplans. Incentives may be needed to help support the early development of hydrogen infrastructure through grants or changes in taxation.
- **Hydrogen safety -** All airports we engaged with raised safety concerns, highlighting that there is more to be done to reassure operators in this area. The early introduction of hydrogen to airports for non-aircraft applications can help support familiarity (for example, backup generation, hydrogen bus fuelling and ground vehicles), which operators could put in place now.
- **Hydrogen availability -** Sourcing green hydrogen in the early years of operations may be challenging while generation, hub and pipeline projects come online. In the Energy Security Strategy, the UK Government has set a target of 10GW hydrogen production by 2030, with 5GW from electrolysis (18). However, there may be competing demands from other sectors. Airports must look outside their local, familiar environment, establish new relationships and consider integration with wider systems. More information is given on this challenge in the ZEFI Roadmap Update.

IMPLEMENTATION REQUIREMENTS

Given that the first hydrogen aircraft will likely be ready for commercial operation by the mid-to-end of this decade, airports need to prepare not only for the refuelling infrastructure but also some of the broader systems needed for hydrogen operations.

The ZEFI programme examined the enabling systems across operations and supporting systems that will be affected by the introduction of hydrogen at airports. Figure 8 shows these systems.

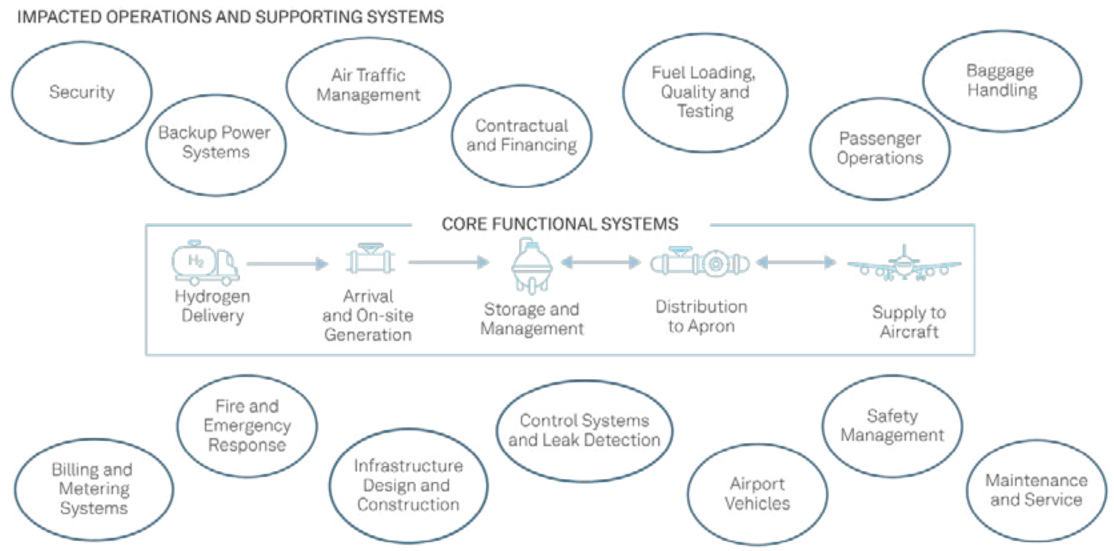


Figure 8: ZEFI Impacted operations and supporting systems

GENERAL REQUIREMENTS

The outcomes of the research identified that there are several requirements that impact implementation across all systems. These are:

- **Safety Distances for Hydrogen –** the commonly adopted safety distance for kerosene during refuelling is three metres (19) which enables parallel activities such as baggage and passenger loading. With hydrogen, it is anticipated that separation distances during refuelling could be as high as 60m for the airport building and 30m for surrounding activities. This suggests that parallel activities can only occur if they are automated. However, working alongside HSE, FlyZero determined that it may in fact be possible to reduce safety zones to 8-10m once the hose connection is secured. A 20m safety zone would still be required during connection and disconnection (20). This hasn't been confirmed with detailed modelling and demonstrations which may be beneficial to validate these findings. It is quite possible that after this process, safety distances could decrease as new data provides increased confidence in the technology, enabling parallel activities.
- **Human Factors –** training and upskilling of airport staff to handle new procedures and technologies will need to be carefully managed, particularly in airports with operations across several different fuel types. Aviation is an industry which has a long history of using liquid hydrocarbon fuels. Whilst the technologies for handling them have evolved, the core infrastructure has remained similar over time. The step change to hydrogen is likely to see very different technologies and handling operations which may create a challenge of acceptance which will need to be overcome. It is worth noting that these challenges are not unique to aviation and other industries transitioning to hydrogen will need to undergo similar changes.
- **Operating Hydrogen and Kerosene/SAF in Parallel –** in our discussions with airports, they highlighted that they may require separate teams working on kerosene and hydrogen operations to avoid any confusion between the two. Additionally, hydrogen operations may need to be located on a specific area of the airfield to minimise the chance of confusion and simplify the installation, storage, operation and maintenance of the different equipment.
- **Regulatory Approval –** it is anticipated that smaller hydrogen aircraft will enter the market first, and therefore smaller airports will be the first to use hydrogen in a commercial setting. They will have to work closely with the regulators to approve commercial use. However, once operational, there will be a period of learning by doing, which will inform the regulations and guidance that will follow these initial use cases. Larger airports can utilise these learnings to de-risk their investment and ensure they have a right-first-time approach to the design of their systems. It is worth stressing that any commercial operations involving passengers will be safe and regulated.

REQUIREMENTS FOR AIRPORTS' ENABLING SYSTEMS

Table 16 and Table 17 show the key requirements for each of the Enabling Systems. These systems have been categorised into two groups: "airside and apron operations" and "fuelling infrastructure and systems". These aim to give airports and other stakeholders an indication of some of the broader considerations to enable a hydrogen transition. Further detail on these requirements can be found in the "Hydrogen Infrastructure Options for Airports: Supplementary Report".

