CATAPULT Connected Places

Jacobs
Challenging today.
Reinventing tomorrow.

ZERO EMISSION AIRPORTS 2040

ZEFI Draft Transition Plan

July 2024

RF: Hydrogen Regulators Forum
TA: International Air Transport Association
AO: International Civil Aviation Organization
C: International Electrotechnical Commission
aS: Integrated Refrigeration and Storage
O: International Standards Organisation
D: Learning By Doing
HS: Low Carbon Hydrogen Standard
2: Liquid Hydrogen
R: Local Nature Reserves
: Learning Rate
A: Mitigation Action
APP: Major Accident Prevention Policy
ASA: National Aeronautics and Space Administration
: Narrow-body
FPA: National Fire Protection Association
PPF: National Planning Policy Framework
: Optimism Bias
: Operational Challenge
M: Original Equipment Manufacturer
S: Obstacle Limitation Surfaces

OPEX: Operational Expenditure
ORAT: Operational Readiness Activation and Transition
PED: Pressure Equipment Directive
PEM: Proton Exchange Membrane
PSSR: Pressure System Safety Regulations
ROM: Rough Order of Magnitude
RLV: Redline Version
SAF: Sustainable Aviation Fuel
SOP: Standard Operating Procedure
SPA: Special Protection Areas
SPZ: Source Protection Zone
SR: Safety Risk
SSSI: Site of Special Scientific Interest
TAG: Transport Analysis Guidance
TP: Transition Period
TRL: Technology Readiness Level
ZEA: Zero Emission Airports
ZEF: Zero Emission Flight
ZEFI: Zero Emission Flight Infrastructure
WB: Wide-body
WD: Working Draft

s a nascent technology, there is significant uncertainty ver the future of hydrogen-powered flight. Therefore, the cale of infrastructure requirements for airports are only just eginning to be understood. Technology and timescales will ontinue to evolve, making it difficult for airports to plan for e long-term future. The large-scale investments needed by rports to support ZEF require certainty over the introduction new aircraft. But equally, the development of new novel rcraft requires reassurance that supporting infrastructure is ot only feasible but will also be ready for their introduction.

s a draft transition plan, this guide is not intended to provide efinitive answers and designs, but instead gives the high-vel guidance needed to support initial master planning, lowing airports to safeguard for the future. Through industry ollaboration these guidelines can continue to develop in line th research, trials and technology development. This guide so helps to highlight where early investment in infrastructure needed to support the first gaseous hydrogen aircraft xpected to begin operation within this decade.

he approach to infrastructure development will differ gnificantly by airport, based on factors including size, cation and operating airlines. Therefore, not all sections of e report will be applicable to all airports. For example, small rports may only require a supply of hydrogen by tanker, with o need for large on-site storage, liquefaction or electrolysis.

In addition, not all airports will have the data needed, or insights into their future flight and fuel demand. However, the guidelines can still be used with high-level assumptions and updated in the future as clarity develops.

The transition plan is structured into seven chapters to assess the technical, regulatory and economic aspects of hydrogen-powered aircraft at airports. Where relevant, each of the chapters is divided into a step-by-step methodology and a case study to illustrate the approach.

Chapter 1 identifies relevant net zero targets and how these may influence airports. **Chapter 2** summarises relevant regulations and standards to enable a safe transition to ZEF. **Chapter 3** discusses forecasting hydrogen demand with **Chapter 4** providing a high-level overview of the key hydrogen technologies and the operational pathways available for hydrogen supply to the airport.

This chapter then explor by-step methodology to major infrastructure req based on the hydrogen f Chapter 2. Using these r **Chapter 5** discusses ma considerations and **Cha** the most significant ope challenges. The guidelin **Chapter 7** by providing r magnitude capital and o for infrastructure eleme

Jacobs and Connected F have produced this inde for DfT.

The report represents th views, not those of DfT.

en chapters to assess the technical, aircraft at airports.

targets established and explores how these targets may influence rts in relation to their approach to decarbonisation. This chapter ansition towards zero-carbon emission aircraft is critical.

nal standards, also highlighting gaps in the current regulations to ards zero-carbon emission flight (ZEF).

understand the level of infrastructure they may require and the mentation, is to understand the level of hydrogen demand. Chapter o-down methodology to develop hydrogen forecasts for airports.

w of the key hydrogen technologies relevant for airports, along with rogen supply and refuelling infrastructure. The matrix supports astructure and operational pathway best suits their hydrogen s. A step-by-step methodology on how to estimate the major is also included.

ntify a suitable area to develop hydrogen infrastructure. d, showcasing the list of activities and dependencies between tential timelines for implementation.

nt operational challenges and safety risks for the operation of with the necessary mitigation actions, enabling airports to identify n the short, medium and long term to reduce the risks and to enable

nitude capital and operational costs for the different hydrogen nable airports to estimate, indicatively, the total costs of ent supply pathways.

The chapter is divided into the following sections:

1.1 Roadmap to a 2050 net zero aviation.

1.2 Infrastructure and operational considerations that airports will need to assess **to be ready for the net zero target.**

by 2050 will require an ports are set to play an

complex technological and operational challenges it
he premium cost of alternative fuels such as sustainable
stakeholders in the aviation industry have already taken
uding emission-reduction targets, SAF targets, and

The UK Government has also set national targets for the UK aviatio
Agreement. To support this ultimate ambition, the UK Government
Jet Zero Council, a partnership between the government and the a
fast-track zero-carbon emission flight and incentivise the productio

ate: 10% SAF in the UK jet fuel mix

: In-setor interim target of 35.4MtCO$_2$e

ion: zero-carbon emission routes
cting different parts of the UK

ion: 10GW of UK low carbon hydrogen
ction

International SAF targets:
US: 15%
EU: 6%
Japan: 10%

2035

Target from the CCC: 78% reduction in UK territorial emissions between 1990 and 2035 [3]

Ambition: First large zero-carbon emission commercial aircraft expected to enter into service

EU SAF target: 20%

2040

Target: All airport operations in England zero-carbon emission[1]

Target: All UK domestic flights net zero[1]

Target: In-sector interim target of 28.4MtCO$_2$e

EU SAF target: 32%

y 2040 are technically and
hout challenges

ng

n, no one solution will be sufficient. In addition to the scale up
rts will need to implement in-house measures to make their
sures will involve infrastructure and operational implementations
ditioned air supply for aircraft, enabling the electrification of the
rface access, and enabling the reconfiguration of the airspace.

nable infrastructure: It is anticipated that by 2040, commercially
allow airports to fully achieve zero-carbon emissions. This
astructure, but also other assets such as cars and ground
, airports will need to make their airport more energy-efficient,
est in facilities to promote a circular economy such as waste
is transition will, in many cases, require changing assets before
nd, in most cases, replace them for technology with significantly
ow and 2040, airports will need to decide what infrastructure
eeds and, in some cases, whether to write off assets with
placing them with 'greener' alternative solutions even though
omic case.
UK airspace modernisation programme will also have
most UK airports. However, as this process has already started,
from those already planned for are not expected.

Focus area	Ambition statement	Impact on airports' decision makir
Domestic Net Zero Aviation	"Reach domestic net zero aviation by 2040" "All airport operations in England to be zero emissions by 2040"	**Operations:** - **Operational disruption:** Operat with large fleets are likely to en costs of these replacements, as these changes. For medium and but these airports are more ser which may occur when replacin airports will need to carefully pl affected parties to ensure the a both passenger experience and - **Training**: The reconfiguration of the form of redesigned approac runway hold times, additional c staff will need to be trained on - **Public awareness:** Achieving ze adoption of electric cars and pu **Commercial:** There will be a number of commerc - Some UK airports are regulated investment required to support this new technology will have in investment. Regulated airports the system in place is flexible e zero-carbon emissions airport t - Airports, especially small-scale support may be needed to aid a or additionally – airports could d decarbonisation. However, unle to other airports which, in turn,

kely to play a key role in reaching

tion target means that by 2050 airports are required to reduce
hile the 2040 zero emissions target will have paved the way for UK
emissions at airports can be Scope 3 (emissions from assets not
that the airport indirectly affects in its value chain), mainly from
al measures (i.e., SAF, new clean airport infrastructure, airspace
ented. These will include zero-carbon emission flight (ZEF), carbon
r airports, zero-carbon emission flight will have the most impact.

arbon emission flight (i.e., electric and hydrogen powered aircraft) is
nisation of aviation. These aircraft, especially hydrogen aircraft, will
es at airports. Therefore, airports will need to identify infrastructure
d long term, and identify suitable locations for accommodating
hat airports plan for this infrastructure in advance as congested
or repurpose large areas within their footprint. Incorporating these
gain support and understanding from the local planning authorities
planning permits can be obtained without delaying the uptake of ZEF.
ture across UK and global airports will be key to ensure airports do
n emissions aircraft adoption. Although manufacturers are likely to
ed to be engaged in the whole hydrogen value chain.

F could include extended turnaround times, new safety and operational
ments for employees. Airports will need to engage with all stakeholders
nsition to hydrogen operations. The first step towards achieving ZEF is
perations from which the industry can learn. Small airports with less
e in a better position to provide this learning platform.

rbon emission aircraft will be CAPEX and OPEX intensive. Airports will
ory organisations to secure the capital needed to invest in the required
ations as those identified for the funding of SAF could also be explored.

ATIONS
ANDARDS

POLICY, REGULATIONS AND STANDARDS

At the end of this chapter, airports will understand the following:

The **policies, regulations and standards** that are relevant to the introduction of hydrogen aircraft at airports – from the **production to the distribution and end-use.**

The **key stakeholders** involved in the development of the hydrogen regulation.

The main **gaps in the regulation.**

Chapter 2 identifies **existing or developing policies, regulations and standards relevant for the introduction of hydrogen in the aviation ecosystem.** The research includes national and internation regulations from the public realm.

e regulatory landscape

ng where there are gaps in the current regulation to enable

standards will need to be adapted to ZEF activities.
s as shown in the dashboard below.

exhaustive. It is the intention of this chapter to provide an
ocus needs to be.

Standards have been further classifiec

Zero-carbon emssion flight Standards require significant adaptation

Relevance Peripherally

Airports Not airport scope and/or unlikely to directly impac airport operations

orage

Liquefaction

Liquid or gas storage

Distribution

Vehicle transport

Pipelines

End-Use (Aircraft)

Refuelling vehicle

Safety

Training

Planning permits/land use

A secure and reliable source of hydrogen will be essential for future
location, production may be airport-specific, or a regional productio
production is likely to require de-risking via long-term off-take cont

	ZEF	Airports
	🟧	🟧
	🟧	🟩
	🟧	🟧

lysis – Industrial, commercial, and residential applications

rements of modular or factory-matched hydrogen gas
mercial uses. Excludes producers that generate electricity

uce hydrogen on-site. Otherwise, relevant to installations
be adapted to suit the airport environment.

stics of hydrogen fuel as distributed for utilisation in
be replaced by ISO/DIS 14687.

n for procurement and supply contracts. The standard
and combustion) requirements.

ncluding purity requirements for water used in electrolysis

s comply with the standard when procuring the hydrogen
eed to ensure compliance with standard.

🇬🇧 UK Low Carbon Hydrogen Standard (LCHS) v3 (2023)

Defines what constitutes 'low carbon hydrogen' at the po
methodology for calculating emissions associated with h
hydrogen producers are expected to take to prove comp

- **Relevance** – Airports will need to ensure hydrogen eit
  comply with the standard.

🇬🇧 Low Carbon Hydrogen Certification Scheme (HCS)

Expected by 2025. Certification mechanism to connect p
verifying and tracing the emissions of low carbon hydrog
carbon credentials of their hydrogen. Mass balance and

- **Relevance** – Airports will need to ensure hydrogen eit
  comply with the standard.

Other standards that might be relevant:

- ASTM WK85474 – Fuel quality / Specification for Avia
- BS ISO/DS 19880-9 Gaseous hydrogen – Fuelling Sta
- BS ISO/CD 1988-8 Gaseous hydrogen – Fuelling Stati

ZEF **Airports**

operation. Instead, all codes and standards applicable to the
hould be considered (e.g. pressure vessels, pipes, etc.)

MAH (2015)

es that store/use hazardous substances, based on
nined by the total quantity of hydrogen and other
a compressed or liquefied state. COMAH has two tiers,
igher quantities of dangerous substances. For petroleum
ers are 2,500 and 25,000 tonnes, respectively. For
iers are 5 and 50 tonnes, respectively. Where multiple
equired to determine whether applicable limits have been
ule is provided for the case study airport in Chapter 4:

ly to become COMAH establishments and they will

)

nsent procedures and enforcement. A lower tier consent is
n upper tier consent is required where storing five of more

processes must be followed if airports need to store

Hydrogen storage on site will be required by all airports. This could
uses on site (e.g., aircraft and ground vehicles).

EN 13458 Cryogenic Vessels - Static Vacuum Insulated Ve

- This European standard specifies the fundamental re
designed for a maximum allowable pressure greater t
vessels built on-site.
- **Relevance** – irports storing hydrogen on-site will nee
document is not specific for storage at an airport; the

EIGA Doc 06/19 Safety in storage, handling and distributi

- Provides recommendations on the storage, handling
to the layout, design and operation of fixed storage a
tankers or tank containers, by road, sea and rail, to fix
- **Relevance** – Airports storing hydrogen on-site will ne
standards. The document is not specific for storage a

BCGA CP33 The Bulk Storage of Gaseous Hydrogen at Us

- This Code of Practice covers the location, design, inst
equipment for the bulk storage and supply of compre
- **Relevance** – Airports storing gaseous hydrogen on si
comply with the relevant standards. The document is
adjustments may be required.

Other standards that might be relevant:

- EIGA Doc 100/03/E Hydrogen cylinders and transport
- BS ISO/DIS 19887 Gaseous Hydrogen – Fuel system co

	ZEF	Airports
Pressure Equipment (Amendment) Regulations (2011) tive requirements that must be met to transport dangerous e classification of dangerous goods to packaging, labelling, ts although potential restrictions on tunnels might be ies.	🟩	🟧
g, safety accessories, pressure accessories and at qualifying vessels must satisfy. Includes details of irements that must be satisfied, and the conformity d infrastructure and vehicles comply with the relevant	🟧	🟧
ks (2006) el tanks for liquid hydrogen used in land vehicles as well as e level of protection from loss of life and property resulting el tanks intended to be permanently attached to land 5. e compliant with the relevant standards.	🟩	🟧

Most airports are unlikely to generate hydrogen on-site, instead rel
pipelines or tankers from local or regional hydrogen sources. There
Options fall within three main categories: repurposing existing natu
distribution via road, rail or barge.

ISO 20421-1:2019 Cryogenic Vessels – Large Transportabl
inspection and testing (2019)

Specifies requirements for the design, fabrication, inspe
cryogenic vessels of more than 450 litre volume, which a
(demountable tanks and portable tanks) attached to a m

- **Relevance** – Airports will need to ensure suppliers co

ISO 20421-2:2017 Cryogenic Vessels – Large Transportabl
Part 2 Operational Requirements (2017)

Specifies operational requirements for large transportab
requirements include putting into service, filling, withdra
periodic inspection and emergency procedures. For the
sea and air, additional requirements can apply; these are

- **Relevance** – Airports will need to ensure suppliers co

Other standards that might be relevant:

- Pressure Equipment Regulations, PED Directive 97/2
- ISO 19881:2018 Gaseous hydrogen. Land vehicle fuel c
- ISO 19882:2018 Gaseous hydrogen. Thermally activat
  fuel containers

Most airports are unlikely to generate hydrogen on-site, instead rel
pipelines or tankers from local or regional hydrogen sources. There
Options fall within three main categories: repurposing existing natu
distribution via road, rail or barge.

ZEF	Airports
🟧	🟧

Act and is regulated as part of the gas network. Parties
nnection, or smart metering must be licenced. Licences
as network and provisions relating to price controls. Parties
quire a licence, involving demonstration of a credible plan to
risk assessment. The Net Zero Hydrogen Strategy made a
e powers and responsibilities for a decarbonised gas future.

transportation must be licensed under the Gas Act.

004)

ZEF	Airports
🟩	🟧

and distribution piping systems carrying pure hydrogen
s to further the understanding of those engaged in the safe
distribution systems. It is not intended to be a mandatory
ndustrial practices and is based upon the combined
ucers in Europe and North America.

line supply, this standard is potentially relevant to the
mpliant with the relevant standards.

ISO 13623:2017 Petroleum and natural gas industries. Pi

Specifies requirements and gives recommendations for
maintenance and abandonment of pipeline systems use
industries.

- **Relevance** – For airports with gaseous hydrogen pipe
  supplier. Airports will need to ensure suppliers are co

The Pipelines Safety Regulations (1996)

Defines an integrated, goal-setting, risk-based approach
pipelines. Determines requirements for pipeline design
decommissioning. Includes safety and operability princi

- **Relevance** – For airports with gaseous hydrogen pipe
  supplier. Airports will need to ensure suppliers are co

Other standards that might be relevant:

- CGA G-5.4 Standard for hydrogen piping systems at u
- PD 8010-1:2015+A1:2016 Pipeline systems – Steel pipe
- Iron Main Risk Reduction Programme

Refuelling infrastructure and vehicles will be needed at airports, po
vehicles. These vehicles are anticipated to have varying infrastructu
processes.

ZEF 🟥 **Airports** ⬜

cles have been identified.
t.

drogen-fuelled vehicles. Part 1: Design and development

eous hydrogen.

dard or proactively engage with the regulatory body to

Stations Part 10: Mobile fuelling stations (Drafting)
ons Part 2: Dispensers and dispensing systems (Drafting)

🟩 🟩

e of designers and operators of gaseous hydrogen stations.
on aims to achieve the primary objective of improving the
covers gaseous hydrogen, compression, purification, filling
tes. It does not include production, transport or distribution
use and application of the gas in technical or chemical

relevant to any gaseous application at airports, including
ling need to be developed.

Hydrogen hydrant system

No standards for hydrogen hydrant systems have been i

ISO 19880-1:2020 Gaseous Hydrogen Fuelling Stations Pa

This document defines the minimum design, installation
requirements, for the safety, and, where appropriate, for
that dispense gaseous hydrogen to light duty road vehic
applicable to the dispensing of cryogenic hydrogen appl
compression, gaseous hydrogen buffer storage, pre-cool
standards (19880) that defines general requirements, dis
fuel quality control and sampling.

- **Relevance** – Directly relevant to any refuelling infrast
  refuelling need to be developed.

ISO 13984:1999 Liquid Hydrogen – Land Vehicle Fuelling S

This International standard specifies the characteristics
land vehicles of all types, in order to reduce the risk of fir
to provide a reasonable level of protection from loss of li
the design and installation of liquid hydrogen (LH2) fuelli
by ISO/WD 13984.

- **Relevance** – Airports will need to ensure that any refu

Refuelling infrastructure and vehicles will be needed at airports, po
vehicles. These vehicles are anticipated to have varying infrastructu
processes.

	ZEF	Airports
g connection devices (2020)	🟩	🟩

characteristics of gaseous hydrogen land vehicle (GHLV)
st of the following components, as applicable:

ich have nominal working pressures or hydrogen service
refuelling connectors dispensing blends of hydrogen with

ts for any refuelling system on-site and airport vehicles

	ZEF	Airports
ng Connection Devices (2015)	🟩	🟩

sed Hydrogen Surface Vehicle fuelling connectors, nozzles,
n have Pressure Classes of H11, H25, H35, H50 or H70.

ts for any refuelling system on site and airport vehicles

tions. Dispenser hoses and hoses assemblies
aft)
g/s (Draft)
(Draft)
ns Part 7 O-rings

SAE J2799 Hydrogen Surface Vehicle to Station Commur

This standard specifies the communications hardware a
vehicles (HSV), such as fuel cell vehicles, but may also be
busses) and industrial trucks (e.g., forklifts) with compre
communications hardware and communications protoco
standard is to enable harmonised development and impl
standard is intended to be used in conjunction with the I
receptacles conforming with SAE J2600.

- **Relevance** – May inform policies and standards relate
  system on-site and airport vehicles fuelled by hydrog

BGCA CP41 The design, construction, maintenance and c
dispensing gaseous fuels (2018)

This code of practice covers the location, design, installa
inspection of equipment used in a filling station for the c
Natural Gas (CNG), or Liquefied Natural Gas (LNG), with c
petrol, diesel, Liquefied Petroleum Gas (LPG) etc.

- **Relevance** – May inform policies and risk assessment
  fuelled by hydrogen.

Airports are accountable for the safety of staff, passengers, crew a
to existing fuels and its implementation will require new suites of p
infrastructure standards.

ZEF **Airports**

🟩 🟩

egulations (2022)

rs from fire and explosion risks related to dangerous
n gases under pressure and substances corrosive to
cations of hydrogen.

ydrogen is produced or stored. Airports should be
easures.

f Hydrogen Systems (2015) 🟩 🟩

s and liquid forms as well as its storage in either of these
oncerns, hazards and risks, and describes the properties of
uirements associated with specific hydrogen applications
eplaced by ISO/AWI TR 15916 (under development).

ons for general hydrogen systems, applicable to most

🟧 🟧

ulators, covering environmental, safety, markets,
ify, prioritise and implement changes to existing non-
port the hydrogen economy. Although membership is
thering will be required, giving airports an opportunity to

be involved. However, as the forum will require evidence,
evidence.

Gas Safety (Management) Regulations (1996)

Applies to the conveyance of natural gas (methane) thro
potentially be updated to cover hydrogen.

- **Relevance** – If the regulation is updated to include hy
  of hydrogen to airports with pipeline delivery.

Pressure System Safety Regulations (PSSR) (2000)

Under the Pressure Systems Safety Regulations 2000, us
demonstrate that they know the safe operating limits (p
that they are safe under those conditions. They need to
place before the system is operated. They also need to e
written scheme of examination.

