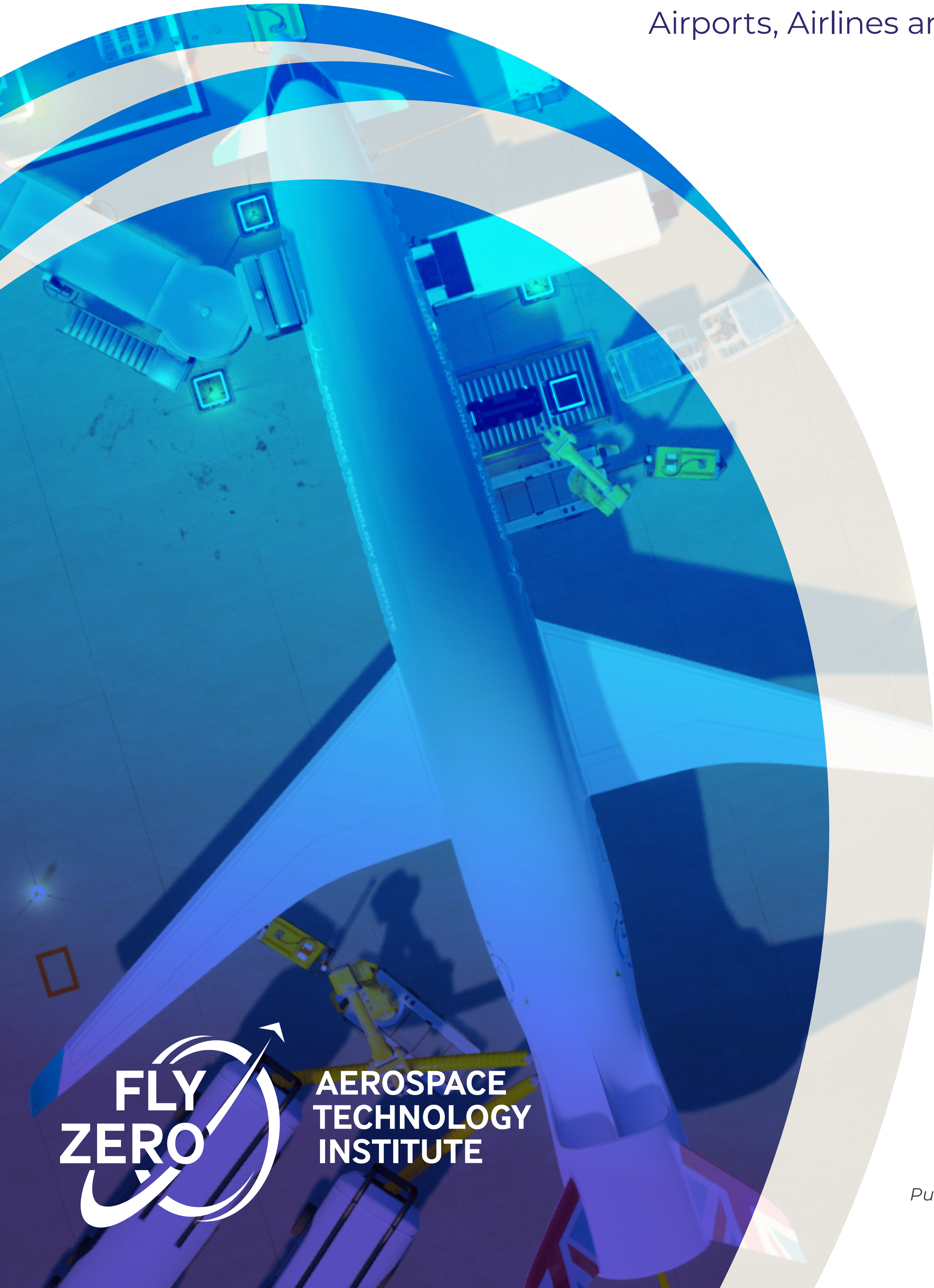
HYDROGEN INFRASTRUCTURE AND OPERATIONS

Airports, Airlines and Airspace



FLY ZERO
AEROSPACE TECHNOLOGY INSTITUTE

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ABOUT FLYZERO

Led by the Aerospace Technology Institute and backed by the UK Government, FlyZero began in early 2021 as an intensive research project investigating zero-carbon emission commercial flight. This independent study has brought together experts from across the UK to assess the design challenges, manufacturing demands, operational requirements and market opportunity of potential zero-carbon emission aircraft concepts.

FlyZero has concluded that green liquid hydrogen is the most viable zero-carbon emission fuel with the potential to scale to larger aircraft utilising fuel cell, gas turbine and hybrid systems. This has guided the focus, conclusions and recommendations of the project.

This report forms part of a suite of FlyZero outputs which will help shape the future of global aviation with the intention of gearing up the UK to stand at the forefront of sustainable flight in design, manufacture, technology and skills for years to come.

To discover more and download the FlyZero reports, visit **ati.org.uk.**

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01. EXECUTIVE SUMMARY

Realising liquid hydrogen powered aircraft has the potential to revolutionise the future of global air travel keeping families, businesses and nations connected while addressing the sector's carbon emissions.

However, generating, transporting and storing this fuel will be a significant challenge. Generating the vast amounts of hydrogen needed will require unprecedented renewable energy capacity, transporting hydrogen to airports will require gaseous pipelines or liquid hydrogen tanker deliveries, and the refuelling and servicing of aircraft will need to take place safely and efficiently alongside conventional aircraft. This report presents a vision for the future of liquid hydrogen enabled airports and airline operations, essential to realising zero-carbon emission commercial flight.

The method to generate and deliver hydrogen to the airport will depend on the airport's size, location, geography and the scale of hydrogen demand. It is anticipated that most airports will initially be supplied with liquid hydrogen generated and liquefied off-site, transported by tanker to the airport. However, as demand increases, particularly for large airports, supplying hydrogen by road or rail may become infeasible, requiring an alternative approach. While it would be possible to generate hydrogen at an airport, the high energy requirement will likely result in on-site electrolysis being unattractive. Therefore, hydrogen supply through a gaseous pipeline with on-site liquefaction at the airport may become the preferred solution. Whether liquefied off-site or at the airport, aviation's unique requirements for liquid hydrogen would likely make it one of the largest users of hydrogen liquefaction.

Similarly, the on-airport distribution of liquid hydrogen to the aircraft is initially likely to be through mobile bowsers. However, as demand increases, a liquid hydrogen hydrant system may be required. Due to the properties of liquid hydrogen, the hydrant installation would be more complex than that used currently for kerosene, requiring cryogenic pipelines and storage. While most technology required for supplying hydrogen to airports and aircraft already exists, developing the infrastructure at the scale required for airports will be challenging.

Refuelling aircraft using liquid hydrogen presents unique challenges in maintaining turnaround speed and safety. As liquid hydrogen has a lower density than kerosene, larger diameter fuel hoses will be required, and the additional safety constraints of hydrogen may require an expanded fuel safety zone. However, automation or remote control of ground support equipment and new safety procedures could help maintain competitive turnaround times.

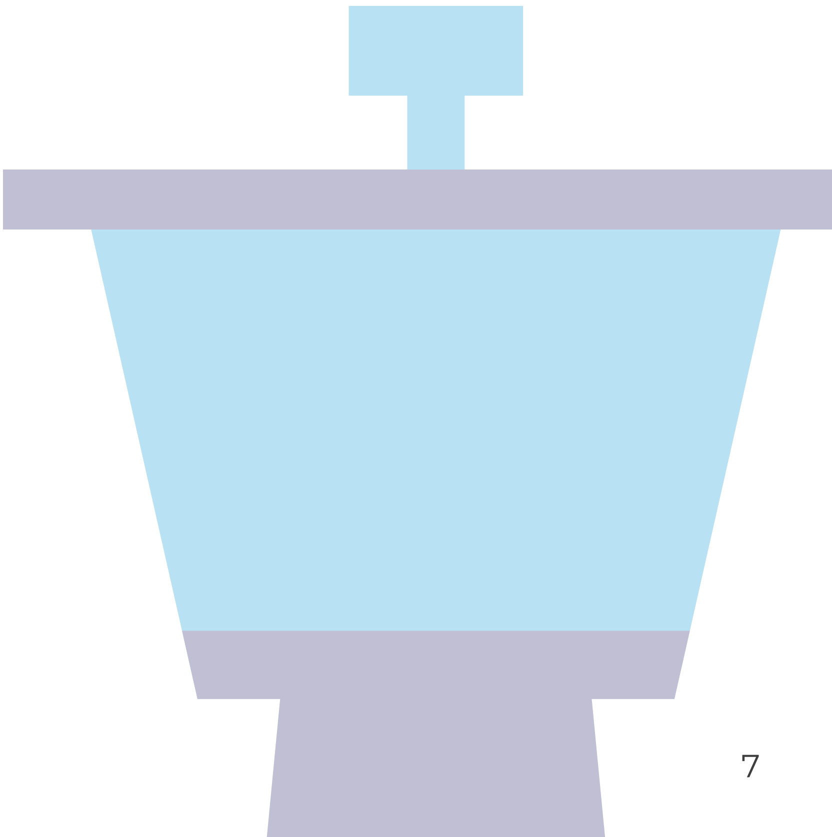
To maximise the reduction in carbon emissions this next generation aircraft will bring, it is essential to prepare the airspace and optimise its efficiency. Through a focus on air traffic management operations, it is possible to not only enable gradual reductions in CO_2 and non-CO_2 impacts in advance of zero-carbon emission flights, but also to enable efficient flight operations and a reduction in fuel associated costs for future hydrogen powered aircraft. Typical measures and initiatives that facilitate this include optimised trajectory-based flight paths in free route airspace, collaborative decision making between airspace managers, airport operators and airlines, and defined benefits of high-resolution weather data for headwind and contrail avoidance, and formation flying. While each initiative alone may have a small impact, the sum of these marginal gains can provide significant benefits.

02. SCOPE

This paper begins by outlining the hydrogen supply chain and the potential for aviation to integrate within a national supply network (**Section 3**). Airport specific infrastructure is then evaluated, investigating the options and feasibility for supply to the airport, the indicative scale of facilities required and methods for hydrogen supply to the aircraft within the airport (**Section 4**). Indicative infrastructure cost estimates are shown in **Section 5**. **Section 6** evaluates the technology readiness levels (TRL) of the infrastructure required for the operation of hydrogen aircraft at airports, and identifies steps required to develop further.

Section 7 continues by assessing hydrogen aircraft ground operations, analysing the potential aircraft turnaround times, refuelling operations and weight and balance issues. Ground operations are further evaluated by investigating the potential for automated ground services equipment (**Section 8**) and safety issues are investigated in **Section 9**. **Section 10** proposes recommendations for developing the turnaround process.

Finally, **Section 11** discusses airspace opportunities to reduce the environmental impact of aircraft operations, both for future hydrogen and existing kerosene aircraft. These opportunities are presented as examples of operational techniques and supporting technologies that enable the reduction of fuel burn, directly contributing to a reduction of CO_2 emissions and, in the case of zero-carbon aircraft operations, contributing to a reduction in the requirement for hydrogen production, transport and storage.



03. HYDROGEN SUPPLY

The supply of hydrogen to airports presents unique challenges and opportunities compared with the supply of kerosene fuel.

03.1 PROPERTIES OF HYDROGEN

At ambient temperature and pressure, hydrogen exists in the form of a gas. However, as hydrogen gas has a very low volumetric energy density, hydrogen stored in its liquid state has a greater potential to scale to commercial aviation applications [1]. To be stored as a liquid, hydrogen must be cooled to a temperature of -253˚C. Due to this low boiling point, it is essential to use high-performance insulation to prevent boil-off. If one litre of liquid hydrogen vaporises at ambient pressure it will occupy a space of 845 litres. Hydrogen storage tanks therefore need to be equipped with pressure sensors and relief valves to avoid overpressure, which if unmitigated could lead to the vessel's failure.

Unlike kerosene, the energy in hydrogen can be accessed without releasing any carbon emissions. In addition, the specific energy of hydrogen (energy per mass) is approximately three times greater than that of kerosene, which is a significant benefit for limiting the aircraft weight. However, the energy density of liquid hydrogen (energy in a given volume) is only one quarter of kerosene resulting in a larger requirement for storage facilities.

Hydrogen has many other properties that are very different to kerosene, which need considering in the design and operation of hydrogen aircraft enabled airports. For example, to the human senses, hydrogen gas is colourless, odourless, tasteless and nontoxic. In addition, hydrogen burns with an almost invisible bluish flame meaning that both the gas and flame are difficult to observe.

Hydrogen is the lightest of all gases and, with approximately one-fourteenth the density of air, is very buoyant at ambient temperatures. This characteristic helps to limit the pooling of a liquid hydrogen spill as the resulting vaporised hydrogen will naturally dissipate, provided that it is not within an enclosed space.

While liquid hydrogen itself does not burn, if spills occur the liquid vaporises and the resulting hydrogen gas can be very easily ignited. Liquid hydrogen and its associated cryogenic boil-off will also cause extreme cold burns if they come in to contact with a person’s skin.

	Jet A-1 (kerosene)	Cryogenic hydrogen, LH_2	Implications
Boiling Point (°C)	*167-266*	*-253*	*Frostbite, hydrogen boil-off, material embrittlement*
Flammability Limits (%)	*0.6-4.7*	*4-75*	*High likelihood of hydrogen fire, but higher concentration required to start it*
Min. ignition energy (mJ)	*0.25*	*0.02*	*High likelihood of hydrogen fire with weak sparks*
Burning velocity (cm/s)	*18*	*265-325*	*A hydrogen fire would burn out faster than a kerosene one*
Buoyancy	*-*	*14x lighter than air, rises at 20 m/s*	*Gaseous hydrogen disperses quickly*
Self Ignition Temp (°C)	*210*	*585*	*Harder to ignite with pure heat*
Fire heat radiative fraction	*30-40%*	*10-20%*	*Hydrogen fires could be less destructive, as they radiate less heat, but present challenges due to invisible flame*

Table 1 – Selected properties of Jet A-1 (kerosene) fuel compared to liquefied hydrogen [2]

03.2 HYDROGEN GENERATION

Three common hydrogen generation methods result in what are termed, grey, blue and green hydrogen. Currently the most common process is steam methane reforming (SMR) which uses methane (CH_4) from natural gas as a feedstock, generating carbon dioxide emissions as a by-product of splitting the carbon from the hydrogen in the methane molecule. If this CO_2 is released into the atmosphere, while combustion of the hydrogen is carbon-free, its lifecycle is far from zero-carbon. This type of hydrogen is referred to as grey hydrogen and is not a solution for decarbonisation of aviation. If the wasted CO_2 is captured and permanently stored such that it is not released to the atmosphere, the hydrogen is referred to as blue hydrogen. While this can lead to the generation of hydrogen that has a low carbon impact on the atmosphere, it nevertheless relies on an extractive process to obtain the feedstock: natural gas.

Green hydrogen is created by the electrolysis of water, which uses electricity to split water into its constituent elements: hydrogen and oxygen. If the electricity is generated in a carbon-free way, then the resulting hydrogen's lifecycle is also carbon-free.

Ideally aviation would use green hydrogen from renewable sources of electricity thereby offering both a low-carbon and a sustainable fuel solution. However, the technology for producing large quantities of green hydrogen is less mature and in the short-term costs are likely to be higher. Delivering the volumes of green liquid hydrogen for aviation applications will require significant infrastructure development and investment in clean energy production.

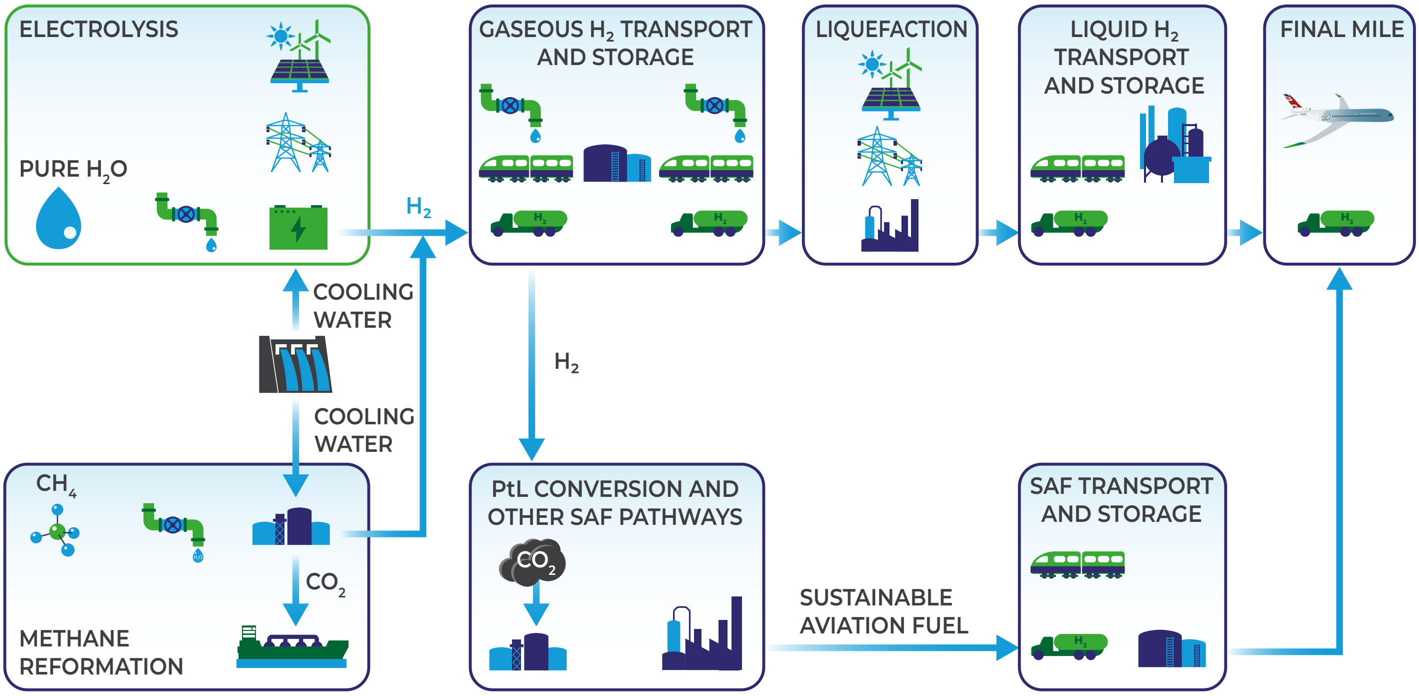


Figure 1 – Hydrogen and power to liquid (PtL) SAF generation pathways (Source: Arup)

03.3 HYDROGEN IN THE NATIONAL CONTEXT

Seen from the perspective of UK aviation alone, the transition from kerosene, at least partially, to hydrogen may appear challenging. If production of hydrogen is to be UK based, then just the aviation demands in 2050 will exceed the UK's recent annual hydrogen production (27 TWh). However, seen from a UK national energy perspective, whether in 2020 or in 2050, just the energy losses in the national electrical and gas network are of a similar magnitude to the entire energy requirement for UK aviation in 2050 [3]. Therefore, the transition to hydrogen in aviation should be seen in the context of a much larger transition of the nation's energy sources and supply.

The National Grid forecast three Future Energy Scenarios (FES) for 2050, each anticipating different annual quantities of hydrogen production and introduction into the network [3]:

- Consumer Transformation – 149 TWh
- Leading the Way – 297 TWh
- System Transformation – 475 TWh

In 2050, the FES allocate a combined energy use of 121 TWh for the aviation and maritime sectors, including fossil fuels, hydrogen and bio-energy. Out of this, 80 TWh are estimated to be supplied by hydrogen. Assuming the energy split between aviation and maritime in 2050 is the same as 2019, the aviation element would represent the majority of this hydrogen use. The upper and lower FlyZero forecasts require 134 TWh and 56 TWh of hydrogen respectively by 2050, however the total aviation hydrogen demand is likely to be higher when combined with other alternative low emission fuels, such as PtL SAF. Notwithstanding the large uncertainty, the broad magnitude of demand is similar.

The "System Transformation" scenario is based on generating blue hydrogen (over 90% of the network's 475 TWh of hydrogen coming via this pathway). At this scale, the decision to use a non-renewable source of energy rests with national policymakers rather than with the aviation sector. In contrast, in the "Leading the Way" scenario all hydrogen (297 TWh) comes from either imports (43 TWh) or electrolysis, itself supplied with electricity from a mix of networked and non-networked, renewable sources.

The UK government's ambition to create 5 GW (44 TWh) of low carbon hydrogen production annually by 2030 is particularly significant **[4]**. This would easily meet aviation demands for hydrogen out to 2040, while still leaving scope for other uses. However, how much of this 5 GW remains available for aviation will depend on competition from other users. The key factor is that the hydrogen supply will be developed ahead of aviation demand and, as such, will not need to be linked to an airport location. Hydrogen can be blended into the gas network, therefore early developers of hydrogen production capacity should have access, subject to price agreements, to a ready market without having to wait for aviation to stimulate demand. However, to ensure that adequate hydrogen remains available when required for aviation, both the use of hydrogen as a sustainable aviation fuel (SAF) feedstock and for use as a direct fuel should be included within demand forecasts.

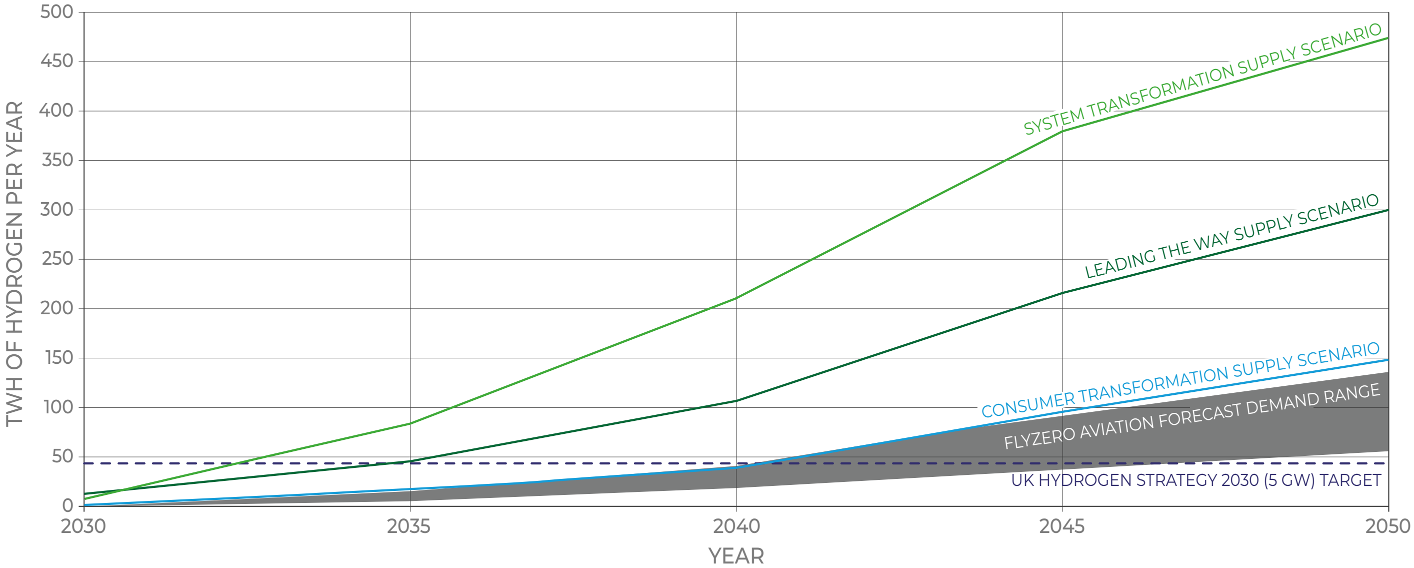


Figure 2 – Forecast hydrogen demand with Future Energy Scenarios

03.4 ENERGY TRANSITION

The UK's energy infrastructure is forecast by the National Grid to go through a radical transformation by 2050, as the UK decarbonises. From a 2020 baseline where the UK consumes 1577 TWh of energy annually, all three future scenarios anticipate a reduction in total energy requirements to between 1094 and 1369 TWh, due to efficiency improvements. However, in 2020 only 22% of energy was generated from renewable sources, whereas by 2050 the National Grid forecasts that this will increase to between 60-95%. For example, combined onshore and offshore wind generation rises almost six-fold from 89 TWh in 2020 to 526 TWh in 2050, in the "Leading the Way" scenario.

Transitioning aircraft from kerosene to hydrogen will increase the demand for renewable energy, assuming hydrogen is generated through electrolysis. However, this increased demand applies not only to direct hydrogen use, but also to battery-electric aircraft and all SAF, but specifically those generated through the power to liquid (PtL) pathway.

A FlyZero commissioned study produced comparative figures for energy (in MJ) required to produce 1 MJ of stored energy via different pathways. Expressed as ratios, these range from:

- 0.19 for kerosene - essentially the energy used is for the oil extraction and refinement rather than kerosene's "creation".
- 1.09 for battery storage - indicating that, from an energetic point of view, battery storage of electricity is efficient. However, this does not show the effect of very poor gravimetric and volumetric energy densities inherent in battery storage, which are of critical of importance in aviation.
- 1.63 for liquid green hydrogen via electrolysis.
- 2.55 for power to liquid (PtL) SAF.

From these different pathways, liquid hydrogen represents the best energetic option without the carbon impact of kerosene, or the weight penalty of batteries. However, decarbonising aviation will inevitably increase the future demand for renewable electricity, whichever pathway is used.

03.5 GLOBAL AVIATION DEMAND AND HYDROGEN

Under certain scenarios, FlyZero estimates that more than 70 million tonnes of liquefied hydrogen could be required to meet the possible global aviation demand in 2050. It is also estimated that this would require approximately 3,800 TWh of electricity to produce as green hydrogen. The cost of electricity is a key determinant in the ultimate cost of green hydrogen, therefore it is likely that production will also be inherently cheaper in regions with abundant renewable resources, such as the Gulf, North Africa, South America, or Australia. However, as gas price increases in 2021 have shown, there are supply security advantages of local production, which need to be balanced against the cost premium.

To understand the scale of global demand, if this energy were to be generated using offshore wind-generated electricity, it is estimated that approximately 175,000 km^2 of installed wind farms would be required to meet the global aviation hydrogen demand. This area equates to approximately 30% of the North Sea.

If this energy were to be generated through photo-voltaic electricity, in regions with high sunlight intensity, it is estimated that approximately 50,000 km^2 of installed solar panels would be required. This equates to approximately 0.6% of Australia's land area or 2.2% of Saudi Arabia's land area.

To produce this quantity of green hydrogen through electrolysis would also require approximately 1,400 million tonnes of water per year, which can be sourced from purified seawater, limiting the potential conflict of scarce water resources.

03.6 HYDROGEN SUPPLY NETWORK

In the near-term, hydrogen supply is likely to be developed ahead of aviation demand and as such will not necessarily be linked to an airport location.