Table 16: Implementation requirements for airside and apron operations

Enabling system	Implementation Requirements
Airport Security	Airports should assess whether the impact and likelihood of existing security risks are substantially worse for liquid hydrogen than kerosene (e.g. terrorist attack). Security risks would need re-assessment to ensure appropriate controls remain in place to manage these.
	As with existing airport operations for kerosene, hydrogen storage tanks at the airport must be designed with sufficient buffer stock to maintain airport operations for an agreed period.
	Security of hydrogen delivery to the airport should be managed in the same way that kerosene delivery is currently handled, e.g., through redundant supply infrastructure and emergency supply contracts.
Airport Vehicles	Airport vehicles such as buses for passengers or certain light-duty vehicles, may transition to hydrogen fuel cells to enable the airport to become familiar with handling hydrogen. Unlike much of the hydrogen technology in this report, hydrogen fuel cell cars, vans and buses are available already, and could be put in place immediately. As an example, TfL currently operate a hydrogen fuel cell bus along its 444 bus route (21). To enable this to happen at airports, a hydrogen refuelling station for vehicles would need to be installed (22).
Air Traffic Management	The airports that will be designated as diversion airports for hydrogen aircraft need to be determined. This will likely be done using the Aeronautical Information Publication (AIP) which highlights airport facilities. Once hydrogen infrastructure is added to airports, this will be reflected in the AIP. Airline flight ops should then review this new information and identify suitable diversion airports for hydrogen flights.
	Designated diversion airports must meet ICAO regulations regarding Rescue and Fire Fighting Service (RFFS) equipment and trained staff. Additionally, they will need to have the following in place: • If the airport does not usually operate hydrogen flights as part of their BAU, there will need to be arrangements for liquid hydrogen or hydrogen gas to be delivered to the airport by a delivery truck in the event of a diversion. • Refuelling equipment that is compatible with the refuelling pipe nozzle on the aircraft. • A compatible refuelling control system and process between the delivery truck and the aircraft. • A delivery truck operator trained in the process of refuelling aircraft or personnel at the airport who have that training.
Baggage Handling	If baggage loading is planned to take place at the same time as refuelling, automated baggage loading equipment may be required to maintain safety distances.
Emergency Response	Thermal imaging cameras will be required to see hydrogen flames.
	Cryogenic PPE will be required for the emergency response team.
	Gas-tight dampers may be required on airport buildings to prevent hydrogen from entering.
	Define inspection and testing protocols for hydrogen infrastructure components.
Maintenance Requirements for Airport Infrastructure	A maintenance contract must be implemented between the airport and a maintenance company that is experienced and competent in hydrogen infrastructure.
	The airport must conduct audits of maintenance contractor staff training, record system[3] and expected system reliability, to compare against what is planned.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

Enabling system	Implementation Requirements
Safety Management	The CAA will need to determine their requirements for hydrogen operations. This could be through collaboration with ICAO, FAA, IATA and EASA. This will allow the modification of CAP 642, 670, 699, 728 and 748 to enable hydrogen operations.
	Airport level requirements for processes and procedures: • Collaboration with regulatory bodies, airlines, ground handlers and hydrogen suppliers to inform airports' safety management systems. • Development of a Safety Management System for the airport size and archetype, based on the requirements of ICAO, FAA, CAA, IATA, EASA and best practices defined by the Airport Operators Association.
	Airport staff training requirements: • Create a staff training plan for safety-related roles and responsibilities. • Implement a training plan before the start of hydrogen operations, as well as when new staff start and on a defined refresh cycle. Additional suggestions for consideration: • Invest in a hydrogen live-fire facility at the airport (costing in the order of millions of pounds). • Invest in a simulation-based training facility.
	Airport level requirements for safety systems: • Design the integration of the hydrogen safety monitoring and control system into the existing safety monitoring and control system. • Upgrade existing aircraft maintenance facilities to comply with hydrogen codes and standards, e.g. active/passive ventilation, gas/flame detectors and alarms.

In order to help transition airside and apron operations to hydrogen, airports may wish to trial hydrogen operations at a smaller scale to develop familiarity. This could be done immediately to enable airports to develop their knowledge base, as well as being able to gather real-world data to inform future planning decisions for ZEFI.

There is an opportunity to transition airport vehicles, plant equipment or space heating systems to hydrogen. While the technology is ready, hydrogen-powered airport vehicles such as plant equipment will need to be developed by manufacturers to allow this to happen (22).

3. The maintenance contractor will have a quality assurance / quality control system (in compliance with an accredited quality management system e.g. ISO 9001) that will require the contractor to maintain records of the maintenance and failure response. The audit will be of these records.

4.Carbon intensity refers to how many grams of carbon is emitted, per unit of useful output. In the case of hydrogen production, it could be measured in kg CO2e/kg H2.

Table 17: Implementation requirements for fuelling infrastructure and systems

Enabling system	Implementation Requirements
Billing and Metering	Flow meters are used to ensure aircraft are refuelled accurately and airlines can be billed accordingly. Accurate flow meters that withstand temperatures of -253°C are required to measure LH_2 dispensing.
Contracts for Fuel Purchasing	A generic model of the contractual arrangements for the supply and storage of liquid hydrogen needs to be agreed upon between airports, airlines and suppliers. This will consider topics such as: • price hedging and fixing • matching supply with variable demand • ownership of boil-off gas • security of supply • certification of the carbon intensity[4] of the supplied hydrogen • certification of the purity of the supplied hydrogen gas Airports will need to have their hydrogen supply contracts in place in time for their first hydrogen flight. Exactly when this will be will depend on the airport archetype, but smaller airports may have hydrogen flights operating before the end of this decade. Typically, procurement processes for fuel contracts take up to 6 months. For hydrogen, it could take up to a couple of years to establish budgets, gateways and procurement for initial hydrogen contracts.
Fuelling of Aircraft	Pipework, pumps and systems to recover boil-off gas from liquid hydrogen will be required to avoid revenue loss from venting and environmental concerns (hydrogen is itself a greenhouse gas (23))
	Robotic fuelling arms will need to be developed to maintain safety distances during the refuelling process.
	Cryogenic PPE will be required for workers handling liquid hydrogen. This already exists for use in other industrial sectors and should be relatively straight forward for airports to implement.
	Separate piers will be required for refuelling to maintain safety distances.
	Hydrogen analysis will be needed to ensure hydrogen is of appropriate purity for fuel cell aircraft or hydrogen turbines. Generally, polymer electrolyte membrane (PEM) fuel cells require higher purity than hydrogen turbines. The international standard ISO 14687:2019 (24) specifies maximum permissible concentrations for many key impurities depending on use for vehicular and stationary applications. This may need to be adopted for use in aviation.
Generator and Uninterruptible Power Supply	System designs need to con¬sider the risks of power loss for each system component and the requirement for uninterrupted power supply (UPS) as risk mitigation. UPS will most likely be provided as batteries within each system package.
Infrastructure Design and Construction	Airports, aircraft manufacturers and fuel suppliers must collaborate on developing, designing and building hydrogen equipment and control systems that do not currently exist for airport applications. These may include refuelling bowsers, transfer tanks and hydrant systems.
	Advanced planning is required for design and construction of hydrogen infrastructure as there are only a small number of vendors for some of the critical pieces of equipment (e.g. liquid hydrogen storage tanks, vaporisers, liquefaction systems and liquid hydrogen pipelines). This could mean lead times of 1 to 2 years in many cases.
	Upgrades to existing aircraft maintenance facilities will be required and must be carefully managed to enable a seamless transition to hydrogen aircraft operation and maintenance. Assuming the design is known (therefore there is an understanding of how the system will work and the equipment needed), lead times will be approximately 2 years.
Leak Detection	Point gas detectors will be required to automatically detect hydrogen leaks.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