- **Relevance** – Airports will need to ensure a written sch
  will be required specific for operating at an airport.

ISO 26142:2010 Hydrogen Detection Apparatus (2010)

Defines the performance requirements and test method
measure and monitor hydrogen concentrations in statio
detection apparatus used to achieve the single and/or m
ventilation and/or system shut-off corresponding to the
used for certification purposes.

- **Relevance** – Airports will need to ensure that safety t
  procuring detection equipment.

	ZEF	Airports
ons. Protection against hydrogen hazards for vehicles	🟩	🟩

s (FCV) with respect to the protection of persons and the
ogen-related hazards. Applies to FCV where compressed
ot apply to manufacturing, maintenance, and repair.

oad vehicles fuelled by gaseous hydrogen (with a fuel cell),

	ZEF	Airports
ehicle safety	🟩	🟩

integration of the fuel cell system, the hydrogen fuel
l systems into the overall Fuel Cell Vehicle. The document
ombustion engines.

ny fuel cell vehicle procured by the airport

	ZEF	Airports
safety and separation distances (2007)	🟧	🟩

y ensuring that the effects of an event do not cause a risk

nd potential safety distances from the hydrogen
ts and is likely to require adjustments for ZEF applications.

Airports are accountable for the safety of staff, passengers, crew a
to existing fuels and its implementation will require new suites of p
infrastructure standards.

BS EN IEC 60079-10-1:2021 Explosive atmospheres – Clas

Deals with the classification of areas where flammable g
a basis to support the proper design, construction, opera
areas.

- **Relevance** –Potentially relevant for airports storing a

ISO 31000:2018 Risk Management (2018)

ISO 31000 is an international standard that provides prin
comprehensive approach to identifying, analysing, evalua
an organization.

- **Relevance** –Although not specific for airports, may be
that could be adopted for hydrogen operations.

Other standards that might be relevant:

- ISO 21266-1:2018 Road Vehicles. Compressed gaseous
systems (2018)
- IEC 62282-4-101:2022 RLV Fuel cell technologies - Par
industrial trucks – Safety
- ISO 19882:2018 Gaseous hydrogen. Thermally activate
fuel containers
- ISO 17268:2020 Gaseous hydrogen land vehicle refuel
- UKCA Marking / CE Marking
- ANSI/AIAA G-095A-2017 Guide to Safety of Hydrogen
- SAE J2579 Standard for Fuel Systems in Fuel Cell and
- SAE J2990/1 (WIP) Gaseous Hydrogen and Fuel Cell V
Practice (2019)
- NFPA 2: Hydrogen Technologies Code (2023)

	ZEF	Airports
	🟧	🟧

safely repurpose existing natural gas equipment for
en gas installers.

capacity in fitters and installers. Airports can monitor
ess any local supply chain growth that could support the

018)	🟧	🟩

al safety knowledge which needs to be understood
Doc 23 Safety Training of Employees for the various
y training for a variety of specific jobs.

cific training for airport staff handling hydrogen

The safe operation of hydrogen infrastructure will require a compet

Depending on the size and scale of infrastructure required either a
be required.

Planning permits & Land use

Planning Act 2008

Sets out the thresholds above which certain types of inf
significant infrastructure projects, thereby requiring a De
hydrogen production projects have required a Secretary

- **Relevance** – Airports will need to determine whether
precedence from other hydrogen projects and the siz
at the airport.

Town and Country Planning Act (1990)

Regulates consent for smaller projects or pipelines. Can
to be stored on a site or there are pipelines carrying hyd
hydrogen production sites with a capacity of 50 MW or le

- **Relevance** – Airports will require planning and conser

rage

Liquefaction

Liquid or gas storage

ndards for liquefaction plants from the oil and
: industries could be used as basis of design, but
ustments will be required to adapt them to an airport
ironment.

ere are standards and regulations in place for storing
h liquid and gaseous hydrogen. However, these are not
ecific for storing hydrogen at an airport, so adjustments
ght be required.

Distribution

Vehicle transport

Pipelines

Distribution of hydrogen by road and pipeline is common in other industries. Therefore, standards are more mature and may be transferable for airport supply.

Regulation and standards for hydrogen distribution are currently evolving, with many initiatives running to update existing gas codes and to publish appropriate standards.

End-Use (Aircraft)

Refuelling vehicle

Hydrogen refuelling vehi
standards have not yet b
be used as a basis but ne
such as pressure and ter

Fuelling stations for road
likely to be applicable fo
accommodate these.

vehicles. Some
n industry operational

Training

There is some material covering training requirements for handling hydrogen equipment, but there is a need to develop standards for specific operations and training relating to aviation and automation of operations.

Planning permit regulati
hydrogen infrastructure
cover airport needs.

YDROGEN
EMAND

HYDROGEN DEMAND

At the end of this chapter, airports will understand the following:

The **potential annual demand for hydrogen and when** they could expect the first hydrogen aircraft to land at their airport.

The **key stakeholders** they need to coordinate with to understand the potential of hydrogen aircraft at their airport.

The **key drivers of hydrogen demand** for an airport.

The first step for airports to understand the level of infrastructure they may require, as well as potential timelines for its implementation, is to know what the demand for hydrogen aircraft could be at their airport. Given the novelty of zero-carbon emission (ZE) aircraft and the uncertainty regarding technology readiness and airline adoption rates, a **top-down approach** is recommended to develop hydrogen demand forecasts for aviation.

ment forecast (i)

traffic forecast covering a period of at least 20 to 30 years
. Hydrogen demand only needs to be estimated for the
ude departing flights.

elevant time horizon)

is recommended that aircraft are categorised based on
otion. A potential aircraft categorisation is included below.
t fleet mix:

egional: 11 to 20 seats
0-seater: 61 to 120 seats
id-size: 201 – 280 seats

ircraft, such as the B777 and A380, are likely to transition to
gorised separately.

iii **Assign the annual number of ATMs by airline.** The adoption o
between all airlines. Therefore, it is important to understand
hydrogen demand. This allows the annual ATMs needed to be

For future years, the distribution should be informed by the airlines

Following this step, long-term traffic forecasts showing the annual
been obtained, as exhibited in the example on the following page.

Data you will need

- Current and expected airline movements distribution (i.e., %
- Airlines' plans for the airport, including potential new route

From whom

Airlines

The table in the next page presents the output for the case study a
Step 3.1.

One airline (labelled as 'Airline A') accounts for almost 50% of the tr
the other airlines. This will allow applying specific hydrogen aircraft

If limited data is available, initial assumptions can be made to sup
a later stage.

ment forecast (ii)

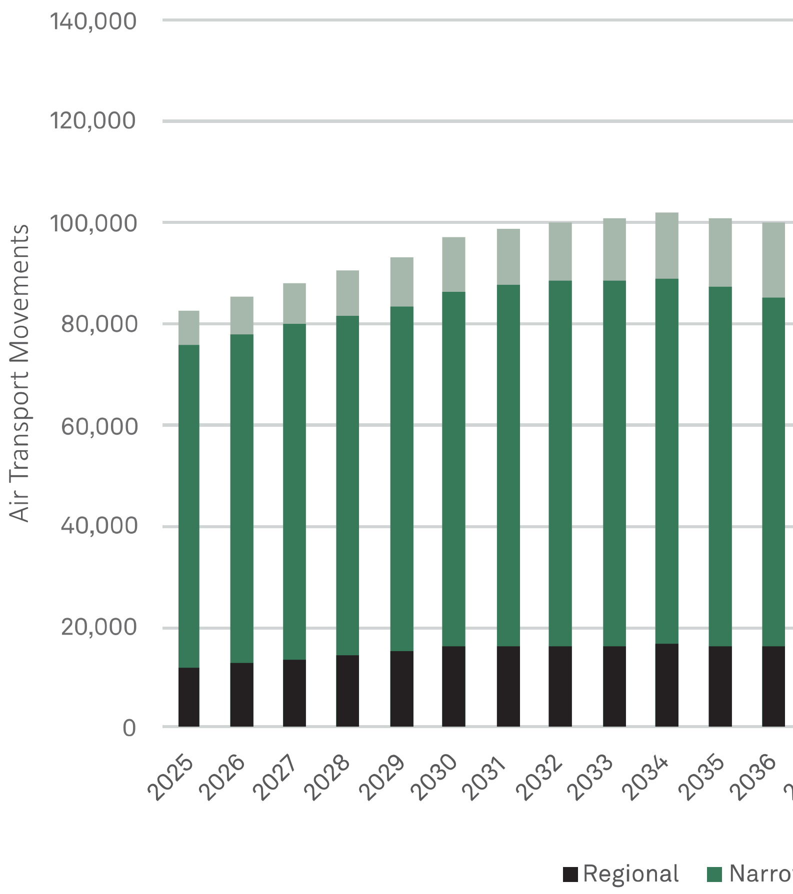
sport movements at just below 125k by 2050. Narrow body craft (e.g., A321, B787) accounting for 20% of the mix and nd turboprops.

35	2040	2045	2050
500	97,200	109,450	123,950
00	41,999	45,550	52,050
050	33,050	39,050	40,050
50	8,850	10,500	12,000
00	55,300	59,900	71,900
00	15,900	16,950	18,450
750	28,500	30,000	38,650
50	10,900	12,950	14,800

Case study output for 3.1-iii

forecast.

Air transport movements forecas



rameters (i)

gory. For the short-term, this could be obtained from the
erm, an annual growth on the average sector distance could
ng between a 0.1% and 0.4% annual increase. This growth, if
nt schedules.

type for the case study airport is shown below.

35	2040	2045	2050
28	328	328	328
00	900	900	900
50	650	650	650
30	376	401	420
97	1,353	1,335	1,312
20	1,895	1,931	1,957

Case study output for 3.2-i

ii **Estimate kerosene consumption rates for each aircraft c**
airlines. When not available, airports could use the ICAO fu
consumption by stage length for a set of specific aircraft t
obtained by plotting the relationship between fuel consum

$$Fuel\ per\ ATM\ (kg) = C1_i{}^{*}km_i + C2_i$$

Where:
i aircraft category

It should be noted that the ICAO formula can provide fuel consump
it is recommended to liaise with the airlines to obtain accurate fue

Data you will need

- ICAO fuel consumption formula
- Average sector length (output from Step 3.2-i)

From whom

Aviation organisations (ICAO)

<<< Previous steps

rameters (ii)

00

.2-ii

For the case study airport, the ICAO fuel consumption estimates were adjusted based on discussions with ‘Airline A’. The C1 and C2 parameters obtained are shown below.

	C1	C2
Commuter	0.09	82.72
Regional	0.16	52.25
Large Regional	1.17	628.82
90-seater	1.08	740.15
Narrow-body	2.32	1609.24
Mid-size	2.99	1457.73

Case study output for 3.2-ii

iii **Introduce future fuel engine efficiencies.** The ICAO
which means it does not consider how the average
years. Historical trends observed during the last de
decreased on average by 1% annually [7].

Data you will need

> Fuel engine efficiency factor

From whom

Market research

iv **Add demand from reserve fuel.** The ICAO formula c
allowance for reserves should be added. Reserves r
on the aircraft type. However, as reserves are not al
reducing the overall addition required at the airport
airline operators to understand the additional reser

Data you will need

> Additional fuel demand due to reserves

From whom

Airlines

For the case study airport, a 5% reserve fuel has been cor

drive the hydrogen demand

category. Given the novelty of the ZE aircraft technology, ainty. The next page presents an EIS range based on the be used as a starting point for discussions with relevant

turers, the EIS considered were:

on rates, ideally from airlines operating at the airport. If timated based on the following parameters:
existing fleet of the airlines. Typical retirement cycles are ears for narrow-body and mid-size aircraft.
lines to better understand their views on ZE aircraft and aft once they reach the end of their operating life (if ZE
ngage with aircraft manufacturers to understand feasible

The table introduces the penetration rates used for the cas obtained directly from the airline. For the other airlines, the aircraft manufacturer on feasible ZE aircraft production rat

Data you will need

- EIS years and retirement cycles by aircraft type
- Airline adoption rates of ZE aircraft
- Age of fleet mix by airline
- Rate of zero-carbon emission aircraft production

From whom

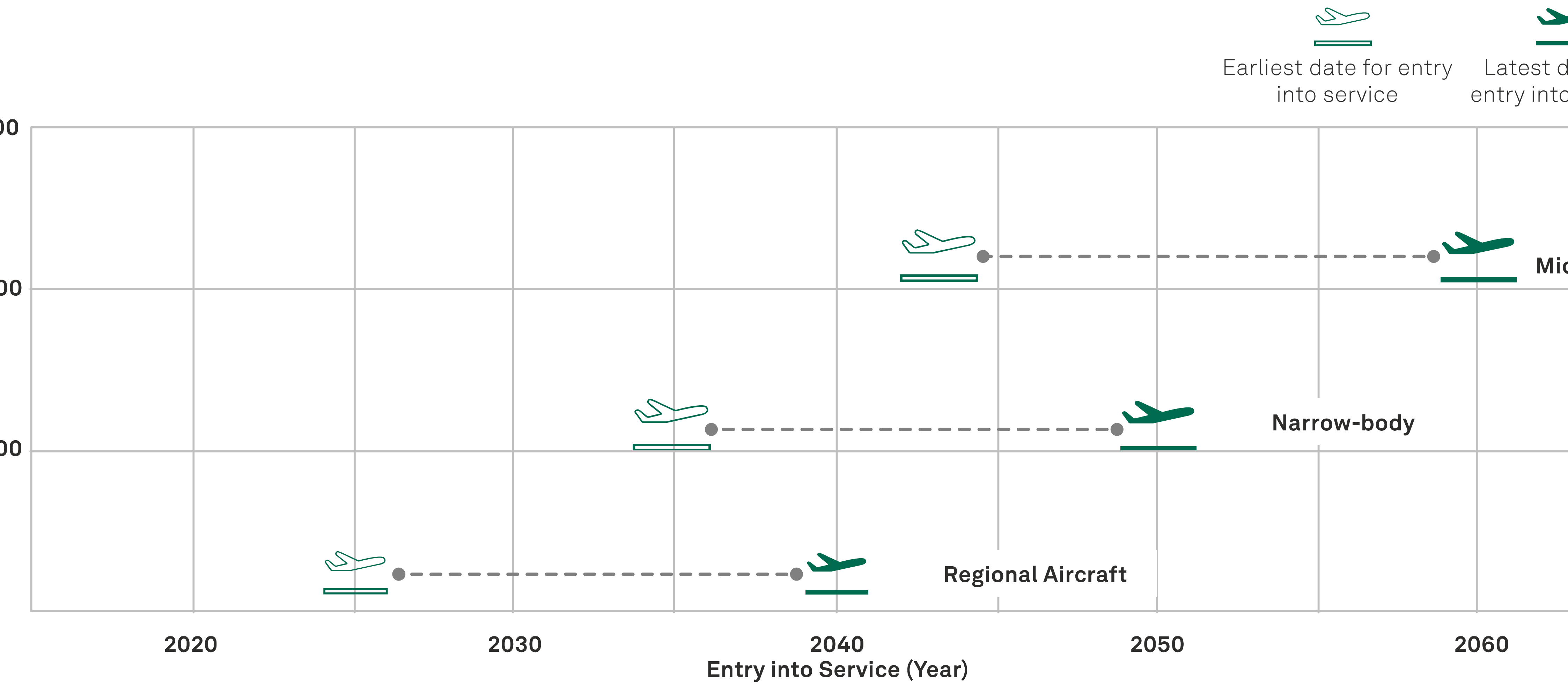
Aircraft manufacturers

Airlines

Mar

	2030	2035
Airport	<1%	2%
Airline A		
Narrow-body	0%	0%
Mid-size	0%	0%
Other Airlines		
Regional	4%	15%
Narrow-body	0%	0%
Mid-size	0%	0%

carbon emission aircraft are
eir technology



kering at their hub airports

ling FlyZero have assessed the potential of hydrogen
n the outbound sector for the return flight without
weight of hydrogen [8].

flight length, which is directly related to the aircraft type.
kering to be viable for regional and narrow-body aircraft is
asible option.

future routes (or % of routes) would be eligible for
es. At the end of this step, airports would obtain an output

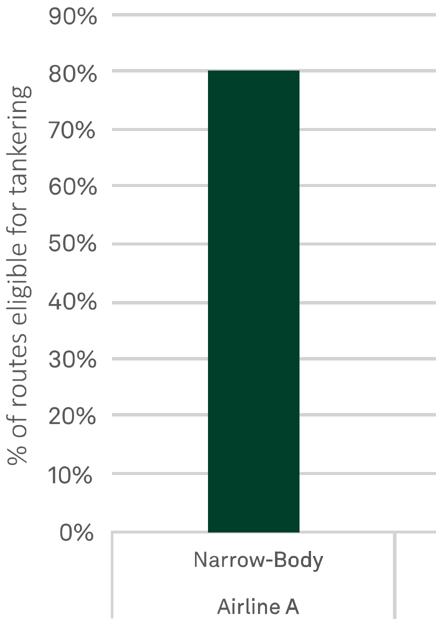
ene tankering was highlighted by FlyZero. From that
nd 1.3% [8].

nes

ket research

For the case study airport, around 80% of the narrow-body
the airlines, around 50% of the regional and narrow-body ro
use tankering will be less than those eligible and should be
years if destination airports have limited hydrogen facilities

Given the novelty of the zero-emission aircraft technology, t
study should be validated and, if needed, updated based on



v

Introduce boil-off loses. The hydrogen losses due to
significant. However, it would be expected that most
for aircraft or non-aircraft uses.

For the case study airport, the additional hydrogen demar

s of hydrogen aircraft

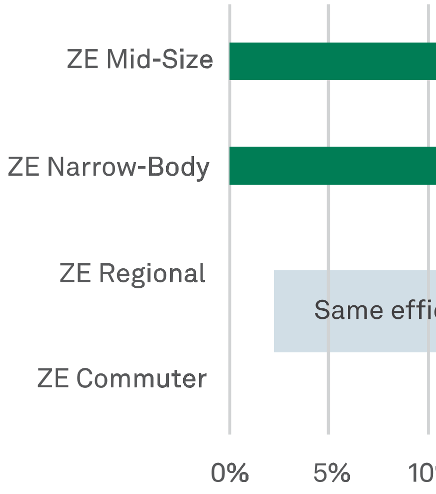
ed on existing studies and market intelligence. Energy
ogy improves, new aircraft may be more efficient than their
at overcoming the challenges of using hydrogen as a fuel

cy factors compared to their equivalent kerosene aircraft [8].

wer energy efficiencies, and thus,

ies have been considered.