Figure 3 below identifies regions with high densities of domestic gas usage and fleet vehicles, and locations where hydrogen production has been proposed. Many of these regions are close to airport locations and combine areas of high potential hydrogen demand with characteristics that make them favourable for hydrogen production:

- Close to significant offshore wind generation potential that could be used for green hydrogen
- Close to existing natural gas import terminals and oil and gas fields that could be converted for carbon storage
- Port access for imported liquid hydrogen

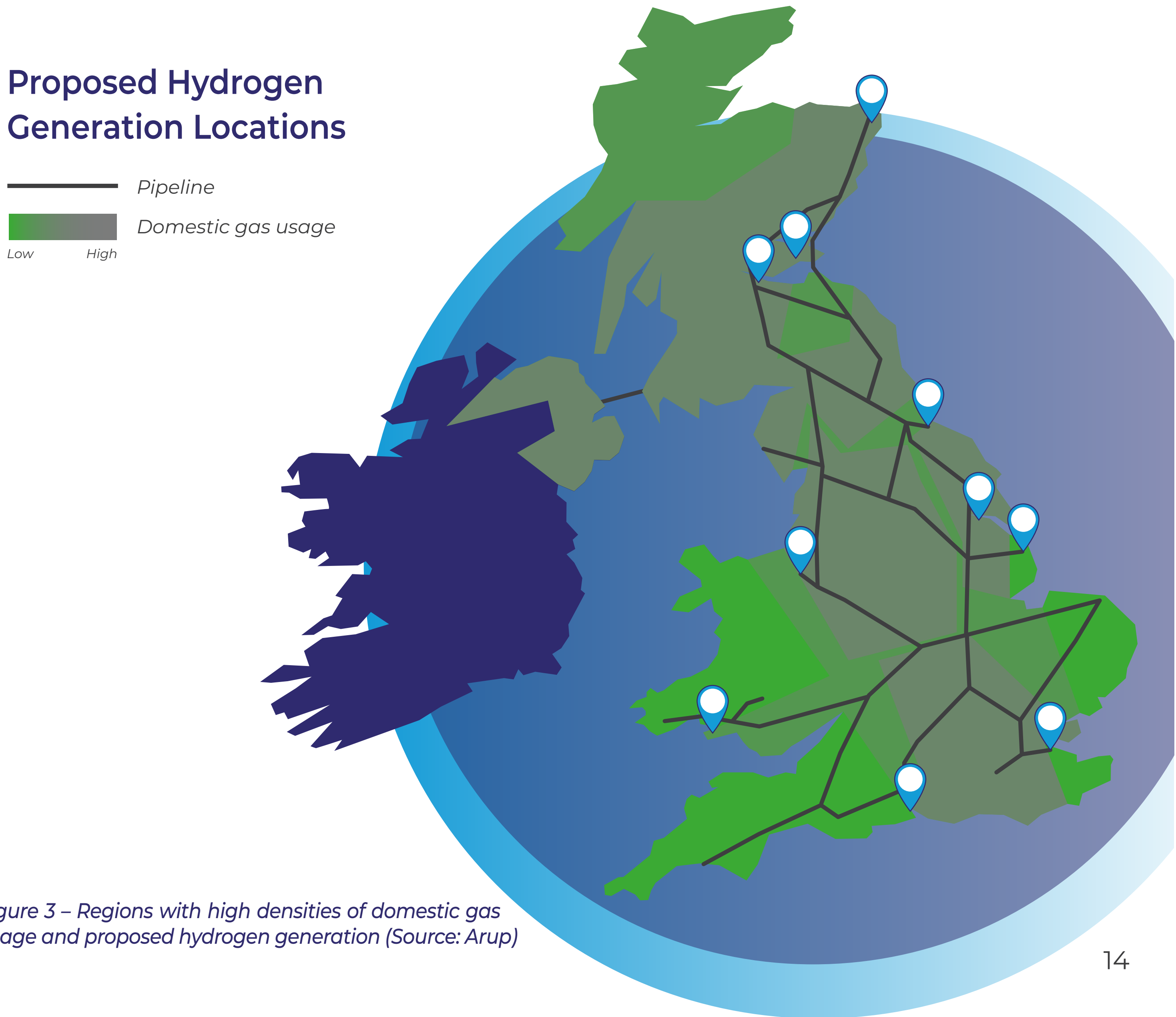


Figure 3 – Regions with high densities of domestic gas usage and proposed hydrogen generation (Source: Arup)

It is plausible that hydrogen production will be established in these regions ahead of aviation demand. Given that these regions have access to land and substantial electrical supplies, they could be expected to develop liquefaction capability to support aviation requirements. The road transport distances and relatively low intensity of deliveries mean that this is a feasible supply route for the near and medium-term.

In the longer term, all three National Grid scenarios exceed the 5GW supply ambition. By this time however, the actual national supply pathway will have been defined. Depending on the combination of national scenario and hydrogen aviation growth scenario, aviation could require between 10% to 30% of the national demand. Therefore, while aviation is a large potential user of hydrogen, it is the wider market that will be the driver for hydrogen production capacity.

Aviation's particular need for liquefaction of hydrogen at scale will require technical development and investment, which may not necessarily be part of the wider hydrogen economy. That said, production facilities will have access to large quantities of electrical power and space, so will be well-placed to liquefy hydrogen too – especially if they have access to cheap electricity.

If surface transport of liquid hydrogen from such locations becomes too intense as demand increases, then there may be a case for more distributed liquefaction plants, making use of hydrogen piped via the national network, to regional industrial locations (with access to sufficient electrical power) where hydrogen is liquefied and tankered (by road and/or rail) to the nearby airport(s).

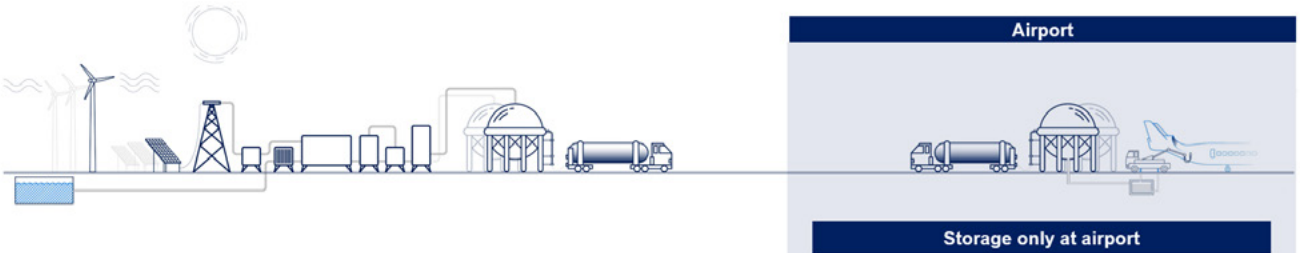
Liquefaction at an airport is also an option, subject to sufficient space being made available. Furthermore, access to a hydrogen pipeline and low-cost electricity are also necessary. The circumstances under which on-airport liquefaction becomes necessary due to surface access mitations and constraints tend to go together with the increasing quantity of hydrogen required.

03.7
AIRPORT HYDROGEN SUPPLY

How hydrogen is delivered to the airport will likely depend on the size of the airport, the location and geography of the airport and the scale of hydrogen demand. Some airports may transition between different supply options as demand increases.

The potential hydrogen delivery methods can be summarised by the three scenarios below:

- **Scenario 1 –** Hydrogen generated and liquefied off-site, supplied by road tankers to the airport.



- **Scenario 2 –** Hydrogen generated off-site, supplied in a gas pipeline to the airport and liquefied at the airport.

- **Scenario 3 –** Hydrogen produced and liquefied locally at the airport.

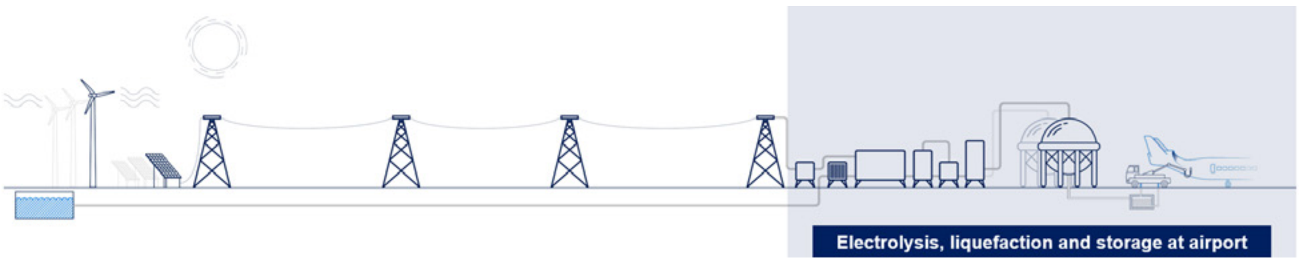


Figure 4 – Airport hydrogen supply scenarios (Source: Jacobs/FlyZero)

Scenario 1 is likely to be the preference for most airports in the initial years of aircraft operation due to its lower capital cost compared to scenarios 2 and 3. However, when the frequency of tanker deliveries increases to a level that may cause congestion on local roads or the off-load point, then either scenario 2 or 3 may be the preferred solution. For example, at larger airports, by 2050 almost 500 tanker deliveries a day could be required.

The choice between scenario 2 or 3 will be based on the most economically advantageous approach in the context of a particular airport. However, in scenario 3, for large airports, the energy requirement for electrolysis is likely to be very high, making this an unattractive option. For example, by the year 2050 a typical large hub airport could require between 3.5 – 4.5 GW (30 – 40 TWh) for electrolysis and liquefaction, compared with an existing requirement of approximately 50-90 MW. Therefore, it is anticipated that for most airports, once tanker delivery is no longer viable, there will be a requirement for a gaseous hydrogen pipeline supply feeding on-airport liquefaction. A pipeline would also be able to supply gaseous hydrogen for alternative use cases at airports, such as heating and ground support equipment.

Airport Size	*2035*	*2040*	*2045*	*2050*
Large	*Scenario 1 or 2*	*Scenario 2*	*Scenario 2*	*Scenario 2*
Medium	*Scenario 1*	*Scenario 2*	*Scenario 2*	*Scenario 2*
Small	*Scenario 1*	*Scenario 1*	*Scenario 1*	*Scenario 1*

Table 2 – Likely airport hydrogen delivery scenarios

04. AIRPORT HYDROGEN INFRASTRUCTURE

The airport infrastructure required will depend on the hydrogen delivery scenario. Based on the baseline FlyZero forecast, assuming the development of a regional hydrogen aircraft first, this section assesses the anticipated infrastructure requirements.

04.1 SCENARIO 1 – LIQUID HYDROGEN DELIVERED TO THE AIRPORT

The simplest distribution scenario is based on the principle of liquid hydrogen being delivered to the airport by road tankers, where it is offloaded into storage tanks. These storage tanks are used to supply the distribution system and are sized to meet the airport demand. For the purposes of illustration, sizes shown in this report assume that an airport will need to hold a two-day fuel buffer stock in case of disruption to the hydrogen supply. The actual buffer will depend on the certainty and resilience of supply, together with the risk analysis on the impact of fuel disruption.

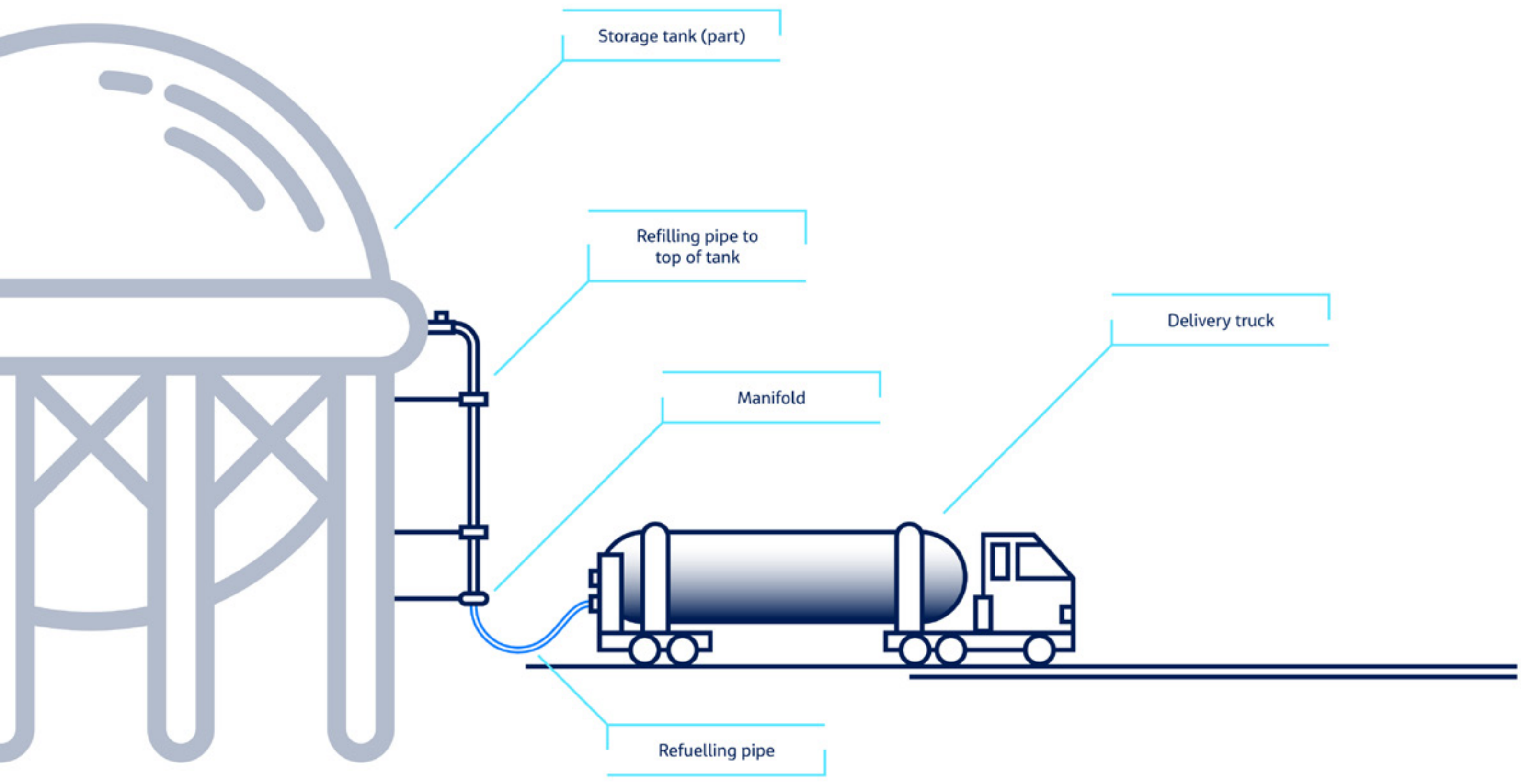


Figure 5 – Scenario 1 – Liquid hydrogen delivered to airport storage tanks (Source: Jacobs)

All cryogenic liquids have to be stored in highly insulated tanks to prevent the temperature of the liquid rising to a point where it vaporises. Liquid hydrogen storage is not a new concept and there is already an established industry with manufacturers that can supply products to meet the infrastructure demand.

Cryogenic temperatures are difficult to maintain and a significant amount of energy is required to cool a system down to -253˚C. Therefore, maintaining a tank's cryogenic temperature and not allowing the temperature to return to ambient is important for the efficient operation of a liquid hydrogen storage system. Not only does maintaining a consistent cryogenic temperature help with operational energy efficiency, but it also affects the material of the storage tank. Any significant expansion and contraction of the tank occurring due to emptying and refilling the tank, could lead to fatigue cracking if the cycle is repeated frequently. Therefore, although having a highly insulated storage tank is important, in all scenarios, the vessel needs to work synergistically with the distribution system.

Airport Size	*Small*		*Medium*		*Large*	
Year	*2035*	*2050*	*2035*	*2050*	*2035*	*2050*
Million Passengers Per Annum (MPPA)	*7.5*	*10*	*35*	*50*	*110*	*135*
Average Daily LH_2 Demand (million litres)	*0.1*	*0.7*	*0.6*	*6.5*	*1.5*	*22*
LH_2 Tanker Deliveries Per Day	*4*	*20*	*20*	*180*	*40*	*480*
Frequency of Tanker Deliveries (mins between deliveries)	*370*	*75*	*80*	*8*	*36*	*3*
LH_2 Storage Requirement (million litres)	*0.5*	*2.5*	*1.5*	*16*	*3.5*	*52*
Space Requirement (sqm)	*2,000*	*11,000*	*6,500*	*50,000*	*15,000*	*110,000*

Table 3 – Scenario 1 summary – Liquid hydrogen delivered to the airport

04.2 SCENARIO 2 – GASEOUS HYDROGEN PIPELINE SUPPLY TO THE AIRPORT

As hydrogen demand increases, an alternative to tanker deliveries may be required to remove the pressure on local road infrastructure and airport operations. Scenario 2 removes the need for tankers by replacing them with a pipeline supplying gaseous hydrogen to the airport. However, as the aircraft require liquid hydrogen, the gas needs to be liquified in a liquefaction facility before being transferred to the storage tanks.

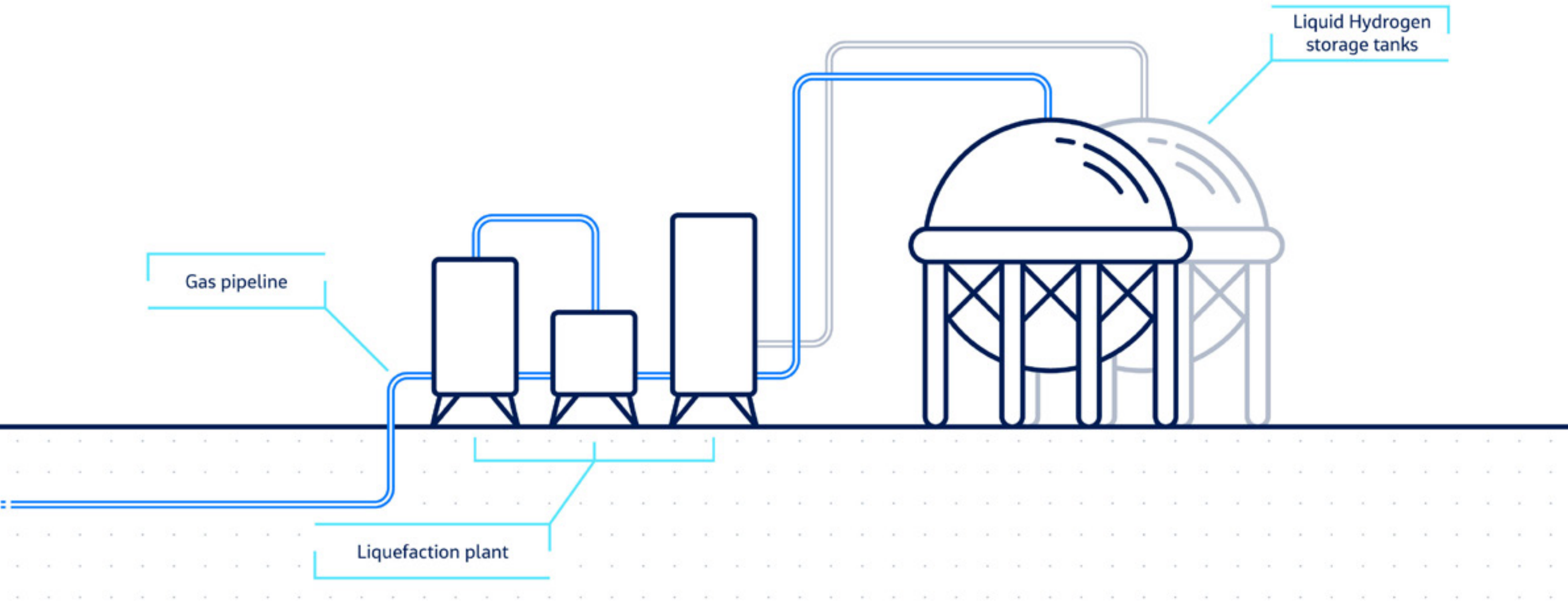


Figure 6 – Scenario 2 - Gaseous hydrogen pipeline supply to the airport with on-site liquefaction (Source: Jacobs)

The pipeline diameter will vary depending on many variables, including airport size, uptake of hydrogen aircraft, pipe length, the pressure differential and the number of bends and valves. Distribution of hydrogen gas by pipeline over long distances is a feasible technology and is likely to be widely adopted in the future, through both the construction of purpose-built hydrogen pipelines and repurposed natural gas pipelines.

Pipeline transport of hydrogen is the most effective method of moving large volumes of gaseous hydrogen and can be achieved either as pure hydrogen at different pressures or by blending into natural gas transmission and distribution pipeline systems at various blend percentages and pressures. However, it is unlikely that blending would be an effective method of transporting hydrogen for large demand users of hydrogen, particularly once the widespread use of natural gas has reduced.

Pipeline transport requires a large capital investment to construct the new pipeline and associated compression facilities and other above ground installations. Reuse of steel natural gas high pressure transmission pipelines is a challenge due to the propensity for hydrogen embrittlement, which could lead to leakage. Reuse of the natural gas distribution system pipelines is likely to be less of a challenge as replacement of the cast iron mains with polyethylene (PE) means that the gas distribution networks are substantially hydrogen ready.

Airport Size	*Small*		*Medium*		*Large*	
Year	*2035*	*2050*	*2035*	*2050*	*2035*	*2050*
Million Passengers Per Annum (MPPA)	*7.5*	*10*	*35*	*50*	*110*	*135*
Average Daily LH_2 Demand (million litres)	*0.1*	*0.7*	*0.6*	*6.5*	*1.5*	*22*
Gaseous Pipe Supply to Airport (mm)	*75*	*150*	*100*	*300*	*150*	*450*
Liquefaction Power Requirement (MW)	*5*	*20*	*20*	*200*	*50*	*650*
LH_2 Storage Requirement (million litres)	*0.5*	*2.5*	*1.5*	*16*	*3.5*	*52*
Space Requirement (sqm)	*3,000*	*13,000*	*10,000*	*75,000*	*20,000*	*180,000*

Table 4 – Scenario 2 summary – Gaseous hydrogen delivered to the airport

04.3 SCENARIO 3 – HYDROGEN GENERATED ON-SITE

The final scenario assumes that hydrogen is produced at the airport using electrolysis. The off-site inputs into this system are therefore electricity from the power grid and water from the local water network. Electrolysis and, to a lesser extent, liquefaction requires significant electrical power. If located at the airport this will require high power electrical lines to deliver the energy required. Electrical power lines can transport large amounts of energy, although not as much as large diameter gas pipelines. For example, to supply a large airport with electricity for electrolysis may require multiple dedicated 400 kV overhead power lines, compared with a single pipeline to supply the equivalent hydrogen to the airport. Due to these high power requirements, it is unlikely that this scenario will be suitable at most airports.

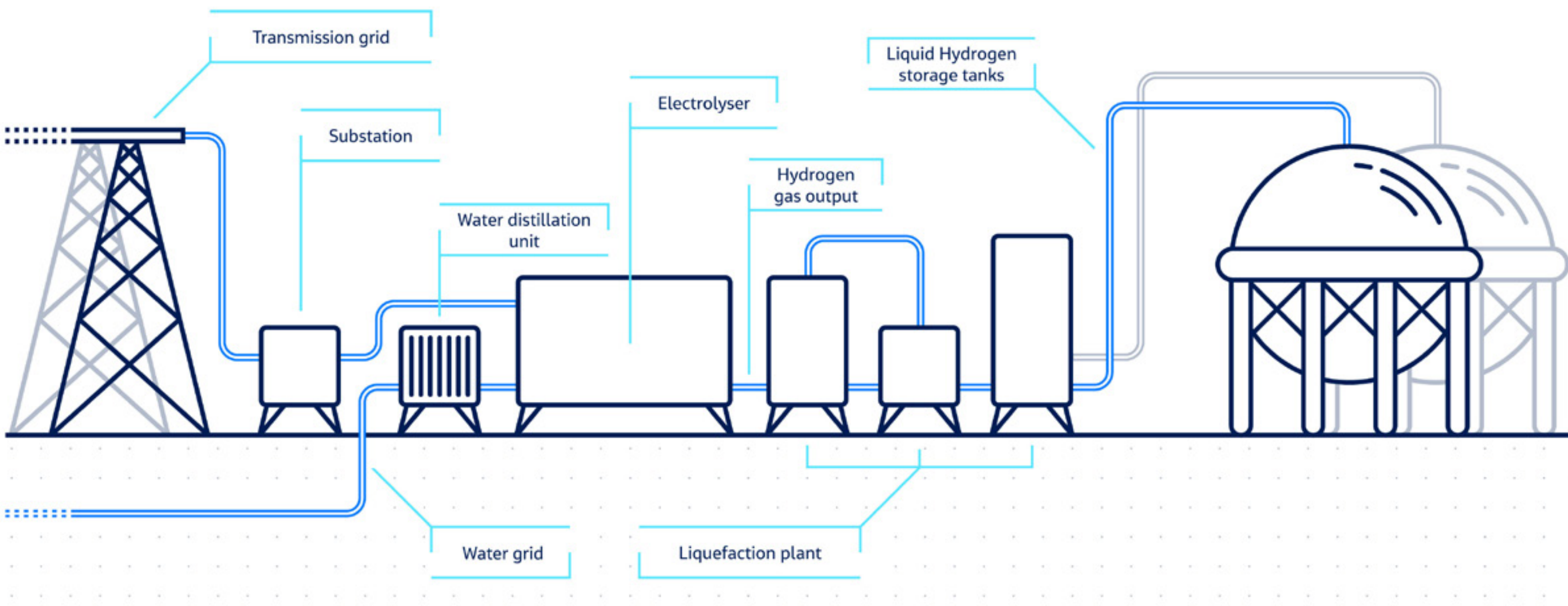


Figure 7 – Scenario 3 - On-site electrolysis and liquefaction (Source: Jacobs)

Electrolysis is the process of using electricity to split water into hydrogen and oxygen in an electrolyser. The carbon footprint of this green hydrogen depends upon the carbon footprint of the source electricity and electrolysis efficiency. Electrolysers typically generate high purity hydrogen directly for use in fuel cell applications.

Airport Size	Small		Medium		Large	
Year	2035	2050	2035	2050	2035	2050
Million Passengers Per Annum (MPPA)	7.5	10	35	50	110	135
Average Daily LH_2 Demand (million litres)	0.1	0.7	0.6	6.5	1.5	22
Electrolyser Power Requirement (MW)	30	150	125	1,500	300	4,250
Electrolysis Water Requirement (litres/hr)	5,000	25,000	22,500	250,000	50,000	725,000
Liquefaction Power Requirement (MW)	5	20	20	200	50	650
LH_2 Storage Requirement (million litres)	0.5	2.5	1.5	16	3.5	50
Space Requirement (sqm)	4,000	18,000	13,000	130,000	30,000	325,000

Table 5 – Scenario 3 summary – Hydrogen generated on-airport

04.4 SPACE REQUIREMENTS SUMMARY

The figure below summarises the overall spatial requirements at typical airports for each infrastructure scenario in 2050.