GENERAL FINDINGS

Liquid hydrogen pipelines may need to be developed to supply hydrogen to the largest airports

Hydrogen pipeline projects are in the early stages of development in the UK, with most as small projects between local industry and a hydrogen supplier. Over time, there are plans for projects to interconnect, and a more significant transition of the gas National Transmission System (NTS) towards Hydrogen (25). Many of the smaller projects will not be able to supply the volumes of hydrogen necessary for aviation use as we approach 2050. Given the investment needed for pipeline connections, the choice of supplier or network is critical. Airports may wish to collaborate directly with large-scale suppliers to establish local projects and dedicated supplies (26).

To manage the significant quantities of hydrogen required for the UK's largest airports, liquid hydrogen delivery to the site may exceed the volume of road traffic that could be handled, and the size of liquefaction plants may restrict the options for gaseous pipeline supply. Large-scale liquid hydrogen pipelines are unlikely to be feasible due to the relationship between pipe length and boil-off and therefore, pipeline delivery of liquid hydrogen may only be possible from areas close to the airport's boundary. A hybrid approach may be needed to offer multiple delivery pathways to the airport, and other options, such as liquid hydrogen delivery by rail, should be considered.

Storage typically takes up the most space

If included in an operational pathway, hydrogen storage commonly takes up the most space compared to the other infrastructure required. While this can be minimised by storing hydrogen in more energy dense forms (as high-pressure gas or liquid), there will always be a trade-off between the number of days of hydrogen in reserve, and its space requirement.

Our modelling has assumed that three days' storage of hydrogen will be needed at airports, similar to that required for conventional fuels.

Naturally, this will have a greater impact on airports that are space constrained. This is typically Archetypes 3 and 4, however this will also impact the largest airports in Archetype 5 because of the sheer volume of hydrogen that will need to be stored. Archetypes 1 and 2 are commonly situated in less crowded locations, meaning that they typically have additional space to cope with the space requirement for hydrogen storage.

Airports will need to decide what infrastructure they want to have on-site

Ultimately it is up to airports to decide what infrastructure must be on the airport site and what can be offsite. For the smaller airports, there is more freedom to choose onsite electrolysis and liquefaction as there are fewer space constraints. However, consideration will also need to be given to the power demands of these systems which may exceed the airport's grid connection. In this case, onsite (or near-to-site) renewable energy generation may be able to provide the power needed.

For larger airports, often the space requirements and power demands for onsite electrolysis rules this out as an option. Depending on the airport, onsite liquefaction with a gaseous hydrogen pipeline delivery may be the optimal choice. However, if this is still not possible due to its space and/or power demands, a liquid hydrogen pipeline delivery from a nearby production facility may be the only viable option.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

CONCLUSION

For hydrogen-powered flight to be adopted, there is a need for airports to understand the infrastructure requirements and how their operations may change.

In this report, we have presented hydrogen infrastructure options for a range of airport archetypes to enable ZEF.

We have presented outputs from the ZEFI model which evaluates different operational pathways, or hydrogen systems, for a particular flight schedule demand. The model allowed us to see which operational pathways rank highest based on a particular priority. In this report, we have ranked options based on CAPEX and presented the top three pathways for each airport archetype. However, we understand that CAPEX may not be the top priority for airports, as each will have their individual priorities and constraints. In future phases of ZEFI, there is an aspiration to allow airports to choose how the model will rank operational pathways, for example, based on the space requirement or OPEX, and for the model to present results which are more tailored to their needs. For this to occur, more time is needed to develop the model, as well as a more thorough dataset, particularly in order to account for the regional differences of airports. This may be in the form of additional data points beyond the "low", "base" and "upper" scenarios.

The model outputs for each archetype were explored in their relevant sections, with a summary of these results found in Table 1 in the Executive Summary.

The model results have highlighted some important key points:

- Gaseous hydrogen demand for aircraft will only be likely in the smaller airports (Archetypes 1 and 2). Archetypes 3, 4 and 5 will likely use liquid hydrogen for > 99% of their operations.
- Direct gaseous and liquid refuelling vehicles are identified as the most cost-effective way of supplying hydrogen to the aircraft across Archetype 1 and 2, as well as Archetype 3 in 2030 scenarios.
- Pathways including gaseous pipelines feeding into onsite liquefaction facilities are identified as viable options across Archetype 3, 4 and 5. However, liquid tanker deliveries are the lowest CAPEX option for all scenarios, with the exception of Archetype 5 in 2050, where the number of deliveries cannot effectively meet the demand.
- Hydrogen storage often takes up the most space for a particular system. While more energy dense forms of storage, such as liquid hydrogen or high-pressure gaseous, can help to reduce the footprint, there will always be a trade-off between the number of days of hydrogen in reserve and its space requirement.
- Liquid hydrogen pipelines may be required for the biggest airports to move the liquefaction plant offsite, particularly if they are space constrained. There is a balance between pipe length and boil-off and therefore any offsite liquefaction will need to be close to the airport boundary.
- Onsite electrolysis is only feasible for the smallest airport archetypes. For larger airports, the space and power requirements for onsite electrolysis are likely to be too high.

- The optimal solution, with regards to costs, is dependent on a balance of geography, demand and available space. Based on current understanding of costs, for liquid hydrogen:
  - ◊ Where demand is low and delivery is viable, then direct liquid refuelling will always be the optimal methodology.
  - ◊ Where this is not possible, or as demand begins to increase with airport size, then liquid tanker and liquid hydrant delivery becomes the optimal solution, due to the best combination of CAPEX and OPEX costs. However, if space is at a premium, then Liquid Tanker and Liquid Refueller delivery is optimal.
  - ◊ Supplying hydrogen to the UK's largest airports will not be possible using tankers and will instead require a pipeline. The current cost data suggests a medium pressure gaseous pipeline, on-site liquefaction and hydrant delivery system is the preferred solution, based on an optimal combination of CAPEX and OPEX.
- For Archetypes 1-4, the annual OPEX is nearly as high as the total CAPEX for many pathways. Whilst CAPEX costs may be higher than modelled here, once individual airport constraints are taken into account, it is likely that the largest outgoing will be recurring OPEX costs. Airports should be cognisant of optimising both OPEX and CAPEX costs.
- Based on the modelling, exposure to exchange rates is unlikely to have a very significant impact on the optimal pathway final costs for Archetypes 1-4, however this is not the case for Archetype 5 and work should be done to minimise this risk.
- Inflation has the potential to significantly impact OPEX costs. Further work should be done to identify what the likely inflation impact would be for specific pathway options, and airports should carefully consider the possible impact of inflation when performing any financial modelling of ZEFI installation costs.