Energy efficiency: H2



In this case, the number of annual movements of the B787 i

For the regional and commuter aircraft, given the FlyZero st
assumption was made that hydrogen aircraft would be as e

Data you will need

Energy efficiency factors per aircraft category

From whom

Aircraft manufacturers

hydrogen demand (i)

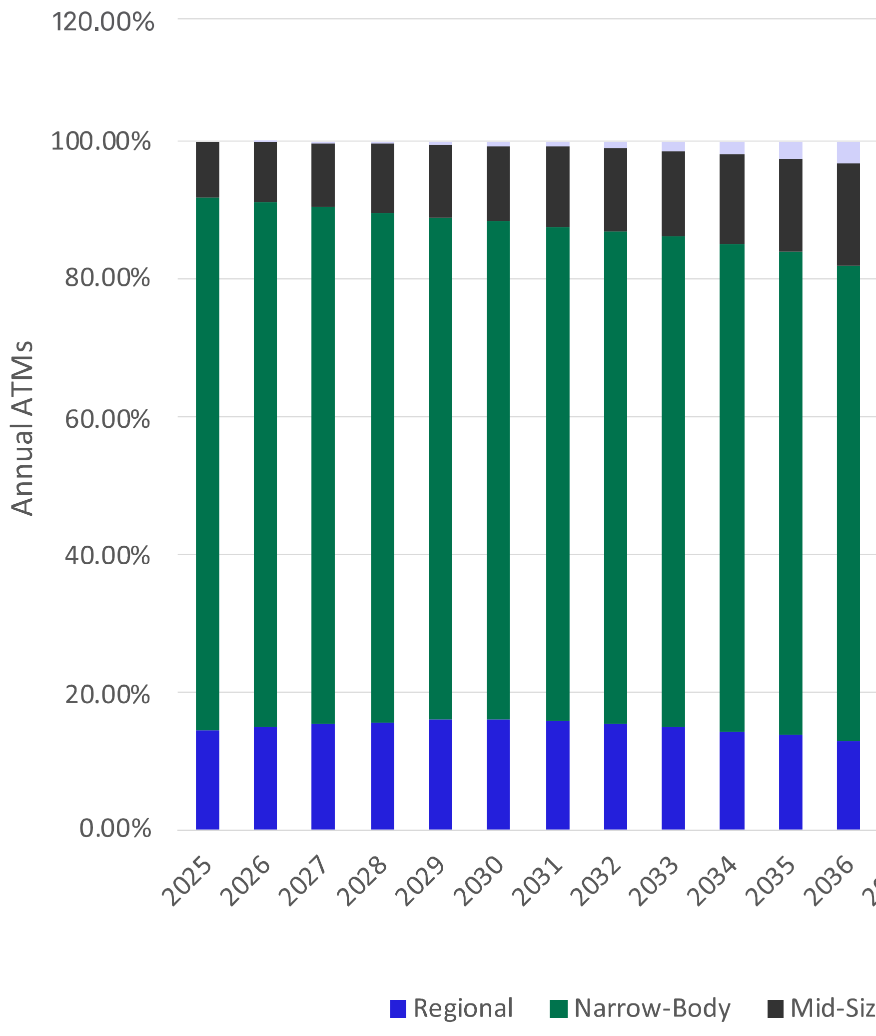
osene or SAF and hydrogen aircraft (in % of annual ATMs).

or each airline.

raft category (output from Step 3.1-iii)

p 3.3-ii)

d be available for each assessed airline, showing a

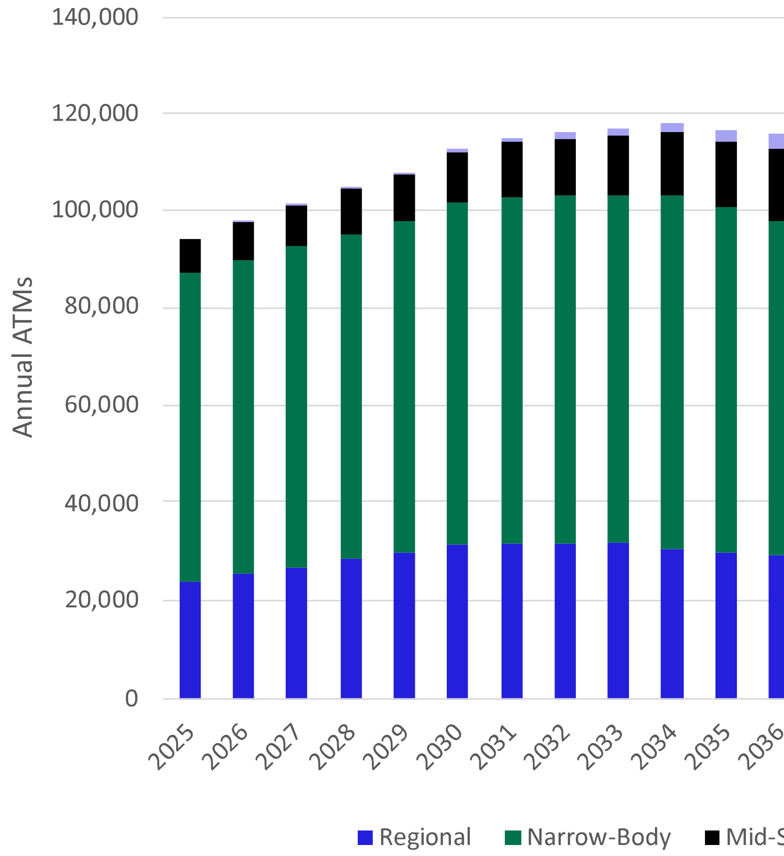


hydrogen demand (ii)

oy airline and aircraft type, by applying the following

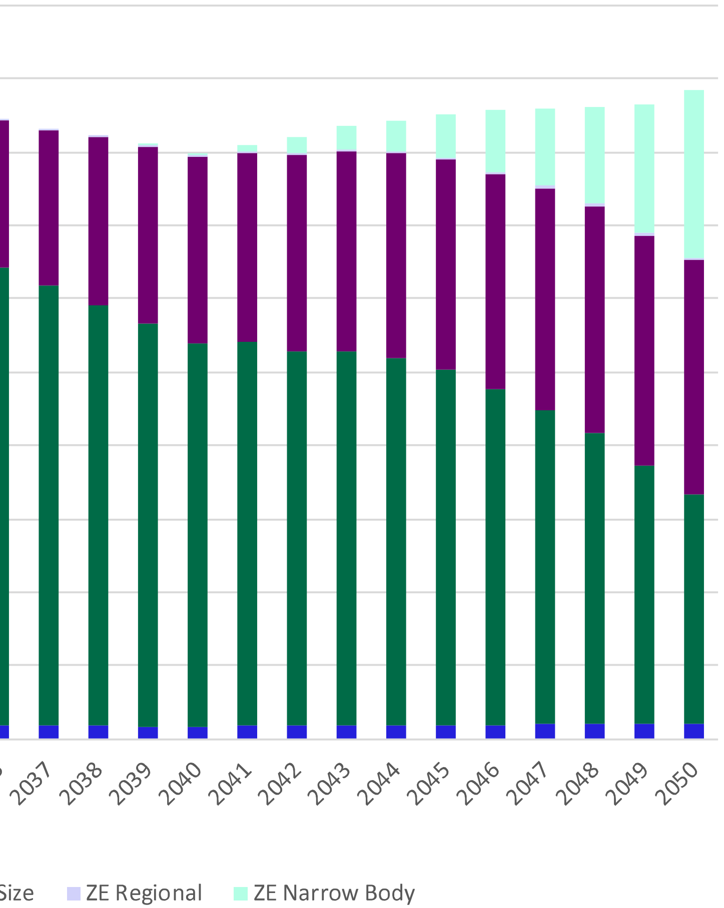
l aircraft category (output from Step 3.1-iii)

ing the annual ATMs for each assessed airline.



hydrogen demand (iii)

gen aircraft. In this step the demand factors previously
plied. Hydrogen demand only needs to be estimated for the
d to be halved if these include arrivals and departures.



Case study output for 3.5-iii (Airport wide)

Annual energy required from H2 aircraft (MJ) $_{i,j}$
=[(Specific Energy of Jet A (MJ/kg) * Annual H2 ATM (Dep)$_{i,j}$ **** (Ave***
**** (1+(1 +Fuel burn penalty for tankering (%)) * % ATMs eligible for t***
**** (1 – ZE aircraft efficiency factor***$_{i}$***)]***

Where:
i: Aircraft category
j: Airline

Data you will need

- Annual hydrogen ATMs (output from Step 3.5-i)
- Average sector distance (output from Step 3.2-i)
- C1 and C2 (output from Step 3.2-ii)
- Fuel burn penalty for tankering (output from Step 3.3-iv)
- % ATMs eligible for tankering (output from Step 3.3-iv)
- ZE aircraft efficiency factor (output from Step 3.4-i)
- Specific energy Jet A (42.8 MJ/kg)

From whom

- Previous steps

For the case study, the following factors were assumed to build t

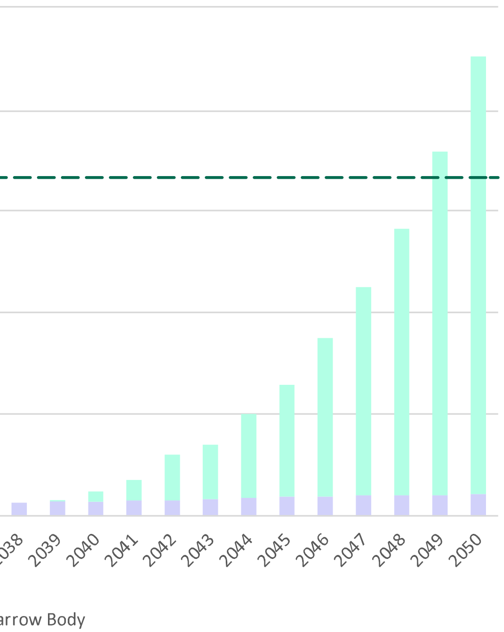
- ‘Airline A’ uses tankering on 50% of eligible routes with a fuel l
- The remaining airlines do not tanker at the airport

hydrogen demand (iv)

specific energy factor of hydrogen, and include the
osses.

m Step 3.3-v)

om Step 3.2-iv)



Case study output for 3.5-iv (Airport wide)

The central scenario for the case study airport projects an annual
'Airline A' does not tanker fuel, the demand in 2050 would be reduc

For airports operating small aircraft (i.e., below 20 seats), a distinct
required. As a reference, any aircraft above 20 seats will likely requi
to use gaseous hydrogen.

v If preferred, **transform the tonnes of hydrogen required in**

Data you will need

- Annual tonnes of hydrogen (output from Step 3.5-iv)
- Density of liquid hydrogen (0.0708 kg/l)
- Density of gaseous hydrogen at 20K (0.0013 kg/l)

From whom

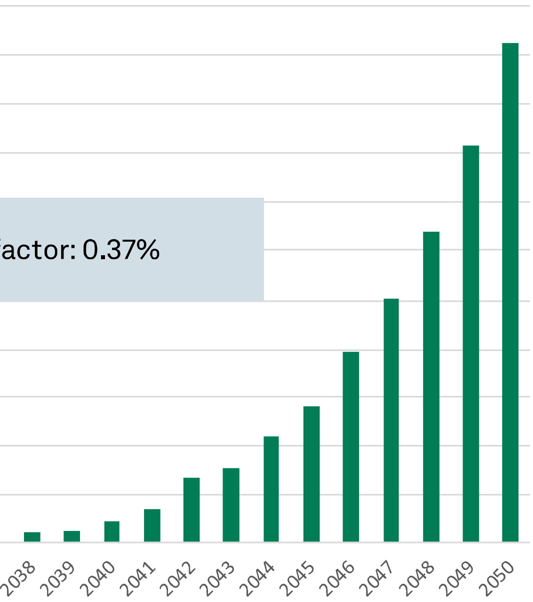
- Previous steps

vi **Calculate the peak day demand.** To determine the peak day
fuel demand ratio based on historical data, and then multip
this factor.

It should be considered that the peak to annual demand co
traffic demand and a change in the demand profile.

The case study airport is expected to require slightly over o

hydrogen demand (v)



Case study output for 3.5-vi

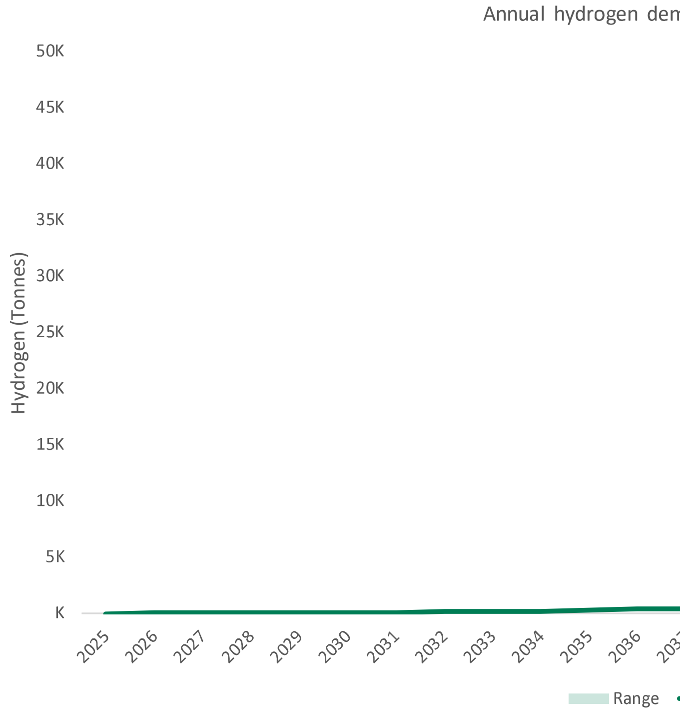
enarios

ommended to produce low, central and high hydrogen
scenarios include:

on – switch off" option so that it is easy to test their

ed as follows:

	High
al	As central
of central s central	'Airline A': 2x central Other airlines: As central
ng	Airline A + other airlines



The high scenario projects a hydrogen demand 1.8 times hig
approximately 40k tonnes of hydrogen. The low scenario for
at ~13k tonnes.

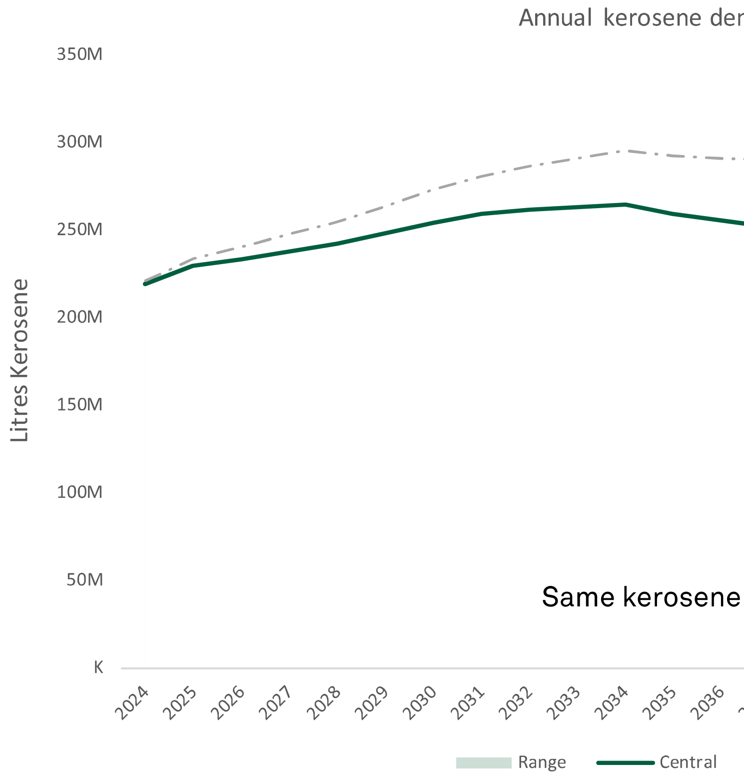
mand

jet fuel demand will decrease. This step is to estimate
s for future jet fuel farm expansion. In this analysis, no
e Aviation Fuels (SAF).

s to be estimated for the departure flights and hence, the
rivals and departures.

l aircraft type (output from Step 3.5-i)

$$se\ year - Year\ Z * (1 + \%\ Reserves)$$



In this example, kerosene annual demand remains the same
hydrogen powered aircraft begin to operate. A year-on-year
period 2040-2050, there is a year-on-year 2.0% decrease (ce

If the future annual fuel efficiency improvement of 1% is not
higher.

GEN
TRUCTURE

HYDROGEN INFRASTRUCTURE

At the end of this chapter, airports will understand the following:

The **principal hydrogen infrastructure components that may be required at airports** and their key technical and operational characteristics.

The **factors or barriers that could influence airports' decision making** regarding the infrastructure elements they are likely to require in the future.

How airports can **estimate specific infrastructure needs** based on their projected hydrogen demand.

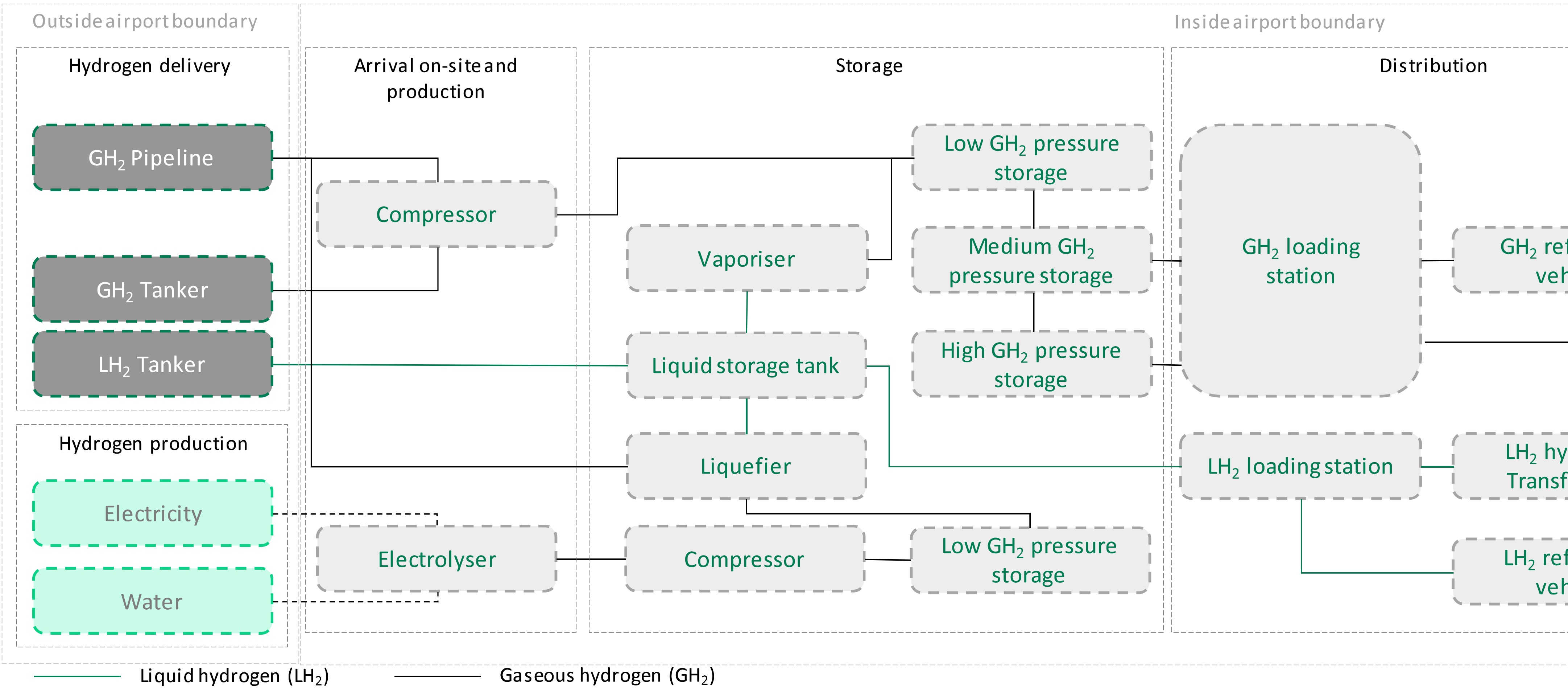
Chapter 4 is divided into three sections. The first section provides a **high-level overview of the key hydrogen technologies** that may be relevant for airports. The second section lists and describes the **key technological and operational challenges** that could influence the airports' decision-making when **establishing which supply and refuelling infrastructure best suits** their demand and site conditions. Finally, the third section provides a **step-by-step methodology on how to estimate the major infrastructure requirements** based on the hydrogen demand established in Chapter 3. The methodology to estimate the smaller infrastructure components such as compressors, vaporisers or pumps is out of scope of this report as it requires detailed modelling, to be undertaken by hydrogen specialists at later stages.

rational pathways

e,

on

n



ure relevant to airports (i)

is principle of modularisation could be an attractive option airports as their hydrogen demand increases over time.

rrently, there are a number of electrolyser vendors such as ug Power, ITM, Siemens, Cummins, and Nel Hydrogen that uld deliver electrolysers with suitable capacities for airports.

quefier: Liquefaction is the process of turning gaseous drogen into liquid. Liquefaction is expected to be required larger airports receiving gaseous hydrogen via pipelines. wever, there are two main challenges related to performing uefaction at an airport:

- The current production limit is about 70 tonnes/day [9]. It is expected that large airports will require higher production volumes
- The current technology is highly energy intense – in the range of 12 to 15 kWh/kg [9]

sting technology is likely to be suitable for early phases of drogen technology deployment at airports. In the long-term, wever, there will be the need for larger and more efficient uefaction facilities.

this regard, manufacturers are looking at the development more energy efficient facilities (target is about 6 kWh/kg], [54]) and with higher production capacities (up to 1,000 t/ y). This is likely to take at least seven to ten years from now. wever, considering the timelines presented in Chapter 3, s unlikely airports will perform liquefaction on-site any ne sooner.

anufacturers of large-scale liquefaction plants include Linde, Products, Kawasaki and Air Liquide.

Liquid hydrogen storage: With any cryogenic liquid, it is important to store the liquid in a highly insulated tank to prevent the temperature of the liquid rising to a point where it vaporises. Technology for LH2 storage is well established, with volumes that range from:

- 3,800m^3 or 270 tonnes for large spherical tanks (world's largest liquid hydrogen tank located at Kennedy Space Centre in Florida – NASA)
- 750-950k litres or 54-67 tonnes for horizontal cylindrical tanks
- 115k litres or 8 tonnes for vertical cylindrical tanks

The liquid hydrogen storage industry is progressing larger volumes, with Kawasaki and CB&I Storage Solutions exploring the feasibility of producing tanks with a 40 million litre capacity. However, timelines for these are unknown.

There are various companies specialised in the manufacture of cryogenic tanks. These include Linde, Chart Industries, CB&I and Kawasaki Heavy Industries.

Gaseous hydrogen storage: Hydrogen can also be stored as a compressed gas. When compressed, hydrogen increases its density and, therefore, reduces the volume necessary for its storage and transport. Hydrogen can be compressed up to different final pressures. The higher the pressure, the higher the density of the hydrogen, but also the higher the energy required for its compression up to the final pressure.

The technology for high-pressure gaseous hydrogen storage is well-established, with pressures up to 700 – 875 bar being feasible. To meet the needs of high-pressure storage at

air
tar
me
in a
the

Ma
hig
wid

Lov
but
hyc
to a
tec
of r
sim

De
be
far
sol
the

Ho
hyc
cor
gas
be

Ga
bet
tar

ure relevant to airports (ii)

rrent large hydrogen stations, such as the ones from Linde, Liquide, Power Tech or Nel Hydrogen, have daily capacities aching 1,800 kg/day [10].

per the standard SAE J2601, the hydrogen flow rate nnot exceed 60g/s at any time during the fuelling process. gh-throughput refuelling technologies are currently in velopment with the target of achieving 10kg/min [73]. erefore, existing standards will need to be adjusted to be lised at airports, or new protocols developed. Although gher flow rates are targeted, the key challenge for distribution ations is likely to be the duration of the fill time and how this n impact the number of refuelling lanes to be provided at e station.

poriser: Converting liquid hydrogen to gas is performed passing the liquid through an ambient air or water bath poriser (heat exchanger). This technology is well developed d manufacturers such as Chart Industries and Linde anufacture vaporises.

pical flow rates for vaporisers are:
Low flow rate: Less than 10kg/hr
Medium flow rate: 10kg/hr to 50 kg/hr
High flow rate: 50kg/hr to 500 kg/hr
Very high flow rate: 500kg/hr and above

fuelling vehicle: The refuelling vehicle will transport hydrogen uid or gaseous) from the distribution station to the stand to ill the aircraft. The technology will therefore be very similar the existing hydrogen delivery tankers – which include hoses, zzles, control systems and monitoring instrumentation.