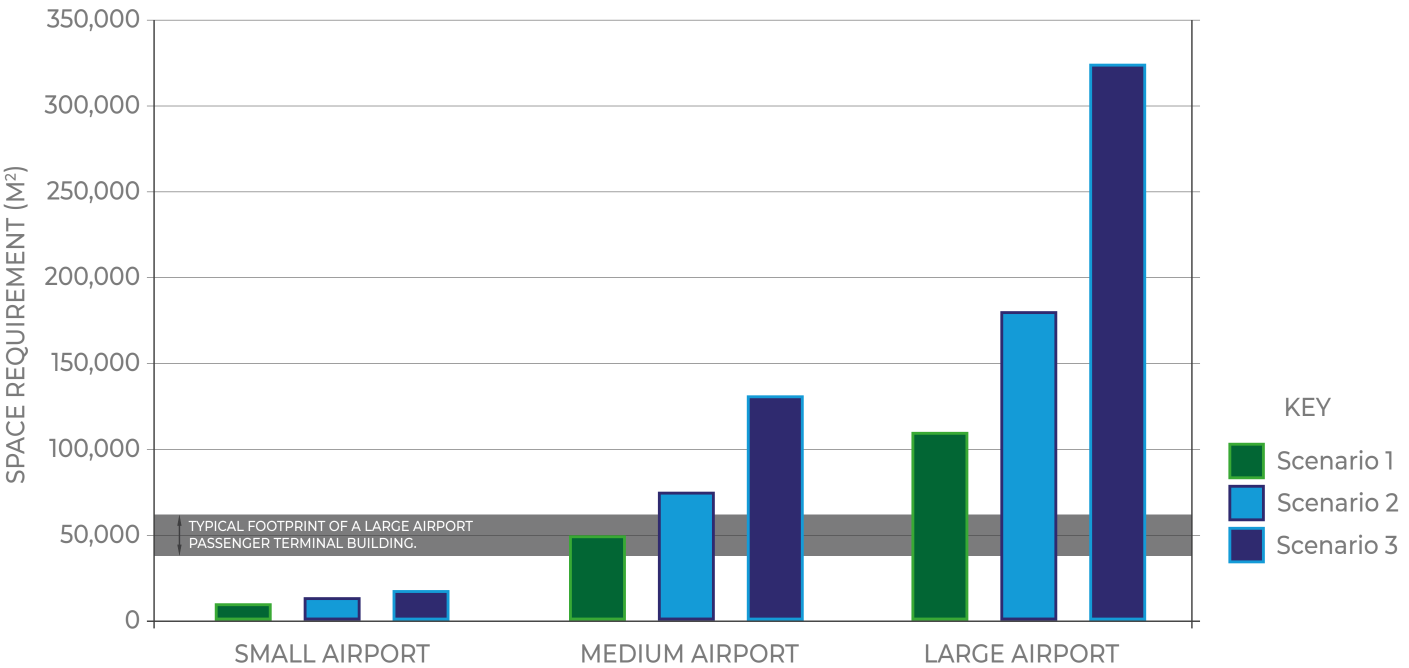


Figure 8 – Hydrogen infrastructure spatial summary requirements by 2050

04.5
HYDROGEN DELIVERY TO THE AIRCRAFT

Whichever way hydrogen is delivered to the airport, after storage, a method of delivery to the aircraft is required. At all airports, bowser refuelling is likely to be the preferred option in the initial years of hydrogen aircraft operation, due to the lower capital cost. However, a hydrant system may be required when the bowser operation begins to cause congestion at the refuelling point and on the internal road network.

The decision as to the need to adopt a hydrant system would depend on each individual airport, however based on an assessment of typical bowser demand, Table 6 indicates when a hydrant system may be required, based on the FlyZero forecasts.

Airport Size	*2035*	*2040*	*2045*	*2050*
Large	*Bowser*	*Consider Hydrant*	*Hydrant*	*Hydrant*
Medium	*Bowser*	*Bowser*	*Consider Hydrant*	*Hydrant*
Small	*Bowser*	*Bowser*	*Bowser*	*Bowser*

Table 6 – Indicative timescale for the introduction of a hydrogen hydrant refuelling system

04.5.1
BOWSER REFUELLING CONCEPT

Unlike bowsers currently used for kerosene, storage tanks of a hydrogen bowser will need to be insulated to maintain hydrogen in its liquid form.

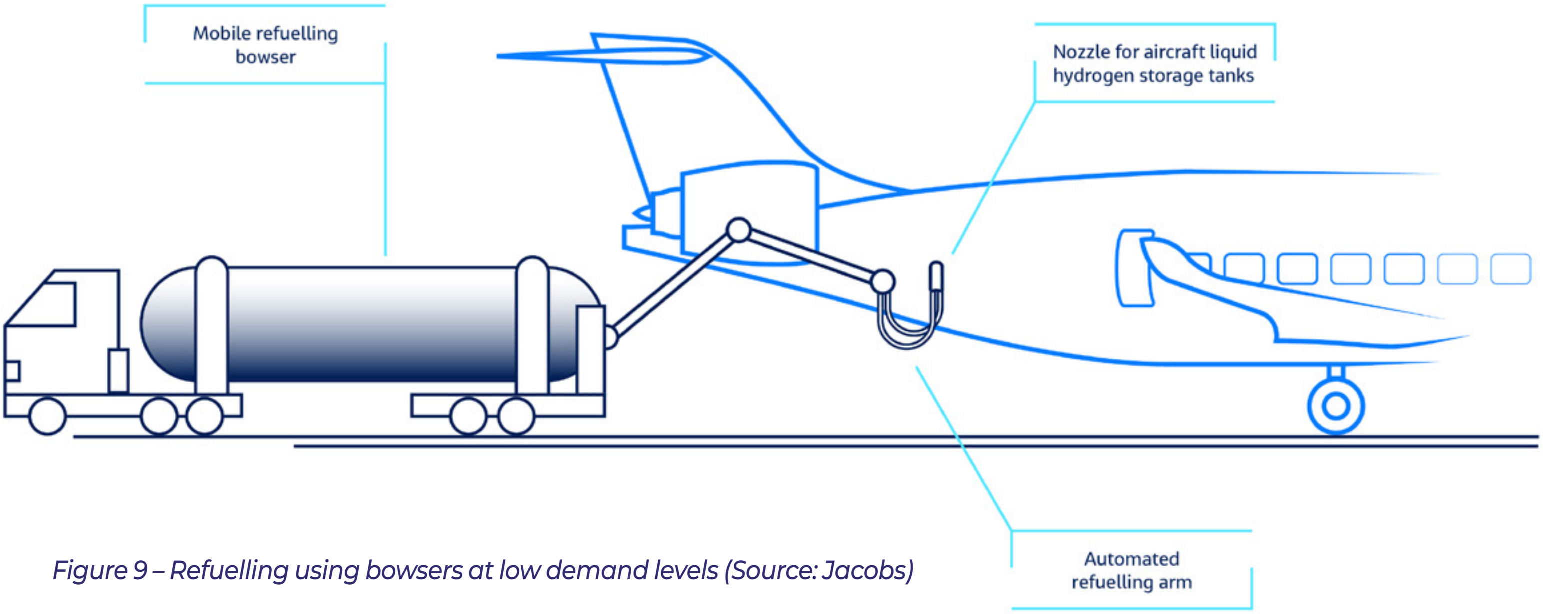


Figure 9 – Refuelling using bowsers at low demand levels (Source: Jacobs)

Refuelling using bowsers is likely to be manageable until the demand increases to a level where airside road congestion becomes significant, or the number of bowsers increases to unmanageable levels. Based on analysis of typical airports, Table 7 below indicates the number of 20,000 or 40,000 litre bowsers potentially required to meet the demand for hydrogen, assuming that aircraft are refuelled to meet their flight requirements rather than maximum tank size. The operation of tankering for return flights, or extended flight range would increase the number of bowsers required. Due to the lower energy density of liquid hydrogen by volume compared with kerosene, the threshold for requiring a hydrant will be reached sooner for hydrogen operations.

Airport Size	Small		Medium		Large	
Year	2035	2050	2035	2050	2035	2050
No. of 20,000 litre tankers	1	5	2	25	6	90
No. of 40,000 litre tankers	1	4	2	20	5	70

Table 7 – Indicative bowser requirement to meet hydrogen aircraft demand

04.5.2 HYDRANT REFUELLING CONCEPT

A hydrant system would need to use a cryogenic pipeline to transport liquid hydrogen from the storage location, directly to the aircraft stand. The proposed hydrant system has many similarities to the kerosene hydrant distribution system that is currently used at large airports around the world today.

However, there are two significant differences. First, the system needs to be capable of distributing liquid hydrogen at -253 °C. Second, the means of moving the liquid hydrogen through the pipes from the storage tanks to the aircraft tanks should minimise the use of pumps, as these would add energy to the liquid hydrogen, increasing boil-off.

There are two types of pipe technology that can be used to distribute liquid hydrogen from the storage tanks to the refuelling stands: vacuum jacket or solid insulation pipes. The most common solution, a vacuum jacket pipe, would require a culvert below the surface of the airport's taxiways and aprons. It is anticipated that the culvert would need to be large enough for a person to walk along, enabling the pipe to be visually inspected and the vacuum maintained. In addition, the top of the culvert would need to be open to prevent the possibility of gas accumulating in the event of hydrogen leakage. **Figure 10** illustrates a concept of the culvert configuration. Downsides of this type of installation are the potential disruption to the airport's operations that may be caused during the installation of the culvert and the likelihood that the hydrant route would clash with already installed utilities. This clash may require the diversion of existing utilities, adding significantly to the construction costs.

The system proposed in **Figure 10** includes a liquid hydrogen vacuum jacket pipe, with a secondary return pipe for hydrogen gas boil-off. It may also be possible to integrate the boil-off within an outer layer of the pipe, helping to minimise heat loss from the liquid hydrogen central core. The gaseous hydrogen can be re-liquefied for aircraft use or utilised for other applications, such as direct combustion for airport boilers or to refill fuel cells for gaseous hydrogen ground support equipment. Potential alternative systems may also be considered for further investigation:

- **A looped hydrant system** which would keep liquid hydrogen flowing to reduce boil-off, however this would increase costs and may create challenges with pressure differentials.
- **A cryogenic hydrogen gas pipeline** would be easier to install and operate, however it would require multiple liquefaction systems at stands.

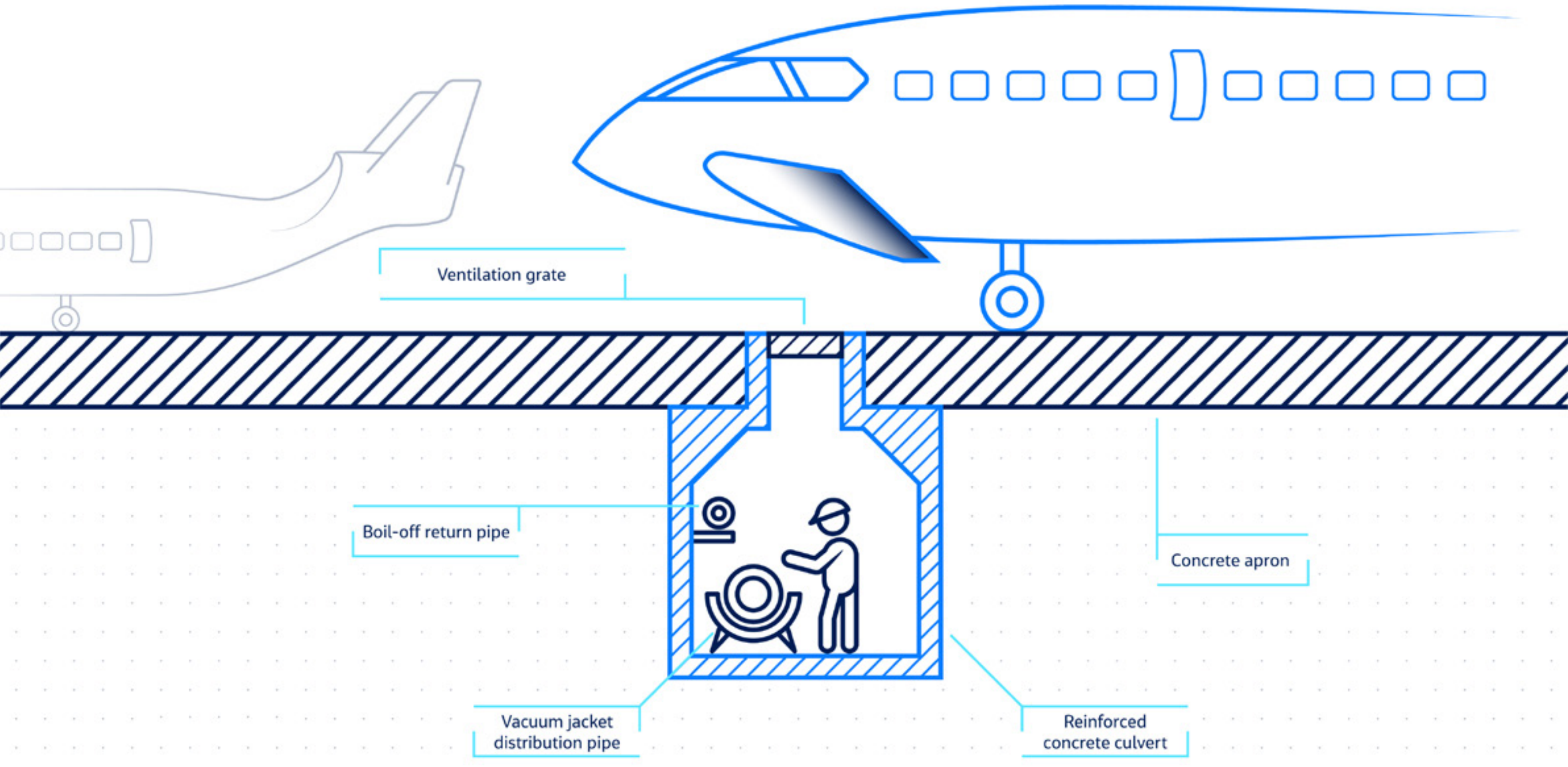


Figure 10 – Hydrant system concept (Source: Jacobs)

An initial evaluation for a typical mid to large airport installation suggests a hydrant with a diameter of approximately 500 mm, however a more detailed analysis would be required to understand this further.

The means of creating flow in the pipe will most likely be through creating a pressure differential between the storage tank and the receiving tank. The pressure differential is created by a frequently used method of pressurising the storage tank, which utilises the expansion properties of cryogenic hydrogen gas. The volume ratio between liquid hydrogen and hydrogen gas at ambient temperature is 1:845. Therefore, to create pressure in the storage tank an amount of liquid hydrogen is removed from the storage tank and allowed to vaporise. It is then introduced back into the tank so that as it gradually warms it expands and applies pressure to the liquid hydrogen. Once the required pressure has been achieved the outlet valve on the tank is opened and the hydrogen flows to the destination tank.

In the case of hydrogen infrastructure at airports this process would occur on a continuous basis during the operating hours across the tanks in the storage fuel farm. One area of complexity that this method introduces is maintaining a controllable pressure at the point at which the aircraft is being refuelled. It is quite probable that the aircraft stands will be located a kilometre or more from the storage tanks and it is certain that there will be multiple aircraft being refuelled at the same time.

If a hydrant pipe network is laid out similarly to a kerosene pipe network, where there is a single backbone pipe with branches to each stand, it will be very difficult to accurately control the pressure differential from the storage tank to the stand. Therefore, a solution will be required at the stand to adjust the pressure of the liquid hydrogen from the hydrant to the pressure required for refuelling the aircraft's tanks. An alternative to this would be to have individual pipes from the fuel farm to each stand. However, this is likely to be hugely expensive and would impose significant maintenance demands on the airport.

A potential proposed solution to these challenges is to use a transfer tank, or tanks, located at each stand. The transfer tank would be sized to match the maximum fuel tank size of the aircraft using the stand. Given that installing a hydrant system will only be cost effective at the larger airports it is unlikely that a transfer tank sized for a regional aircraft will be required. Therefore, a transfer tank with a capacity of 40,000 litres would be required at stands servicing narrowbody aircraft and transfer tanks with a combined capacity of 160,000 litres, equivalent to four 40,000 litre tanks, would be required at stands for the larger midsize, aircraft.

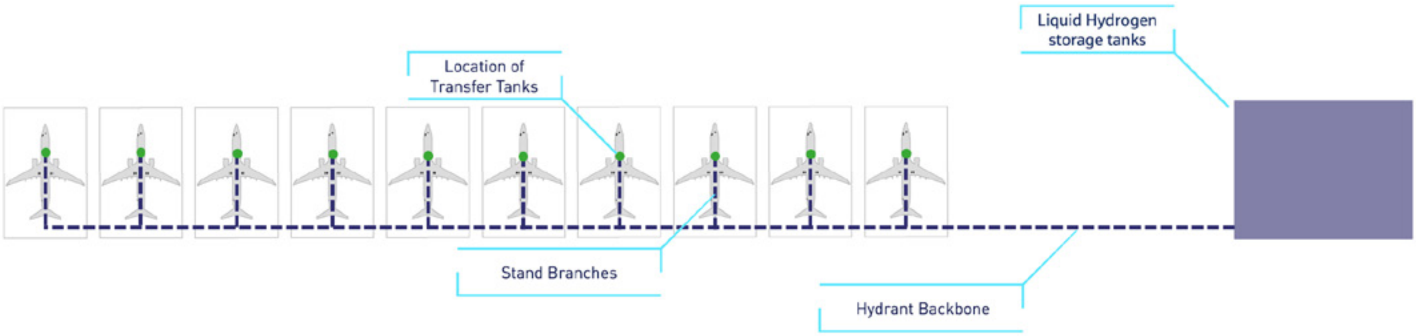


Figure 11 – Hydrogen hydrant concept layout

Transfer tanks could feasibly be located below or above ground.

- Below ground transfer tanks would be buried under the surface of the stand, having the advantage of minimising space intrusion on the stand. However, there would be a significant cost related to building an underground reinforced concrete and steel lined tank or tanks, which would be difficult to replace at the end of their working life. Initial estimates suggest that installing one tank could cost up to £450,000.
- Above ground tanks have the advantage of being a standard design that could be cheaper than the buried tank and easier to replace. However, they would take up valuable space at the stand, which is only likely to be available at those airports where the stands are well spaced out, or at new terminals where the stands can be designed based on this requirement. As these tanks may need to be located further away from the aircraft than a below ground tank, the increased length of pipework may limit the benefit of the reduced tank costs.

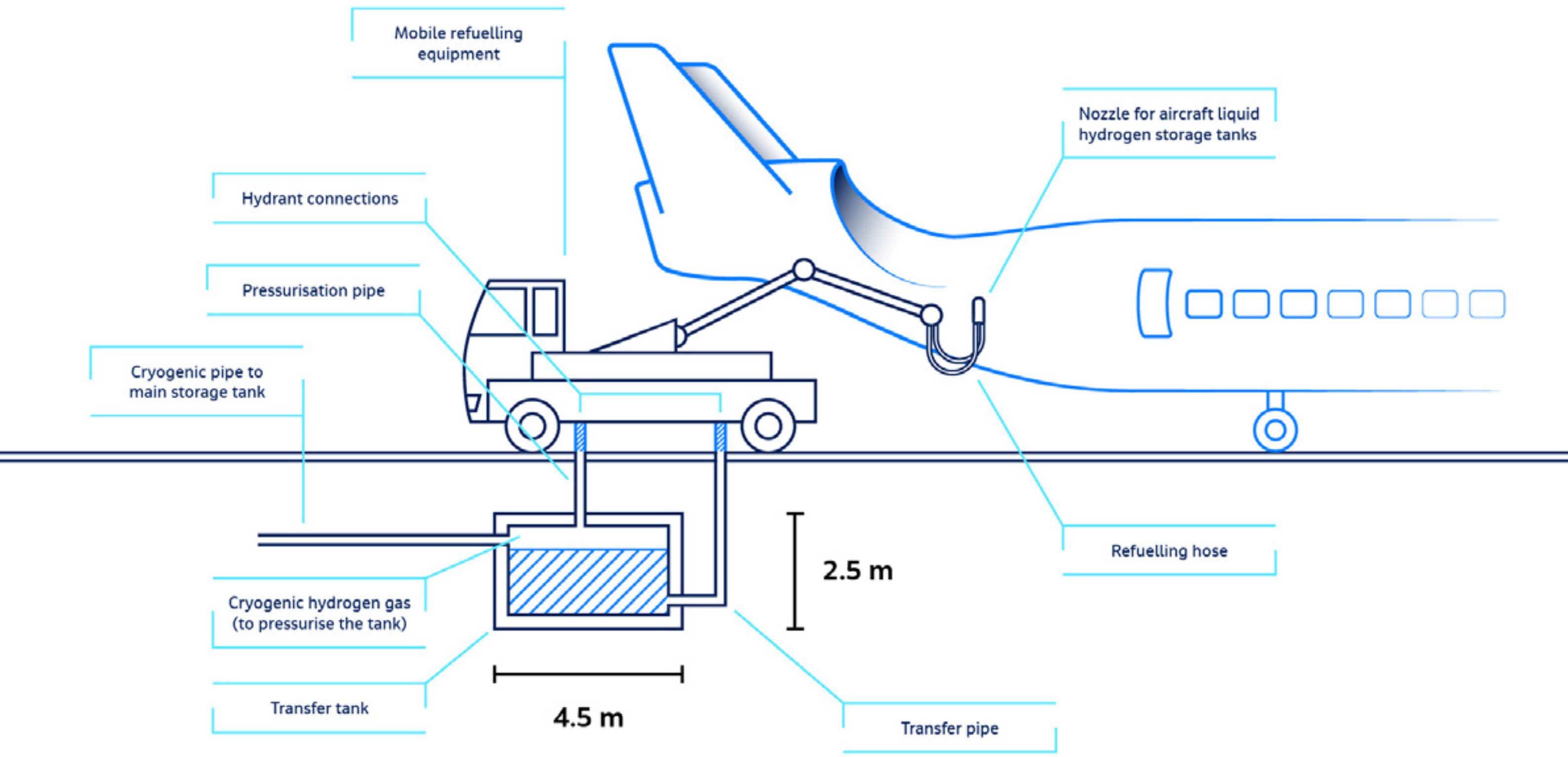


Figure 12 – Below ground transfer tank concept (Source: Jacobs)

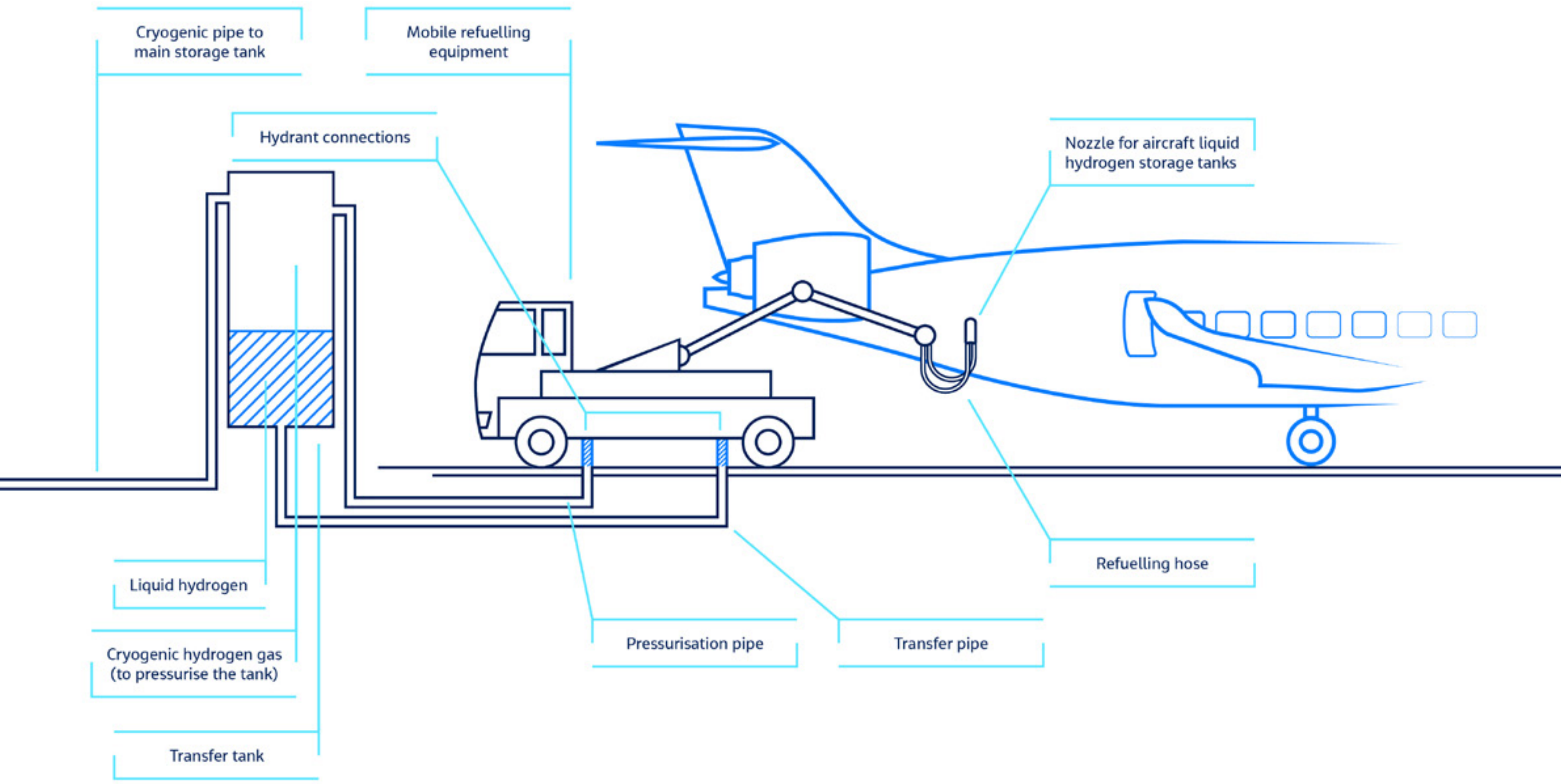


Figure 13 – Above ground transfer tank concept (Source: Jacobs)

05. INFRASTRUCTURE COSTS

The use of liquid hydrogen at the scale required for aviation is untested, therefore cost estimates vary considerably. However, based on current benchmarked sources of data for the major components of the hydrogen infrastructure system, the two tables below show a range of potential costs. These estimates represent aggregated costs from 2030 to 2050. The highest and lowest benchmarks have been used to calculate upper and lower bound capital cost forecasts. A median figure is shown, however given the complexities, uncertainties and risks involved in building new infrastructure at an airport, it is reasonable to assume that the actual costs may lie closer to the upper bound figure. All figures are shown in millions of Pound Sterling (GBP).

Airport Size	*SCENARIO 1: Liquid hydrogen delivered to the airport*		*SCENARIO 2: Gaseous hydrogen pipeline supply to the airport*		*SCENARIO 3: Hydrogen generated on-airport*	
	Median cost	*+/-*	*Median cost*	*+/-*	*Median cost*	*+/-*
Large	*325*	*225*	*625*	*500*	*2,500*	*1,300*
Medium	*100*	*60*	*200*	*150*	*850*	*400*
Small	*20*	*10*	*25*	*25*	*100*	*50*

Table 8 – Cost estimate assuming bowser operation (£m).

Airport Size	*SCENARIO 1: Liquid hydrogen delivered to the airport*		*SCENARIO 2: Gaseous hydrogen pipeline supply to the airport*		*SCENARIO 3: Hydrogen generated on-airport*	
	Median cost	*+/-*	*Median cost*	*+/-*	*Median cost*	*+/-*
Large	*525*	*250*	*850*	*525*	*2,750*	*1,300*
Medium	*175*	*75*	*275*	*175*	*925*	*425*
Small	*40*	*15*	*50*	*25*	*115*	*50*

Table 9 – Cost estimate assuming hydrant operation (£m)

To mitigate some of the investment costs, the move towards a UK-wide hydrogen economy may present potential revenue opportunities. In all hydrogen supply scenarios, facilities such as the storage tanks will be sized based on the peak aircraft refuelling demand. During off-peak periods, there is likely to be capacity that is surplus to operational requirements. This surplus will vary on a daily or seasonal basis. Hydrogen that is surplus to demand could potentially be used elsewhere at the airport or sold to third parties to generate additional revenue for the supplier. It may also be possible to oversize facilities further to allow for surplus hydrogen even during the peak aircraft demand period, providing continuous additional revenue for the airport or supplier. Potential alternative uses including filling stations for cars, buses or cargo vehicles, trains, ground support equipment (GSE), back-up power, nearby industry or connection into a wider or national hydrogen grid. Heating provides a particular opportunity, as often airport demand for aircraft fuel is lower in the winter, when fuel demand for heating is high.

06. AIRPORT INFRASTRUCTURE TECHNOLOGY READINESS LEVELS

Technology readiness levels (TRLs) were originally developed by NASA in the 1970s to measure the maturity of technology throughout its research, development, and deployment phase progression. TRLs are based on a scale from 1 to 9, with 9 being the most mature technology.