To understand the challenges and constraints for airports to transition to a hydrogen future, we engaged with a range of airports. From these discussions it was clear that the challenges between different airport archetypes were slightly different and could generally be grouped together. These challenges are summarised in Table 18 below.

Table 18: Key challenges / constraints in the hydrogen transition for the ZEFI archetypes

Archetypes	Key Challenges
All	• **Safety distances** – the safety distance for hydrogen during refuelling is anticipated to be as high as 60m for the airport building and 30m for surrounding activities. • **Human Factors** – training and upskilling of airport staff to handle new procedures and technologies will need to be carefully managed. • **Operating Hydrogen and Kerosene/SAF in Parallel** – there must be no confusion between kerosene and hydrogen operations. • **Regulatory Approval** – Early adopters will have to work closely with the regulators to approve commercial use.
1-2	• **Logistics** – Challenges with smaller, more isolated airports are focussed on the logistics of getting the hydrogen to site, particularly due to their road infrastructure, power connections, staffing and, for some, their island location. As an example, Kirkwall Airport has a green hydrogen production facility close to their airport, meaning they can use hydrogen to power and heat the airport too (27).
3-4	• **Space** – Medium sized airports are often space constrained, particularly if they are in a city and therefore do not have the land to allocate to hydrogen operations.
5	• **Hydrogen Demand** – The hydrogen demand for the largest international airports will be so significant that their main challenge will be getting the vast quantities of hydrogen to site. Pipelines may be the only option; however, this requires on-site liquefaction which will take up a significant amount of space and will be a challenge if these airports have limited spare land. This will also be a challenge for the UK hydrogen economy to produce and distribute these vast quantities of hydrogen.

Changes to airports will not be limited to the refuelling infrastructure and consideration must be given to the implications of hydrogen operations on some of the wider enabling systems. These are systems which are not directly involved in the distribution and use of hydrogen for aircraft but will need to be adapted to manage the requirements of this new fuel, such as emergency services, safety management and airport security. The implementation requirements presented in this report allow for airports to understand the wider changes that will need planning in preparation for the introduction of hydrogen operations.

ZERO EMISSION FLIGHT INFRASTRUCTURE 2: HYDROGEN INFRASTRUCTURE OPTIONS FOR AIRPORTS

NEXT STEPS FOR ZEFI

The work summarised in this report has fed into our updated ZEFI roadmap which will be published alongside this report. We have also created a Standards Advisory Group, with the British Standards Institution (BSI), to ensure the self-sustaining status of standards governance and development for the design, operation and certification of ZEFI. The findings in this report will help to inform the discussion on priority areas for standards development.

We recommend that future work could involve the creation of a network of Living Labs. This should help reduce uncertainty for industry and support in the provision of real-world data to deliver urgently needed guidance and regulation. These "sandbox" environments at representative airfields and airports will trial the necessary processes, techniques, infrastructure, technologies and systems for ZEFI.

In future phases of ZEFI, we also hope to grow the capability of the model by offering more flexibility, including the ability to rank model outputs based on airports' individual needs and modify some operational pathways. This will enable industry to model complex relationships, as well as help decision making and planning. It is hoped that this tool can continue to be enhanced and use more accurate estimates as technology matures and more product data becomes available.

RECOMMENDATIONS

The need for aviation to transition to ZEF is clear. Industry and government should work internationally to bring large zero-emission aircraft to market as soon as possible.

This report helps to highlight the need to urgently invest in green energy infrastructure in order to supply the vast amount of hydrogen required for ZEF. This will include reinforcement of the electricity grid, as well as delivering a network of hydrogen production and distribution facilities across the UK. Government has a key part to play in supporting infrastructure changes, facilitating research and providing the regulatory environment to enable the scale up of ZEF.

The UK has a network of organisations and is well placed to facilitate these needs, including: Aerospace Technology Institute (ATI); the Aerospace Growth Partnership; and the Jet Zero Council. The Catapult network is also well placed to support, being a key part of the Hydrogen Innovation Initiative (HII) which aims to develop UK hydrogen supply chains, accelerate key technology innovations in hydrogen technology and drive a thriving hydrogen economy. For more information on this initiative, please see the National Composites Centre website (28).

Using these resources, the UK can play a leading role in taking forward the development of ZEFI, through a coordinated series of actions that can contribute to achieving Net Zero aviation.

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CONTRIBUTORS

We would like to thank the range of aviation professionals, original equipment manufacturers (OEMs) and airports whose input has enabled us to provide more useful and robust findings. Those that wished to be named are credited below:

- Jacobs
- Costain
- KPMG
- Edinburgh Systems
- Highlands and Island Airports Limited (HIAL)
- Manchester Airport Group (MAG)
- London City Airport
- Gatwick Airport
- NanoSun
- Isles of Scilly Travel
- University of Strathclyde
- EDF R&D UK Centre
- Next Hydrogen
- Advanced Manufacturing Research Centre (AMRC)
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APPENDICES

AIRPORT TABLE

Table 19 shows all the commercial UK airports considered in this report and highlights if they are in proximity to a rail station, port or major road. For this report, a major road has been defined as an "A" road or higher. The distances are split into three categories: close proximity (< 1 mile – highlighted in green); medium proximity (1-10 miles – highlighted in yellow); and more distant proximity (10-25 miles – highlighted in orange). Anything further afield than this, or if these facilities aren't available to the airport, their boxes are left blank. These distances are straight line distances from the airport location and do not follow a road route. These proximities are aiming to give a rough indication as to the facilities that may be available to airports, in order to help them determine ways of getting hydrogen to the airport and which operational pathways may be suitable. Airports themselves will know their situation better, and these should only be taken as a guideline or indicator. Doncaster Sheffield airport has been included should this airport become operational again.

This table also names some hydrogen projects which could potentially be used to source hydrogen for the airports. These are taken from the sample of potential hydrogen projects document on Gov.uk (29). It should be noted that not all of these projects may be able to be used to provide hydrogen for airports, but the closest estimated projects, where applicable, have been named. Not all projects are included in this list and there may be some projects that are closer than those listed. This is again a rough guideline for signposting only. Distances have not been included as exact locations are unknown.