However, there are still some technology gaps that will need to be addressed before these vehicles can be used in an airport environment. These include the need to develop more programable communication links between the hydrogen tanker and the aircraft tank to automate the refuelling process.

Current capacities of liquid hydrogen tanker trucks are in the range of 3,000 – 4,500 kg of hydrogen [12]. For gaseous hydrogen, this is reduced to between 560 – 1,100 kg [11], [12].

Transfer tank: The concept of a transfer tank under each stand was first introduced by FlyZero [47]. The objective of this tank is to adjust the pressure of the liquid hydrogen out of the hydrant to the pressure required for refueling the aircraft's tank, so that the refueling process can be completed within the target turnaround time. Therefore, the transfer tank would only be needed by airports with a hydrogen hydrant system.

This tank would be designed to match the capacity of the largest aircraft fuel tank to use the stand. Transfer tanks are not a new concept, however, the design of a below ground transfer tank suitable for use in an airport environment does not currently exist.

Dispenser vehicle: The LH_2 dispensing vehicle will be used to connect the LH_2 hydrant system to the aircraft for the management of the refuelling process.

These vehicles do not currently exist, although there are some similarities with existing hydrant dispensers. However, these are likely to be more complex due to the equipment needed to initiate and manage the pressure differential between hydrant transfer tanks and the aircraft storage tank.

So
au
to
the

Lic
exi
dis

-
-

For
sui
rur
und
the
cor
hyd
TR

) of hydrogen infrastructure and

aturity level of a technology through its research,
ased on a scale from one to nine, with nine being the most
. of the main hydrogen infrastructure components and the
end of technology roll out phase) and/or reach a maturity
of each asset is also included. These should be used to

Technology status	Technology availability
ent capacities achieve up to 2 tonnes per day, airports producing their own ill need larger production capacities. Systems capable of producing 100s of tonnes of hydrogen are expected in the next five years.	Lead time for delivery is currently between 12 to 18 months. However, nev manufacturing capacity has an investment lead time of 3-4 years [13].
gh the liquefaction of hydrogen gas is a well-established technology, the duction limit and efficiency of the process needs to improve to be deployed at a larger scale.	Lead times for hydrogen liquefiers could take up to several years. Advancem on current liquefaction process and facilities is estimated to take at leas 7 to 10 years.
cale LH_2 storage tanks have reached a relatively high level of technology d are in common usage globally. NASA is currently exploring the Integrated geration and Storage (IRaS) technology to reduce the boil-off effect.	Current cryogenic storage technology is available and lead times for liqui hydrogen tanks are in the range of months. IRaS technology is currently ma and commercially available, but the high cost of the equipment and operat cost is likely to limit its use in the short term
ssed hydrogen storage is well established, and no significant technology ents are required to meet the needs for airport gaseous hydrogen storage.	Current compressed hydrogen gas storage technology is available and lea times are in the range of months.
logy used in hydrogen compressors is well established and there are many companies that produce them.	Currently, order lead times are about 12 to 18 months. These could increase the medium-term due to the expansion of the hydrogen production secto

) of hydrogen infrastructure and

Technology status	Technology availability
nology for hydrogen loading stations is well established, there is ongoing dispensing technology to improve the efficiency of the system and reduce refilling time and capital costs.	A hydrogen loading station includes several components such as disper compressors, pumps, etc, each of them with different lead times. These c in the range of 12 to 18 months, similar to the compressor's delivery times. technological advancements are expected in the next 3 years with the inc demand and deployment.
urn liquid hydrogen into gaseous hydrogen is a well-established technology.	Lead times for air ambient vaporisers is in the range of a few months and he not likely to be the constraining component.
en technology for the refuelling vehicle already exists. However, there will be nore programable communication links between the LH_2/GH_2 tanker and the aircraft storage tank to automate the refuelling process.	Liquid hydrogen refuelling vehicles need to be suitable for an airport envir The design, testing and certification process is likely to take at least three years.
r tank is not novel. However, the design of an underground tank suitable for use in airports does not currently exist.	Current technology is not suitable for use in an airport environment. The testing and certification process is likely to take at least three to five ye
ot currently exist and, although there will be some similarities with existing , these will be more complex due to the need to purge the aircraft tank and ssurise the transfer tank and avoid leaks. There is the potential to introduce robotic automation into the process.	This technology does not currently exist. The design, testing and certificatio is likely to take at least three to five years.
ipes to transport cryogenic liquids over distances up to a few kilometres ecially in the space and gas sectors. However, developments in the pressure eld are required for existing technology to be suitable for airports.	Although cryogenic pipes currently exist, there is nothing at the scale and co needed by airports. The design, testing, demonstration at scale and certif process is likely to take between five to seven years.

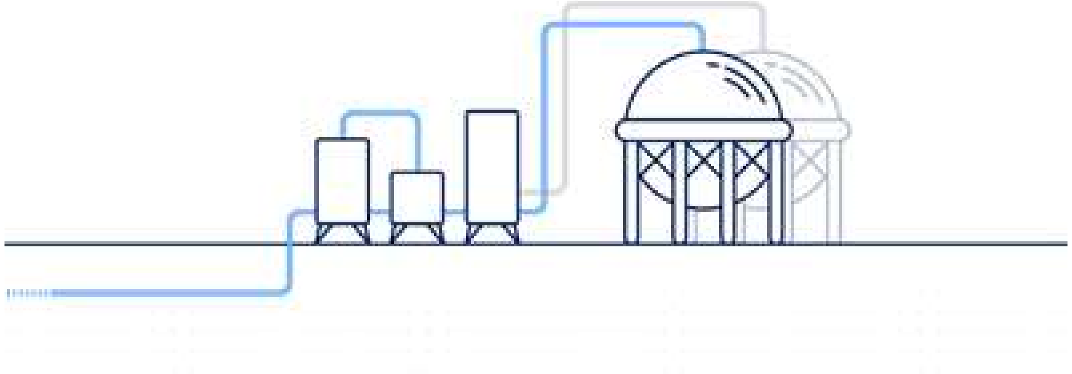
ys

s for hydrogen supply at an airport. It is anticipated that
ending on their specific demands and requirements.
d new technology becomes available.

ace access transport)

demand is low. For many
ndefinitely. However, for
eeds the practical capacity

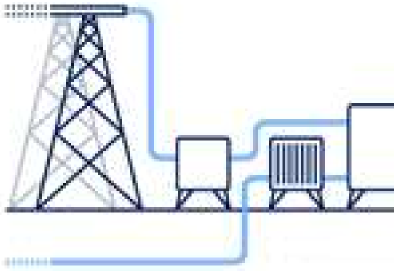
ts and associated capital



Pathway 2: Gaseous hydrogen delivered by pipeline with on-site liquefaction

Once surface access capacity is exceeded gaseous hydrogen delivery by pipeline can be used to meet increased hydrogen demand.

This pathway requires additional airport infrastructure, and liquefaction requires a high-power supply. However, power requirements for liquefaction are considerably less than for electrolysis.



Pathway 3: Hydrogen gene

This pathway allows an air
water. While this scenario
infrastructure costs, it has
gigawatts for large airports

This high power requireme
airports.

ways

th **the decision tree and comparative matrix** represent a
gle point in time and **should therefore be repeated for each
nescale under consideration.** Understanding each individual
int in time then allows a phased transition between
thways to be identified.

Decision tree guidance

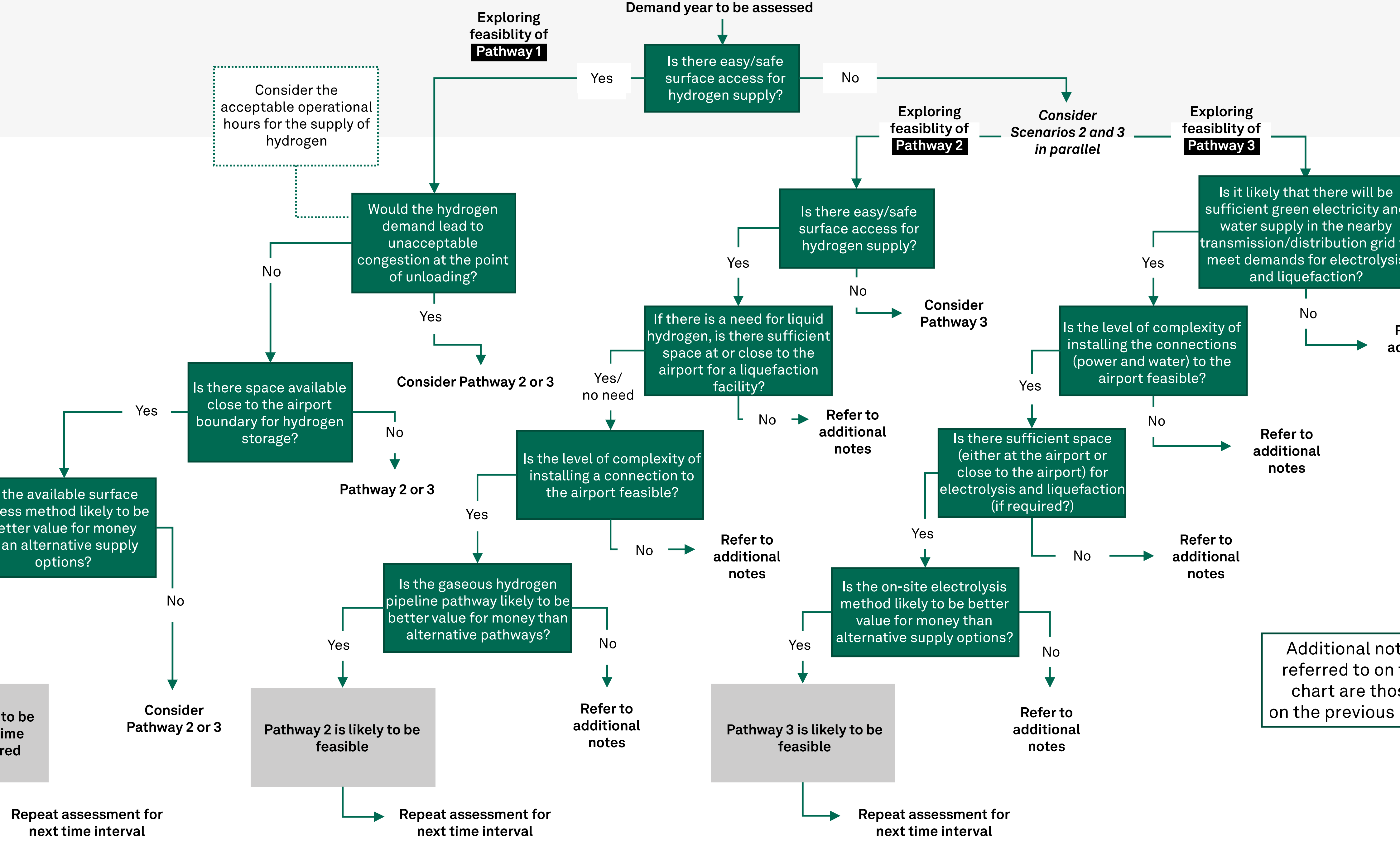
It is possible that during the assessment of options it appears that none of the pathways are feasible, for the timescale being considered. In this situation it is recommended that the following creative actions are considered.

- An investigation into how the feasibility constraints of pathway one can be relaxed. For example, are there any emerging plans to implement a hydrogen production hub in the region? If so, can the airport become a partner in the development of the hub so that it can become an anchor off-taker in support of obtaining development funding? Could the airport contribute funding to the hub to enable it to include hydrogen liquefaction? If no, then could the airport form a development partnership with other potential regional hydrogen (or hydrogen derivative) off-takers to investigate the technoeconomic feasibility of developing a hydrogen hub in the region?

-

-

In u
unc
wit
ass
inf


Demand year to be assessed
Is there easy/safe surface access for hydrogen supply?
Yes
No
Exploring feasiblity of Pathway 1
Consider the acceptable operational hours for the supply of hydrogen
Would the hydrogen demand lead to unacceptable congestion at the point of unloading?
Yes
Consider Pathway 2 or 3
No
Is there space available close to the airport boundary for hydrogen storage?
Yes
No
Pathway 2 or 3
the available surface
ess method likely to be
etter value for money
an alternative supply
options?
No
Consider Pathway 2 or 3
to be
ime
red
Repeat assessment for next time interval
Exploring feasiblity of Pathway 2
Consider Scenarios 2 and 3 in parallel
Exploring feasiblity of Pathway 3
Is there easy/safe surface access for hydrogen supply?
No
Consider Pathway 3
Yes
If there is a need for liquid hydrogen, is there sufficient space at or close to the airport for a liquefaction facility?
No
Refer to additional notes
Yes/ no need
Is the level of complexity of installing a connection to the airport feasible?
No
Refer to additional notes
Yes
Is the gaseous hydrogen pipeline pathway likely to be better value for money than alternative pathways?
Yes
Pathway 2 is likely to be feasible
Repeat assessment for next time interval
No
Refer to additional notes
Is it likely that there will be sufficient green electricity an
water supply in the nearby
transmission/distribution grid
meet demands for electrolysi
and liquefaction?
No
F
ac
Yes
Is the level of complexity of installing the connections (power and water) to the airport feasible?
No
Refer to additional notes
Yes
Is there sufficient space (either at the airport or close to the airport) for electrolysis and liquefaction (if required?)
No
Refer to additional notes
Yes
Is the on-site electrolysis method likely to be better value for money than alternative supply options?
Yes
Pathway 3 is likely to be feasible
Repeat assessment for next time interval
No
Refer to additional notes
Additional not
referred to on
chart are thos
on the previous

matrix

n supply infrastructure and one for hydrogen refuelling infrastructure.
l need to consider when determining which solution for hydrogen

three supply pathways against relevant factors to determine the most

two refuelling pathways against relevant factors to determine the most

n the hydrogen demand level to evaluate which supply and refuelling
n airports how and when to transition between the pathways, if needed.

y some of the options may be impractical,
vourable.

d to repeat this exercise to confirm the infrastructure solutions they have

Supply pathway suitability guidance

Factor affecting airport	Supply pathway suitability guidance			
	1. Service access deliveries	**2. Gaseous pipeline and liquefaction on site**	**3. Electrolysis and liquefaction on site**	
Unsafe and/or congested surface access	May cause congestion or safety issues	No impact	No impact	By 2045-50, the central scenario than one delivery per hour). A deta between viability of surfac **Recommendation: initially s**
Limited operational hours for surface access delivery	May add to confession and logistics challenge	No impact	No impact	None ap **Recom**
Complex / no access to a planned gaseous hydrogen pipeline in the timescale considered	No impact	Challenging if complex access to a pipeline. Not suitable if no access	Challenging if complex access to a pipeline.Not suitable if no access	None of the national hydrogen planned under Project Union runs Project Union is planned to be co delivered be gase **Recommendation: Supply pat** **ambitions suggest that a pi**
Complex / no access to a high-capacity power network able to meet hydrogen demand in the timescale considered	No impact	Liquefaction requires high power. Unlikely to be suitable if no access to high-capacity network	Electrolysis and liquefaction required very high power. Not suitable if no access to high-capacity network	The airport is expected to requi required by the liquifier in 2050 is **current** energy req **Recommendations: To support** **delivers become impract** **on-site electrolysis) unvi**

infrastructure solution should be implemented, but to highlight the barriers an airport may encounter when pursuing any of the available options.

supply pathway suitability

Description
airport, high frequency deliveries by road, rail or barge may irports may need to consider either gaseous pipeline delivery ted that airports may need to seek specialist advice when rk capacity. Section 4.3-a provides a high-level methodology to eliveries required to meet the peak demand.
drogen deliveries at an airport, the frequency of deliveries and levels may lead to either surface access congestion or The airport may need to: hours to spread daily deliveries throughout the day. delivery or electrolysis on site, if feasible.
seous hydrogen pipeline, airports may need to: eliveries or on-site electrolysis, if feasible. s to incorporate the airport into gaseous hydrogen pipeline ational hydrogen hub networks being developed (e.g., Project
ork, electrolysis on-site is likely to be infeasible, especially the large amount of green electricity required for the liquefaction on site could require several GW of power electrolysis on site might be feasible if sufficient green gnificantly less energy than the electrolysis process (~ 6 to 7 power availability. Airports with capacity limitations on their liquefy on site unless network upgrades are completed, or ailable. It should be noted that airports may need to seek as power network capacity.

Factor affecting airport	
Complex access to high-capacity water supply	Without easy access to a plentiful wa infeasible, especially for medium and the electrolysis process. For small ai site is more likely to be feasible.
Limited space at or near the airport to develop hydrogen facilities	If the airport site is constrained and electrolysis and liquefaction on-site requires either at the airport or near significant to meet the expected hyd compared to the pipeline and liquefa access delivery scenario. For smaller pathway could require around twice
Closest green hydrogen production is located at a significant distance from the airport	If the closest green hydrogen produc the airport, the transportation costs understand if any of the other supply assessment of hydrogen delivery opt that for distances up to 7,000km, gas hydrogen compared to liquid hydroge

efuelling pathway suitability

Description

equired to meet the projected level of hydrogen would
ernal road network or around the hydrogen loading facility,

dside road network to allow the operation of a higher number
ting congestion or,

the case study airport. Based on the hydrogen demand

boprop hydrogen aircraft.

duction of hydrogen narrow-body aircraft.

w-body aircraft.

-powered aircraft are expected, which is likely to
um and large airports.

ce	Case study evaluation
ctrolysis uefaction site	
act	By 2045-50, the central scenario projects a frequency of hydrogen deliveries that could create congestion issues (more than one delivery p assessment should be undertaken to understand the tipping point between viability of surface access deliveries and the cost of viability of **Recommendation: initially supply pathway 1 (surface access) will be suitable in all growth scenarios but r become an issue as demand increases.**
act	None application for any phases as 24/7 deliveries can be considered. **Recommendation: Not a consideration for the case study airport.**
ging if x access eline. Not e if no	None of the national hydrogen backbones are planned to connect to the airport. However, the transmission network planned under Project U could create an opportunity for connectivity in the long term. Project Union is planned to be completed by 2035 and the case study airport is n delivered by gaseous pipeline before 2045 (high scenario) or 2049 (central scenario). **Recommendation: Supply pathway 2 (pipeline) will not be viable in early years. However, long-term connectivity ambitions suggest that a that surface access thresholds are exceeded.**
ysis and ction s very wer. table if ess to pacity k	The airport is expected to require liquefaction on-site between 2045 and 2050. Under the central scenario, the energy required by the liqu requirement increases to 70 MW under the high scenario. For reference, **current** energy requirements for large airports can typically be **Recommendations: To support liquefaction the power network is likely to require upgrading before surface access delivers become impra for electrolysis is likely to make pathway 3 on-site electrolysis) unviable, except potentially for early low demand levels or d**

ance	Case study evaluation	App	
3. Electrolysis and liquefaction on site		Before 2040	20 2
Not feasible if no access to high-capacity water supply	Subject to more detailed analysis, unlikely to be applicable for any phases as the airport has access to a water supply nearby. Additionally, a water source is only needed to perform electrolysis on-site, which is unlikely to be required for the airport. **Recommendation: Water supply capacity is unlikely to be the constraining factor in determining suitable pathways.**	–	
Substantial impact on space, which make electrolysis unfeasible.	The airport site is moderately space constrained. It has some undeveloped areas, but these are mostly outside the airport boundary or within protected areas. For the early years, when only space for on-site storage is required, available areas within the airport boundary are likely to be sufficient. **Recommendation: To support pathways 2 or 3 (liquefaction or liquefaction and electrolysis on-site) additional land outside of the existing airport boundary is likely to be required.**	–	Y
No impact	There is no significant green hydrogen production yet in the UK. However, hydrogen production forecasts for projects identified within the airport’s region indicate that an annual hydrogen production of 15 million kilograms could be reached by 2030. **Recommendation: While there is currently no significant green hydrogen production nearby, it is anticipated that future supply is likely to be able to support supply pathways 1 and 2 (surface access or pipeline).**	Yes	Y

Before 2040	2040 – 2045	After 2050
Surface access	Surface access	Surface access
Surface access	Surface access	Surface access (implementation period for g pipeline + Liquefaction*)
Surface access	Surface access (implementation period for gaseous pipeline + liquefaction*)	Gaseous pipeline + liquefaction

reduces or increases, respectively.

dance
nt system

Case study evaluation	Applicat	
	Before 2040	2040-2045
Not applicable for pre-2050 as the number of bowsers required to meet the projected level of hydrogen is unlikely to lead to congestion on the airport internal road network or around the hydrogen loading facility. **Recommendation: Subject to more detailed airside analysis, it is anticipated that bowser refuelling is likely to be the preferred delivery method pre-2050. Beyond 2050, a hydrant system may be required.**	–	–

mary table is obtained, showing the preferred solution and option phasing for hydrogen on-airport distribution.

Before 2040	2040 – 2045	After 2050
Bowser	Bowser	Bowser
Bowser	Bowser	Bowser
Bowser	Bowser	Bowser

educes or increases, respectively.

nfrastructure requirements (i)

e simplest approach to calculating fuel storage is therefore calculate the daily demand and multiply by the number of ys of resilience required. If only one or two days of storage is sumed, then it is essential that demand is based on peak day quirements rather than an average day. However, if multiple ys of storage is assumed then storage can be based on erage daily demand, which could be the average of the year, peak month or week, depending on the specific port profile.

e simple approach assumes that the hydrogen storage is l at the start of each operational day providing adequate pacity for the current and contingency days.

wever, in practice hydrogen will arrive at the airport roughout the day, either 24/7 or during acceptable delivery urs. At the same time, hydrogen will be used throughout the y depleting the storage. A more detailed modelling approach erefore recognises that to maintain a constant buffer of drogen, both the inflow and outflow should be considered. is approach requires a more detailed modelling assessment. multiple days of storage are assumed, there is less need for s detailed approach, particularly in early master planning le assessments, as the relative difference will be minor. wever, if there is limited storage, understanding the daily low and output flow of hydrogen becomes more important optimise the system.