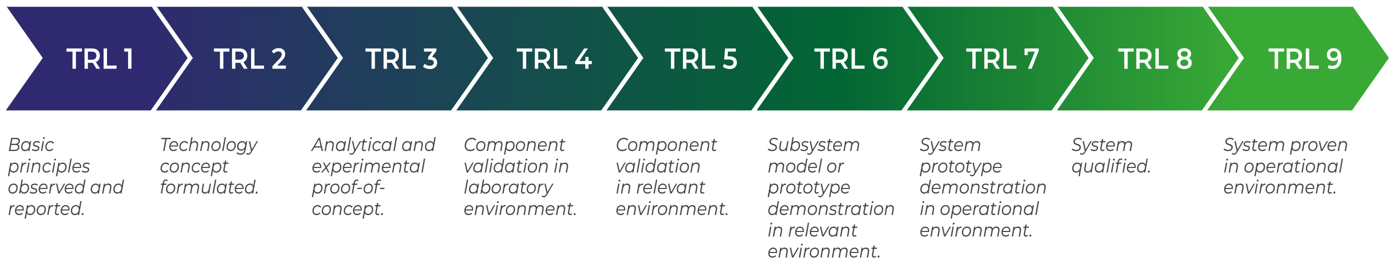


Figure 14 – Technology has been assessed against an adapted NASA Technology Readiness Level (TRL) scale.

Table 10 below identifies where each of the key airport component technologies lie on this scale. For components below TRL8, which represents the end of the technology roll out phase, the table also identifies what is needed to reach that level.

Component	Current TRL	Comment on Current TRL	Action to Reach TRL8
Liquid hydrogen storage tanks	TRL9	Large LH_2 tanks are in common use globally.	n/a
Hydrogen liquefaction system	TRL7-9	Small and large scale liquefiers are in common use globally.	Although liquefiers are in common use these are not at the scale required for future aviation requirements. Operational experience at larger scale needs to be gained.
Electrolysers	TRL7-8	Electrolysers (5 MW) are starting to be deployed.	Projects involving ~100 MW electrolysers have been announced. Operational experience of these need to be gained by 2035 to prove the validity of Scenario 3.
Gas Pipeline	TRL5-6	Pipelines that transport 100% hydrogen gas are used within industrial facilities but not in long-distance applications.	The EU Hydrogen Backbone project intends to develop a network of hydrogen gas pipelines across Europe. This would enable gaseous H_2 to be delivered to an airport in Scenario 2.
Delivery Tankers	TRL9	Liquid hydrogen deliveries by truck are common today.	n/a

Table 10 – Airport hydrogen infrastructure TRL status (continued on next page)

Component	*Current TRL*	*Comment on Current TRL*	*Action to Reach TRL8*
Liquid Hydrogen Hydrant System – Cryogenic Pipe	*TRL5-6*	*Cryogenic pipes for LH_2 are common in the space and gas sectors. However, there are application differences in an airport, i.e. maintaining pressure and preventing boil-off with a large number of branches from a backbone pipe.*	*Analysis is required to model the operation of an LH_2 pipe network at an airport. A demonstration network would need to be built and tested to determine how the integration with the main storage tank would be managed.*
Liquid Hydrogen Hydrant System – Transfer Tank	*TRL2-3*	*The use of a transfer tank is not new, but the design of a below ground tank suitable for use in an airport does not currently exist.*	*A demonstration tank would need to be built and tested through multiple refill cycles to determine the projected reliability and lifetime of the tank, in parallel to the operational concepts of refuelling the aircraft.*
Liquid Hydrogen Hydrant System – Mobile Refueller Vehicle	*TRL1-2*	*A mobile refueller that can be used to connect and disconnect the refuelling hose(s) to the aircraft using robotic automation, purge the aircraft tank and refuelling hoses, pressurise the transfer tank, and avoid leaks does not exist.*	*Much of the hydrogen technology for the vehicle already exists. However, there will be a lot of systems integration and automated control software that will need to be developed. A demonstration vehicle will need to be developed and tested through a comprehensive set of operational scenarios.*
Liquid Hydrogen Hydrant System – Overall System	*TRL1-2*	*Nothing on the scale of the system need for an airport has been developed.*	*A considerable amount of systems design, integration and testing work needs to be undertaken.* *A demonstration system will need to be built and tested through a comprehensive set of operational scenarios.*
Liquid Hydrogen Bowsers – Manually Operated	*TRL3-4*	*The refuelling bowser will be similar to existing hydrogen delivery trucks.*	*A demonstration bowser will need to be designed, built and tested through a comprehensive set of operational scenarios for LH_2, including boil-off capture.*
Liquid Hydrogen Bowsers – Automation Operated	*TRL1-2*	*An automated bowser will be very similar to the mobile refueller vehicle.*	*A demonstration bowser will need to be designed, built and tested through a comprehensive set of operational scenarios.*

Table 10 – Airport hydrogen infrastructure TRL status (continued from previous page)

07. INTRODUCTION OF LIQUID HYDROGEN TO AIRLINE OPERATIONS

While the manufacture, transportation and use of hydrogen in some industries is common today, the introduction of liquid hydrogen refuelling at an airport is a unique and untested process. Airlines and airports currently work to a very safe, efficient and cost-effective schedule to ensure aircraft utilisation and airport capacity are maximised. This section investigates the feasibility of introducing liquid hydrogen refuelling while meeting current turnaround times, through the combined introduction of new technology, regulations, standards and training.

07.1 IMPACT OF HYDROGEN ON AIRCRAFT TURNAROUND

The safety and efficiency of an aircraft turnaround is integral to an airline's operation. Minimising turnaround times enables airlines to maximise an aircraft's flying time, hence maximising revenue and minimising costs. The introduction of liquid hydrogen refuelling is likely to result in unique challenges to the turnaround process, including the possibility of increased turnaround times, larger safety distance requirements and the need for new technology. However, initial FlyZero studies suggest that these challenges can be addressed.

Turnaround times are typically calculated from when an aircraft arrives on stand and is on-blocks to when the aircraft pushes back from the stand and is off-blocks. During this time the aircraft is serviced with many simultaneous activities [5] including, but not limited to:

- Deboarding of inbound passengers
- Unloading inbound cargo and baggage holds
- Cleaning
- Catering
- Fuelling
- Loading outbound cargo and baggage
- Boarding outbound passengers.

Existing minimum turnaround times vary from airline to airline and between aircraft types, but are typically in the region of those shown below:

Aircraft type	*Current Minimum Turnaround Time (mins)*
Midsize	*60 – 90*
Narrowbody	*25 - 30*
Regional	*20 - 25*

Table 11 – Current minimum turnaround times by aircraft type

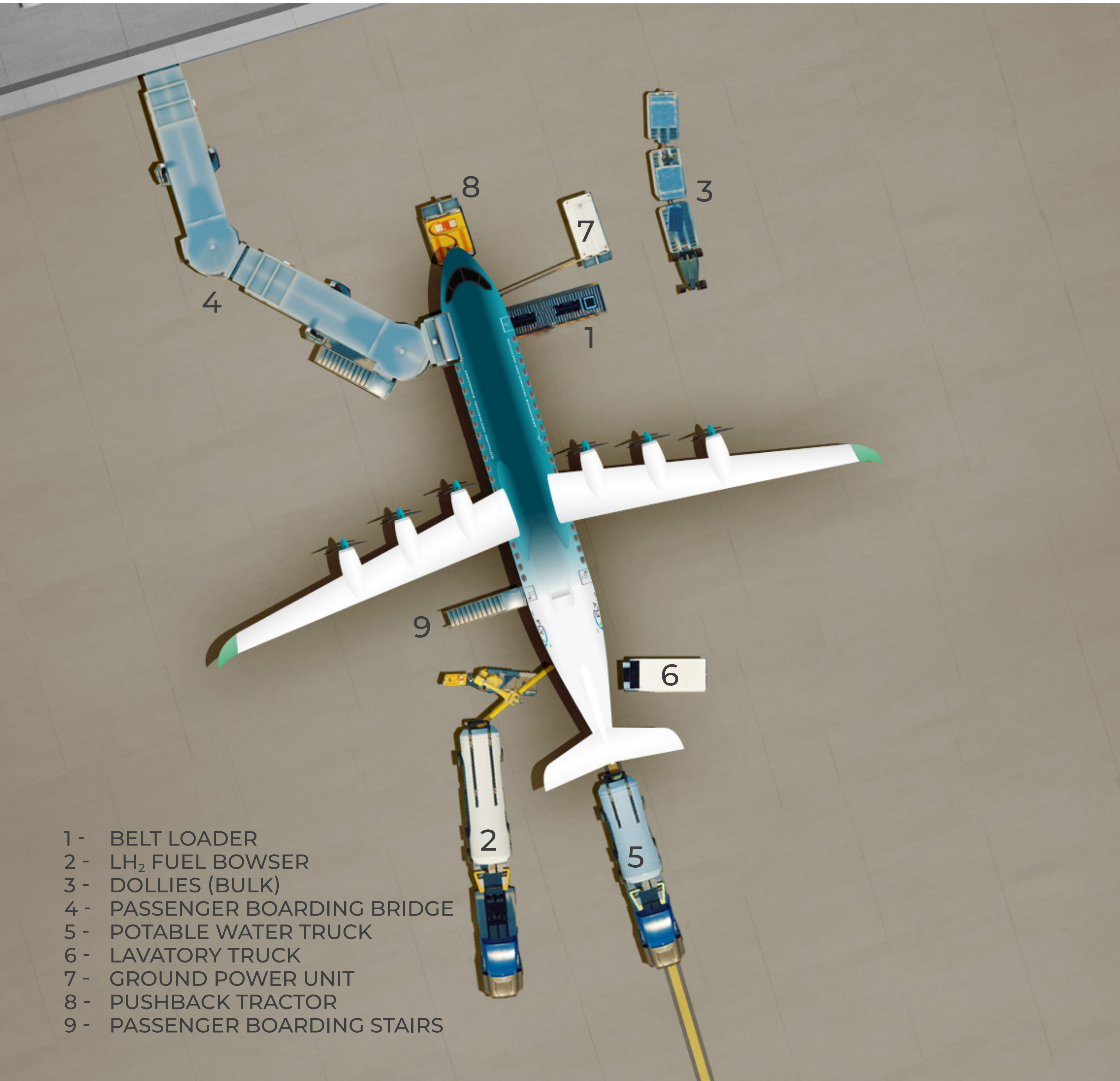


Figure 15a - Ramp handling layout for FlyZero regional concept aircraft

1 - ULD/BELT LOADER
2 - LH_2 FUEL BOWSER
3 - DOLLIES (ULD/BULK)
4 - PASSENGER BOARDING BRIDGE
5 - POTABLE WATER TRUCK
6 - LAVATORY TRUCK
7 - GROUND POWER UNIT
8 - PUSHBACK TRACTOR
9 - CATERING TRUCK
10 - CLEANING TRUCK

Figure 15b - Ramp handling layout for FlyZero narrowbody concept aircraft

Figure 15c - Ramp handling layout for FlyZero midsize concept aircraft

Within the turnaround, some activities can take place simultaneously, while others are interdependent. Currently, activities such as deboarding passengers, servicing the galleys and boarding passengers are on the turnaround's critical path, determining the overall turnaround duration. At many airports, refuelling takes place alongside other activities, however the use of liquid hydrogen, may introduce refuelling into the overall critical path, potentially lengthening turnaround times.

The impact of liquid hydrogen on the critical path will be dependent on the safety exclusion zone required during the refuelling process. The figure below highlights the impact on turnaround times for the FlyZero concept aircraft, if limiting all, or some of the simultaneous activities. To ensure that simultaneous activities can continue, safety rules, regulations and operating procedures must evolve alongside technology. In the below scenarios, the regional aircraft has been refuelled using a single 6'' (15.24 cm) diameter hose, whereas the midsize and narrowbody have been refuelled using two 6'' hoses and a fill velocity of 5 m/s.

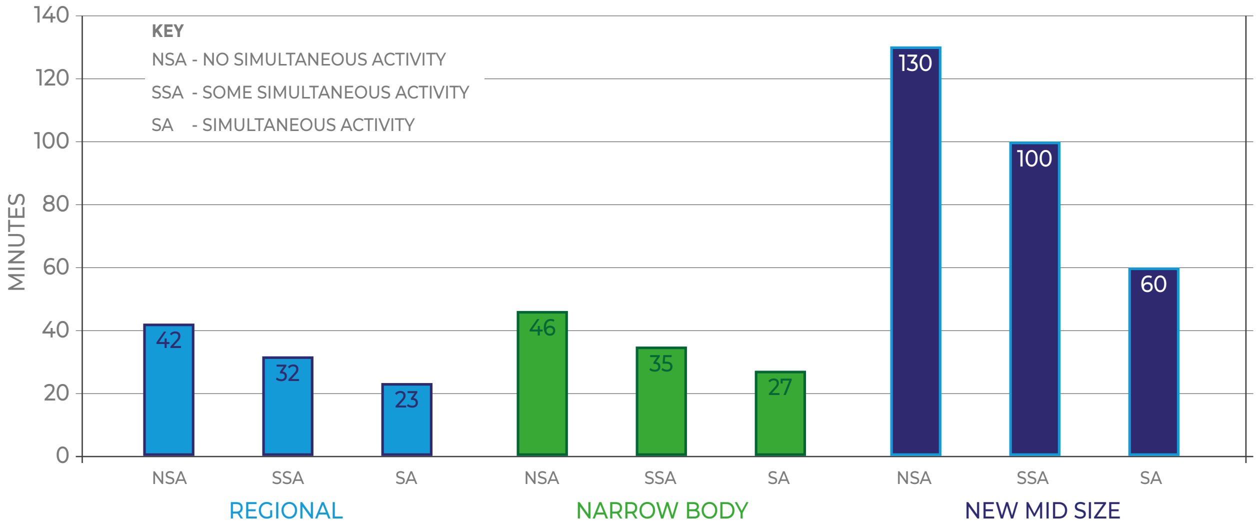


Figure 16 – Estimated turnaround times of FlyZero concept aircraft

07.2
AIRCRAFT FUELLING WITH HYDROGEN

In liquid form, hydrogen has a lower density than kerosene (~71 vs ~800 kg/m^3 **[6, 7]**). Therefore refuelling using liquid hydrogen with the same diameter hose and flow rate would take longer than with kerosene. This highlights the requirement for larger diameter hoses and multiple refuelling hoses used simultaneously to enable a faster refuelling time.

Figure 17 - Multiple refuelling hoses

For each of the FlyZero concept aircraft, the table below compares estimated refuelling times for both 4'' (10.16 cm) and 6'' (15.24 cm) diameter refuelling hoses. Using multiple hoses simultaneously and an increased line velocity may enable existing refuelling times to be maintained and possibly even reduced. FlyZero analysed potential issues with increasing the flow rate beyond that used today in kerosene aircraft to speed-up the refuelling process. No major concerns were found with heat transfer in the lines, erosion in the inner wall of the pipeline or fittings, or electrostatic charge. The main challenge in increasing the flow rate and the diameter of the hose would be the handling of a less flexible and heavy hose. This could be mitigated by a higher level of automation and robotic arm assistance. For turnaround planning purposes, conservative refuelling speeds have been assumed. However, further work carried out by FlyZero suggests that faster flow rates and the use of smaller diameter hoses may be achievable.

Concept	*LH_2 Quantity (kg)*	*Fill Time (2.5 m/s)*		*Fill Time (5 m/s)*		*Fill Time (7 m/s)*	
		4" Line	*6" Line*	*4" Line*	*6" Line*	*4" Line*	*6" Line*
Midsize	*11698*	*175 mins*	*78 mins*	*87 mins*	*39 mins*	*62 mins*	*28 mins*
Narrowbody	*2718*	*41 mins*	*18 mins*	*20 mins*	*9 mins*	*15 mins*	*6 mins*
Regional	*1300*	*19 mins*	*9 mins*	*10 mins*	*4 mins*	*7 mins*	*3 mins*

Table 12 – Estimated liquid hydrogen refuelling times for FlyZero concept aircraft using a single hose (Costain)

07.3 WEIGHT AND BALANCE

During the turnaround process, consideration will need to be given to the weight and balance of the aircraft during the refuelling and loading/unloading process to avoid tipping due to the tanks being in the aft of the aircraft, unlike conventional aircraft. The charts below show the movement of the centre of gravity (CG) during the loading of fuel, passengers and cargo.

Regional Concept – Loading Scenario

- FUEL → PASSENGERS → CARGO
  (Passengers must be loaded without moving CG aft to prevent tipping).

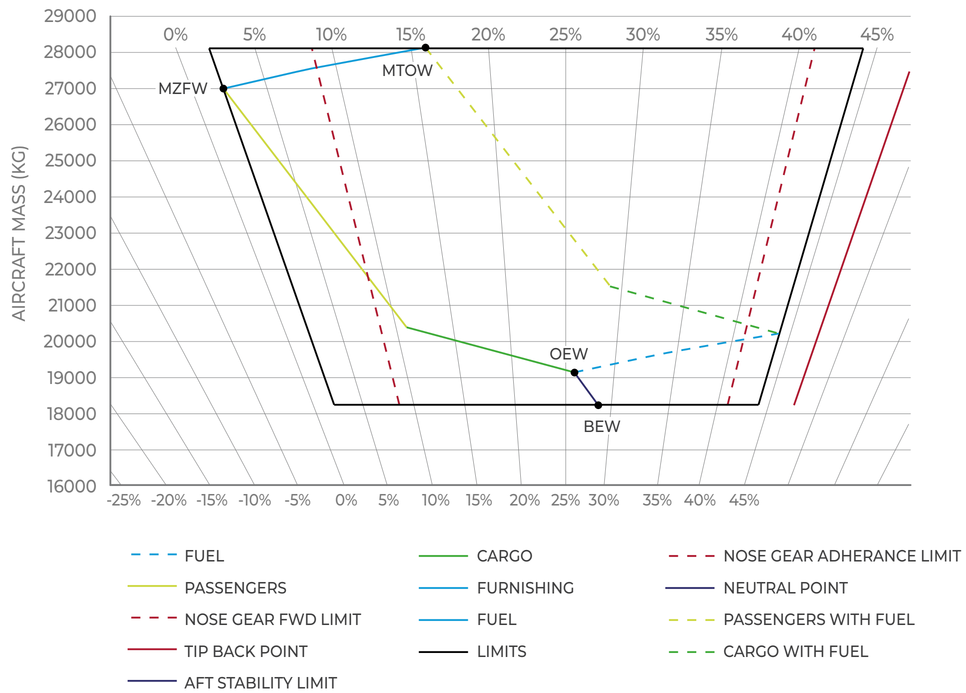


Figure 18 - Regional aircraft mass

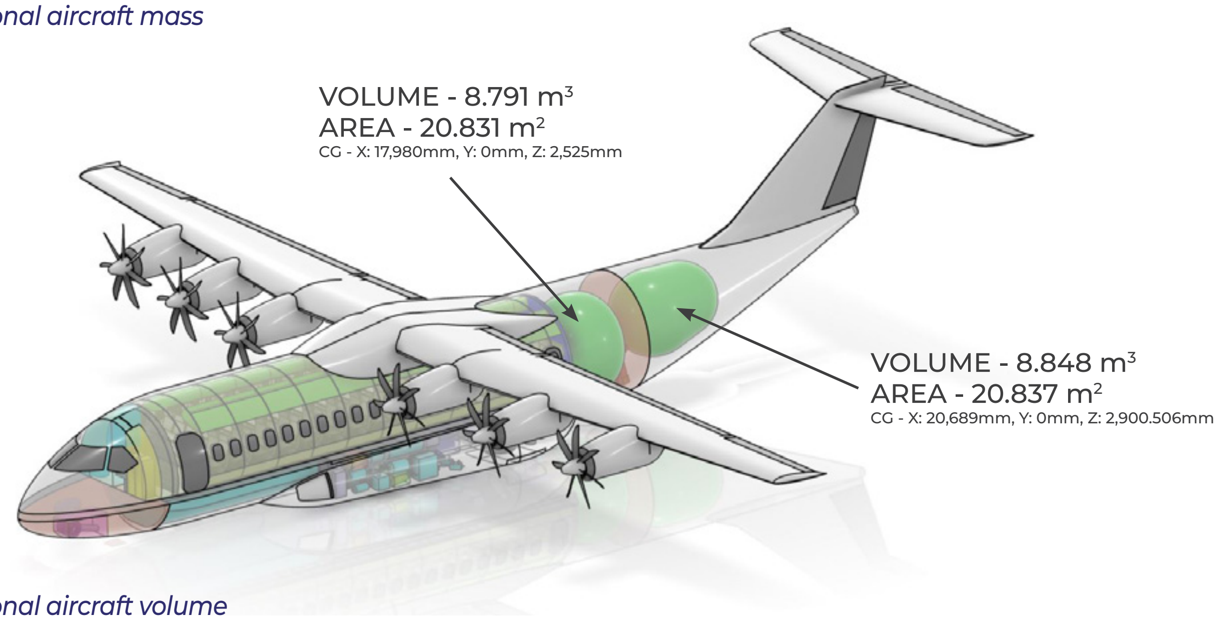


Figure 19 - Regional aircraft volume

Note – Assumes concepts are loaded to MTOW, reduced range missions with less fuel would be more flexible.

Narrowbody Concept – Loading Scenario

- FUEL → PASSENGERS → CARGO
  (Loading of passengers and cargo needs to be from forward to aft to avoid tipping).

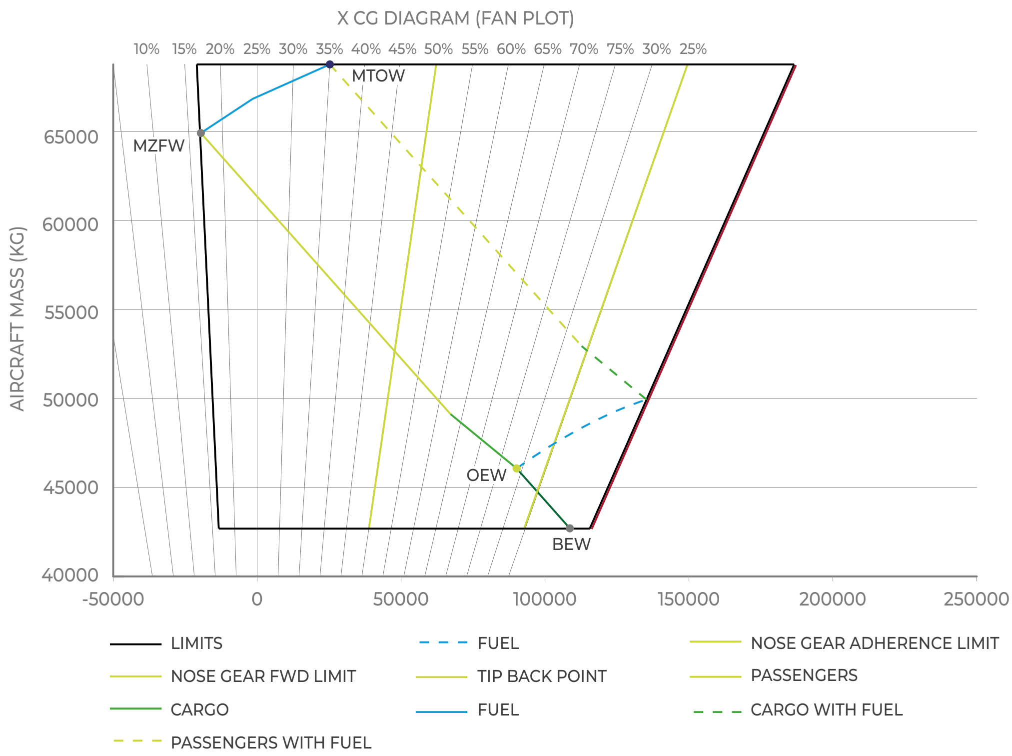


Figure 20 - Narrowbody aircraft mass

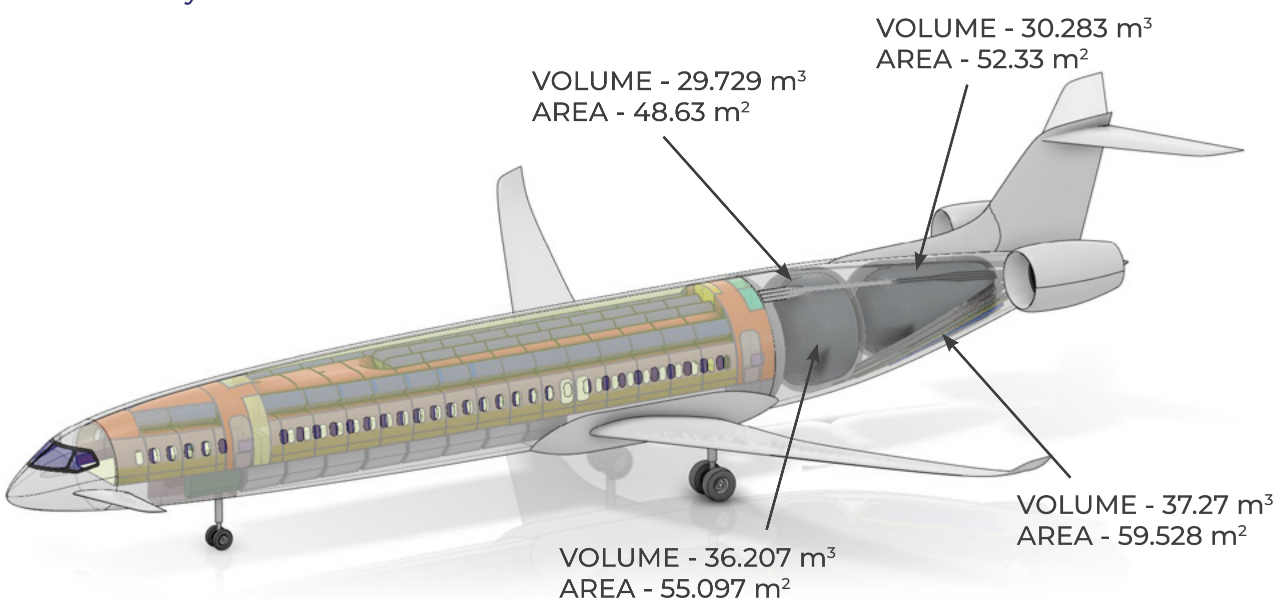


Figure 21 - Narrowbody aircraft volume

Note – Assumes concepts are loaded to MTOW, reduced range missions with less fuel would be more flexible.

Midsize Concept – Loading Scenario

- FUEL (forward tanks) → FUEL (aft tanks) → CARGO (forward hold) → CARGO (aft hold) → PASSENGERS.