Table 19: A table showing UK commercial airports and their proximity to various modal hubs

Airport	Proximity to Port	Proximity to Rail	Proximity to Road	Hydrogen Project (16)
Aberdeen	Yellow	Green	Green	Aberdeen Hydrogen Hub
Barra			Yellow	
Belfast City (George Best)	Yellow	Yellow	Green	NI Water & GenComm / Belfast Met
Belfast International	Orange	Yellow	Green	NI Water & GenComm / Belfast Met
Benbecula	Orange		Yellow	
Birmingham		Yellow	Yellow	Tyseley Energy Park
Bournemouth	Yellow	Yellow	Yellow	Canford Renewable Energy
Bristol	Yellow	Yellow	Yellow	Bristol Airport
Campbeltown	Yellow		Yellow	
Cardiff Wales	Yellow	Yellow	Yellow	South Wales Industrial Cluster
City Of Derry (Eglinton)	Yellow	Yellow	Green	
Coll				
Colonsay				
Doncaster Sheffield	Orange	Yellow	Yellow	Keadby Hydrogen Power Station
Dundee	Orange	Yellow	Green	Dundee Hydrogen Buses
East Midlands International		Yellow	Green	Uniper Humber Hub
Eday				EMEC
Edinburgh	Yellow	Yellow	Yellow	Marubeni
Exeter	Orange	Yellow	Green	
Fair Isle				Shetland Islands Council
Foula				Shetland Islands Council
Gatwick	Orange	Yellow	Green	Shoreham Port Green hydrogen
Glasgow	Yellow	Yellow	Yellow	Whitelee
Heathrow	Orange	Green	Yellow	
Humberside	Yellow	Yellow	Yellow	Yorkshire Energy Park
Inverness	Yellow	Yellow	Yellow	H2 Green Inverness
Islay	Yellow		Green	
Isles Of Scilly (St. Marys)	Yellow		Green	Isles Of Scilly (St.Marys)

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Table 17: A table showing UK commercial airports and their proximity to various modal hubs

Airport	Proximity to Port	Proximity to Rail	Proximity to Road	Hydrogen Project (16)
Kirkwall				Flotta green hydrogen
Lands End (St Just)				
Leeds Bradford				
Lerwick (Tingwall)				Shetland Islands Council
Liverpool (John Lennon)				HyNet
London City				Cavendish
Luton				
Manchester				HyNet
Newcastle				East Coast Hydrogen
Newquay				
North Ronaldsay				Flotta green hydrogen
Norwich				Lowestoft port
Oban				
Papa Westray				Flotta green hydrogen
Prestwick				Whitelee
Sanday				Flotta green hydrogen
Southampton				Southampton Water
Southend				Cavendish
Stansted				
Stornoway				Outer Hebrides Energy Hub
Stronsay				Flotta green hydrogen
Sumburgh				Shetland Islands Council
Teesside International Airport				East Coast Hydrogen
Tiree				
Westray				Flotta green hydrogen
Wick John O Groats				Flotta green hydrogen

OPERATIONAL PATHWAY 13: WATERFALL CHART OF THE 2050 ARCHETYPE 5 CAPEX

The chart shown in Figure 9 details the different cost elements that comprise one of the possible pathways for Archetype 5. The costs of the individual configuration points are based on the baseline cost figures for each which, for this pathway, is dominated by liquefier costs. The costs for each of these figures are based on 2022 data. They are subject to change and are likely to under account for risks associated with delivery, therefore an optimism bias uplift of £2.9b has been added to produce the final £8.1b cost.

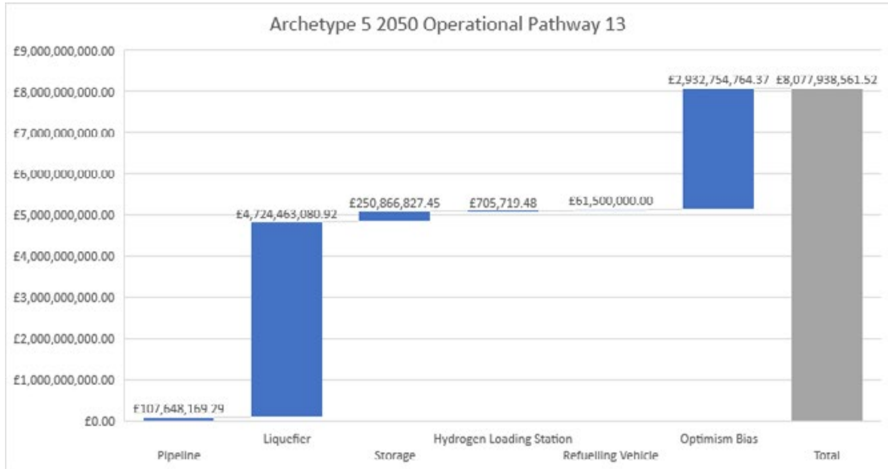

Figure 9: Waterfall Chart of the 2050 Archetype 5 CAPEX

CAPEX AND OPEX COST SCENARIOS:

Table 20 outlines the cost ranges for CAPEX and OPEX based on lower, base and upper scenarios. Cost ranges are based, where possible, on the three most appropriate cost estimates for each paw

Table 20: Low, Base and Upper estimates for CAPEX and OPEX for each selected pathway for each Archetype