In applying a detailed modelling approach, both the inflow and outflow of the system are determined, using delivery profiles into the storage and flows out of storage to refuel aircraft. Balancing these flows can then be used to determine the required storage buffer.

- 'Simple' approach: Based on the peak day demand and days of c understanding of how much storage will be needed at the airpor 4.3-i.a.
- Detailed modelling: Calculates the optimum storage required ba this approach, see Step 4.3-i.b.

Bo
Ho
ap
rec
saf
be

nfrastructure requirements (ii)

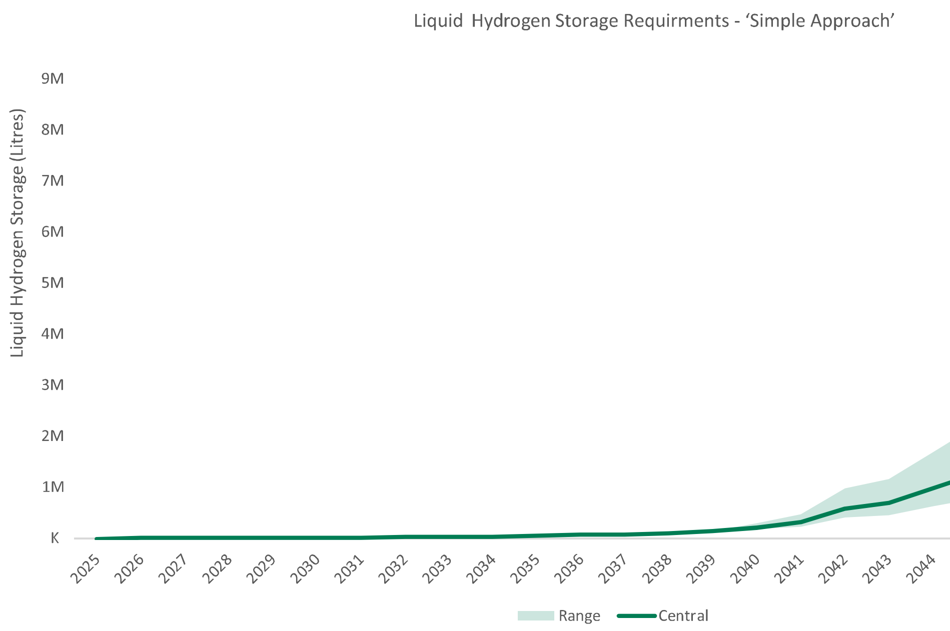
5-vi, the peak to average day demand, and the number of
e demand can be calculated as follows.

*l (kg or L) * Days of H2 contingency storage*

vious steps

he airport’s assessment of risk and supply security and the
ons should be based on the demand profile of the airport.

rage days have been considered for liquid hydrogen



Gaseous hydrogen storage is likely to be required for small a
the 2030s. For the case study airport, while these aircraft re
some movements, creating demand for gaseous hydrogen a
the hydrogen would be sufficient to meet the demand. Thes
average daily GH2 demand at the airport is expected to be a

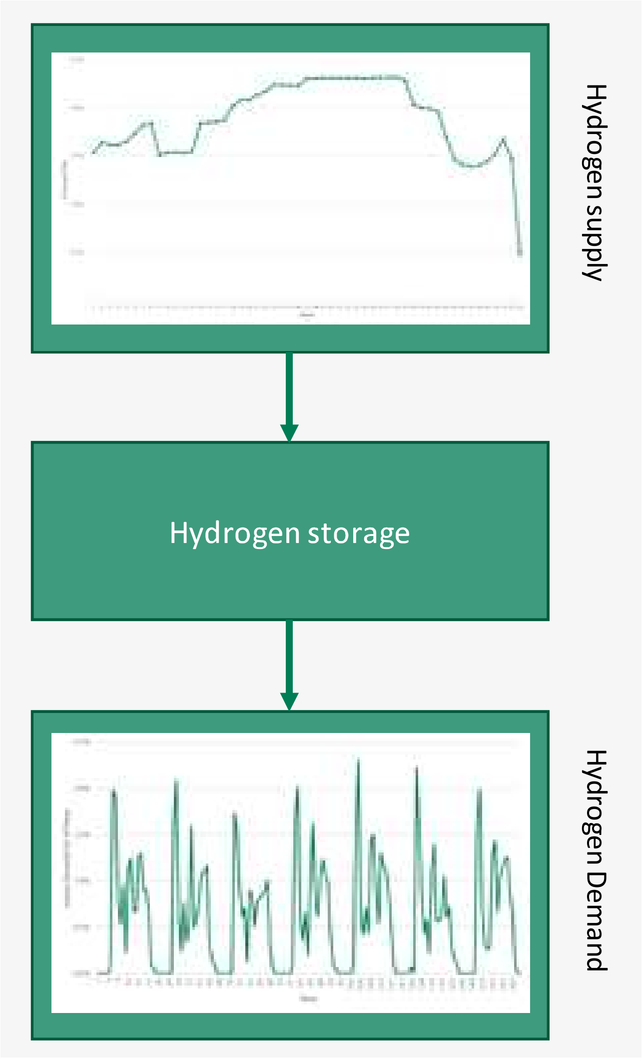
For contingency, the airport may still prefer to opt to have s
vendors offering bulk gaseous hydrogen storage systems, c
standard cubic feet (~350kg) of hydrogen. Tanks with larger
airport these are not required.

nfrastructure requirements (iii)

f hydrogen supply and the outflow of hydrogen into the
to optimise the buffer storage requirement.

e associated hydrogen demand calculated from the annual
ak to annual ATM ratios. Hourly delivery profiles can then
uous pipeline supply, 24/7 tanker deliveries, or restricted

vious steps



Examples for the case study airport.

Using model
across the d
is possible t
demand.

In the case s
year to dete
storage capa
sufficient to

The operatio
requirement

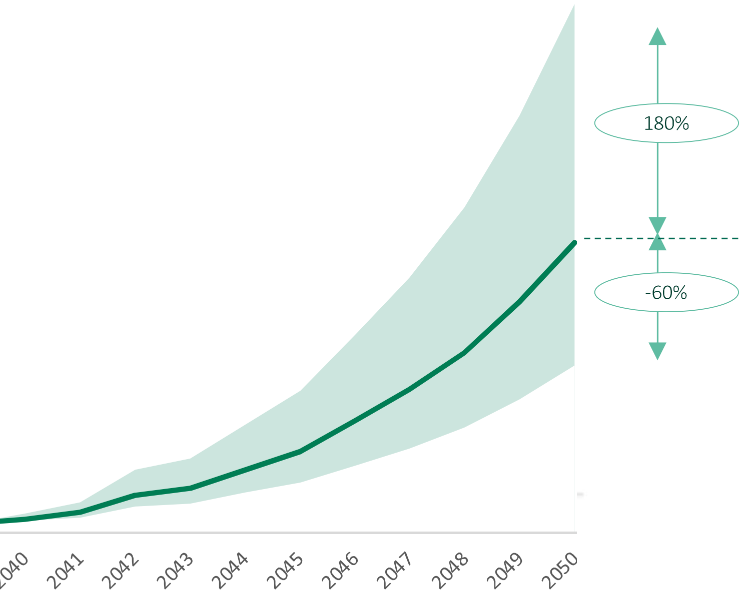
A buffer sto
enough stor
the airport e
power disru

Each airport
is required. F
operational

The next pa

nks required for each phase based on

odelling Approach



Case study output for 4.3-a-i.b

Using the detailed approach, the central demand scenario projects a litres more than with the 'simple' approach), increasing to 9.0 million low scenario.

The difference between both methods for the central case is in the r

ii **Calculate the number of hydrogen storage tanks.** From thi of the demand calculation methodology. The number of hyd requirements from the previous step by the capacity of the

$$No.\ of\ Storage\ tanks = \frac{Max.\ Storage\ demand\ (L)}{Tank\ capacity\ (L)}$$

For each phase, the airport should evaluate which tank capacity is tank capacities are needed at different phases. In early years, lowe term, with an increase in hydrogen and storage demand, higher tan large airports.

For the case study airport, the following tanks have been considere

- Vertical cylindrical LH_2 tank: 8,000 kg (115k litres)
- Horizontal cylindrical LH_2 tank: 66,500 kg (950k litres)

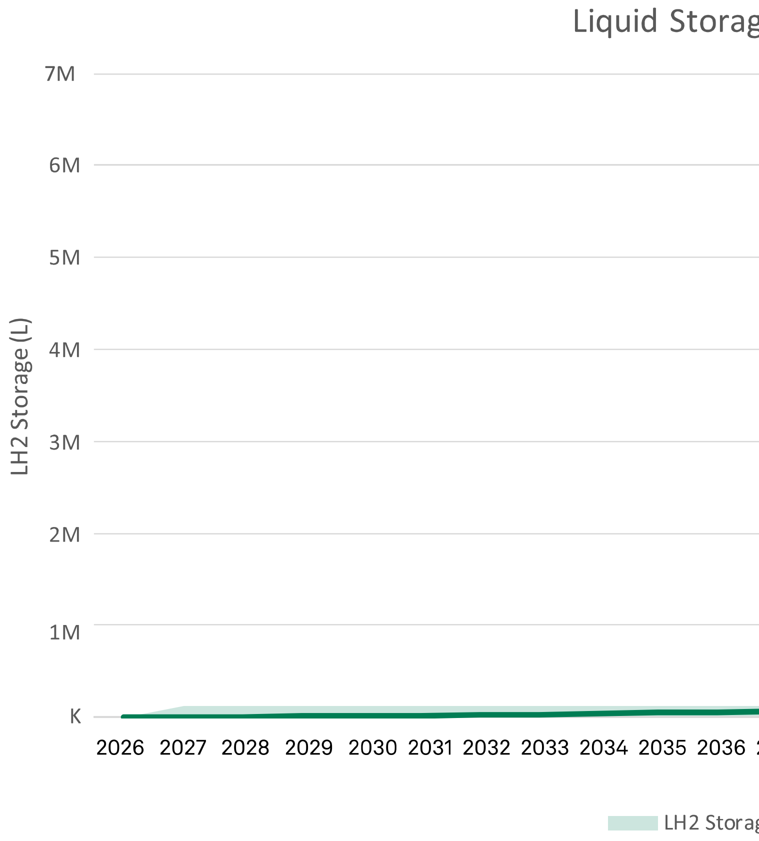
The next page presents the number of storage tanks required by th

nks required for each phase based

of seven liquid hydrogen storage tanks are estimated to be
nd until 2039 with one vertical tank, with a capacity of 115k litres.
storage demand increases, requiring an additional six tanks, each
nt could be met with one large spherical tank similar to the one
age capacity of more than 3.3M litres. However, this tank has a
ne obstacle limitation surfaces of airports.

nks required for Low Demand Scenario		Tanks required for High Demand Scenario	
H_2 Vertical Tanks (115k L)	LH_2 Horizontal Tanks (950k L)	LH_2 Vertical Tanks (115k L)	LH_2 Horizontal Tanks (950k L)
-	-	-	-
1	-	1	-
1	-	1	-
1	-	-	1
2	-	-	1
4	-	1	1
4	-	-	2
-	1	-	2
-	1	-	3
2	1	-	4
-	2	-	5
-	2	-	6
-	3	-	8
-	3	-	10

Case study output for 4.3-a-ii



requirements

of the hydrogen storage tanks, and the number
o calculate the total size of hydrogen storage tanks.

nce

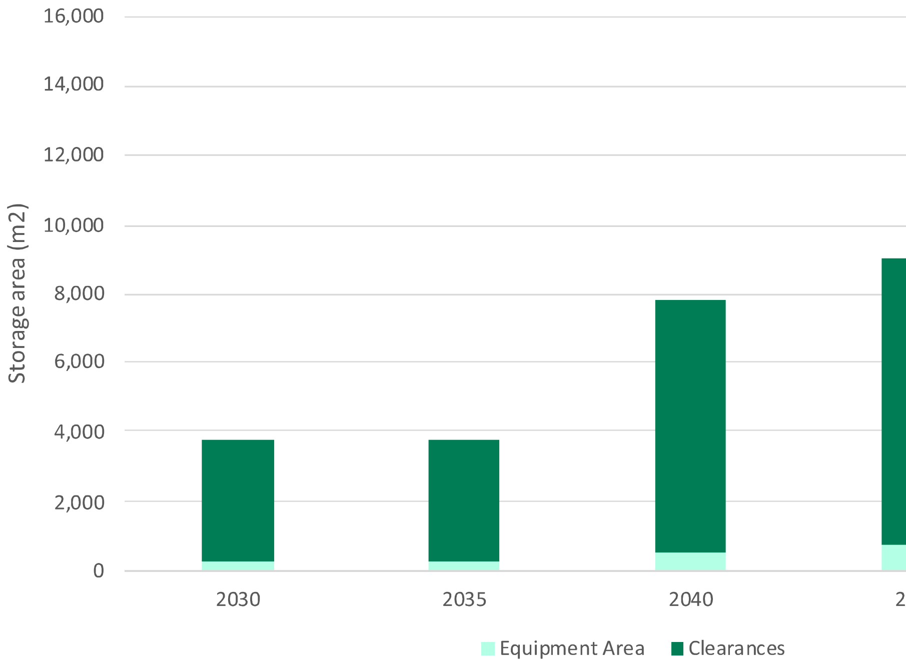
of hydrogen stored for various types of tanks that airports
engagement with potential suppliers. The figures provided

Type of tank	Tank capacity	Average footprint
Tank capacity	Kg (L)	m²/kg
LH_2 Vertical Cylindrical Tank	8,000 (115k)	0.001
LH_2 Horizontal Cylindrical Tank	66,500 (950k)	0.005
LH_2 Spherical Medium Tank	38,000 (545k)	0.008
LH_2 Spherical Large Tank	270,000 (3,850k)	0.004

he large-scale storage of liquid hydrogen at airports in
nsidered, a conservative approach is recommended for
lso allow the inclusion of space for other balance of plant
s for specific airport use cases will need to developed.

Below are the area requirements for the case study airport.
case, clearances of 30m from tanks to objects and 15m betw
are derived from the clearances rather than the tanks.

Demand scenario	Tanks
	m²
High scenario	3,500
Central scenario	2,250
Low scenario	1,250



hydrogen deliveries to evaluate

be feasible to meet the daily demand, while not creating
eed to **calculate the frequency of hydrogen delivery**
the region of 40,000 L for liquid hydrogen and 1,000 kg
ed and the operational hours for deliveries are the main

for liquefaction on-site is a balance between a detailed
and liquefaction facility.

equency exceeds hourly deliveries, the surface access

Results for the case study airport suggest that from 2050, n
demand. However, from 2045-47, the frequency of deliveries
congestion on the surface access roads. To determine the c
gaseous pipeline and liquefaction pathway, a more detailed
This assessment is not detailed in this report and would nee

gen storage, airports are likely to

ntities and an upper tier for higher quantities of dangerous
ower and upper tiers are 2,500 and 25,000 tonnes,
pper tiers are five and 50 tonnes, respectively. Where
uired to determine whether applicable limits have been
en in the same area will need to apply the aggregation rule,

≥ 1

≥ 1

nsidered when applying the aggregation rule.

	2026	2
Kerosene Storage Required (Tonnes)	2,585	2,
Kerosene Lower Tier	1.03	1
Kerosene Upper Tier	0.10	0
Hydrogen Storage Required (tonnes)	<1.00	
Hydrogen Lower Tier	<0.01	0
Hydrogen Upper Tier	<0.01	0
Aggregated Lower Tier	**1.04**	**1**
Aggregated Upper Tier	**0.10**	**0**

The case study airport exceeds the Lower Tier from 2026 a

* Control of Major Accidents and Hazards (COMAH). For more informatio

gen storage, airports are likely to

or exceed the relevant qualifying quantities or the
ding increased reporting requirements and redundancy on

Operator requirements

tion to the competent authority prior to the start of operation.
vention Policy (MAPP). The purpose of a MAPP is to ensure a
man health and the environment. It must set out the operator's
action, the roles and responsibilities of management and its
uously improving the control of major accident hazards.
rity with specific information on the new establishment to make

submitted to the competent authority.
cy plan in coordination with a wide range of internal and external
d be submitted to the competent authority. The operator must
ast every three years.
n on the new establishment to the public. This must be updated

MAH regulations see Chapter 2.3.

or liquefaction and/or

Calculate the number of electrolysis and liquefaction units required by dividing the maximum hourly capacity obtained in the previous step by the capacity of the electrolyser and liquefier selected. For large airports, capacities of existing units may not be sufficient to meet the airport's demand and hence, more than one electrolyser module and liquefier could be required.

$$Liquefiers = \frac{Max\ Hourly\ Capacity_{weeki}\ (tonnes/hr)}{Capacity\ Liquefier\ (tonnes/hr)}$$

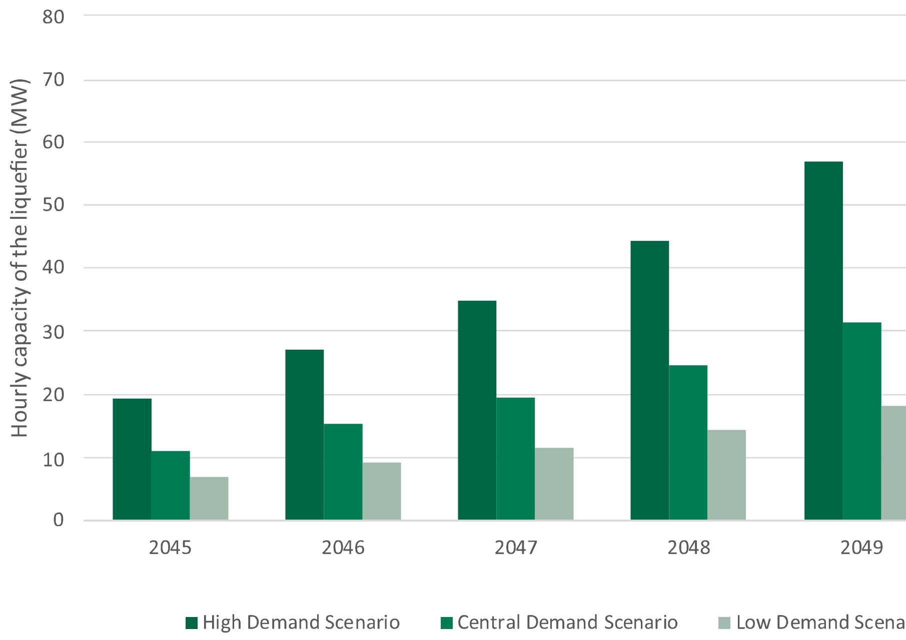
$$Electrolyser = \frac{Max\ Hourly\ Capacity_{weeki}\ (tonnes/hr)}{Capacity\ Electrolyser\ (tonnes/hr)}$$

the case study airport, a liquefier with a capacity of
0kg/hr has been considered. This size of liquefier is
rently being manufactured by OEMs such as Linde and
Liquid. Electrolysis on site is not required for the case
dy airport.

iii **Calculate the hourly energy consumption of the el** energy consumption.

$$Hourly\ Energy\ Consumption_i$$

$$= Hourly\ Capacity\ weeki\ \left(\frac{tonnes}{hr}\right) * Energy\ Consumption\ ($$



or the liquefaction and/or

ysis plant. The land required will primarily depend on the ngement from the selected OEM.

area liquefaction and electrolysis plants require, average . These areas are solely for the equipment required. As with istances should be included.