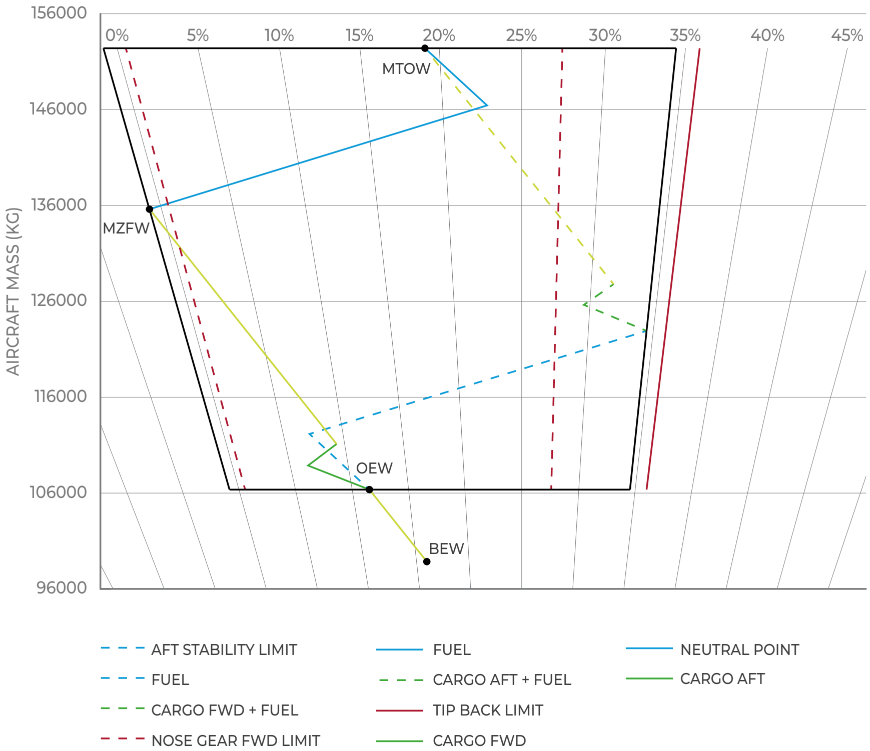


Figure 22 - Midsize aircraft mass

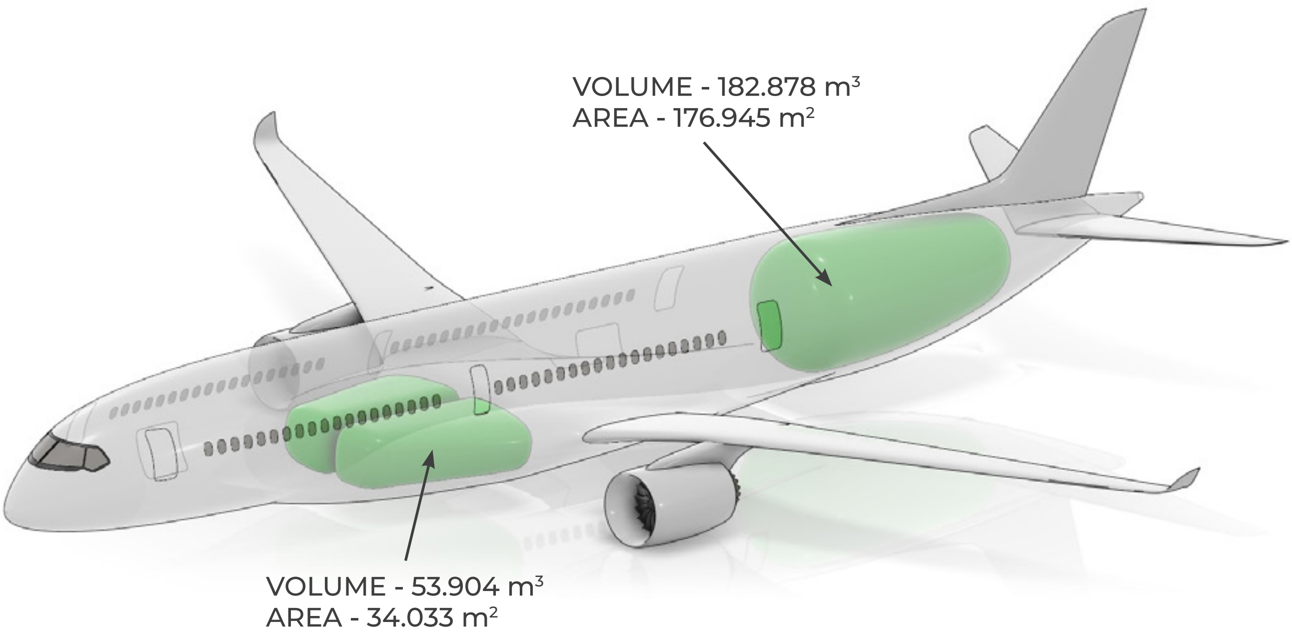


Figure 23 - Midsize aircraft volume

Note – Assumes concepts are loaded to MTOW, reduced range missions with less fuel would be more flexible.

07.4 IMPACT OF HYDROGEN ON AIRPORT CAPACITY AND AIRCRAFT UTILISATION

To ensure commercially efficient operations for both airport and airlines, maintaining fast aircraft turnaround times is important. Slower turnarounds result in aircraft being on stand for longer, reducing the available flying time and occupying airport apron parking capacity. At many airports capacity is constrained, and for most airlines, flight schedules are already optimised leaving little room to allow for extended ground time.

07.4.1 AIRPORT CAPACITY

The effect of longer turnarounds on airport capacity is dependent on the size and demand profile of the airport. While longer turnarounds will increase the time that parking stands are occupied, a FlyZero assessment of UK airports suggests that the effect on peak demand may be limited. Very fast turnarounds are often only critical for short haul flights using smaller aircraft. However, the peak demand at UK airports for these aircraft is typically overnight when an increased minimum turnaround or refuelling time will have minimal impact on capacity. The speed of turnaround has more effect later during the day, at which time there is often spare capacity available. Exceptions do however apply, particularly at larger airports where the later short haul flights may coincide with the peak for larger aircraft.

07.4.2 AIRLINE SCHEDULING

Figures 24 and **25** show the impact of increased turnaround times on a typical low-cost carrier (LCC) narrowbody airline operation. An LCC typically operates three return trips (six sectors) per day to/from its based airport, with some aircraft operating four-sector days on longer routes. First departures are around 06:00, and the last arrivals return between 22:00 and midnight, over a 16-18 hour operating day. At many airports, the length of the operating day is constrained by environmental night restrictions. The analysis in **Figure 24** shows that the impact of longer turnaround times has the greatest impact when aircraft utilisation exceeds about 14 hours in a day. This is the point when the overall length of the operating day is affected. The consequence of longer turnaround times would be that an LCC airline would have to schedule aircraft with a different mix of four-sector and six-sector flights, resulting in an overall loss of aircraft utilisation and productivity. This loss of utilisation could be mitigated by tankering return-trip fuel on shorter sectors, as discussed in **section 7.5**.

Figure 25 shows similar analysis for a regional aircraft operation. A regional aircraft may fly more, shorter sectors (with more turnarounds) in a day, so the point where increased turnaround times impact on the overall operating day occurs sooner – from as little as eight hours of daily aircraft utilisation. Conversely, the multiple short sectors mean that there is greater opportunity to tanker fuel and not to refuel during each turnaround. The overall impact of extended turnaround times on a regional airline will be sensitive to the airlines specific route network. Due to the longer sectors flown by larger aircraft, the midsize concept is less affected by increased turnaround times.

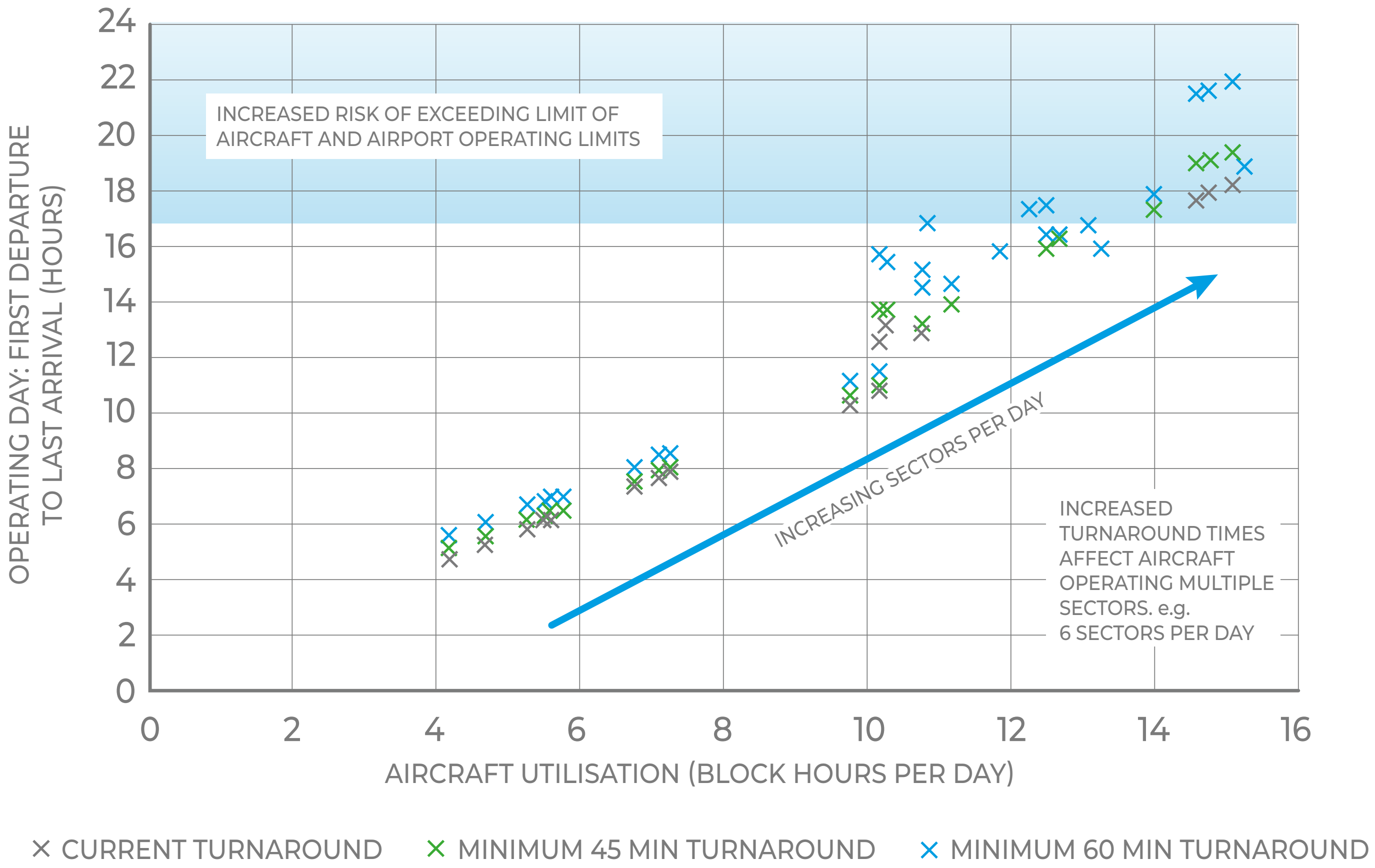


Figure 24 – Impact of longer turnaround times on typical low-cost airline schedule (Narrowbody aircraft)

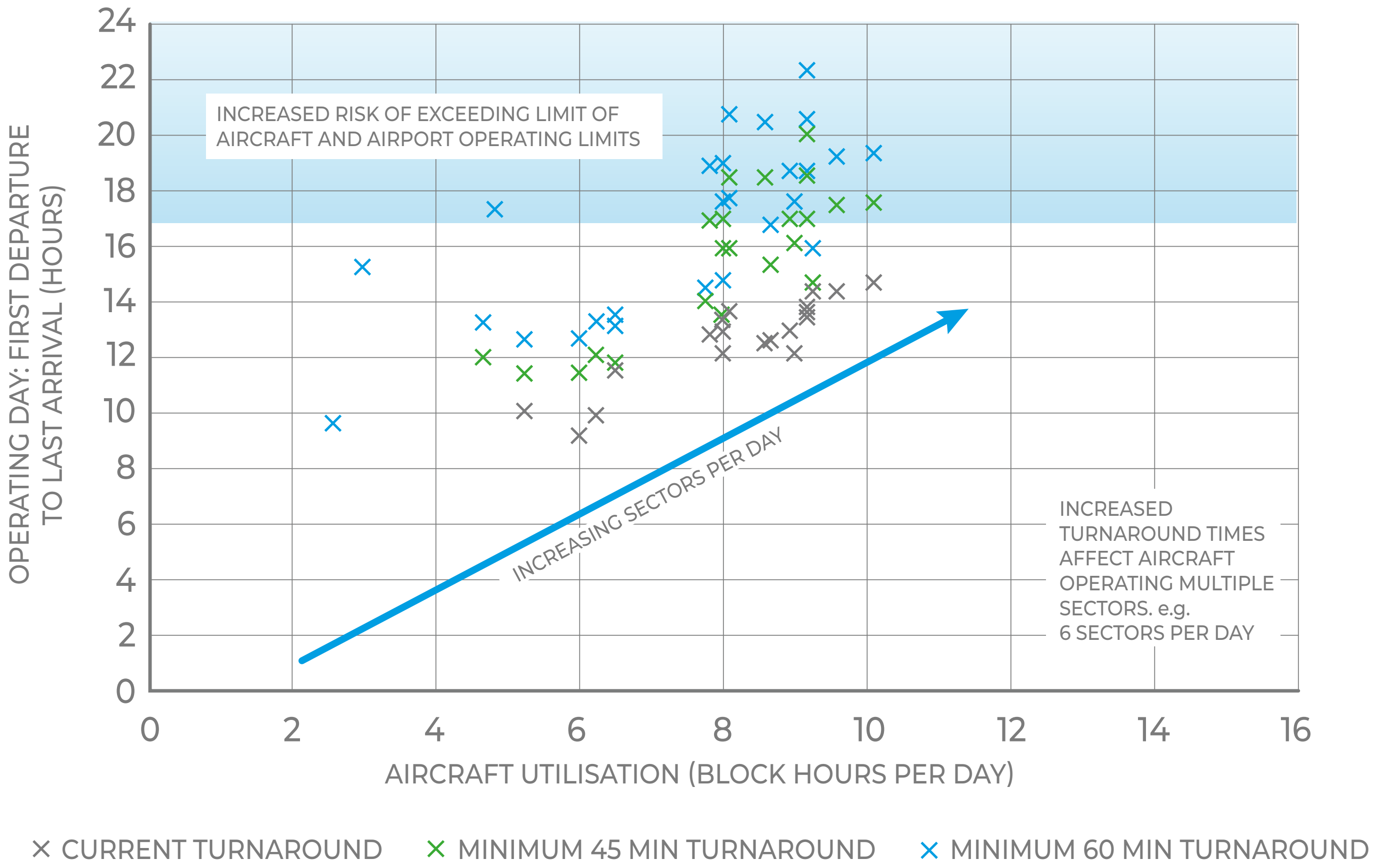


Figure 25 – Impact of longer turnaround times on typical low-cost airline schedule (Regional aircraft)

07.5 FUEL TANKERING

Fuel tankering is currently used by airlines when there are fuel shortages or it is more cost effective to fill the aircraft fuel tanks to full at the departure airport, to enable minimum or no refuelling activities to take place for the return flight. Operating tankering with kerosene has weight and environmental implications. Due to the light weight of liquid hydrogen, the additional fuel required to tanker a return trip of fuel is much less for a hydrogen aircraft. Over a 1000 nmi sector, the narrowbody concept aircraft needs 1.3% extra fuel with tankering, compared with 6.3% extra for an A320neo.

With the introduction of aircraft operating with liquid hydrogen, not every airport will have the necessary infrastructure to enable a refuelling operation to take place. Tankering will allow airlines to operate a commercially viable network, including to destinations that do not yet have liquid hydrogen refuelling infrastructure in the early years of liquid hydrogen aircraft entering service. Tankering would also help in reducing turnaround times at outstations if refuelling times are longer than anticipated. The benefits are:

- Tankering return fuel has a minimal cost penalty for lightweight hydrogen compared with kerosene
- For narrowbody route networks, typically about 80% of flights are within a 1000 nmi tankering range
- Reduced average turnaround times without refuelling at outstations
- Minimising the number of hydrogen-capable airports required on the network in the early years

Fuel tankering will also be a benefit to the FlyZero regional aircraft concept. It has a maximum range of 800 nmi, so could feasibly tanker sectors up to about 350 nmi, which covers almost 90% of current turboprop routes and 62% of all regional routes (including those operated currently by regional jets). Tankering is less attractive over long sector distances, such as those operated by the midsize concept aircraft and is less likely to be adopted by airlines in this segment.

07.6 LIQUID HYDROGEN FUEL TANK MANAGEMENT

The temperature difference between the liquid hydrogen and the outside air will normally be in excess of 250 °C. Despite good insulation, it will be inevitable that after a long period of time, heat will be transferred to the liquid hydrogen warming it up and causing it to boil. If not actively cooled, this will cause a pressure rise in the tank which will require some gaseous hydrogen to be extracted. This section discusses the management of liquid and gaseous hydrogen interactions during long periods of dormancy.

07.6.1 LIQUID HYDROGEN FUEL TANK DORMANCY AND VENTING

In a passive cooling system, temperature and pressure are controlled through efficient insulation, venting and pressurisation. During flight the discharge of fuel from the tank to the engines reduces the volume and pressure. Pressurant (gaseous hydrogen) is introduced to recover the pressure drop and maintain the fuel temperature. However, on the ground, heat will leak into the tank, increasing the fuel temperature and pressure, which will eventually need to be vented to avoid damage to the tank. In normal service, hydrogen venting will need to be avoided, as it has an indirect greenhouse gas effect.

As aircraft are often refuelled well in advance of departure, the hydrogen tanks will need to be able to maintain temperature and pressure long enough to allow the planned flight and post flight operations, without the need for venting. The FlyZero concept aircraft have been designed to allow up to ten hours dormancy between refuelling and flight, and three hours dormancy after the flight. While actual aircraft and tanks may behave differently, the overall principle will affect the turnaround operation. If aircraft are on the ground for extended periods, to prevent venting, they will need to be connected to ground support equipment capable of allowing vented hydrogen to be contained and reused.

To illustrate the main phases in managing tank pressure, the following diagram highlights the expected pressure throughout the flight operation duration. The full flight cycle is divided into three periods:

- **Pre-flight dormancy period** (shown as ten hours in the FlyZero concept example) – allowing refuelling in advance of departure, in which time the pressure in the tank rises proportionately to the rate of heat leak into the tank.
- **Flight time** – in which active tank pressurisation maintains a normal operating pressure range.
- **Post-flight dormancy period** (shown as three hours in the FlyZero concept example) – allowing a period of time before refuelling or the tank being connected to ground support equipment, in which the pressure of the tank will continue to rise proportionately to the rate of heat leak in the tank.

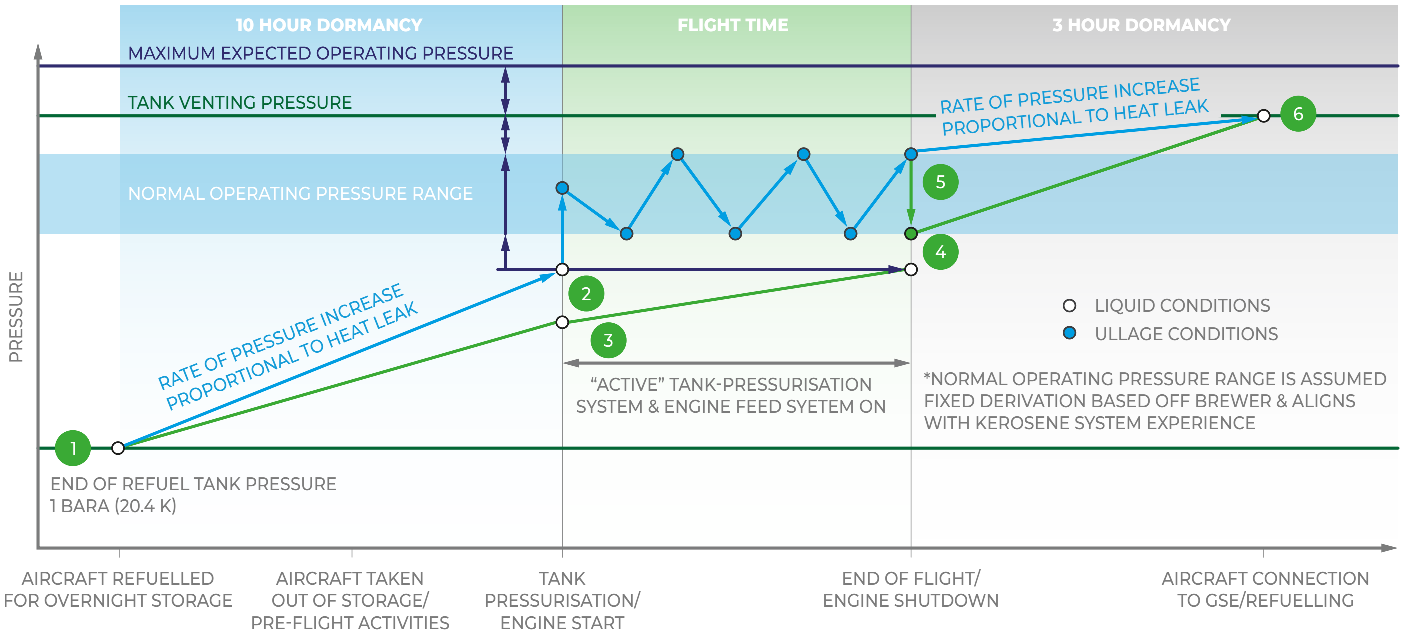


Figure 26 – Liquid hydrogen tank pressure variation during different flight cycle phases [8]

08. AUTOMATED GROUND SUPPORT EQUIPMENT

To enable a safe simultaneous turnaround operation, automated GSE would allow activities to continue during the refuelling process while minimising risk to people.

Figure 27 – Automated GSE

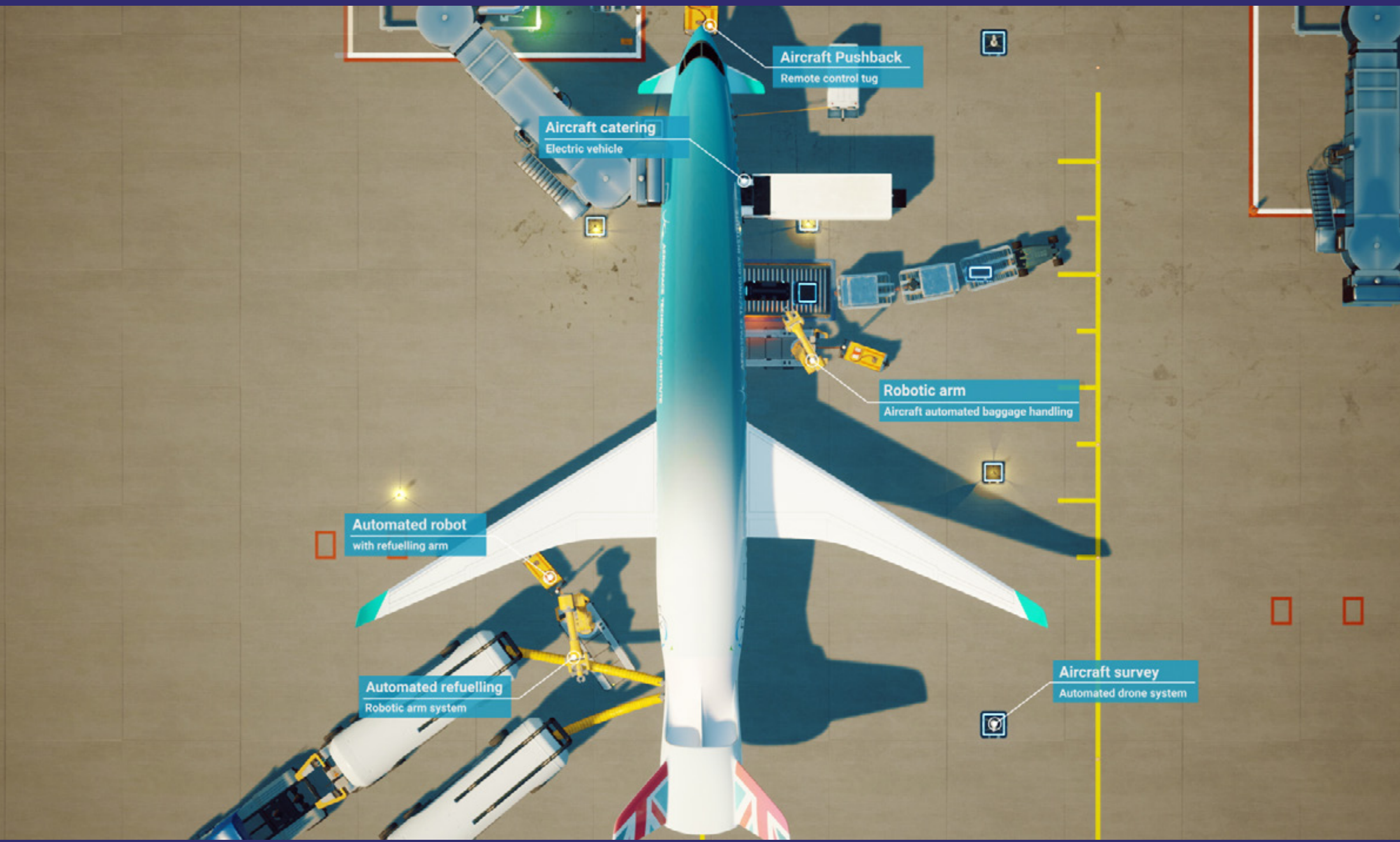


Figure 28 – Stand layout with GSE for FlyZero narrowbody concept refuelling with liquid hydrogen

Activies, including baggage loading and catering, are likely to take place during the fuelling process within the safety exclusion zone for both the narrowbody and midsize aircraft. To ensure the safety and efficiency of the operation, all electrical and mechanical ground support equipment, including vehicles, would need to be reclassified for use in hazardous areas. The purpose of hazardous area classification is to determine where a flammable atmosphere may exist and how much of the time it may be present, with the purpose of avoiding ignition of a flammable atmosphere. Hazardous area classification also determines the design requirements for electrical and mechanical equipment. Redesigning GSE to operate in this area would enable the introduction of automation to assist with maintaining simultaneous activities and improve or maintain turnaround times and safety. The roadmap on this page shows an estimated timeline for development and implementation.

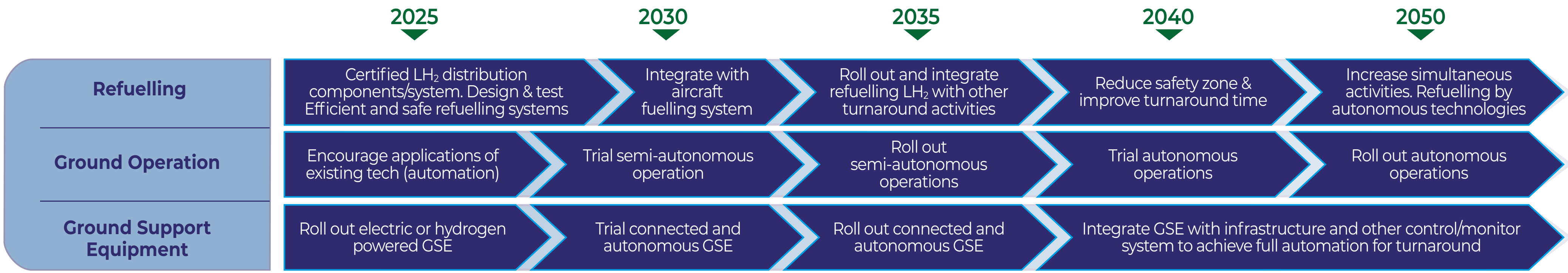


Figure 29 – Roadmap for GSE development for liquid hydrogen operations (Costain)

09. GROUND OPERATIONS SAFETY

09.1 A SAFE TRANSITION TO LIQUID HYDROGEN

Many of the safety considerations for hydrogen relate to its physical properties, such as its wide flammable range and low minimum ignition energy (**Table 1**). There are a wide range of scenarios where hydrogen could ignite, such as a spark from nearby equipment. Any form of static discharge has the potential to ignite a mixture of hydrogen in air, provided that the flammable limits are met.