Archetype	Pathway	CAPEX			OPEX		
Archetype 1	Operational Pathway 42	13.5m	16.5m	19.0m	2.0m	4.0m	7.0m
2030	Operational Pathway 33	14.5m	23.0m	33.5m	3.5m	6.5m	10.5m
Medium Pressure	Operational Pathway 39	32.0m	40.5m	58.5m	8.0m	14.5m	20.0m
Archetype 1	Operational Pathway 41	11.0m	13.5m	16.0m	1.5m	3.0m	5.5m
2050	Operational Pathway 37	30.0m	35.5m	51.0m	8.0m	13.5m	18.5m
Medium Pressure	Operational Pathway 19	27.5m	38.0m	68.5m	4.0m	7.5m	12.0m
Archetype 1	Operational Pathway 42	12.0m	15.0m	17.0m	2.0m	3.5m	6.5m
2030	Operational Pathway 33	14.5m	22.5m	33.0m	4.0m	8.0m	14.5m
High Pressure	Operational Pathway 39	30.5m	39.0m	58.0m	7.5m	14.0m	20.0m
Archetype 1	Operational Pathway 42	13.5m	16.5m	19.0m	2.0m	4.0m	7.0m
2050	Operational Pathway 33	14.5m	23.0m	33.5m	3.5m	6.5m	10.5m
High Pressure	Operational Pathway 39	32.0m	40.5m	58.5m	8.0m	14.5m	20.0m
Archetype 1	Operational Pathway 51	3.0m	3.5m	4.5m	0.5m	1.0m	1.5m
2030	Operational Pathway 35	8.5m	11.5m	17.0m	7.0m	10.5m	20.5m
Liquid	Operational Pathway 43	46.0m	50.5m	68.0m	10.5m	18.0m	26.5m
Archetype 1	Operational Pathway 51	3.0m	3.5m	4.5m	0.5m	10.m	1.5m
2050	Operational Pathway 35	8.5m	11.5m	17.0m	4.5m	7.0m	9.5m
Liquid	Operational Pathway 43	47.5m	52.0m	69.5m	10.0m	17.5m	23.5m
Archetype 2	Operational Pathway 51	17.5m	21.5m	26.0m	2.5m	5.5m	9.5m
2030	Operational Pathway 35	23.0m	31.0m	47.0m	20.5m	31.5m	61.0m
Liquid & 8 gaseous tanker 2	Operational Pathway 36	23.0m	36.5m	56.0m	19.5m	30.0m	57.5m
Archetype 2	Operational Pathway 51	25.0m	31.0m	37.5m	4.0m	7.5m	14.0m
2050	Operational Pathway 35	30.0m	43.0m	72.5m	27.0m	37.0m	47.5m
Liquid & 8 gaseous tanker 2	Operational Pathway 36	30.0m	47.5m	80.5m	26.0m	35.0m	44.0m

Table 20: Low, Base and Upper estimates for CAPEX and OPEX for each selected pathway for each Archetype

Archetype	Pathway	CAPEX			OPEX		
Archetype 3	Operational Pathway 51	7.0m	9.0m	10.5m	1.0m	2.0m	4.0m
2030	Operational Pathway 35	22.5m	30.5m	44.5m	18.5m	28.5m	54.5m
Liquid & 1 gaseous tanker	Operational Pathway 36	18.5m	33.5m	53.5m	16.0m	23.5m	46.0m
Archetype 3	Operational Pathway 35	88.5m	142.0m	290.0m	141.5m	187.0m	228.0m
2050	Operational Pathway 36	87.5m	149.5m	309.0m	139.0m	182.0m	219.5m
Liquid & 1 gaseous tanker	Operational Pathway 13	880.0m	969.5m	1247.0m	201.0m	321.5m	441.5m
Archetype 4	Operational Pathway 35	41.5m	58.5m	95.0m	50.5m	76.0m	147.5m
2030	Operational Pathway 36	33.0m	60.0m	106.0m	46.5m	68.0m	133.0m
Liquid	Operational Pathway 11	223.5m	247.0m	319.0m	63.0m	104.5m	192.5m
Archetype 4	Operational Pathway 35	100.5m	158.0m	314.0m	148.5m	197.0m	242.5m
2050	Operational Pathway 36	93.5m	161.5m	331.0m	144.0m	189.0m	227.5m
Liquid	Operational Pathway 14	912.0m	1016.5m	1321.0m	206.5m	329.0m	449.5m
Archetype 5	Operational Pathway 35	95.5m	128.5m	190.0m	77.5m	120.0m	231.0m
2030	Operational Pathway 36	152.0m	297.5m	429.0m	67.5m	100.0m	193.0m
Liquid	Operational Pathway 11	453.0m	538.5m	720.0m	97.5m	163.5m	301.5m
Archetype 5	Operational Pathway 13	7,370.0m	8078.0m	10395.0m	1683.5m	2684.5m	3678.5m
2050	Operational Pathway 15	7380.5m	8100.5m	10491.0m	1684.5m	2684.5m	3679.0m
Liquid	Operational Pathway 14	7444.5m	8246.5m	10697.0m	1673.5m	2664.5m	3640.5m

CAPEX EXCHANGE RATE SENSITIVITY TESTING

Table 21 shows the percentage CAPEX impact of applying either the lower or upper exchange rate sensitivity.

Table 21: Impact of exchange rate sensitivities on CAPEX estimate

		Exchange rate sensitivity % impact on baseline CAPEX estimate			
Archetype	Pathway	2030		2050	
		Upper	Lower	Upper	Lower
Archetype 1	Medium Pressure Direct Refuelling Vehicle (41)	0.0%	0.0%	0.0%	0.0%
	Electrolyser and Medium Pressure Refueller (37)	-4.5%	8.0%	-4.5%	8.0%
	Low Pressure Tanker and Medium Pressure Refueller (19)	-3.5%	6.5%	-4.0%	7.5%
	High Pressure Direct Refuelling Vehicle (42)	0.0%	0.0%	0.0%	0.0%
	Liquid Tanker and Vaporiser to High Pressure Refueller (33)	-6.5%	12.5%	-7.0%	12.5%
	Electrolyser and High Pressure Refueller (39)	-4.0%	7.5%	-4.0%	7.5%
	Direct Liquid Refuelling (51)	0.0%	0.0%	0.0%	0.0%
	Liquid Tanker and Liquid Refueller (35)	-0.2%	0.3%	-0.2%	0.3%
	Electrolyser and Liquefier to Liquid Refueller (43)	-10.5%	19.0%	-10.5%	19.0%
Archetype 2	Direct Liquid Refuelling (51)*	0.0%	0.0%	0.0%	0.0%
	Liquid Tanker and Liquid Refueller (35)*	-0.1%	0.1%	0.0%	0.1%
	Liquid Tanker and Liquid Hydrant (36)*	-5.0%	9.5%	-3.5%	7.0%
Archetype 3	Direct Liquid Refuelling (51)*	0.0%	0.0%	N/A	
	Liquid Tanker and Liquid Refueller (35)*	-0.2%	0.3%	0.0%	0.1%
	Liquid Tanker and Liquid Hydrant (36)*	-8.0%	15.0%	-1.5%	3.0%
	Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Liquid Refueller (13)*	N/A		-20.8%	38.5%