Liquefier	Electrolyser
m^2/kW	m^2/kW
0.006 – 0.01	0.017-0.025

$$\textit{required for liquefier and or electrolyser}$$

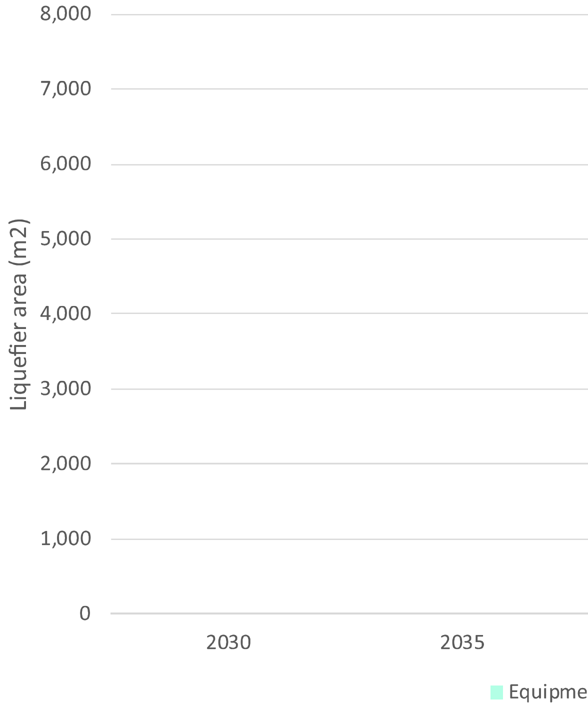
$$\textit{ant Capacity}\ (kW) * \textit{Footprint}\left(\frac{m2}{kW}\right) + \textit{Clearance}$$

se study airport. These include both the liquefaction uired. For clearances and additional areas for other and 10m between liquefier modules have been

ased on clearances rather than equipment.

cy of hydrogen deliveries, liquefaction is expected to the high demand scenario. No liquefaction is required

Demand scenario	Liquefiers
	m^2
High scenario	750
Central scenario	500
Low scenario	



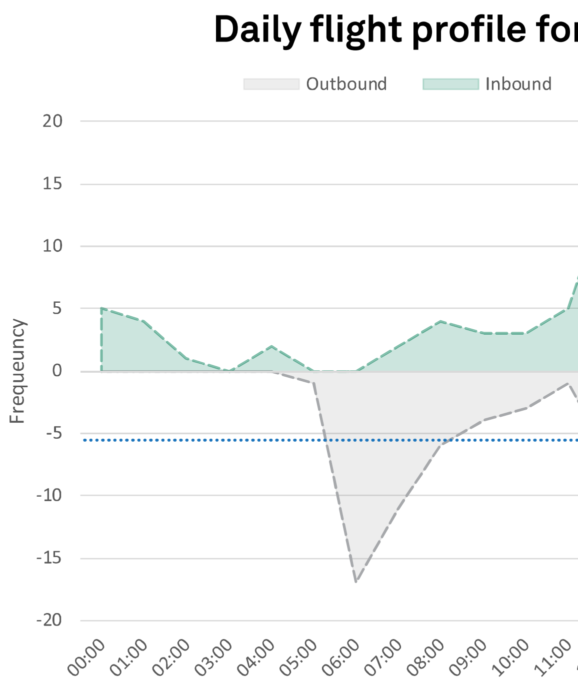
rogen refuelling bowsers required to

ichever approach is used, the results will need to be justed to reflect the forecast mix of hydrogen versus rosene aircraft. This can either be done by making individual sumptions in the current flight schedule, or proportionally justing the results based on the mix of aircraft.

detailed flight schedule is not available, it can also be ssible to develop high-level bowser forecasts by determining e peak departure period in the airport and estimating the mber of aircraft needing refuelling in the same period. wever, ideally this approach should also consider the period her side of the peak as this will determine if there is any erlapping requirement, which, depending on the bowser lisation time, would increase the total bowser requirement.

e to this overlapping consideration, often the peak period bowsers may be different to the flight departure peak. For e case study airport, the peak departure period is in the early orning. However, as most of these aircraft will have been rked overnight, the refuelling activity can take place over onger period, reducing the need for simultaneous use of ltiple bowsers.

How long aircraft can be refuelled prior to departure will depend on t the aircraft can remain parked without experiencing hydrogen boil-of



In the case study airport, the departure peak is in the morning. How the simultaneous need for bowsers.

rogen refuelling bowsers required to

ts or estimating demand using a peak hour calculation,

ght range)

f the aircraft. The tank size will also determine whether a

aircraft. The capacities following are based on the FlyZero

Aircraft type (fuel)	Tank capacity (litres)
Regional (H_2)	12,000
Narrow-body (H_2)	38,000
Mid-size (H_2)	165,000

Bowser capacity

Refuelling bowsers are expected to have capacities up to 40,000 litres of hydrogen, which has been assumed for the case study airport. However, specification of specific bowsers for refuelling hydrogen aircraft are still to be confirmed.

Fuel uplift requirements

While the tank capacity of the aircraft may represent the maximum refuelling requirements, typically aircraft fuel uplift volumes are based on the flight range. The volume of hydrogen required may be significantly less than the full aircraft tank capacity.

In c
to
ma
up
wh
tar
the

Sp

The
tim
bo
and
be
bo
Hy
exi
cas
be

rogen refuelling bowsers required to

ii

Case study requirement

Considering the demand profile and factors outlined in the previous sections, the hydrogen bowser requirement was calculated based on both a minimum and maximum fuel uplift assumption. The minimum requirement assumes only a percentage of hydrogen is uplifted to supply the average flight distance, and the maximum requirement assumes the aircraft tanks are fully refuelled during each turnaround.

No. Browers	2023	2030	2035	2040	2045	2050
H_2 Browers (minimum)	–	1	1	2	2	3
H_2 Browers (maximum)	–	2	2	4	4	6

Case study output for 4.3-c-ii (Central demand scenario)

iii

Calculate approximate parking and circulation are

Accurate space requirements can be determined thr
and considering vehicle swept path analysis. Howeve
dimensions. The areas need to accommodate both p
study airport, a hydrant system will not be required p

The parking area will depend on the size of the refuelling vehi
40,000L. Available hydrogen trailers of capacities between 30
widths of around 2.6m. An allowance of at least ~0.5m each s

Additionally, provision should be made for circulation areas a

Approximate areas for the case study in 2050 are shown belo
vehicle was assumed to be 15m by 3.5m with a circulation are
demand case and maximum fuel uplift, which requires six bov

Demand scenario	Parking
	m^2
High scenario	550
Central scenario	315
Low scenario	315

uelling stations

As well as the number and demand for bowsers, the refilling time is also a critical factor in understanding the station requirements, based on the potential dispenser rate. As refilling stations do not currently exist for airports, a range of dispenser rates should be tested to obtain a distribution of refilling durations, and the subsequent demand on stations required. The refuelling duration assumption is also used in the previous section for determining bowser requirements.

The refilling time can be calculated as follows.

$$\mathit{Refilling\ time\ (minutes)} = \frac{\mathit{Hydrogen\ per\ refill\ (kg)}}{\mathit{Dispenser\ rate}\ \left(\frac{kg}{min}\right)}$$

For the case study airport, a dispenser rate of between 8kg/min and 20kg/min has been used. The latter has been tested as an optimistic sensitivity. At these rates, each refilling event would take as much as two hours, with a minimum duration of 45 minutes. When using the most conservative dispenser rate of 8kg/min, five stations would be needed. With the higher refuelling rate, the demand could be reduced to two stations.

ii

Once the number of potential refuelling stations is obtained, **an approximate space requirement can be estimated.**

The area of the loading station will be the area required for the equipment (i.e., storage tank, pumps, dispensers, etc), loading positions or lanes plus area required for circulation and clearances.

The area for the equipment will depend on the arrangement of the station and its storage capacity. The area for the lanes will be linked to the length and width of the refuelling vehicles. Available hydrogen trailers of capacities between 30,000L to 70,000L have lengths ranging from 8.5m to 16.2m with widths of around 2.6m.

In the table on the following page, the approximate space considered for each element and the overall space requirement for the case study airport are shown as a guide. Airports will need to evaluate these requirements based on the refuelling station design and the site conditions.

on footprint

s of the refuelling station.

Factor
10m (L) x 3m (W)
15m (L) x 3.5m (W)
50% of the area required for the equipment and lanes

ement.

Clearance	Total area (2050)
m²	m²
375	1,125
225	675
225	675

Case study output for 4.3-d-ii

Due to the uncertainty of future technology and flow rates, for the ca
been used for determining the number of filling stations required. Th
allow for future variability.

In this case study example, the requirement for gaseous hydrogen is
future, hydrogen trailers coming to the airport would be used to store
basis no provision has been made for a gaseous loading station. How
be required.

If the airport preference is to store gaseous hydrogen on site for con
loading station may also be required. Additionally, when the airport is
hydrogen by vaporising stored liquid hydrogen, which would also requ

nds that may be used by

gen aircraft.

y unknown. From an airport capacity perspective, ideally
e able to use the same parking stands. Restricting
l efficiency. However, particularly in the early phases of
s hydrogen aircraft may require segregated parking, or
hydrogen hydrants are required, it may also not be possible
same stand. In these situations, it is important to estimate
rations.

similar way to estimating total stand requirements for an
uld be to use a flight schedule, which contains links for
lan.

ed to reflect forecast hydrogen movements. Alternatively, if a
adapted to reflect hydrogen demand forecasts, and further

n is suggested. This estimates the number of hydrogen

e-body operations to determine how many code C and code

$$Hydrogen\ Stand_{NB/WB} = \%\ H2\ Annual\ ATMs_{NB/WB} * Total\ Stands_{NB/WB}$$

Based on the demand estimated for the case study airport, the need
Therefore, the allocation of stands has not been modelled.

Data you will need

> H_2 arrival peak hour movements

or

> Annual hydrogen ATMs (%) (output from Step 3.5-i)

From whom

Airport forecasting team

<<< Previous steps

rea requirements for the

2030		2035		2040		
Qty./Capacity	Footprint	Qty./Capacity	Footprint	Qty./Capacity	Footprint	Qty./Capacity
1 / 8.0t	3,750	1 / 8.0t	3,750	2 / 74.6t	7,750	3 / 141.0t
2	350	2	350	4	650	4
1	150	1	150	3	400	3
	4,250		**4,250**		**8,800**	

2030		2035		2040		
	4,250		**4,250**		**5,800**	

2030		2035		2040		
	4,250		**4,250**		**9,100**	

ASTER PLANNING
ONSIDERATIONS

MASTER PLANNING CONSIDERATIONS

At the end of this chapter, airports will understand the following:

- The relevant **planning parameters** to consider when identifying a **suitable location for the hydrogen farm.**
- How to develop a **Hydrogen Roadmap** for the airport.
- Who the relevant **internal and external stakeholders** are that airports will need to engage with in their transition towards hydrogen aircraft and by when.

Once the level of infrastructure needed is determined, the next step is to introduce these requirements into the wider airport master plan. Chapter 5 provides a step-by-step methodology summarising the actions that airports will need to carry out to identify a **suitable area for developing the hydrogen farm**. The intent of this chapter is not to provide advice on all the specific planning challenges surrounding hydrogen, as this should be undertaken by specialists, but to provide a general knowledge on the activities required to enable a successful transition to ZEF. A **Hydrogen Roadmap** showcasing the dependencies between the activities, key milestones and rough timelines for implementation is also presented.

onditions and constraints (i)

ify the site constraints.
f the site, its constraints, future developments and any
e current master plan.

derstood before proceeding to the identification of

. land?

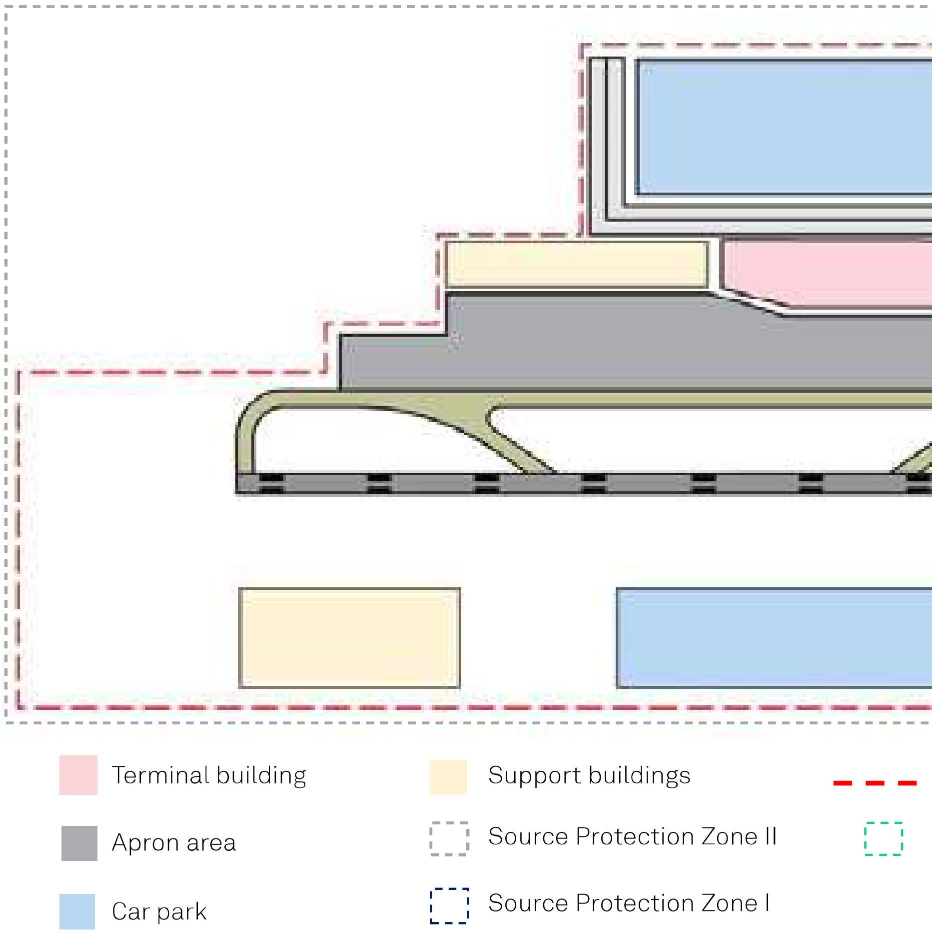
undary?

nt airport master plan?

e relocated or are not in use?

itation surfaces (OLS), rivers, challenging topography, etc?

An indicative site plan of the case study airport is shown below, ic
apron areas, and site constraints. The following page describes th
detail. It should be noted that although keeping the key site chara
simplified and modified for the purpose of illustration.



onditions and constraints (ii)

otected areas

dditional to the ‘Green Belt’, protected areas are also present thin a 10km radius from the airport. These include a Site of pecial Scientific Interest (SSSI), Special Protection Areas (SPAs) nd Local Nature Reserves (LNRs).

NRs are established and managed by local authorities and as uch, are protected by local policy rather than legislation. Any npacts on an LNR would be taken into account as part of a anning application.

nally, the airport is also located within a principal aquifer that used for supplying drinking water. These areas are protected om pollution by the Environmental Agency. Areas supplying inking water have been given a non-statutory designation ased on the potential risk to the source from contamination. hese are referred to as Groundwater Source Protection ones (SPZs).

ne existing airport is partially within a Zone II SPZ, which is an uter protection zone. Also, east of the airport, there is an inner otection zone, and hence, any development in that area is likely be objected to by the Environmental Agency and additional drogeological risk assessment or mitigation may be required.

Current undeveloped areas

There are three primary areas within the current airport footprint that remain undeveloped at present – identified in the plan on the following page:

- Not in use and no future allocation identified yet (Option 3)
- Not in use but allocated for other purposes (Option 1)
- Not in use but marked as Nature Conservation Enhancement Area (Option 4)

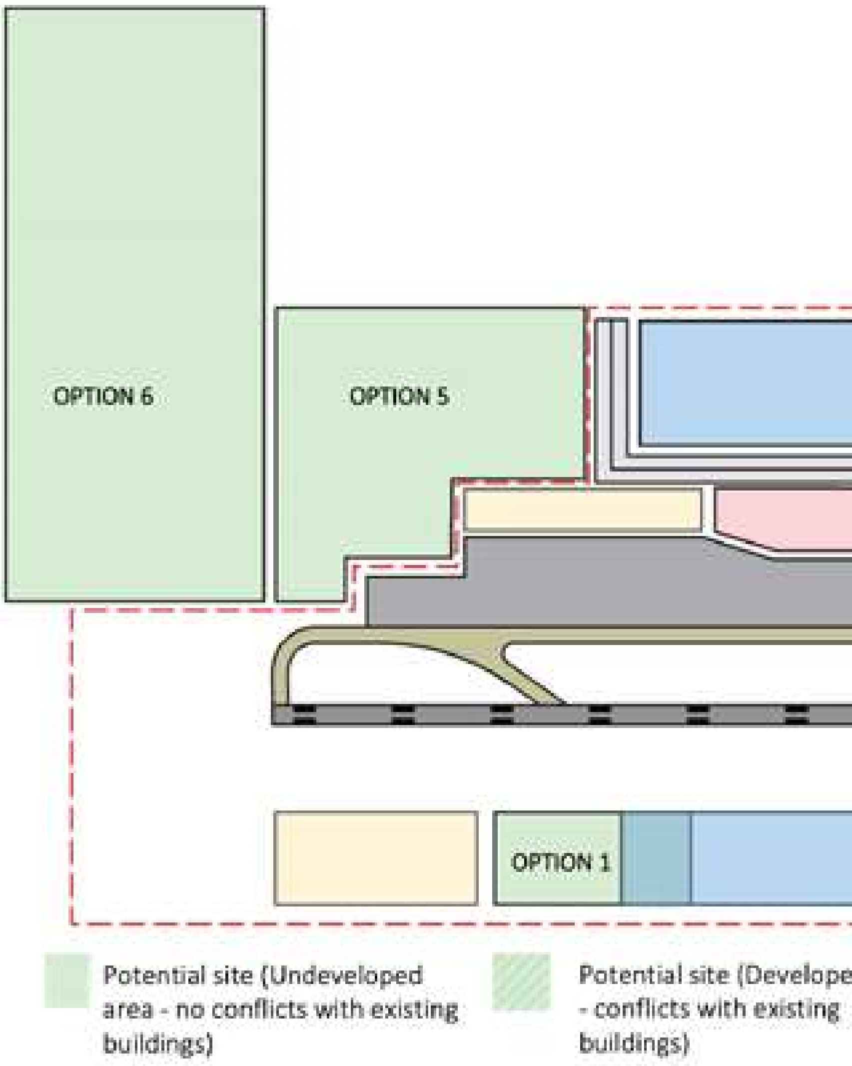
develop the hydrogen fuel farm

undary that could be utilised to develop the hydrogen g point for the location optioneering exercise. However, it is acilities may provide an attractive site for the hydrogen

ning principles. Undertake a pros and cons evaluation of ferred location(s). To do so, the airport will need to define e this decision. The table on the following page provides an onsidered during the evaluation process. Airports will need

re than one suitable option is selected for further

in the case study as potential sites to develop the Options 1 to 4, as well as Options 5 and 6 outside the ree example options are shown on the following pages.



the airport's planning parameters

Planning Parameter
e the space requirements identified.
e populations should be avoided. The minimum safety radius an airport environment is not currently established, however, adius of ~30m.
ng should consider splitting the hydrogen fuel farm between enic pipe length (if required) and enhance resilience.
voided as this would increase costs.
hey allow for a greater flexibility and optimisation of the future shapes.
enfield areas to minimise planning requirements and land
e or airside location for the hydrogen storage tanks is more connection to an airside dispensing location(s) would minimise e-airside boundary. However, this solution would require space und pipe connection, which is likely to increase the cost of
urrent and future stands to minimise either pipeline length or .
protected areas.

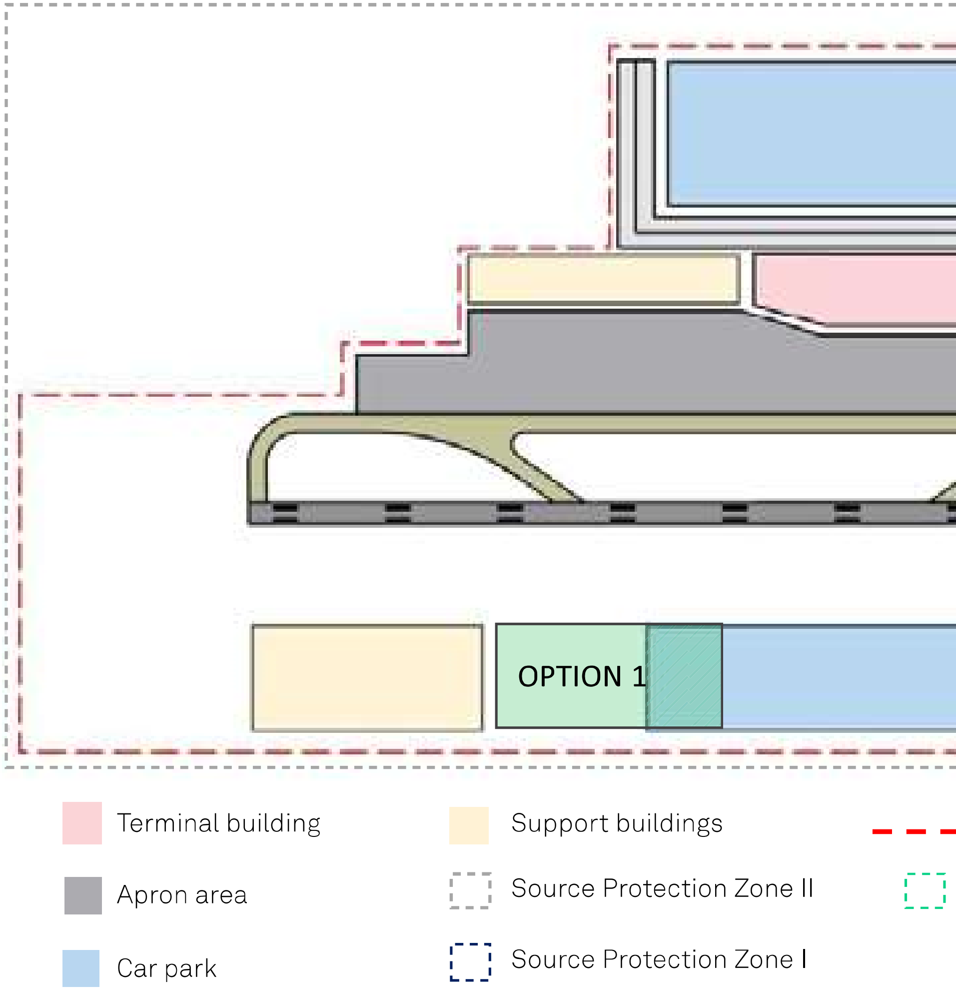
Item	
Obstacle Limitation Surfaces	The location should avoid interference wit public safety zones associated with aircra
Distance from fuel farm	Airports should evaluate whether co-locat technically feasible and (ii) operationally o
Airside and landside connectivity	The site should have a good airside road c congestion. For those airports with hydrog connectivity should be considered.
Runway crossings	The site should minimise the number of ru
Impact to facilities	Airports should consider impacts to existi planned car parking spaces and aircraft st
Utility connections	Proximity to existing utilities and service c
Phasing and expandability	Airports should consider sites than enable
High-value areas	Airports should consider if any of the sites such as apron, terminal, car park or real es
Land ownership	Sites already owned by the airport are pre increased costs.