When spilt, kerosene forms a flammable spray and/or a pool of liquid, however liquid hydrogen vaporises rapidly and does not normally form a liquid pool unless a large quantity is released. Notably the lower end of the flammable range is 4 vol% for hydrogen compared to ~1% for Jet A-1. Therefore, the dissipation of hydrogen from a leak to safe levels may be faster than with kerosene. Adequate ventilation and leak detection will therefore be important.

Hydrogen is colourless, however a release of cryogenic liquid hydrogen can cause air to cool rapidly, condensing and forming a very cold white cloud, potentially drifting at low levels for tens of metres. Large spills may also cool the air sufficiently to condense to solid air, enriched with oxygen, which can lead to an explosion if the hydrogen cloud ignites. Typically, in an unconfined outdoor setting, ignition of a hydrogen cloud would lead to a flash fire and, if the release continued, to a jet fire, although this would be very rare. Comparisons between Jet A-1 and liquid hydrogen in an airport environment are set out below.

Parameter	*Jet A-1 (kerosene)*	*Liquid Hydrogen*
Storage Temperature	*Ambient*	*-253 °C / 20 K*
Flammable Range in Air	*0.6 to 4.7 vol%*	*4.0 to 75 vol%*
Minimum Ignition Energy	*0.25 mJ*	*0.02 mJ*
CO^2 in Exhaust Emissions	*Yes*	*No*
Fuel Safety Zone Distance 2021	*3 m*	*30 – 60 m to be reduced over time (9.2)*
Fuel Safety Zone Distance 2030+	*3 m*	*20m during connection/disconnection 8 m during fuel flow*
Simultaneous Boarding & Refuelling (2021)	*Yes*	*No*
Typical Mass Density (kg/m³)	*775 to 850 kg/m³*	*71 kg/m³*
Fuel Line/Hose Size	*3"*	*4" or 6"*
Fuel Line/Hose Handling	*Manual*	*Automated*
Location for Refuelling	*On Pier*	*Off Pier <2030 On Pier >2030*

Table 13 – Key comparison of Jet A-1 (kerosene) and liquid hydrogen [2]

The lightweight nature of hydrogen results from its small molecular size, and while this could mean additional measures are needed to prevent and detect the permeation and leakage of hydrogen, the low density of hydrogen would also mean that it could be expected to disperse rapidly if a release occurs. However, the physical storage conditions of very low temperature liquid hydrogen, which are needed to achieve an acceptable energy density for aviation, can increase the density, meaning that dispersion is less rapid. The hydrogen industry has managed to handle and store hydrogen safely for decades by means of hydrogen detection technologies mentioned in **section 9.3**.

09.2 FUEL SAFETY ZONE

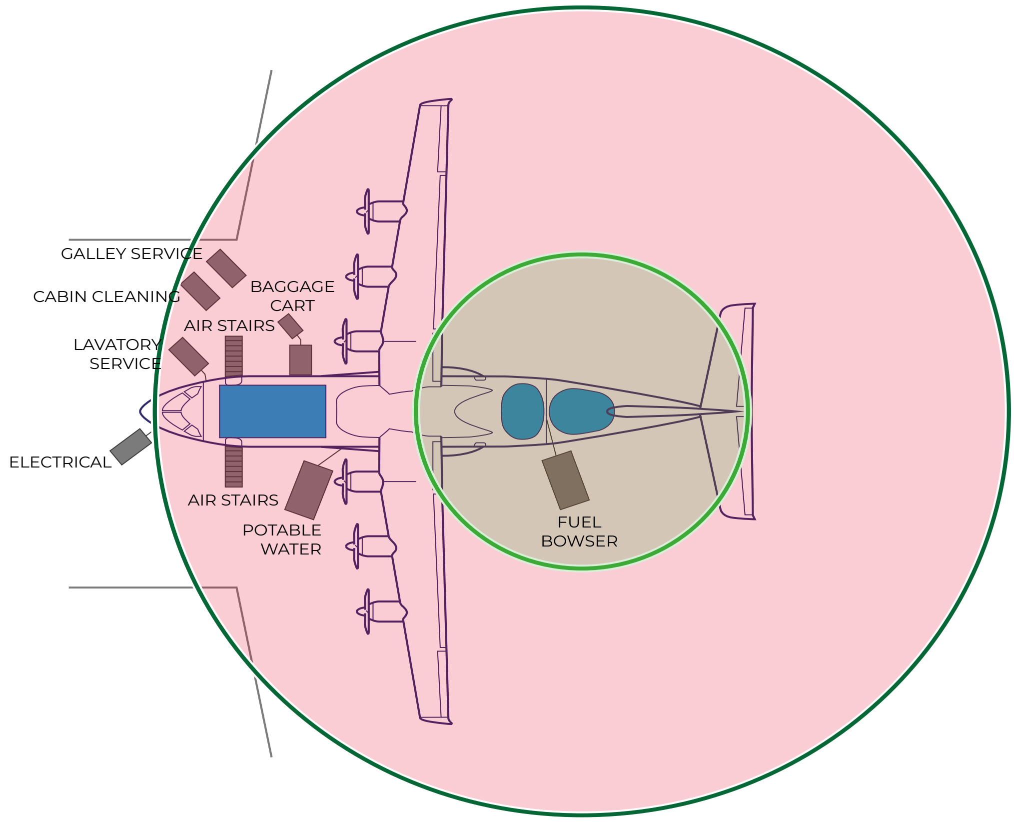
Separation distances from regulatory standards in other industries were reviewed, including those from the National Aeronautics and Space Administration (NASA) who have experience of handling hydrogen for space travel. Other UK and international standards for handling compressed gas were also investigated.

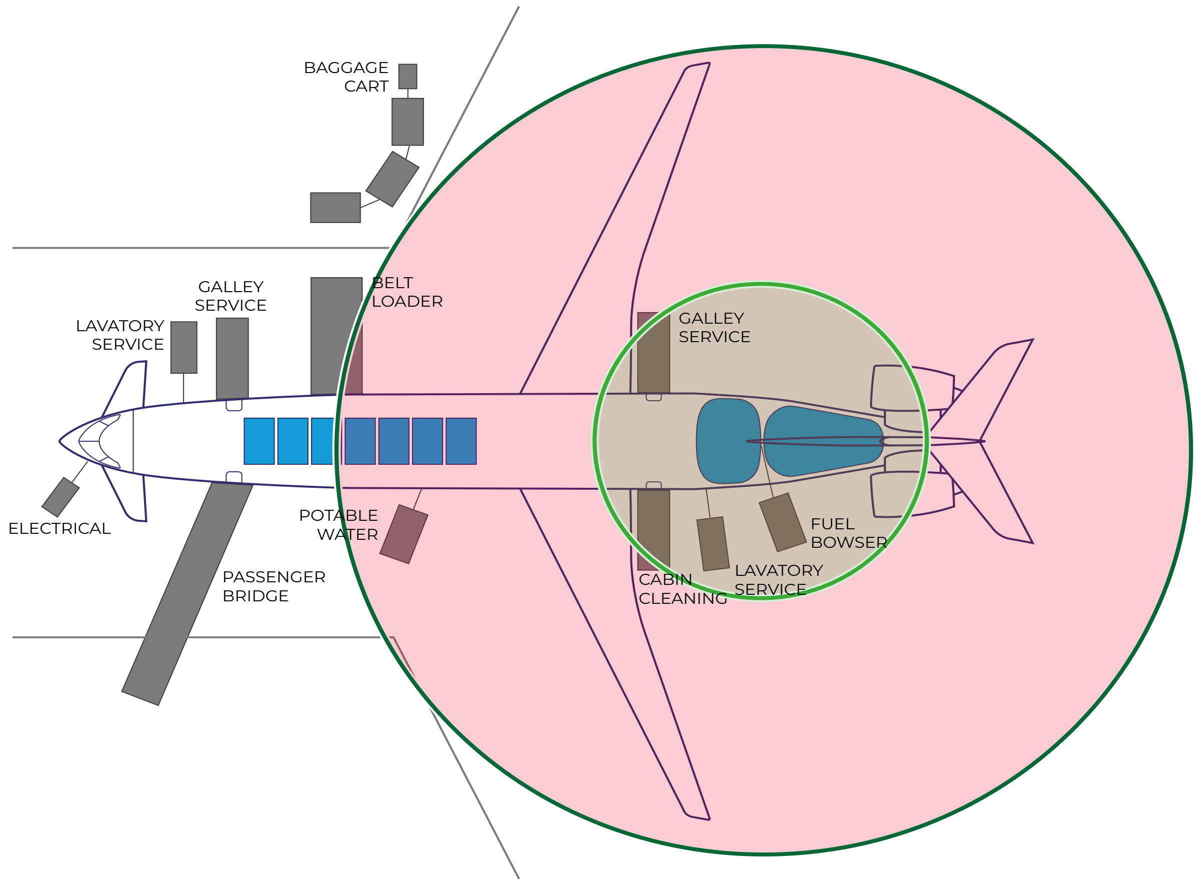
This research indicates a range of separation distances, which if transferred into the aviation sector could see fuel safety zones initially required to be between 20-60 metres due to the proximity to the public.

Description	BCGA	BSi	EIGA	NFPA	NASA
Place of public assembly			20	23	22.9
Public establishments			60		
Compressor, ventilator and air conditioning intakes	15	15	20	23	22.9
Any combustible liquids			10	30.5	30.5
Other LH_2 fixed storage			1.5	1.5	1.5
Other LH_2 tanker			3		
Vehicle parking storage	8			7.6	
Electricity cable and pylons	1.5	10	10		
Applicability	$LH_2 \leq$ 5,000 kg	$LH_2 \leq$ 5,000 kg		4,032 - 20,157 kg	4,032 - 20,157 kg

Table 14 – Current recommended minimum separation distances in industry for liquid hydrogen

However, initial desktop studies for FlyZero by the Health and Safety Executive (HSE) suggest that although a 20 metre safety zone may be required during connection and disconnection of the fuelling hoses, it may be possible to reduce to 8-10 metres once the connection is secured, subject to testing and assessments.





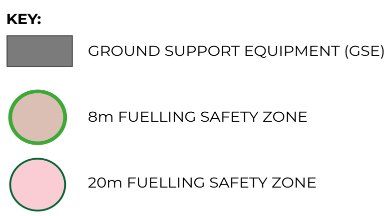


Figure 30a – Regional (top) and narrowbody (bottom) aircraft concepts fuel safety zones

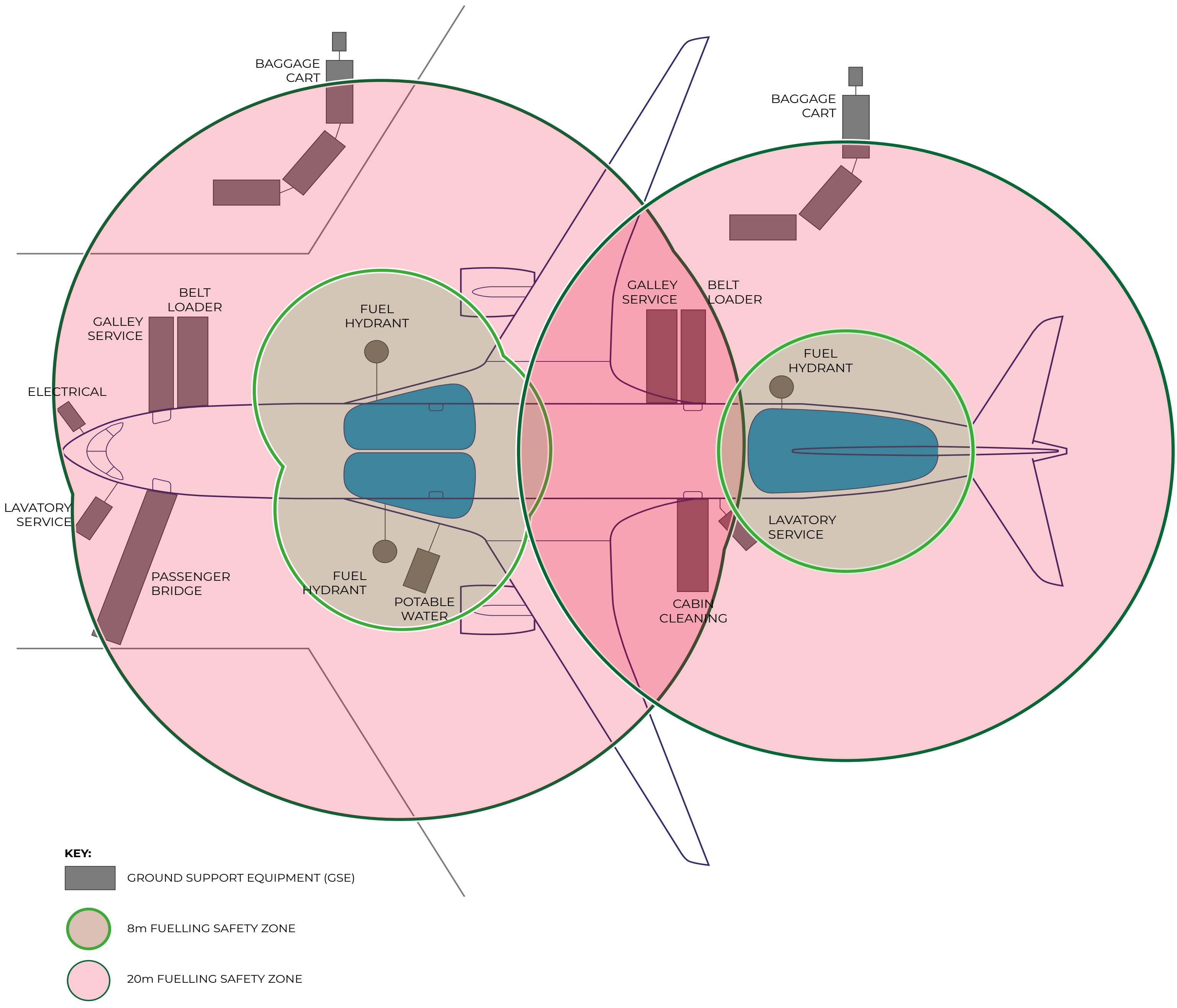


Figure 30b – Midsize aircraft concept fuel safety zones

09.3 MANAGING LEAKS AND SPILLS

In the event of a spill or leak of liquid hydrogen during transport, storage or refuelling, requirements according to British Compressed Gases Association (BCGA) are to:

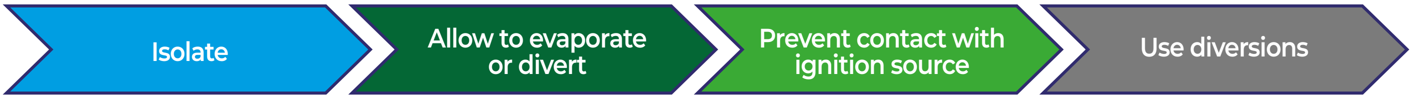


Figure 31 – Actions for spills and leaks of liquid hydrogen

To assist with spillage and leak detection, consideration needs to be given to possible leak points from pipework and the potential impact on other infrastructure. Leak detection instrumentation, sensors and gauges will be needed throughout the transportation, storage and refuelling process to ensure leaks are detected as early as possible to minimise the hazard. The most likely place for a leak to occur is from joints, glands and couplings.

There are different types of gas detection technologies that could be considered for detecting hydrogen leaks at various points in the event of a gas release on the airport ramp, the earlier the leak is detected the lower the consequences will be.

Within the airport ramp environment, a combination of leak detection technology will be needed to assist with early leak detection. Outdoor locations can benefit from ultrasonic gas leak detection sensors which sense airborne ultrasound emitting from gas leaking at high pressure. These sensors allow fast detection of small leaks and are unaffected by changing weather conditions, such as the wind direction. Leak detection tape can be used as an additional safety measure on the aircraft and ramp where it can be wrapped around pipes, flanges, fittings, valves and access panels to identify the location of a hydrogen leak. When exposed to hydrogen the tape changes colour permanently and identifies the location of the leak.

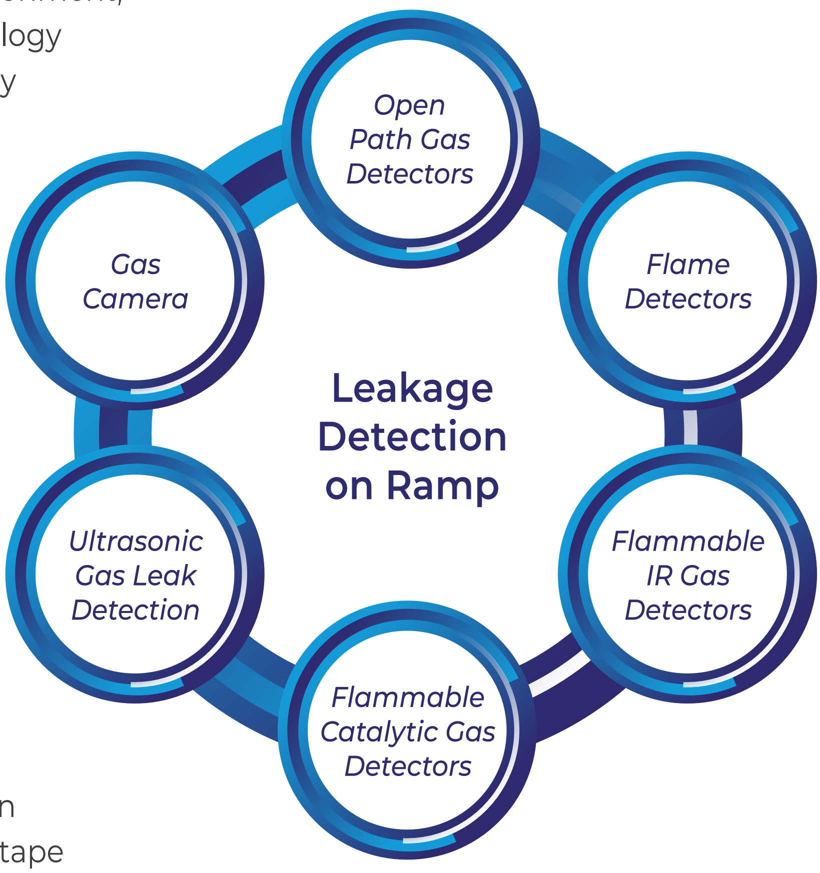


Figure 32 – Leak detection technology

09.4 CONTROL OF MAJOR ACCIDENTS AND HAZARDS

09.4.1 COMAH REGULATIONS

COMAH regulations (Control of Major Accidents and Hazards) apply to sites handling hazardous substances in the UK. A COMAH site is considered as a site that stores sufficient dangerous substances that fall into either an upper or lower tier site [9]. The threshold capacity for the use of hydrogen is lower than for kerosene, therefore airports are likely to become COMAH establishments. Potential impacts of COMAH include increased requirements for reporting, sensors/instrumentation, and redundancy in safety systems.

Hydrogen COMAH Requirements		
COMAH Site	*Amount (tonne)*	*Operator Requirements*
Lower Tier	*5 t*	• *Notify basic details to the Competent Authority (normally lead by HSE).* • *Take all measures necessary to prevent major accidents and limit their consequences to people and the environment.* • *Prepare a major accident prevention policy (MAPP).*
Upper Tier	*50 t +*	*All lower tier requirements plus:* • *Prepare a Safety Report to be submitted to competent authority (HSE).* • *Prepare and test an internal emergency plan.* • *Supply information to local authorities for external emergency planning purposes.* • *Provide certain information to the public about their activities.*

Table 15 – COMAH requirements

09.5
HUMAN FACTORS

Human factors and change management will be a significant process in the introduction of liquid hydrogen fuelling, storage and transportation at an airport. Consideration will need to be given to the initial use and management of liquid hydrogen as most airports and airlines will be operating using a mix of fuel types, requiring an understanding of several different operating regulations, processes and procedures. As airports become COMAH sites there is a requirement for lower and upper tier establishments to regulate major hazards by having a clear framework to inspect human factors **[10]**.

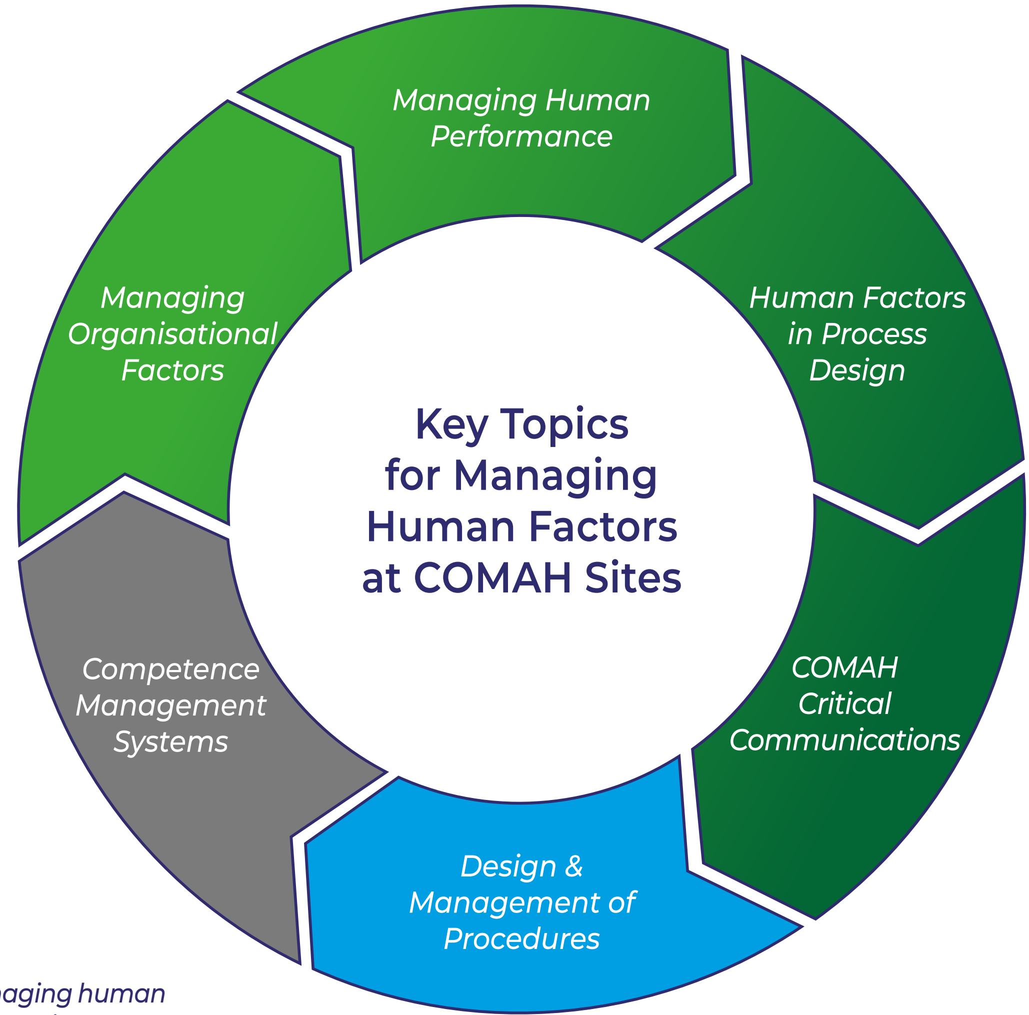


Figure 33 – Managing human factors at COMAH sites

09.6
PERSONAL PROTECTIVE EQUIPMENT

As hydrogen has a very low minimum ignition energy, identifying suitable anti-static and fire retardant PPE, suitable for use with hydrogen, will be required. This could include (but is not limited to) cryogenic eye protection, gloves and apron, safety boots, and flame retardant and anti-static overalls.

10. DEVELOPING THE TURNAROUND PROCESS - NEXT STEPS

Refuelling an aircraft with liquid hydrogen in a safe and efficient manner will be vital to the operation of hydrogen aircraft. Collaboration and integration across the aviation industry will be crucial to ensure aircraft, airport infrastructure, regulations and ground servicing equipment are developed together.

The next steps would require:

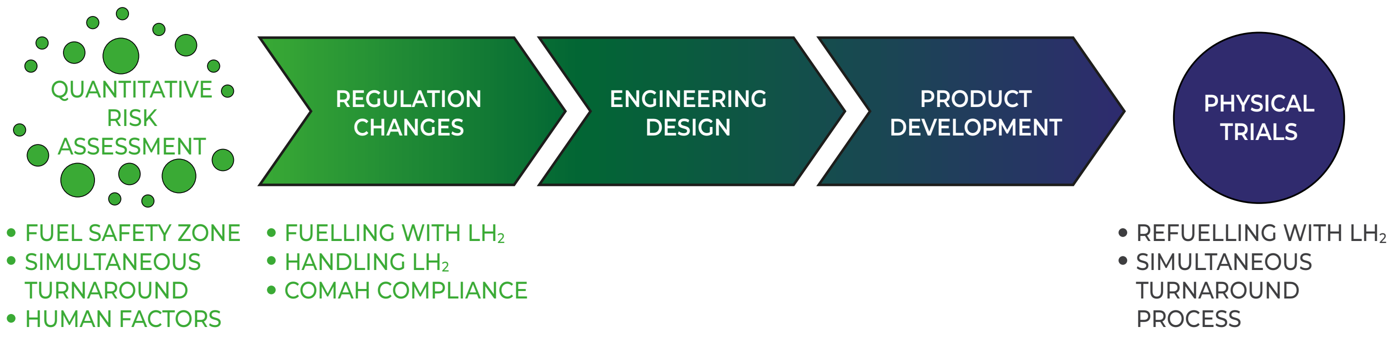


Figure 34 – Developing the turnaround process

Specific solution areas of focus for future work are:

Aircraft Design	• Locate refuelling points at rear of the aircraft to keep hazardous zone away from the terminal • Collaborate with aircraft manufacturers to enable multiple, simultaneous fuelling points to reduce the turnaround time
Ground Handling Equipment	• Develop ground handling equipment to enable operations within the hazardous zone (ATEX Category 3)
Stand Infrastructure	• Create “stand of the future” to incorporate liquid hydrogen GSE for safe operations
Human Factors	• Evolving enhanced stand operations and exploration of automation
Learning	• Explore technology, techniques and operations from other industries to gain improvements on safety and time factors
Analysis of Whole System	• Minimise, capture and handle ‘Boil-off’ from liquid hydrogen • Identify goals and purpose to create effective systems and procedures

Table 16 – Solution areas for future work

Recommendations:

Aircraft Design	• **Objective** - Locate the liquid hydrogen filling point at the optimum location for the aircraft and stand • **Recommendation** - Establish a collaboration forum where the interaction between aircraft design and stand design can be managed as a key interface
GSE	• **Objective** - Ensure ground servicing equipment can operate safely within the hazardous zone • **Recommendation** - Commence a programme of re-design of handling equipment to meet safety standards and operational needs
Stand Infrastructure	• **Objective** - Creating the “stand of the future” where liquid hydrogen handling equipment can be safely installed for operation • **Recommendation** - Invest in a design programme to introduce new infrastructure needed for hydrogen operation, evaluating the likely need for hydrant supply
Human Factors	• **Objective** - Seek automated solutions for enhanced stand operations and exploration of automation • **Recommendation** - Invest in the development of automated technology that can remove the risk posed by human interaction
Learning	• **Objective** - Avoid reinventing the wheel • **Recommendation** - Explore techniques and operations that other sectors/industries, such as motorsport, have introduced to improve time factors, which could enhance hydrogen operations.

Table 17 – Recommendations for future turnaround process

All the next steps, solutions and areas for commitment are incorporated in the timeline below.