Table 21: Impact of exchange rate sensitivities on CAPEX estimate

Archetype	Pathway	Exchange rate sensitivity % impact on baseline CAPEX estimate			
		2030		2050	
		Upper	Lower	Upper	Lower
Archetype 4	Liquid Tanker and Liquid Refueller (35)	-0.1%	0.3%	-0.1%	0.1%
	Liquid Tanker and Liquid Hydrant (36)	-6.0%	11.0%	-2.0%	4.0%
	Low Pressure Gaseous Pipeline (7 bar) and Liquefier to Liquid Refueller (11)	-17.0%	31.0%	N/A	
	Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Hydrant (14)	N/A		-21.0%	38.5%
Archetype 5	Liquid Tanker and Liquid Refueller (35)	-0.2%	0.3%	N/A	
	Liquid Tanker and Liquid Hydrant (36)	-16.5%	30.5%		
	Low Pressure Gaseous Pipeline (7 bar) and Liquefier to Liquid Refueller (11)	-11.0%	20.5%		
	Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Liquid Refueller (13)	N/A		-21.0%	39.0%
	High Pressure Gaseous Pipeline (80 bar) and Liquefier to Liquid Refueller (15)			-21.0%	39.0%
	Medium Pressure Gaseous Pipeline (50 bar) and Liquefier to Hydrant (14)			-21.0%	39.0%

ASSUMPTIONS LOG

General Cost Modelling Assumptions

Assumption	Source	Detail
Cost accuracy	Jacobs/Costain	Assumptions detailed in this report were applied so that the limited cost data that was sourced could be used to indicate values. The values in the spreadsheet should not be understood as precise values but as indications of where the actual value may be. It is important to note that the costs from this deliverable are highly volatile and not likely to remain the same. They will be subject to significant variability because of the current economic climate and impact on global supply chains and labour markets.
Cost Scenario	n/a	The model provides Low, Base and High scenarios. Where possible, the costs for these have been estimated for each scenario. Where only a high and low-cost estimate is available, the base cost is calculated as the midpoint between the high and low estimate. Where only a base case is available, the lower and upper scenarios are assumed to be +/- 50% of the base case. Other assumptions have been made to match the most suitable substitute to a configuration point where data for the exact configuration point does not exist.
Inflation	CPC Internal	All costs have been presented in 2022 prices. Where the original cost estimate for a configuration point was not in 2022 prices, this has been deflated or inflated to 2022 prices using the May 2022 TAG data book GDP Deflator (30). CAPEX costs have been estimated for one single year. However, OPEX costs: • have been mapped into the future. • have been assumed to not divert significantly from general inflation. • have been assumed to have price rises in line with the May 2022 TAG GDP Deflator.
Optimism Bias	Green Book	Hydrogen Flight Infrastructure projects roughly align with the Green Book non-standard civil engineering projects (31). For these projects, the Green Book advises an initial Optimism Bias (OB) percentage of 66%. This has been applied to the final costs for each pathway except where • Pathways have a low level of complexity - In this case, eight percentage points have been removed from the original 66% figure, in line with Green Book guidance • Pathways do not require a high level of innovation – Where over TRL 7, nine percentage points have been removed from the original 66% figure, in line with Green Book guidance Therefore, a range of 49-66% OB has been applied to all outputs.
Future Costs	Costain	In several cases, data was received for 2035 and 2050. This data was fitted to a simple exponential curve model to estimate values for other years Rough projections of possible future costs based on a Learning By Doing (LBD) methodology, which assumes price reduces as economies of scale improve due to increasing industry learning, experience and growth. LBD has commonly been applied to the energy sector; however, as the results are relatively uncertain, this has not been adopted into any of the cost CAPEX or OPEX modelling and only represents a possible price curve. The learning rate was assumed to be 10% for all technologies, except for compressors, which were given a learning rate of 5% as industry has more experience with this technology, reducing the potential for learning. The LBD curve assumed a 2.5% take-up of hydrogen technology in 2030 and 75% in 2050 – in line with previous FlyZero assumptions.
Exchange Rates	CPC Internal	The GBP/EUR and GBP/USD exchange rates have been calculated using the average exchange rate over the period Jul 2016-Nov 2022 to counter the recent GBP market fluctuations, which may not be representative of the long-term GBP exchange rate.

ASSUMPTIONS LOG

CAPEX Assumptions

Assumption	Source	Detail
Installation Costs	Jacobs/ Costain calculations	Based on previous calculations by Jacobs, the costs of installation are: • 1.2 times higher than the pure capital cost for electrolysers • 1.5 times higher than the pure capital cost for hydrogen storage Therefore 20-50% was added to the pure equipment costs, except liquefaction equipment costs, which were already based on total costs. This uplift does not necessarily represent the total final cost for each archetype. To provide a more accurate estimate of total costs, a better understanding of the relevant site requirements (e.g. geography, brownfield vs greenfield, modular vs traditional construction) is required. Costs may not fully represent elements such as design, transportation and labour and should instead be interpreted as a reasonable minimum. For example, Costain estimate that overall costs for complete, installed systems could be up to 5-6 times higher than the sum of component prices point estimates. However, it is unrealistic to attempt to estimate these true costs without completing a concept design.

OPEX Assumptions

Assumption	Source	Detail
Cost Calculations	Costain/Jacobs	Where data is available, OPEX costs have been based on actual cost estimates for each configuration point. Alternatively, OPEX costs are estimated as a percentage of CAPEX costs using percentages provided sourced via an internal literature review or 3rd party contractors. Whilst the cost of hydrogen fuel and electricity usage are included within OPEX costs, the cost of water supply has not been calculated at this stage. Where OPEX costs are available for only one scenario (Low, Base or Higher), it has been assumed that the lower and higher scenarios are 50% less or 50% more than the base scenario, respectively. Where no OPEX estimate exists for a configuration point, it has been assumed that OPEX costs are a percentage of CAPEX costs within the range of 1%-10%, which is the range of OPEX costs calculated for other configuration points. The impact of energy price increases and inflationary pressures is not assessed in the OPEX modelling as the granularity of the data for many of the OPEX configuration points does not enable us to make changes on this basis and modelling was not robust enough to warrant covering this cost driver. Future, more in-depth modelling should take these impacts into account.
Future OPEX Costs	CPC Internal	OPEX costs have been estimated for the year 2022; costs have been presented at the annual level but also over a range of ten years. 2022 OPEX costs are used for each year within the ten-year forecast range and are not adjusted for changes in variables such as energy prices, economies of scale or labour costs, as these costs are not understood well enough to make assumptions regarding the impact these variables could have.
Discounting	Green Book	Any future costs are discounted in line with green book guidance.
Lorry / Bowser OPEX		No assumptions have been made on the distance travelled or fuel cost for hydrogen lorries or bowsers. Instead, this data has been aggregated from the configuration point data collection exercise into a typical OPEX per lorry or bowser.