Typical planning parameters

mple.
ay

	Cons
cient to lity and	• Area available not sufficient to cover the high demand scenario in the long term. Also, not sufficient land to co-locate the fuel and hydrogen farms together, should this be the preferred option. • Inside the SPZ Zone II
ces rside	• Landside location, which means an airside dispensing site + underground pipe would be needed to avoid recurring landside-airside crossings by vehicles • Far from all the stands, which would lead to either runway crossings or an extensive pipe network, increasing the capital and operational costs • Close to populated buildings • Inside the transitional surface
	• Impact to car parks, which is a high-value facility for the airport
	• Far from the main intake substation
for	• Future expansion would further reduce car park spaces

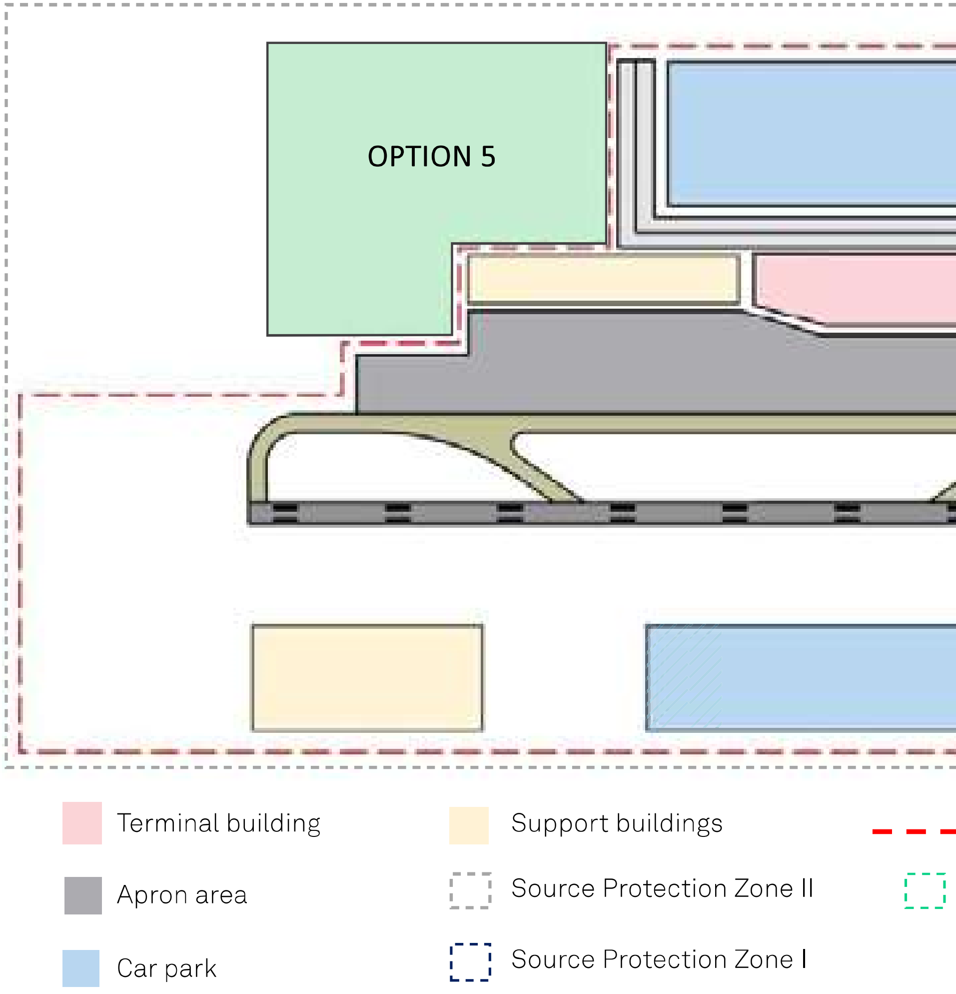
Option discarded due to the impact to existing car parking facilit runway crossings and insufficient land for the long-term requirem



mple.
ay (location 1)

	Cons
o cover all nd tion. Given ed for other rminal	- Land not owned by the airport – land acquisition is required, increasing the cost - Inside the Source Protection Zone II
times d they be	- Landside location, which means an airside dispensing site + underground pipe would be needed to avoid recurring landside-airside crossings by vehicles - Far from the eastern stands, which could experience long turnaround times or require extensive pipe networks - Partially inside the transitional surface but with no risk of penetration - Not highly accessible from the existing road network for hydrogen deliveries
s no impact	- None
	- Far from the water and electricity point intakes
d to be e easily	- Potentially impacts apron development under the current master plan

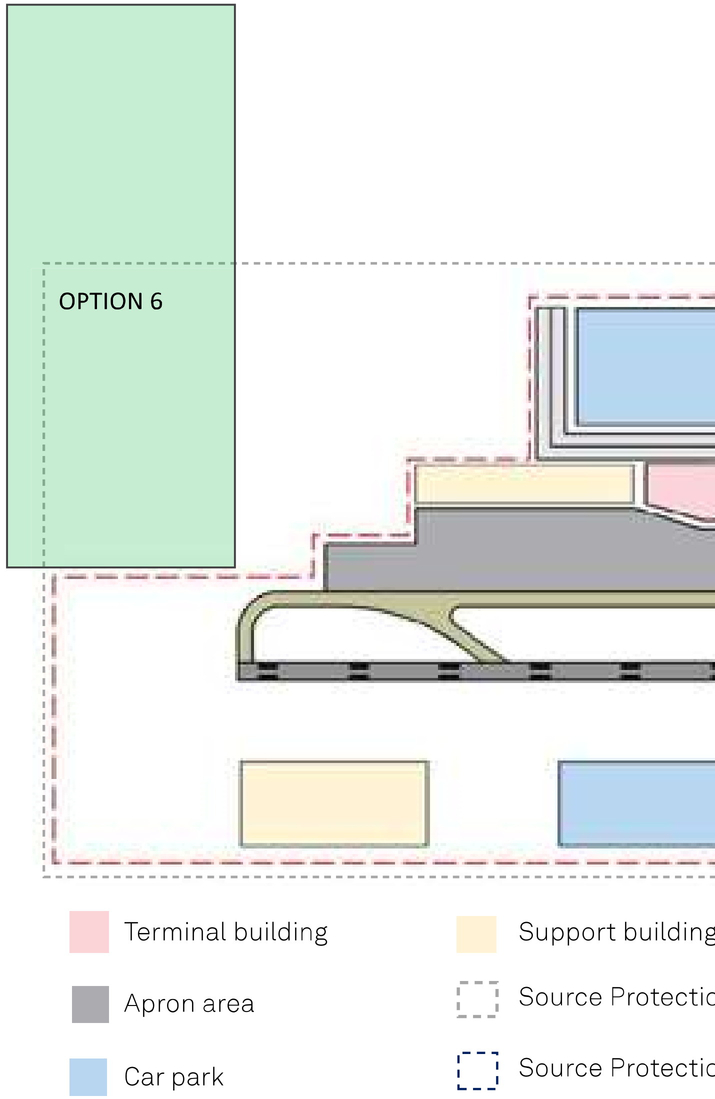
Option shortlisted as it can accommodate the long-term require
and is outside the SPZ Zone I.



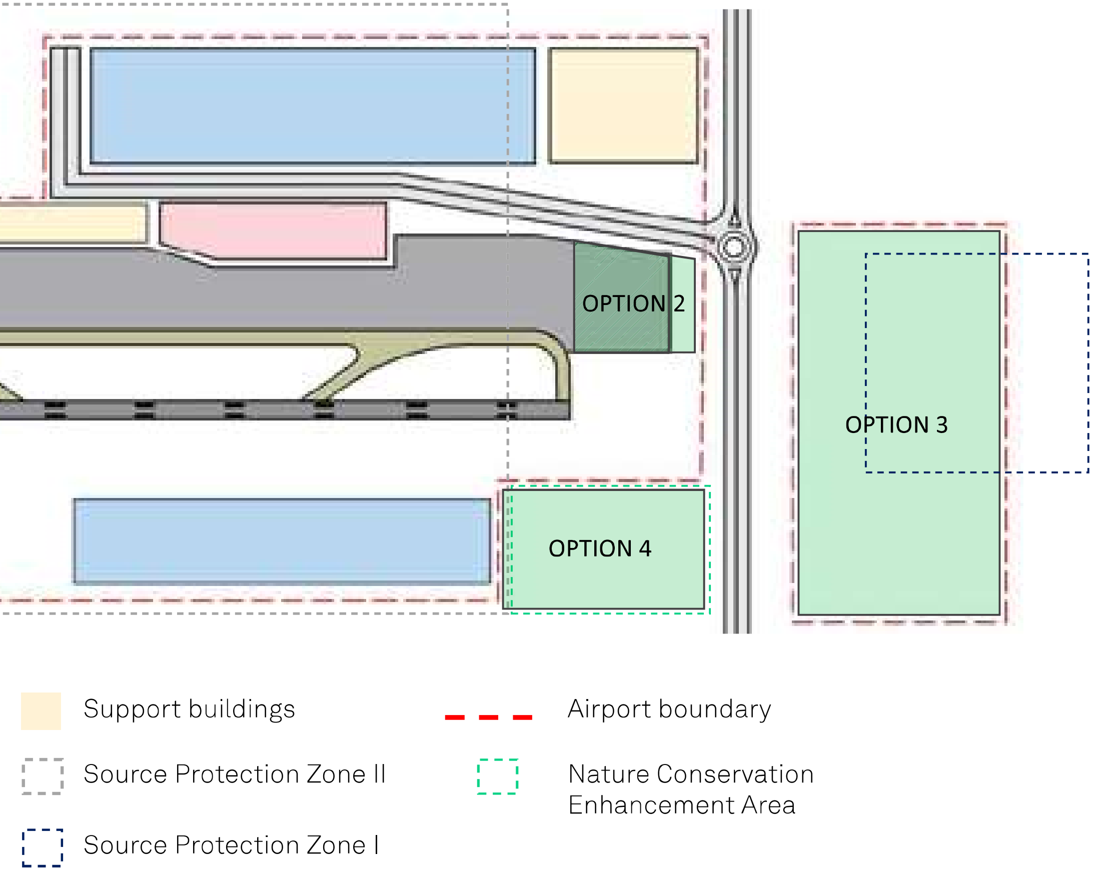
ample.
ay (location 2)

	Cons
er all rogen arge n-value s nisation	• Land not owned by the airport – land acquisition is required, increasing the cost • Inside the Source Protection Zone II
s for led in	• Landside location, which means an airside dispensing site + underground pipe would be needed to avoid recurring landside-airside crossings by vehicles • Far from the eastern stands, which could experience long turnaround times or require extensive pipe networks • Partially inside the transitional surface but with no risk of penetration • Not highly accessible from the existing road network for hydrogen deliveries
mpact to	• None
	• Far from the water and electricity point intakes
e ily	• Potentially impacts apron development under the current master plan

Option shortlisted as it can accommodate the long-term require the SPZ Zone I.



mple.


OPTION 2
OPTION 3
OPTION 4
Support buildings
Source Protection Zone II
Source Protection Zone I
Airport boundary
Nature Conservation Enhancement Area

for each shortlisted location g principles

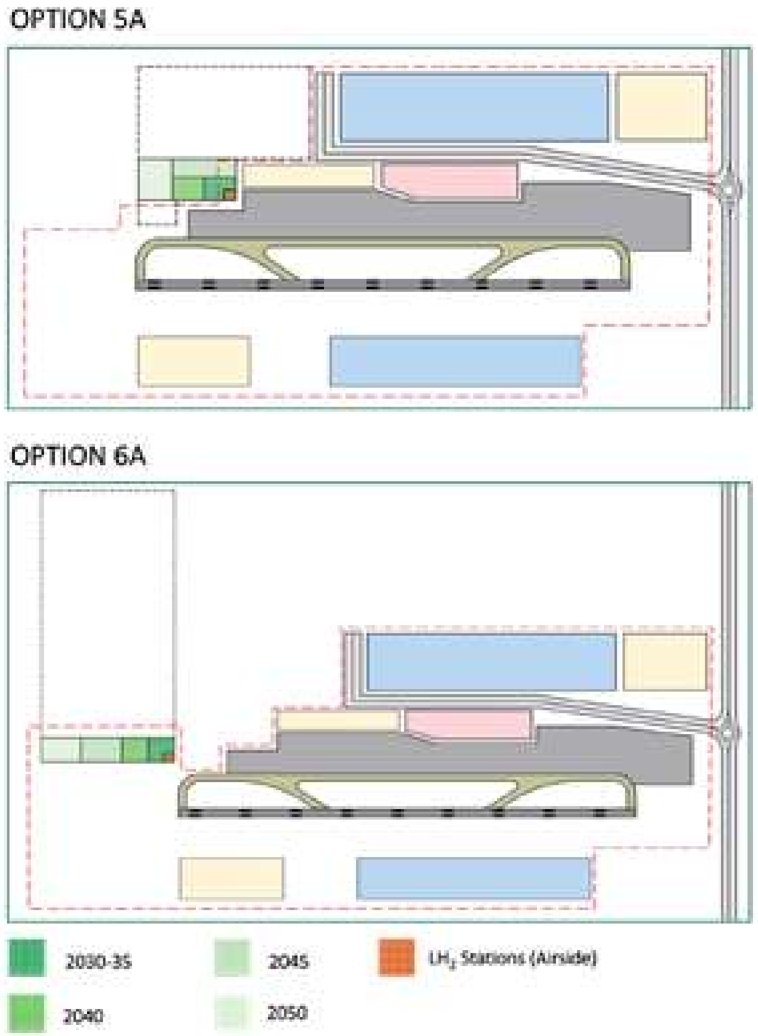
e shortlisted location(s) and phases. test different locations of the various hydrogen

options for two of the shortlisted options for the case orts will need to complete this exercise for all shortlisted ide hydrogen infrastructure specialists, can develop more of the options. Detailed layout design is not included in

he options and sub-options can be evaluated against rred option. The evaluation could also use weighted

most likely outcome. However, the suitability of the site

aluation for two shortlisted options and their sub-options.



Note: Areas safeguarded for the hydrogen complex conside to account for circulation and other operational buildings.

ons for the case study airport

the case study airport were evaluated against key planning parameters. When undertaking this evaluation, airports will need to consider all factors th

	OPTION 5B	OPTION 6A
	• Allows apron expansion to the north and west	• Apron expansion to the west is limited
or the support	• Expansion of the car park is limited	• Does not limit expansion of the car park or the support buildings
	• Farther from the stands compared to all other options. Will require a longer underground pipe to the LH_2 stations located airside, and a longer hydrant system, if this is required beyond 2050	• Close to the western stands
. Avoids the need to e storage tanks and	• Landside location. Requires an underground pipe connecting the storage tanks and the airside refuelling stations to avoid multiple airside-landside crossings, potentially increasing bowser turnaround times	• Airside location (airport fence relocated). Avoids the need to have an underground pipe connecting the storage tanks and the refuelling stations
	• Loss of apron area due to the airside refuelling stations	• No loss of high-value areas
to the support	• Far from the terminal building and support facilities.	• Far from the terminal building and support facilities.
ces but partially	• Outside all OLS surfaces	• Outside the take-off and approach surfaces but partially inside the transitional surface

certainty exists, roadmaps can be helpful in highlighting potential need to develop the associated airport infrastructure. This ions that an airport may need to take, and the other showing the astructure technology required. The roadmaps highlight planning, vice dates, government net zero targets, key decision points and

eed to undertake to successfully transition towards hydrogen- n advance airports will need to prepare for this transition and the high-level overview of when airports will need to engage with y bodies, to ensure the required coordinated effort is in place.

ese activities need to take place at airports, this roadmap has entry-into-service date expected for hydrogen regional aircraft.

y significantly between regional and large airports, a simplified sise that for smaller airports, the transition to zero-carbon ear term.

e

entry-into-service date of hydrogen aircraft

Hydrogen infrastructure roadmap

The hydrogen infrastructure roadmap gives UK airports and airfie periods for the key hydrogen flight infrastructure.

The roadmap shows both the time expected for the development implementation effort, representing the time needed to impleme and standards, training of personnel, ORAT, etc.).

By reading both roadmaps together, airports can identify when ke compare against the required timeline for the airport's requireme

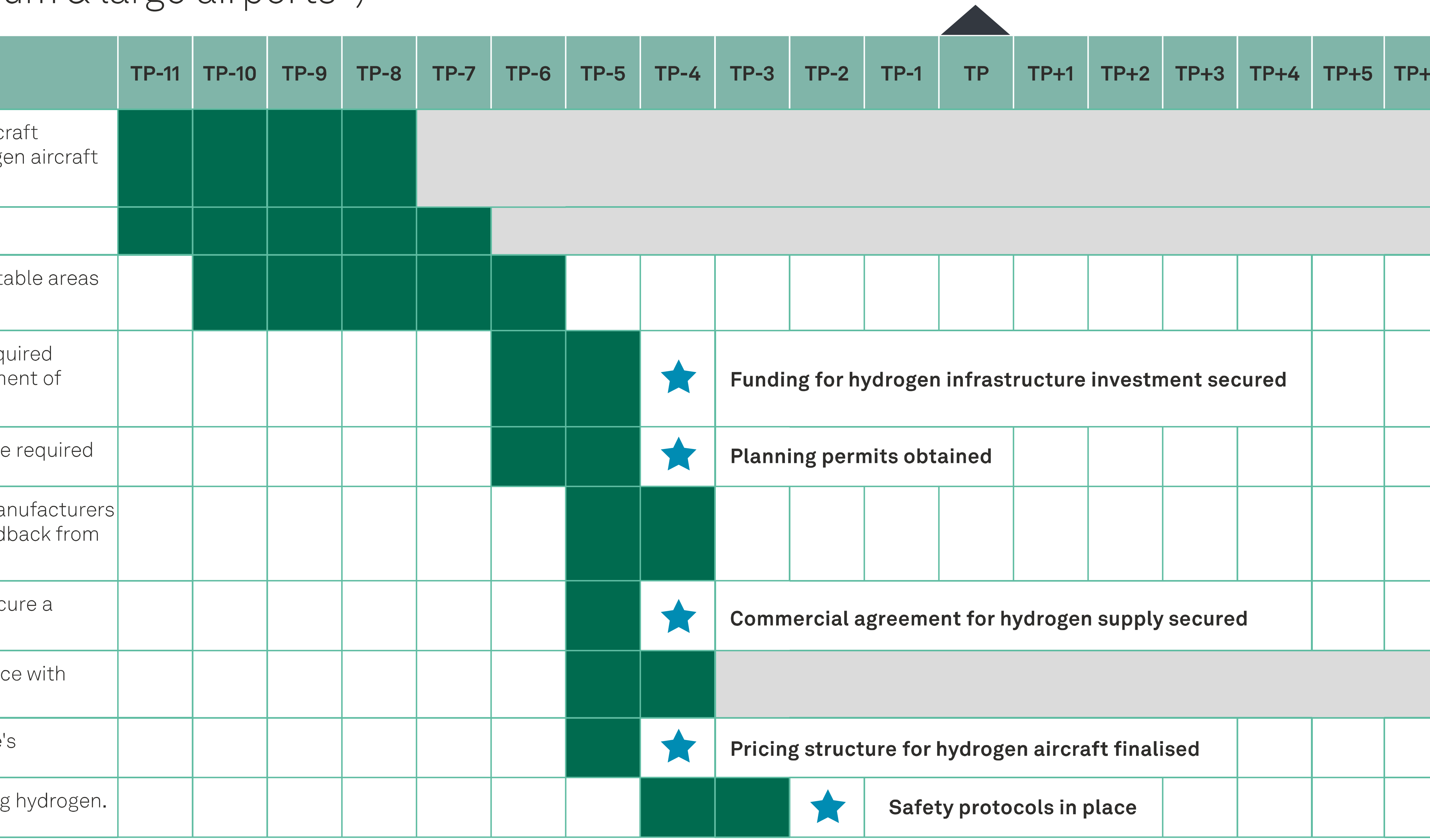
Legend for the roadmap

🟩 Expected aircraft entry-into-service period 🟦

🟦 Technology development period ▲

um & large airports*)

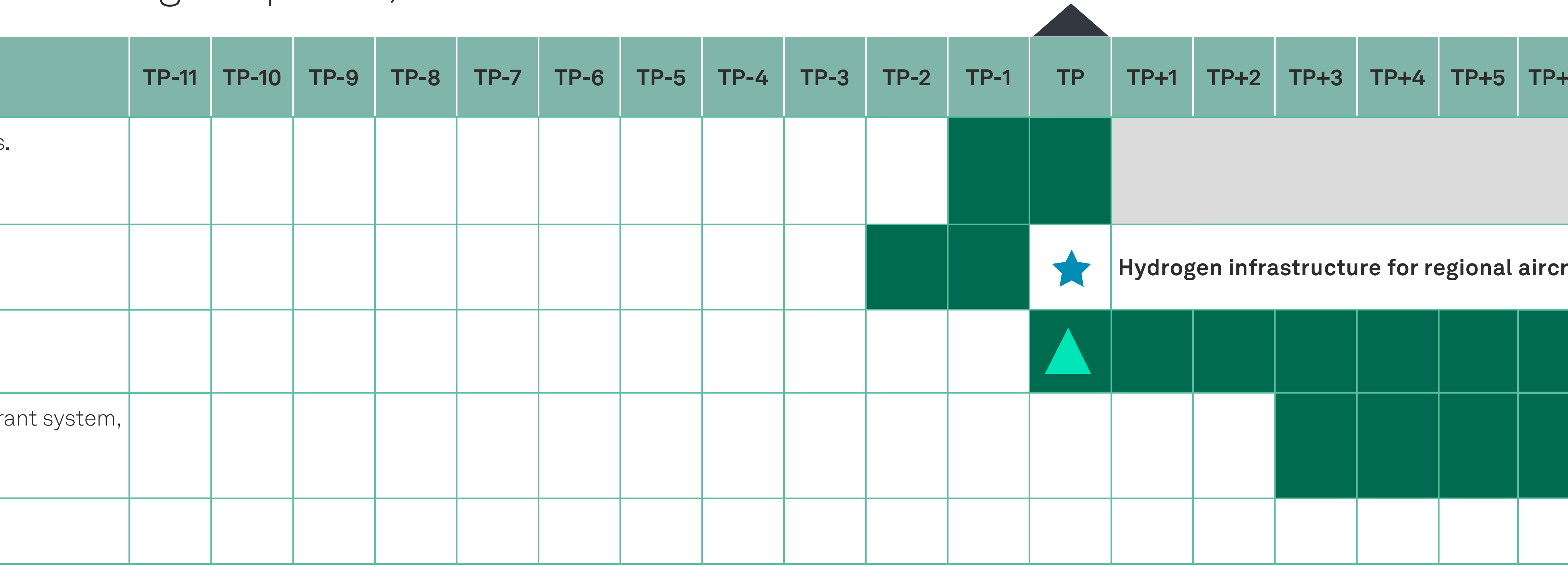
Earliest entry-into-service date of hydrogen air