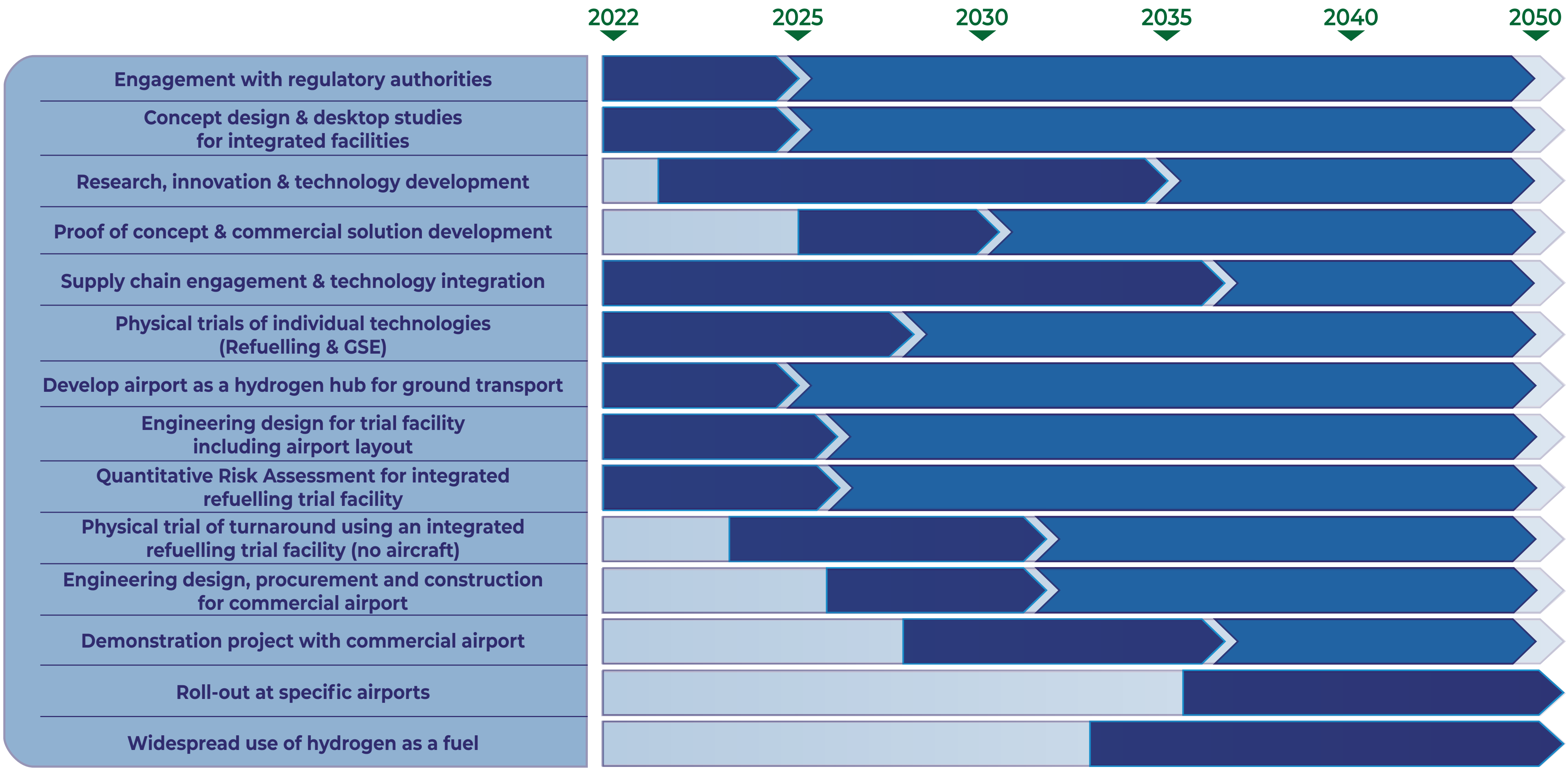


Figure 35 – Timeline of turnaround evolution for the introduction of liquid hydrogen

11. AIRSPACE OPERATIONS AS A SUSTAINABILITY ENABLER

The concepts developed as part of the FlyZero project present a vision for the future of zero-carbon emission flight. However, if the next generation aircraft were forced to fly longer routes than required, along inefficient flight profiles, and spend more time in holding stacks due to compromised capacity at airports and in airspace, their maximum potential range could be affected. Moreover, every unit of energy these aircraft use and waste in flight will need to be produced on the ground at a very high energetic and economic cost, contributing to the overall energy requirement highlighted in section 3. Now more than ever, in-flight energy cannot be wasted. This section shows how selected operational solutions and technologies in air traffic management (ATM) can shape future airspace to enable zero-carbon emission flights to achieve maximised operational efficiency.

Part of the FlyZero project has focused on air traffic management operations to raise awareness of ATM's capability to support and enable the long-awaited zero-carbon emission entrant. An important finding from the project has highlighted that the current FlyZero concepts and their performance characteristics do not display any attributes preventing them from a smooth integration within the ATM system, in their current shape, or as anticipated in the future.

Improvements in air traffic management (ATM) and aircraft operations could achieve CO_2 emission reductions of

6-10%

from global aviation by 2050.

Improvements in aircraft, engine technologies and the subsequent fleet replacement will be the most significant enablers for the reduction of aviation's impact on the environment in the upcoming decades. Launching hydrogen fuelled aircraft will change the way that airports and airlines operate. It will take time for zero-carbon emission flights to become widely operated, however developments in air traffic management and aircraft operations can make an important contribution to reducing aviation's environmental impact in the short to medium term. This contribution is estimated at approximately 6%-10% CO_2 reduction from aviation by 2050[1].

This section provides an overview of the ATM technological and operational solutions that can improve the system's efficiency and contribute towards the reduction of noise and fuel burn. It must be stressed that all solutions emerging from ATM are equally applicable for kerosene and hydrogen powered aircraft. They enable immediate benefits without having to wait for the infrastructure, allowing widespread hydrogen application in commercial aviation. What is more, once the hydrogen aircraft enter operation, the same ATM solutions will give airlines the most efficient fuel management and a reduction of fuel related costs.

[1] - Different sources provide different ranges - ATAG Waypoint 2050 [20] mentions 7%-10% CO_2 emissions reduction from global aviation across various scenarios, while Destination2050 [21] mentions 6% reductions from European aviation.

11.1 FUTURE AIRSPACE

Research by the Department for Transport suggests that without action in airspace modernisation, "1 in 3 flights from all UK airports are expected to depart over half an hour late and the average delay would be 72 times more than in 2015" **[11]**. Such delays and associated flight cancellations could cost the UK around £260 million a year by 2030. Although the quoted research was conducted in 2017 prior to the COVID-19 pandemic, the numbers mentioned for 2030 are not expected to be significantly different as the post-pandemic traffic is likely to catch up with the pre-pandemic levels by 2023 **[12]**. In light of these predictions, it becomes evident that the airspace shaped over the last century will not be able to cope with the future traffic forecasts, without undertaking a complete modernisation program that cannot be left unfinished or postponed.

The ongoing UK airspace modernisation programme is focussed on updating its structural design, with new flight routes redesigned and the implementation of new technologies expected to improve how the air traffic is managed. It is one of the most complex and time intensive programmes aimed at shaping airspace and preparing it for the future operations. The overall objective of airspace modernisation is to deliver more efficient, quieter and cleaner operations and to provide increased capacity for the benefit of both those who use air transport and those who are affected by it.

Airspace of the future shaped by extensive airspace modernisation programme will enable operations with increased traffic volumes forecasted for the upcoming decades. It will be complimented by the implementation of the Digital European Sky programme supporting free route flying, and by anticipated integration of manned and unmanned air traffic management systems. Further solutions that will facilitate the transition will be related to:

- Optimum flight paths realised through the use of continuous descent and climb operations and trajectory-based operations in free route airspace.
- Minimising delays and maximising flight efficiency through introduction of time-based separation and performance-based navigation.
- Cooperation between all stakeholders within the Airport Collaborative Decision Making (A-CDM) concept where supporting technologies improve connectivity, data exchange and air traffic management of arriving and departing traffic, for enhanced organisation of flight operations.
- Application of technologies utilising high resolution weather data for planning and execution of more flexible and optimised flight paths, aiming at perfect flight trajectories and including wake vortex energy retrieval from formation flying and the ability to avoid headwinds and contrail formation regions.

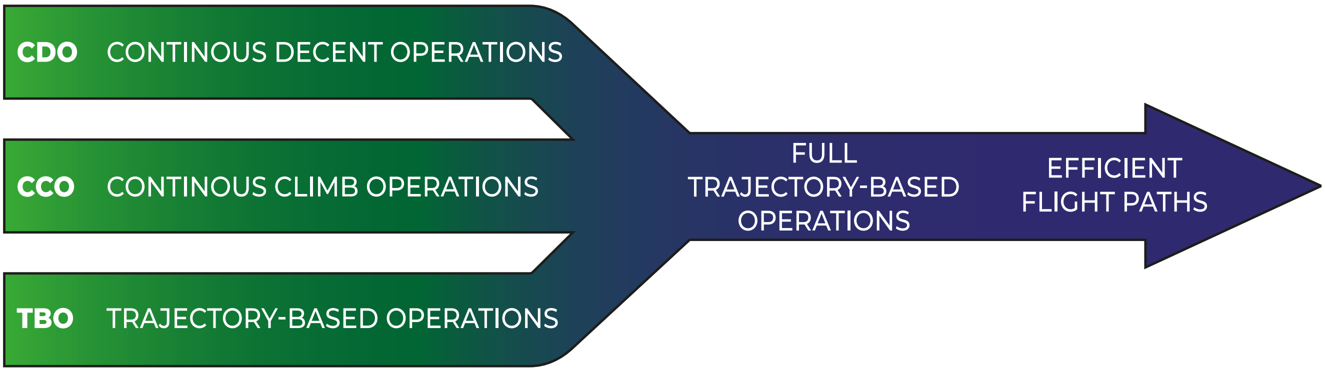


Figure 36 – Main points of focus for the effective flight paths as per ICAO navigation strategy

11.2 DIGITAL EUROPEAN SKY AND FREE ROUTE AIRSPACE

Part of the global transition towards the next generation of ATM system will be achieved by application of a Digital European Sky initiative led by the ongoing air navigation improvement programme, Single European Sky ATM Research (SESAR). It will enable data exchange supporting the concept of trajectory-based operations within the Free Route Airspace (FRA). Trajectory-based free route operations will allow airspace users to better plan and execute their business and mission trajectories within an optimised airspace configuration that meets safety, security and environmental performance targets, as well as stakeholder needs. Free route airspace will allow the most efficient trajectories, reducing fuel burn and CO_2 emissions per flight, which in turn will reduce operating costs for airlines. **Figure 37** shows a schematic representation of current ATM architecture compared with the future architecture based on the Digital European Sky concept **[13]** enabling free routes operations.

CURRENT ARCHITECTURE

AIRSPACE LAYER

- Limited capacity
- Fixed routes
- Fixed national structures

AIR TRAFFIC SERVICES LAYER

- Limited Automation
- Low level of information sharing

PHYSICAL LAYER

- Fragmented ATM infrastructure

FUTURE ARCHITECTURE

HIGHER AIRSPACE OPERATIONS

NETWORK OPERATIONS

- Dynamic & cross-border airspace configuration and management
- Fixed national structures
- Free routes

AIR TRAFFIC SERVICES

- Automation support

DATA & APPLICATION SERVICES U-SPACE OPERATIONS

- Unified information

INFRASTRUCTURE

- Integrated and rationalised ATM infrastructure

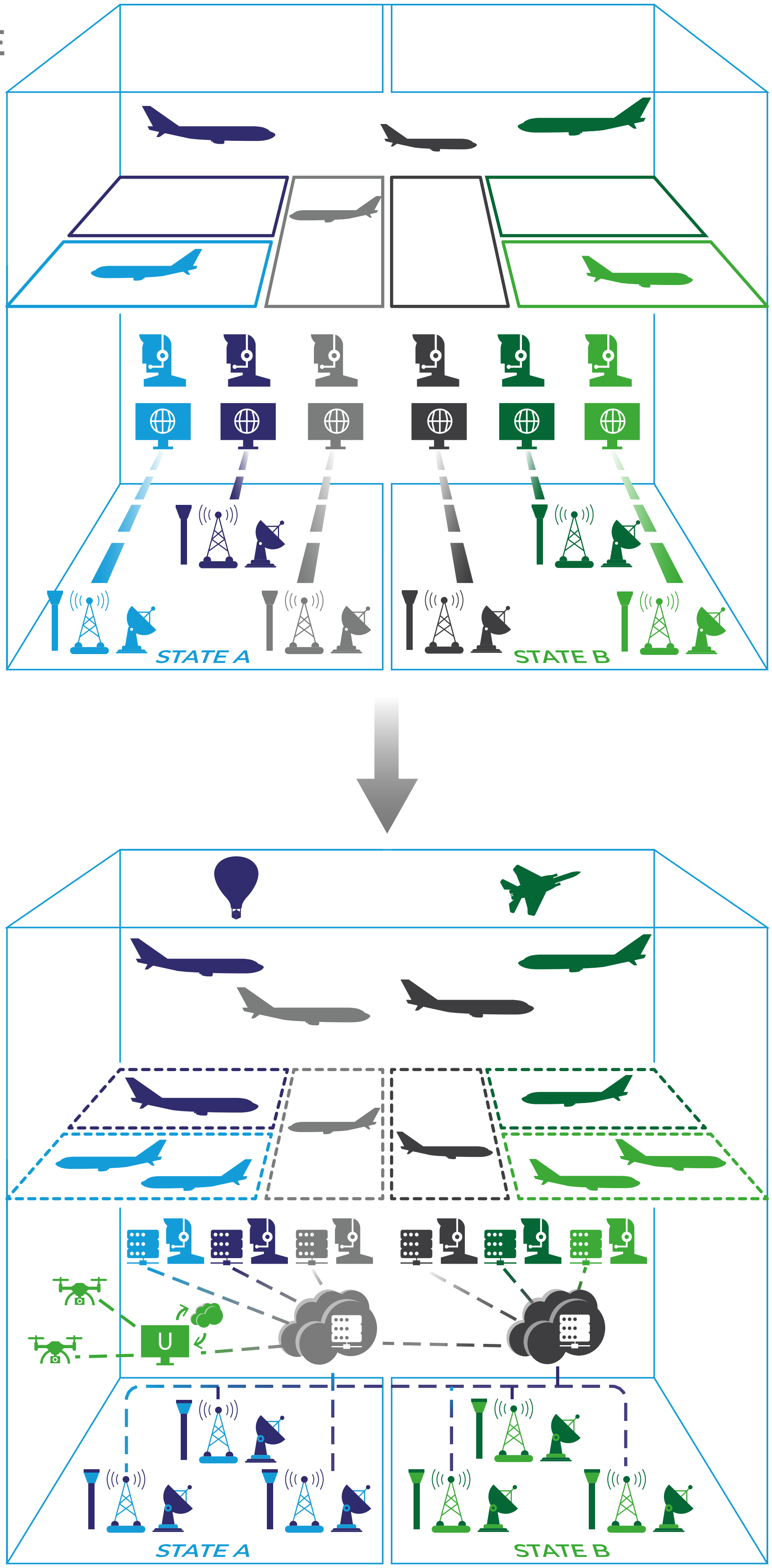


Figure 37 – Evolution from current ATM architecture to the future one based on the SESAR Digital European Sky

11.3 OPTIMUM FLIGHT PATHS

Air navigation has witnessed some important improvements in recent decades. However, a considerable remainder of the global air navigation system is still limited by legacy design approaches that arose in the twentieth century.

These legacy design approaches are responsible for unnecessary greenhouse gas emissions being deposited into our atmosphere and the limiting of air traffic capacity and growth. Furthermore, they also contribute to the inefficiency in the air traffic management network. Due to this, flights in the European network use on average between 8.6% and 11.2% more fuel than the most efficient flights [14].

One of the factors influencing fuel inefficiency is the route network constraints. Addressing these issues on a national and international level is essential to substantially reduce the aviation sector's CO_2 emissions, and support zero-carbon emission aircraft operations. Improving the efficiency of flight paths can be achieved through the wide implementation of:

- **Improved flexibility and efficiency in descent profiles – Continuous Descent Operations (CDO).** Within the CDO concept, the optimum vertical profile takes the form of a continuously descending path, with a minimum of level flight segments only as needed to decelerate and configure the aircraft or to establish on a landing guidance system.

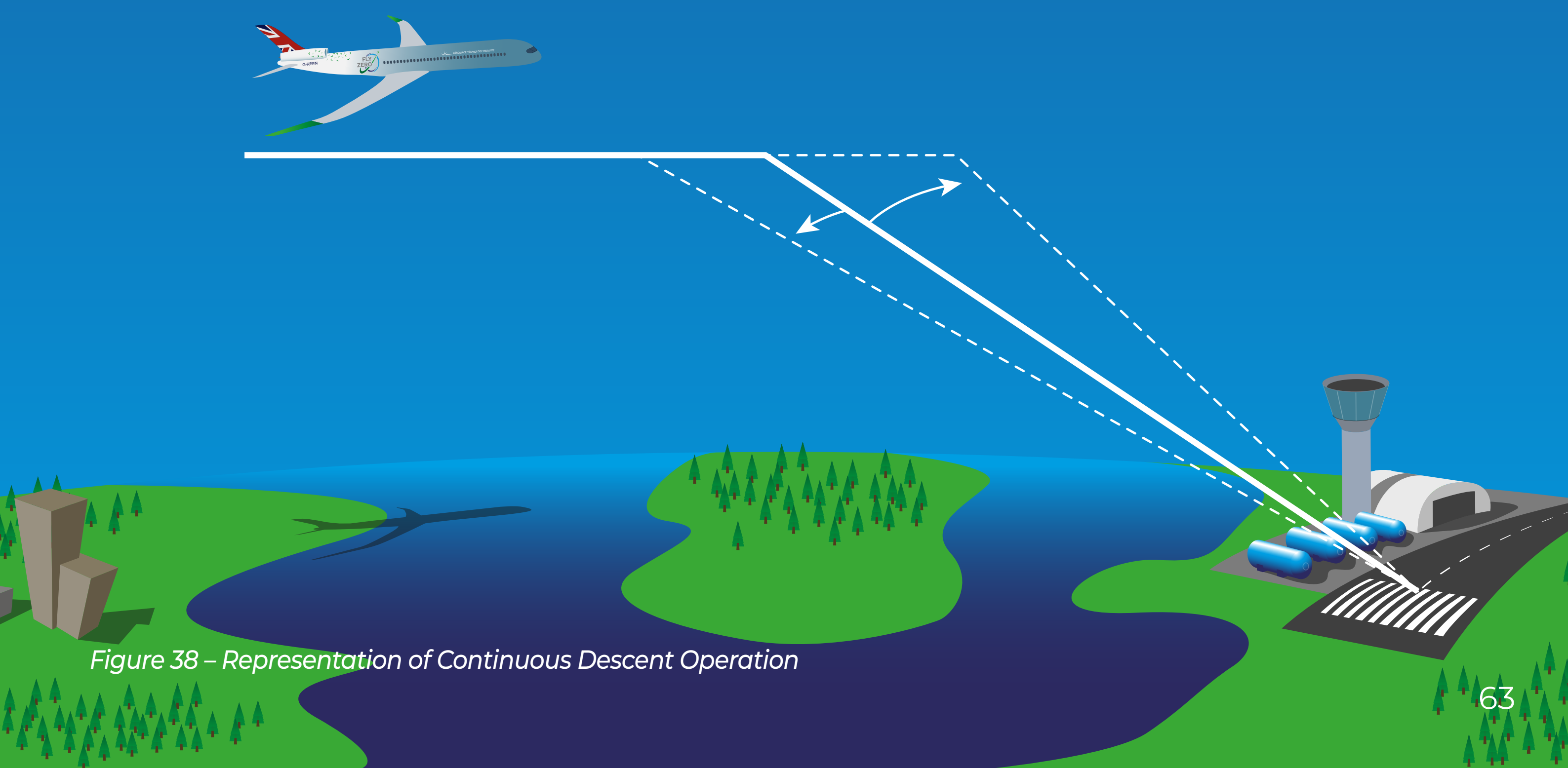


Figure 38 – Representation of Continuous Descent Operation

- **Improved flexibility and efficiency in departure profiles – Continuous Climb Operations (CCO).** CCO is an aircraft operating technique made possible by appropriate airspace and procedure design and appropriate ATC clearances, enabling the execution of a flight profile optimised to the performance of the aircraft. It allows the aircraft to attain initial cruise flight level at optimum air speed with climb optimal engine thrust settings set throughout the climb, thereby reducing total fuel burn and emissions during the whole flight.

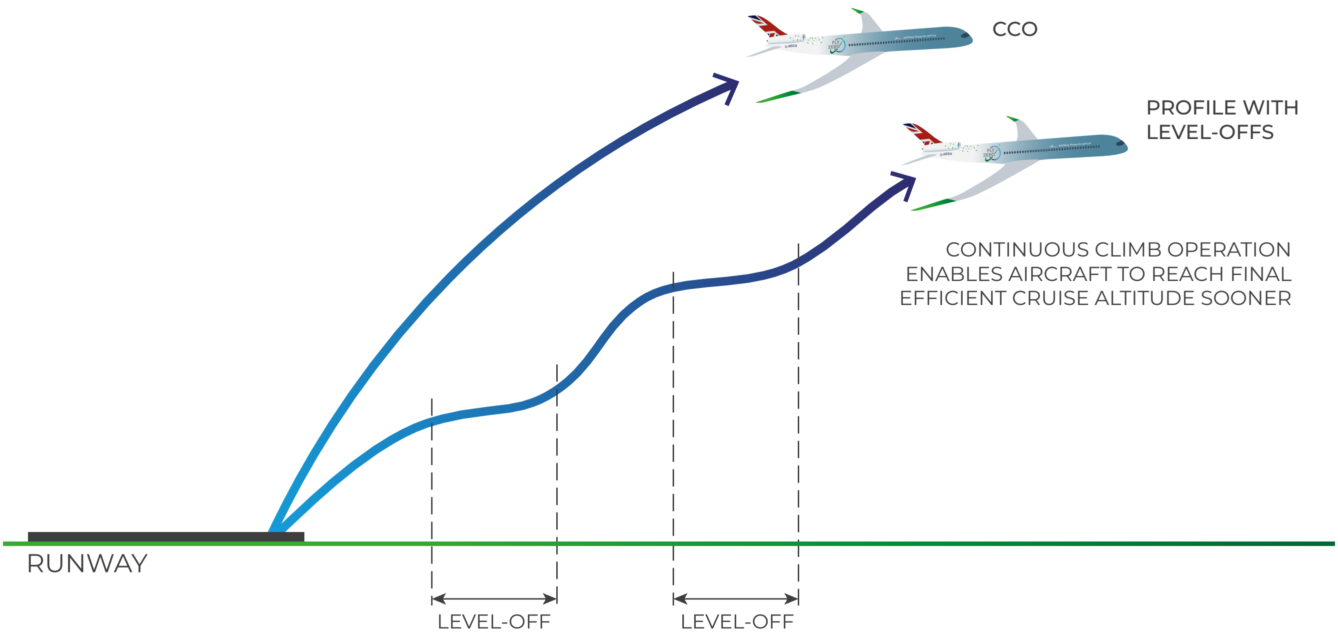


Figure 39 – Schematic representation of Continuous Climb Operation and comparison with conventional departure containing level segments

- **Improved traffic synchronisation and maximising flight efficiency through the introduction of performance-based navigation and Trajectory-Based Operations (TBO).** This concept provides high predictability and accuracy of the trajectory during planning and execution of the flight, with airborne and ground actors sharing consistent information throughout the mission trajectory life cycle. It allows aircraft to fly the preferred trajectory, the shortest route with no level-off segments, while minimising constraints due to airspace and service configuration, thanks to the satellite-based navigation.

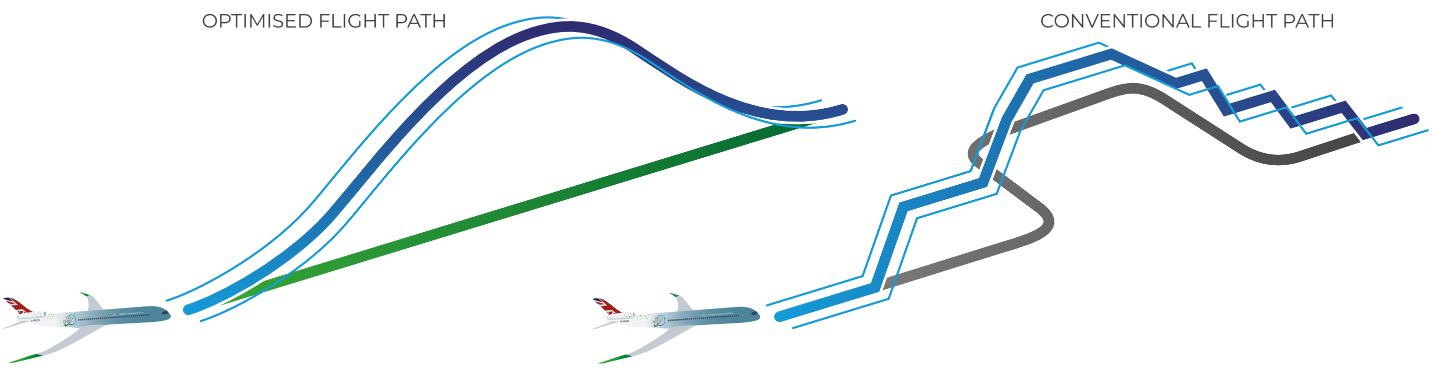


Figure 40 – Schematic comparison between optimised flight path (left) and conventional flight path containing level segments and detours

- **Minimising delays through the introduction of time-based separation (TBS)**. This method has been developed within the SESAR programme to mitigate the risk of capacity constraints. It can be applied to replace the current distance-based separation (DBS) in order to adapt to weather conditions. This separation method provides consistent time-based spacing between arriving aircraft in order to maintain runway approach capacity. Application of this method is based on the so-called RECAT-EU[2] wake turbulence categorisation where each aircraft type is assigned specific wake vortex category. Aircraft powered by novel hydrogen propulsion systems will need to undergo specific analysis ensuring that they are categorised according to their actual wake turbulence. Following the current requirements, such analysis will be necessary for the FlyZero midsize concept, but optional, although recommended, for the regional and narrowbody concepts. As a substantial number of new air vehicles (manned and unmanned) are expected to enter operations in the upcoming decades, it is likely that such analysis will become mandatory regardless of the entrant's size.