ASSUMPTIONS LOG

Model Assumptions

Assumption	Source	Detail
Oversize	Jacobs	Each configuration point is oversized by 10% of daily demand to account for disruptions
Day's Storage	Jacobs	The first point of storage on the airfield of each operational pathway is multiplied by three times the daily demand; all others are just one day's storage. For example, if gaseous hydrogen is piped in and immediately stored in its gaseous form before being liquified and stored as a liquid, three day's storge for the gaseous hydrogen would be provided, whilst only one day's storage would be provided for the liquid hydrogen.
Pipeline Length		The pipeline length is assumed to be fixed at 25km
Pipeline Diameter		Pipeline diameter is assumed to be 32cm, except for Archetype 5 where it is assumed to be 182cm to reasonably accommodate forecasted daily demand
Hydrant Length		The hydrant length is assumed to be: • 300m for Archetype 1 • 850m for Archetype 2 • 1,250m for Archetype 3 • 1,600m for Archetype 4 • 4,000m for Archetype 5.
Hydrant Pits		The number of hydrant pits is assumed to be: • 1 pit for Archetype 1 • 8 pits for Archetype 2 • 16 pits for Archetype 3 • 29 pits for Archetype 4 • 66 pits for Archetype 5.
Required refuelling / dispensing vehicles	Jacobs	The required refuelling / dispensing vehicles is based on the peak two hours from the daily flight schedule, provided by Jacobs. Long-haul twin aisle aircraft are assumed to require two vehicles, whilst short-haul and regional single aisle aircraft are assumed to only require one vehicle. Based on this: • Archetype 1 and 2 would both require 7 vehicles • Archetype 3 would require 17 vehicles • Archetype 4 would require 29 vehicles • Archetype 5 would require 82 vehicles.
Tanker Deliveries		Tanker deliveries have been capped at 144 per day (one every 10 minutes for 24 hours)
Hydrogen Cost	World Bank (32)	The cost of hydrogen has been taken as £2.98, annualised to 2022 and converted to £ from the provided source for renewably generated H2. This has been subtracted from the Electrolyser OPEX to reflect the income an airport would generate from the sale of Hydrogen, not reflected in other arrival methods

LIST OF OPERATIONAL PATHWAYS

Table 22 shows all of the operational pathways run through the model. It also details which specific configuration points are required (and therefore assumed) for each, giving the relevant cost, space and other data as displayed in the main report. Please note that "Low" "Med" and "High" refer to the pressure of the hydrogen for each configuration point.

Table 22: A list of all possible operational pathways and the configuration points required for each

Operational Pathway	Arrival / Generation	Compressor	Storage	Liquefier	Storage	Vaporiser	Storage	Loading Station	Hydrant Station	Refuelling Vehicle	Dispenser Vehicle
1	Low Pipeline	Low	Low + Med					Med		Med	
2	Low Pipeline	Low	Low + Med					Med	Med		Med
3	Low Pipeline	Low	Low + High					High		High	
4	Low Pipeline	Low	Low + High					High	High		High
5	Med Pipeline	Med	Med					Med		Med	
6	Med Pipeline	Med	Med					Med	Med		Med
7	High Pipeline	High	High					High		High	
8	High Pipeline	High	High					High	High		High
9	Low Pipeline	Low	Low	Yes	Liquid	Yes	Low + High	High		High	
10	Low Pipeline	Low	Low	Yes	Liquid	Yes	Low + High	High	High		High
11	Low Pipeline			Yes	Liquid			Liquid		Liquid	
12	Low Pipeline			Yes	Liquid			Liquid	Liquid		Liquid
13	Med Pipeline			Yes	Liquid			Liquid		Liquid	
14	Med Pipeline			Yes	Liquid			Liquid	Liquid		Liquid
15	High Pipeline			Yes	Liquid			Liquid		Liquid	
16	High Pipeline			Yes	Liquid			Liquid	Liquid		Liquid
17	High Tanker + Tube Trailer Swapping	High	High	Yes	Liquid			Liquid		Liquid	

Table : A list of all possible operational pathways and the configuration points required for each

Operational Pathway	Arrival / Generation	Compressor	Storage	Liquefier	Storage	Vaporiser	Storage	Loading Station	Hydrant Station	Refuelling Vehicle	Dispenser Vehicle
18	High Tanker + Tube Trailer Swapping	High	High	Yes	Liquid			Liquid	Liquid		Liquid
19	Low Tanker + Tube Trailer Swapping	Low	Low + Med					Med		Med	
20	Low Tanker + Tube Trailer Swapping	Low	Low + Med					Med	Med		Med
21	Low Tanker + Tube Trailer Swapping	Low	Low + High					High		High	
22	Low Tanker + Tube Trailer Swapping	Low	Low + High					High	High		High
23	Med Tanker + Tube Trailer Swapping	Med	Med					Med		Med	
24	Med Tanker + Tube Trailer Swapping	Med	Med					Med	Med		Med
25	High Tanker + Tube Trailer Swapping	High	High					High		High	
26	High Tanker + Tube Trailer Swapping	High	High					High	High		High
27	Low Tanker + Tube Trailer Swapping	Low	Low	Yes	Liquid	Yes	Low + High	High		High	
28	Low Tanker + Tube Trailer Swapping	Low	Low	Yes	Liquid	Yes	Low + High	High	High		High
29	Low Tanker + Tube Trailer Swapping	Low	Low	Yes	Liquid			Liquid		Liquid	
30	Low Tanker + Tube Trailer Swapping	Low	Low	Yes	Liquid			Liquid	Liquid		Liquid
31	Med Tanker + Tube Trailer Swapping	Med	Med	Yes	Liquid			Liquid		Liquid	
32	Med Tanker + Tube Trailer Swapping	Med	Med	Yes	Liquid			Liquid	Liquid		Liquid
33	Liquid Tanker		Liquid			Yes	High	High		High	

Table : A list of all possible operational pathways and the configuration points required for each

Operational Pathway	Arrival / Generation	Compressor	Storage	Liquefier	Storage	Vaporiser	Storage	Loading Station	Hydrant Station	Refuelling Vehicle	Dispenser Vehicle
34	Liquid Tanker		Liquid			Yes	High	High	High		High
35	Liquid Tanker		Liquid					Liquid		Liquid	
36	Liquid Tanker		Liquid					Liquid	Liquid		Liquid
37	Electrolyser		Low + Med					Med		Med	
38	Electrolyser		Low + Med					Med	Med		Med
39	Electrolyser		Low + High					High		High	
40	Electrolyser		Low + High					High	High		High
41										Med	
42										High	
43	Electrolyser		Low	Yes	Liquid			Liquid		Liquid	
44	Electrolyser		Low	Yes	Liquid			Liquid	Liquid		Liquid
47	Swappable Tanks + Swap Transport										
48	Swappable Cylinders + Swap Transport										
49	Hydrogen Swap Transport										
50										Low	
51										Liquid	

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