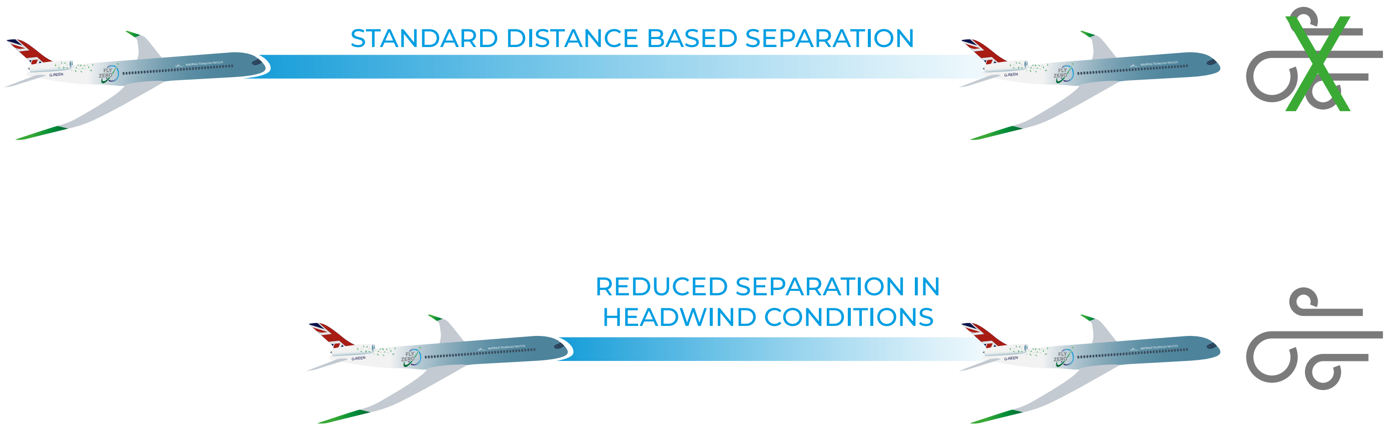


Figure 41 – Schematic representation of difference between distance-based separations and time-based separation in headwind conditions

[2] - *RECAT-EU - European Wake Vortex Re-categorisation*

11.4 COLLABORATIVE DECISION MAKING

Collaborative decision making is one of the most important processes in air traffic management, especially in air traffic flow management and Airport Collaborative Decision Making (A-CDM). It requires all members of the aviation community to work in partnership in decision-making processes that ensure the best outcome based on equity and access. This includes airports, airlines and flight crews, air navigation service providers and the air traffic controllers. The efficiency of this concept depends on operational information being accessible to multiple stakeholders enabling informed discussion and facilitating collaborative decisions and efficient operations. It embraces planning and execution of flight operations on the ground and in the air. This concept is a demonstrator of how the airlines, airports and airspace are interlinked and cannot be treated in isolation from each other when operational and environmental enhancements are considered. This will become especially relevant when dealing with hydrogen-powered aircraft since new operational procedures for ground handling will be required. As mentioned in **sections 7** and **8**, the new requirements such as discharging a liquid hydrogen tank for an aircraft, will demand airlines and airports to communicate and collaborate more than ever before.

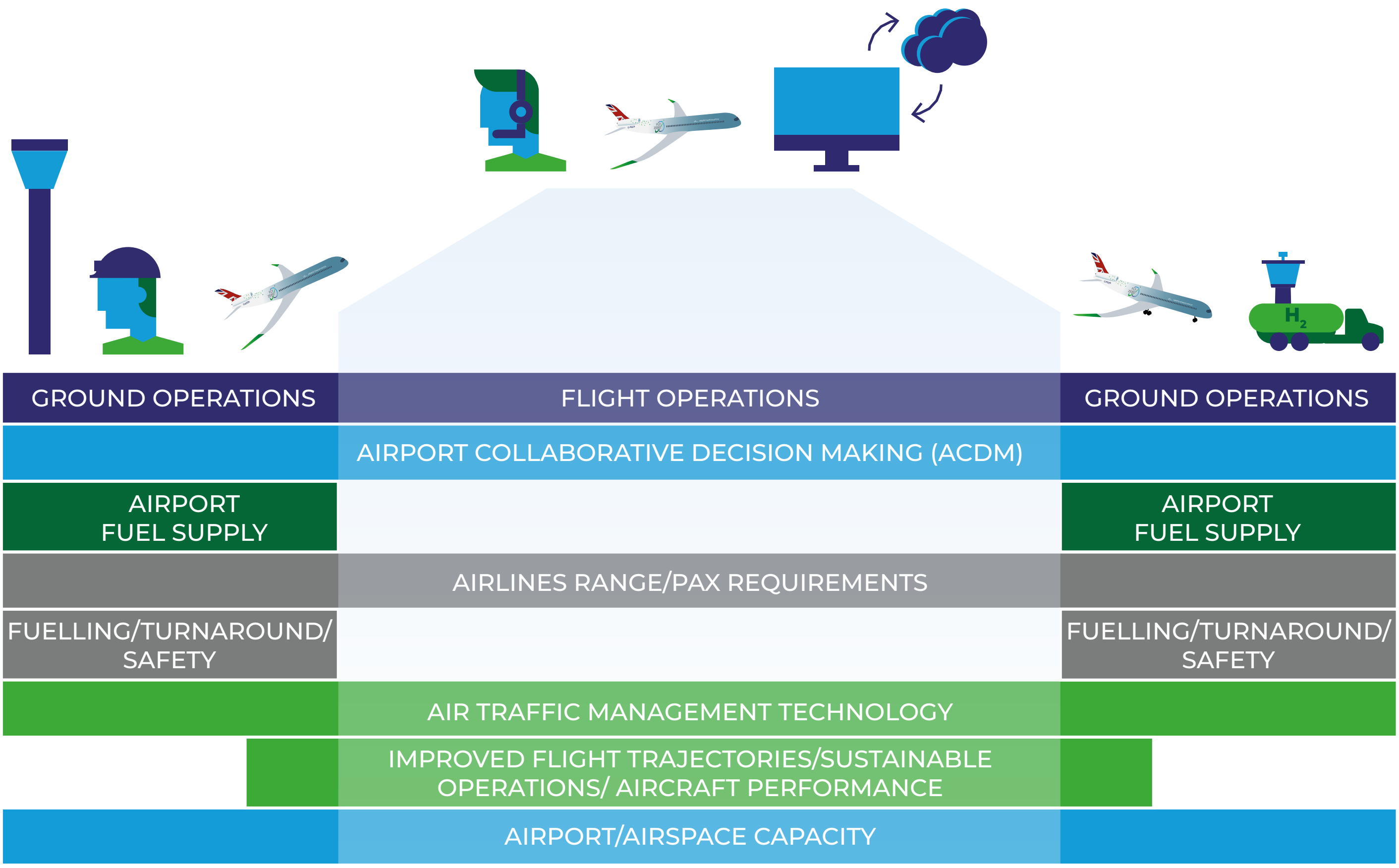


Figure 42 – Airline, airport and airspace integration across ground and flight operations underpinned by A-CDM processes

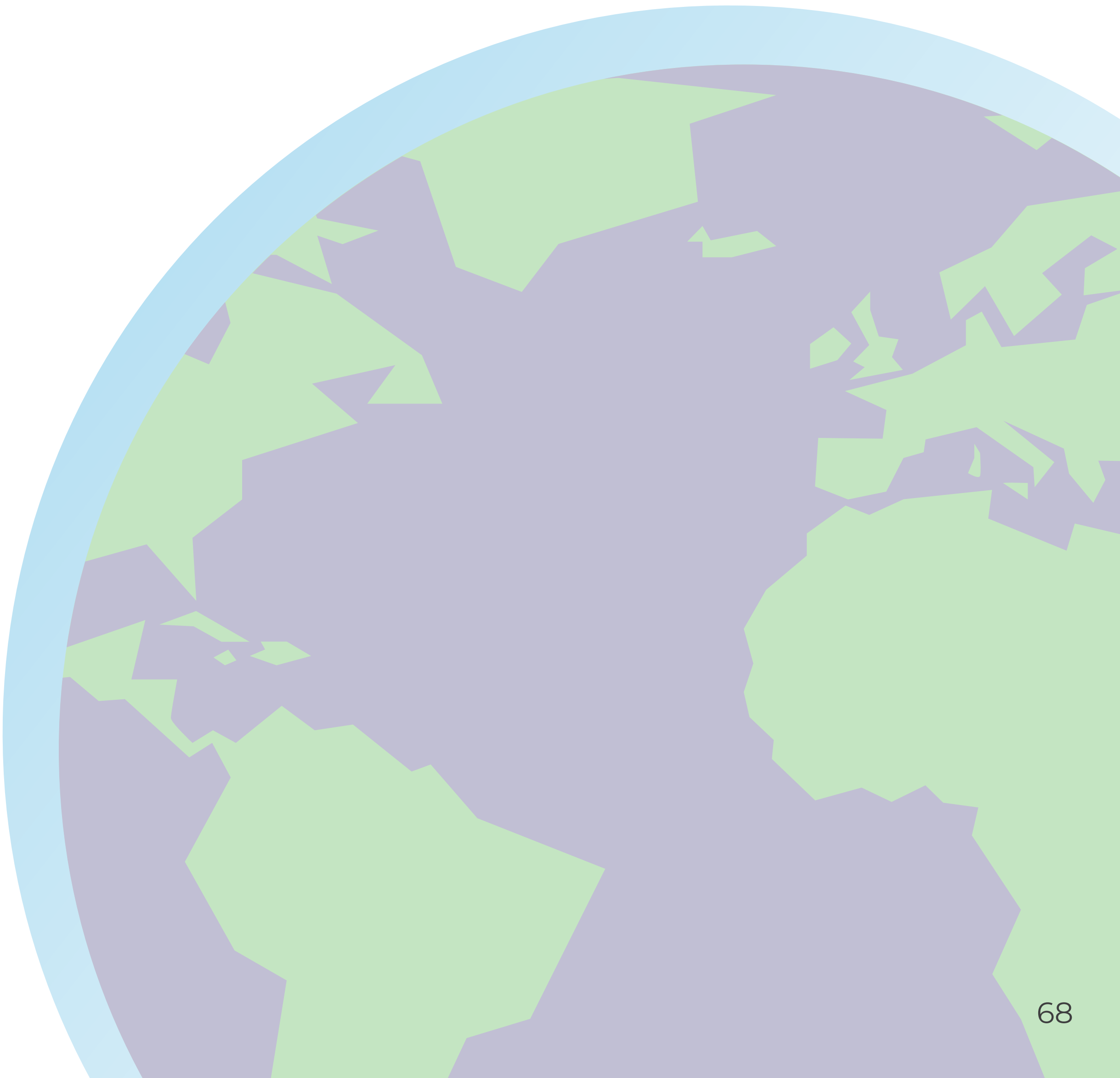
A-CDM originally focused on the most effective planning of departing traffic using Departure Manager (DMAN) as a tool for pre-departure sequencing. However, DMAN is now often used with the integrated Arrival Manager (AMAN) enabling reduction of delays by anticipating the time of arrival and departure and allowing improved flow management on the ground and in the air. Together with other tools supporting efficient ground operations within the A-CDM concept, DMAN and AMAN will be the key enablers to the timely refuelling operations of hydrogen aircraft to avoid pressure build-up on the tank and the unnecessary release of hydrogen into the atmosphere.

Currently the A-CDM concept is being further developed to integrate not only the most relevant operational aspects, but also to cover areas such as noise, biodiversity or water management for the overall airport management process. The non-CO_2 emissions and local air quality will become significant factors in this process, especially regarding the hydrogen-powered aircraft. This development would also improve strategic and tactical decision-making regarding the impact of airport operations on the environment. Due to the collaborative procedures, comprehensive planning and proactive action on foreseeable problems, a major reduction in on-ground and in-air holding would allow a reduction of air pollution and noise in the vicinity of the airport.

11.5 HIGH RESOLUTION WEATHER DATA

Weather information is crucial for flight planning and execution. Using advancements in data analytics and meteorological forecasting makes it possible to predict a daily optimum configuration of airspace and to plan the most optimum mission trajectory, allowing greener operations. Currently observed climate change is expected to increase throughout the century, and consequently, will have an impact on the aviation sector. Therefore, it is vital to understand the character of these changes and to build resilience by application of solutions to enable the reduction of weather impacts on flights.

Technologies utilising high resolution weather data facilitate planning and the execution of more flexible and optimised flight paths. They allow not just thunderstorm avoidance, but also avoidance of headwinds causing extra fuel burn, or the avoidance of regions prone to contrail formations. The capacity to avoid or minimise contrails will be an important enabler to the hydrogen powered aircraft, which will have to minimise all non-CO_2 related climate impacts. The high-resolution weather technologies could also support formation flying operations aimed at wake vortex energy retrieval, resulting in substantial fuel burn reductions.



11.5.1 HEADWIND AVOIDANCE

This solution relies on a tool calculating the cost-optimal flight trajectory based on a selected cost-index, actual performance data such as weight, altitude or speed, and current weather. Information provided to pilots supports them in the selection of the most optimal flight level, which can achieve cruise fuel savings of 1.6%. [15]

By making use of advanced weather data that provides high resolution information on headwinds at cruise altitudes, airlines can save 160 kg of CO_2 [16] emissions per flight for an aircraft like the Boeing 737-800, comparable with the FlyZero narrowbody concept.

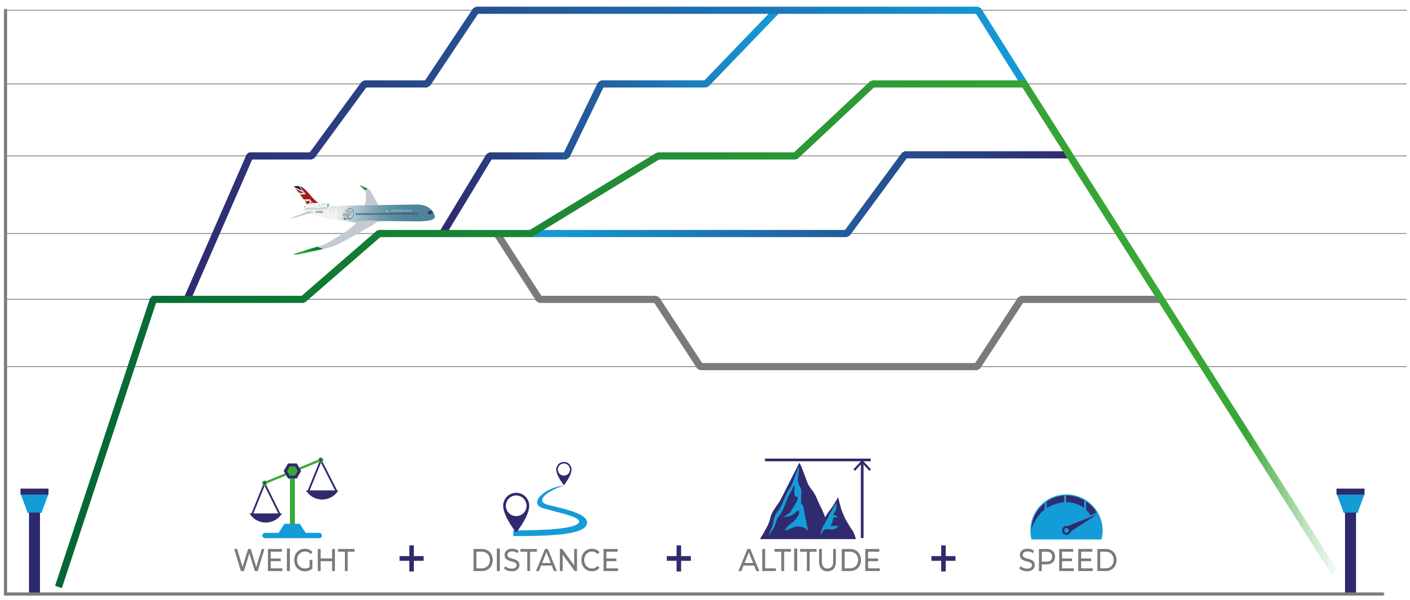


Figure 43 – Schematic representation of algorithm for headwind avoidance advisory

11.5.2
NAVIGATIONAL CONTRAIL AVOIDANCE

Persistent contrail formations are considered one of the most significant contributors to aviation's non-CO_2 climate impact. Currently investigated solutions to reduce this effect assume potential benefits from navigational contrail avoidance by re-routing aircraft away from the regions prone to contrail formation. However, the effects of such techniques on fuel burn and the resulting potential increase in CO_2 emissions need more research. Current science does not provide sufficient information on whether flying into a region prone to contrail formation would result in the creation of a persistent or a short-lived contrail. As the majority of contrails are short-lived, whereas CO_2 lasts in the atmosphere for hundreds of years, the balance between avoidance of all contrail formation regions and potentially increased CO_2 emissions needs careful consideration.Hydrogen powered zero-carbon emission aircraft open up new opportunities for contrail avoidance. Since no carbon is emitted in flight, there is no environmental penalty for rerouting aircraft around contrail forming regions.

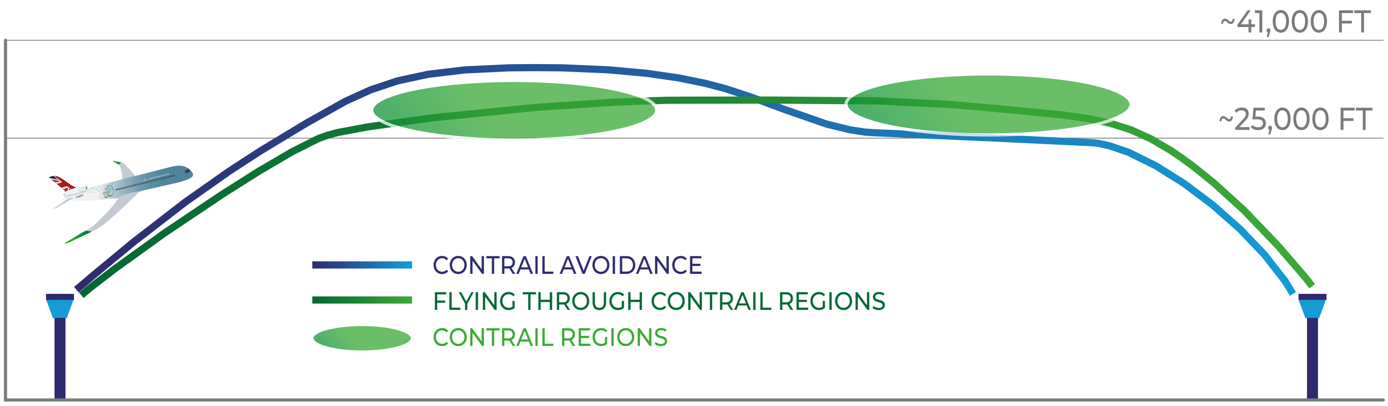


Figure 44 – Schematic representation of navigational contrail avoidance

In addition to the navigational re-routing, another concept for contrail avoidance suggests lowering the cruise levels for hydrogen powered aircraft to below those used by kerosene powered aircraft today. If future research and knowledge into the impact of hydrogen on contrail formation shows definitively that the cruise altitude for aircraft such as the FlyZero concepts should be lowered, and to what level, two major issues will require consideration:

- It might be necessary to study a new design with a service ceiling lower than the ceilings assigned to current FlyZero concepts. Effectively, some of the design parameters obtained so far could require revision and redesign.
- If the aircraft design would be adapted to a potential requirement of lower service ceiling, an impact assessment of such a change on the air traffic management system would be necessary to understand the magnitude of potential changes and prepare the industry for their implementation.

Future studies will be necessary to cover the potential issues related to impact of hydrogen as an aviation fuel on the environment through the persistent contrail formations. Interest is growing among policymakers and across the industry on contrail avoidance, including improving the ability to predict persistent contrails, measure their impact and test the feasibility of avoiding their formation in an operational setting. Aviation's non-CO_2 impacts are increasingly under scrutiny and the opportunities to minimise these should be acted upon now.

11.5.3 FORMATION FLYING

According to ICAO **[17]**, the automated formation of flight operations in cruise, applied to civil aircraft, is one of the most promising ways to reduce fuel burn via air traffic management techniques. However, to enable these operations, active participation by the aviation regulatory authorities and industry is needed at a national and international level.

The value of automated formation flight is linked to the local fuel savings obtained for the follower aircraft while using part of the energy from the wake vortex generated by a leading aircraft. Positioning a trailing aircraft in the right way, in the area where the vortex pushes air upward, enables the trailing aircraft to save 5-10% of fuel per flight. It is expected that between 3 and 4 million tonnes of CO_2 could be saved on widebody operations per year **[18].** Such a technique is currently considered only for long-haul operations, therefore, it would be applicable to the FlyZero midsize concept.

11.6 SUM OF MARGINAL GAINS

Hydrogen powered commercial aircraft, allowing zero-carbon emission flights, is a potentially exciting future for aviation. However, it is also crucial to focus on the present, where the Air Navigation Service Providers (ANSPs) with their air traffic management activities can support airlines and airports, and act as an enabler for emissions and noise reduction in the meantime. However, the governments and regulators also have an important role to play in clarifying the priority between noise and emissions management, defining policy on noise dispersal and noise concentration, and in ensuring that the regulatory procedures for airspace change are efficient in allowing airspace improvement to progress quickly.

Operational developments presented in this section come from a plethora of solutions available to aircraft operators and ANSPs. They aim to increase safety, flight predictability and airspace capacity, while reducing noise, fuel burn and controller-pilot communications; hence also reducing workload and increasing the safety of operations. Examples of environmental advantages emerging from the selected solutions are shown in Table 16. It is important to remember that the numbers presented below are based on current aircraft technologies and pre-pandemic traffic volumes and should be treated as indicative only.

Solution Example	*Potential Benefit/Reduction*	*Remark*
SESAR solutions	*450 kg CO_2 per flight*	*Average estimate for combined set of solutions*
Continuous Descent Operations	*Noise reduction 1.5 dBA at distance 10-25 nmi from landing threshold*	*If descent started at altitude at or above 7000 ft*
	1 tonne fuel / 3 tonnes CO_2 per flight	*If descent started at altitude of 20,000 ft*
Continuous Climb Operations	*3% - 8% of CO_2 per departure*	*Average estimate*
Free Route Airspace	*12,000 tonnes CO_2 per year*	*Only from the FRA implemented above Scotland above altitude 25,000 ft*
Arrival Manager (AMAN) as part of A-CDM	*25,000 tonnes CO_2 per year*	*At London Heathrow alone*
	3,800 tonnes CO_2 per year	*At London Gatwick alone*
Integrated AMAN/DMAN as part of A-CDM	*14 kg fuel per flight*	*Average estimate*
Time Based Separation	*47,000 tonnes CO_2 per year*	*At London Heathrow alone*
Headwind avoidance	*160 kg CO_2 per flight*	*Based on Norwegian airlines fleet data*
	1.6% of cruise fuel per flight	
Formation flying	*5% - 10% fuel per flight*	*Average estimate*
	3 - 4 million tonnes CO_2 per year	*Estimated for the whole widebody operations*

Table 18 – Examples of environmental advantages emerging from the selected solutions

Although isolated benefits that ATM offers might not strike as substantial, it is the sum of marginal gains that provides the most significant result. One of the biggest advantages is the fact these solutions allow fuel burn reductions for kerosene aircraft, and they will also provide the same for the hydrogen powered aircraft. In turn, this will enable reduction of required hydrogen to be manufactured, transported, liquefied and stored, providing considerable cost reductions in the future.

As the COVID-19 pandemic has provided the opportunity to reflect and to reassess priorities, the aviation sector has a unique chance to implement as many solutions as possible and to push for more ambitious foundations to build sustainable airspace of the future. One of the most important next steps is to ensure that stakeholders collaborate with each other rather than work in silos as it has often been the case over the past decades. The model of Airport Collaborative Decision Making should be applied not only to plan and execute efficient flight operations, but also to plan and execute efficient local, national and international strategies and implementations.

12. CONCLUSIONS

For a liquid hydrogen fuelled aircraft to be successful it is essential to understand the impacts on stakeholders, including airports, airlines and air navigation service providers.

Considerable infrastructure development is required, and new regulations and procedures are needed to allow the aircraft to operate safely. Liquid hydrogen presents many challenges, not least operating at cryogenic temperatures of -253˚C.

By 2050, the demand for hydrogen will be significant, exceeding current production. However, it is important to consider aviation's impact in the context of the scale of energy transition required by the UK to achieve decarbonisation. As aviation moves towards the direct use of hydrogen, battery-electric propulsion and the increased use of PtL SAF, the future energy requirements will be significant. The National Grid forecast a requirement of 80 TWh of hydrogen for aviation and maritime by 2050, which is similar to the demand forecast by FlyZero. Depending on the combination of national scenario and hydrogen aviation growth scenario, aviation could require between 10% to 30% of the national demand. While aviation is a large potential user of hydrogen, it is the wider market that will be the driver for hydrogen production capacity.

The UK has signalled its intentions for hydrogen development through the hydrogen strategy. However, the potential for direct burn hydrogen for aviation should be considered and included to ensure a timely supply is available.

Initially it is anticipated that hydrogen will be produced and liquefied remotely utilising facilities generating hydrogen for many different users. Hydrogen would then be delivered to the airport by road or rail tankers. However, as demand increases, at large airports, tanker operations may no longer be viable. At this stage it is likely that hydrogen will need to be delivered to airports by gaseous hydrogen pipelines, with airports liquefying on-site. Although it is feasible for airports to generate their own hydrogen on-site, the extremely high electrical power demand of electrolysis suggests that this is unlikely. While the technology for electrolysis and liquefaction currently exists, the challenge of scaling to the demand levels required for aviation will be considerable.

The demand for high volumes of liquid hydrogen is unique to aviation, requiring the development of large-scale UK liquefaction capability. Similarly, the supply of hydrogen to airports through a gas pipeline, while feasible needs further investigation to understand the complexities, costs and interactions with the wider hydrogen economy. On-airport liquefaction will require considerable power above that available to supply most airports today. Understanding the feasibility of supplying this electricity is needed to ensure on-site liquefaction is achievable.

Distribution of hydrogen throughout the airport to the aircraft will in many ways be similar to the methods currently used with existing fuel. However due to the cryogenic nature of liquid hydrogen, both a bowser operation and a hydrant system for busier airports will require complex solutions to be designed and developed. System concepts suggest liquid hydrogen distribution systems at airports would be feasible, however further work should be directed towards understanding how this infrastructure, unique to airports, can be developed.

Maintaining existing aircraft turnaround times is fundamental to ensure commercially efficient airline and airport operations, which may be challenging, but achievable, for liquid hydrogen aircraft. The energy density by volume of liquid hydrogen is lower than kerosene, therefore, if using existing pipe diameters and flow rates, refuelling an aircraft with liquid hydrogen is likely to take longer than if using kerosene. However, with the implementation of new airport infrastructure, regulations and technology, maintaining similar turnaround times may be feasible. Using multiple, larger refuelling hoses, combined with new processes and automation should enable a turnaround process with a minimal increase in duration above the refuelling times experienced with kerosene.

Safety exclusion zones when refuelling with liquid hydrogen are likely to be larger than existing safety zones. However, early studies suggest that a large safety exclusion zone of 20 m may only be required when refuelling connections are being made or disconnected. Once the connections have been made a smaller exclusion zone of approximately 8 m may be more appropriate. Although larger than current safety zones, 8 m allows some parallel aircraft servicing activities to take place during aircraft refuelling. This is essential for maintaining the option of the current short turnaround times, especially significant for low-cost carriers. However, the increased safety requirements for liquid hydrogen and the increased safety exclusion zones may also lead to the need for more ground servicing automation.

Studies and trials are required for testing and verifying the feasibility of rapid refuelling and aircraft turnaround activities. In addition, risk assessments, simulations and trials will be needed to investigate safety distance requirements and leak detection technology.

The zero-carbon emission aircraft technologies identified through the development of the FlyZero concepts require significant development at pace. The impact of hydrogen powered aircraft on persistent contrail formation remains an open question and calls for more research to verify whether cruise altitudes assumed for FlyZero aircraft could remain unaltered.

Additionally, more research will be required to evaluate the impact of potential changes of cruise altitudes on the air traffic management system. Nevertheless, the current concepts' performance characteristics do not display any attributes preventing their smooth integration within the ATM system. Additionally, this system is undergoing changes that will improve its operational efficiency, directly and indirectly contributing to the reduction of aviation's impact on the environment. These developments will enable two major benefits:

- The reduction of fuel usage (kerosene, SAF or hydrogen) enabling operational cost reductions
- The reduction of tailpipe CO_2 for kerosene aircraft, and non-CO_2 emissions for all aircraft

Therefore, understanding the sum of marginal gains provided by ATM, and facilitating collaborative implementation of anticipated developments, will be a vital step towards shaping more efficient airspace and making it ready for new future entrants. It will also allow using air navigation services as enablers for sustainable flight operations, as part of the decarbonisation roadmap that the aviation industry is focussed on. Minimising the energy used in flight, through airspace initiatives, reduces the infrastructure and renewable energy demand required to generate hydrogen fuel. Further understanding to quantify how airspace initiatives reduce hydrogen demand will allow savings in infrastructure and energy to be evaluated.

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