	TP-11	TP-10	TP-9	TP-8	TP-7	TP-6	TP-5	TP-4	TP-3	TP-2	TP-1	TP	TP+1	TP+2	TP+3	TP+4	TP+5	TP+
craft gen aircraft	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
table areas		🟩	🟩	🟩	🟩	🟩												
quired nent of						🟩	🟩	★	**Funding for hydrogen infrastructure investment secured**									
e required						🟩	🟩	★	**Planning permits obtained**									
anufacturers dback from							🟩	🟩										
cure a							🟩	★	**Commercial agreement for hydrogen supply secured**									
ce with							🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
's							🟩	★	**Pricing structure for hydrogen aircraft finalised**									
g hydrogen.								🟩	🟩	★	**Safety protocols in place**							

um & large airports*). Part 2

Earliest entry-into-service date of hydrogen air



	TP-11	TP-10	TP-9	TP-8	TP-7	TP-6	TP-5	TP-4	TP-3	TP-2	TP-1	TP	TP+1	TP+2	TP+3	TP+4	TP+5	TP+
s.											🟩	🟩	▨	▨	▨	▨	▨	▨
										🟩	🟩	★	**Hydrogen infrastructure for regional aircr**					
												▲	🟩	🟩	🟩	🟩	🟩	🟩
rant system,															🟩	🟩	🟩	🟩

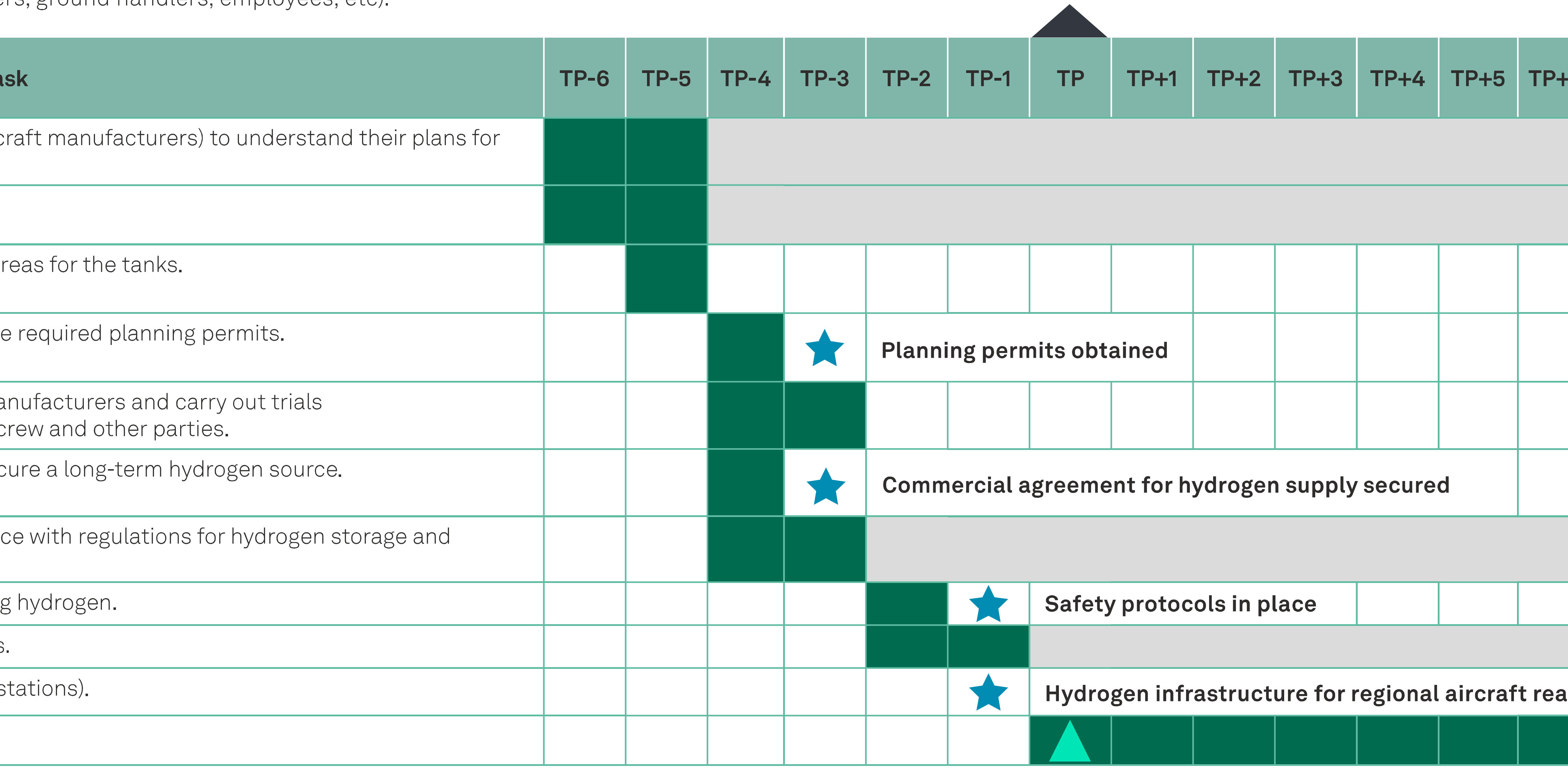
cture report published by Connected Places Catapult

l & regional airports)

regional airports that are likely to require less intrusive infrastructure
vered by road in tankers and only require storage on site (i.e., no

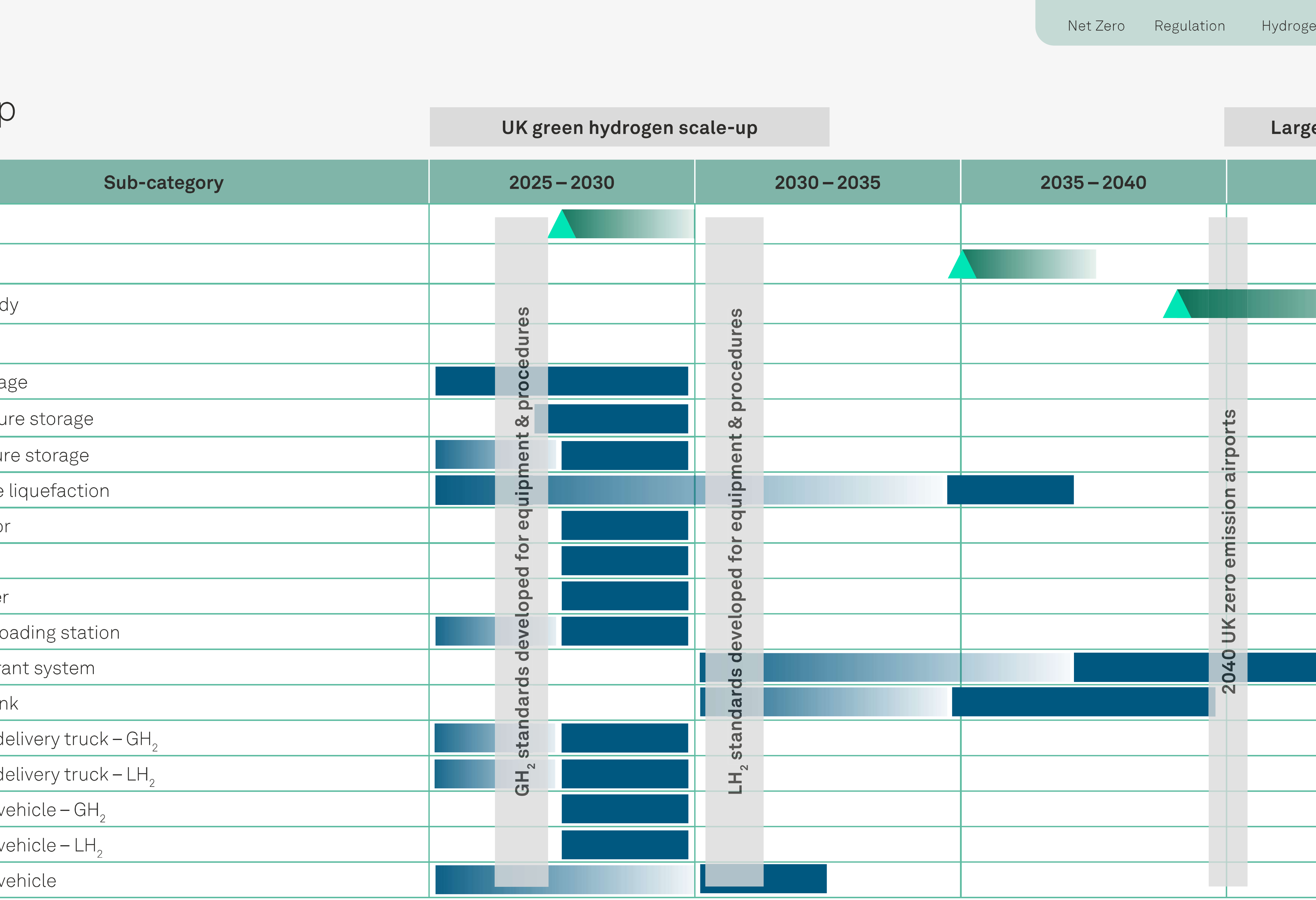
nplexity and time will be significantly lower for small airports due to the
ers, ground handlers, employees, etc).

Earliest entry-into-service date of hydrogen ai



ask	TP-6	TP-5	TP-4	TP-3	TP-2	TP-1	TP	TP+1	TP+2	TP+3	TP+4	TP+5	TP+
craft manufacturers) to understand their plans for	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
reas for the tanks.		🟩											
e required planning permits.			🟩	★	**Planning permits obtained**								
anufacturers and carry out trials crew and other parties.			🟩	🟩									
cure a long-term hydrogen source.			🟩	★	**Commercial agreement for hydrogen supply secured**								
ce with regulations for hydrogen storage and			🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨	▨
g hydrogen.					🟩	★	**Safety protocols in place**						
s.					🟩	🟩	▨	▨	▨	▨	▨	▨	▨
stations).						★	**Hydrogen infrastructure for regional aircraft rea**						
							▲	🟩	🟩	🟩	🟩	🟩	🟩

p


Net Zero
Regulation
Hydroge
UK green hydrogen scale-up
Large
Sub-category
2025 – 2030
2030 – 2035
2035 – 2040
dy
age
ure storage
ure storage
e liquefaction
or
er
oading station
ant system
nk
delivery truck – GH$_2$
delivery truck – LH$_2$
vehicle – GH$_2$
vehicle – LH$_2$
vehicle
GH$_2$ standards developed for equipment & procedures
LH$_2$ standards developed for equipment & procedures
2040 UK zero emission airports

g ‘now’, ‘next’ and ‘later’ actions

ble the transition to zero-carbon emission aircraft can be derived.
w’, ‘next’ and ‘later’ based on their urgency. These actions may
ation and demands. For example, larger airports may not need to
this infrastructure is not needed for the larger aircraft they service.

24 – 2025)	Next (2025 – 2035)	
en demand in conjunction with their airlines ecure an initial gaseous hydrogen supply if	- Engage with local suppliers to secure an initial liquid hydrogen supply - Engage with the relevant authorities to incorporate the airport into hydrogen supply network schemes - Review the hydrogen forecast to estimate the medium and long-term hydrogen demand - Work with other potential local users to investigate the hydrogen hub concept	- Engage with loc - Connect to the
within the supply chain to undertake trials	- Undertake trials and demonstrations with GH_2 aircraft to build operating experience and capability in the personnel, processes and supply chain	- Undertake trials
th authorities to develop standards and unity	- Continue engaging with relevant authorities and working groups, to develop standards. In the early years, focus should be on GH_2. Implement safety protocols and SOP’s for GH_2 aircraft at the airport	- Continue engag standards and p - Implement safe
e potential costs of the hydrogen	- Engage with the key financial stakeholders to explore funding options - Develop and implement, in agreement with relevant parties, the pricing structures and terms	- Secure the requ
nts for the hydrogen farm and identify ning permits	- Establish the location of the hydrogen farm and obtain the relevant planning permits - Start construction of the storage tanks	- Expand the hyd service of narro

PERATIONAL
ND SAFETY
ONSIDERATIONS

OPERATIONAL AND SAFETY CONSIDERATIONS

At the end of this chapter, airports will understand the following:

The **key operational challenges** and safety risks related to hydrogen infrastructure at airports.

The **mitigation actions** airports can implement to avoid or, where not possible, minimise the risks.

Chapter 6 **identifies the most significant Operational Challenges (OC) and Safety Risks (SR)** for the operation of hydrogen at an airport, along with the necessary **Mitigation Actions (MA).**

This guidance enables airports to identify the steps needed, in the short, medium and long term, to reduce risks and to enable the transition to zero-carbon emission aircraft.

allenges and mitigation actions (i)

OC / SR	Event	
Common challenges and risks		
SR	The boil-off (vaporisation) of liquid hydrogen could lead to a build-up of hydrogen gas pressure within pipes and vessels which, in turn, could lead to explosive rupture.	• All hydr designe non-hyc • Install a acciden • Install p • Install h • Integrat • Install h • Install g
SR	Liquid or gaseous hydrogen leaks from pipe flanges and valves due to hydrogen embrittlement of the metals of the pipes and flanges.	
SR	Ignition of hydrogen gas from static electricity or other ignition sources.	
OC	Lack of skilled personnel who are certified to operate the hydrogen equipment, including delivery trucks and refuelling vehicles. This will require a continuous process of recruitment, training, security clearances, certification and frequent recertification.	• Delivery speciali • Operatio • Provide conside A refuel
OC	Contamination of gaseous hydrogen due to impurities when delivered through a pipeline.	• Remove the liqui not nee gaseous than thr meet th

OC – Operational Challenge SR - Safety Risk

allenges and mitigation actions (ii)

Mitigation Actions
a back-up power supply. This could be powered by hydrogen fuel cells cess hydrogen. ydrogen storage buffer to cover multiple days of operations. -site battery energy storage. contingency plans establishing the actions to be undertaken should any interruptions to the production of hydrogen. For instance, having connections to the electricity grid.
uffer hydrogen storage to cover multiple days of operations. contingency plans establishing the actions to be undertaken should any interruptions in the delivery of hydrogen. ous pipeline delivery, have multiple pipelines from independent s.
with the Government to explore options to fund the hydrogen cture. n collaborative industry initiatives to accelerate learning stment. equipment development and purchase with other airports to costs.

OC / SR	Event	
Delivery of liquid hydrogen by road truck		
OC	Congestion of trucks at the off-loading point.	- Provide a
OC	Push-back from the local community due to noise and tail-pipe pollution.	- Use of el pipe poll
OC	Congestion at the airport boundary checkpoints due to delivery trucks going to the off-loading facility located inside the airport.	- Locate th transfer
Storage of liquid hydrogen		
OC	Damage to the insulation between the internal and external tanks when emptied.	- Liquid hy - If the bu - It is impo manager
Refuelling of aircraft		
OC	Turnaround activities on adjacent stands at the same time not allowed due to a safety zone around the aircraft and the bowser during the refuelling process.	- Engage w could as

OC – Operational Challenge SR - Safety Risk

allenges and mitigation actions (iii)

Mitigation Actions
with the relevant authorities to support real-life demonstrations that sess the consequences of all possible safety risk scenarios. ate automation of aircraft servicing procedures to reduce safety risks.
ate robotic technology to assist with refuelling procedure.
ty related concerns, engage with the relevant authorities to support demonstrations that could assess the consequences of all possible sk scenarios. structure required on stands, investigate flexible aprons that allow ft use.

OC / SR	Event	
Refuelling of aircraft (hydrant system specific)		
SR	Over pressurisation of the transfer tank during the refuelling process.	- Impleme safety of
SR	Low usage of the transfer tank leading to an increase in the hydrogen temperature of the cryogenic gas contained in it, which may result in an explosion.	- Ensure f the requ - Venting a - Boil-off g
Production of hydrogen gas with electrolysis		
OC	Water supply disruption, interrupting the hydrogen production activity at the airport.	- Have a b - Develop any inter connect

OC – Operational Challenge SR - Safety Risk

AND POTENTIAL
JE SOURCES

COSTS AND POTENTIAL REVENUE SOURCES

At the end of this chapter, airports will understand the following:

Rough of Order Magnitude (ROM) **CAPEX and OPEX costs** of the various hydrogen infrastructure components.

Expected **trajectory of costs** of hydrogen infrastructure over the next decades.

Other hydrogen uses and applications that could be an **alternative revenue source.**

Chapter 7 presents the **ROM CAPEX and OPEX costs of the hydrog infrastructure elements to support airports understand the high-level financial viability of the different infrastructure pathways** presented in Chapter 4. Cost information for liquid hydrogen production and storage is limited. Therefore, the information shoul be used as an indication only.

Additionally, Chapter 7 identifies, at a high level, **how excess hydrog could be utilised** elsewhere at an airport or sold to third parties **to generate additional revenue** for the supplier.

ude capital costs

ne LBD curves assume that an industry has a Learning Rate R) which defines how the industry increases its expertise nd therefore reduces development costs as time progresses. earning rates in the green hydrogen production sector range om 4% to 20% p.a. [15], [16]. In this report, the LBD curve ssumes a 2.5% take-up of hydrogen technology in 2035 and 5% in 2050, in line with the hydrogen uptake rates considered in e forecast developed in Chapter 3.

this report, only the major infrastructure elements have been osted. Smaller components such as compressors, vaporisers, umps, have not been included.

ne CAPEX values presented in the following tables represent cost estimate for obtaining the technology alone. These costs e not adjusted for inflation, transport, labour, design and other stallation costs. In this report, only airport costs are included e., installation costs of a hydrogen gas pipeline to the airport or ogrades to the power supply are not included).

stallation costs will depend upon factors such as, site onditions, airport location, brownfield or greenfield land.

nerefore, to obtain a high-level installation cost, the commendation is to add an installation cost factor to the pure apital cost of the infrastructure. An approximate installation ctor for each infrastructure component is presented in is report.

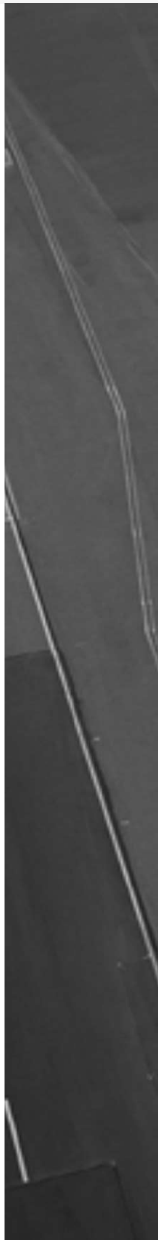
It should be noted, however, that some indirect CAPEX costs (e.g., engineering, project management, insurance) are often neglected in industry benchmarks but can represent a significant share of total capital costs. Estimates for these indirect costs have also been provided for each component.

This tendency to underestimate total costs is known as optimism bias. Hydrogen flight infrastructure projects may be classified as non-standard civil engineering projects. The Green Book advises an initial optimism bias (OB) percentage of 66% [17]. However, this could be reduced in two situations.

- If the overall infrastructure required has a low level of complexity, according to the Green Book, the OB could be reduced by 8%.
- If most of the infrastructure elements have a TRL of 7 or over, the overall OB could be reduced by up to 9%.

The costs presented in this report are based on the knowledge and data available at the time of writing.

The tables are based on 2023 real costs.



ysers

15% of CAPEX

e preparation cost:

and licensing cost:

15% of CAPEX

costs add up to
sts [23], [26].

Case Study:

- Electrolysis on-site is not required for the case study airport.

7.1 Estimating capital costs: liquefact

Liquefier: Costs for liquefaction plants are usually expressed as £/kg H2/day or the total installed costs for a liquefaction plant of certain daily production capacity.

Future capital costs have been projected considering a learning rate of 15%.

The capital costs to install a liquefaction plant decreases significantly as the daily production increases. For liquefaction plants with a low daily production (~10t/day) it is recommended to use the high scenario, while for liquefaction plants with a high production capacity (~70t/day), the low scenario should be used.

Indirect cost factors

- Transportation cost:
- Construction and sit
  Not applicable
- Engineering service a
  1% of CAPEX
- Project contingency:

Figures above already c
costs and, therefore, onl
and contingency indirec
added. Total indirect cos
direct capital cost

Scenario	Units	Current	2035	2050
Low	£/kg/day	2,500	1,800	1,200
Central	£/kg/day	4,000	3,000	2,000
High	£/kg/day	6,000	4,400	3,000

Source references: [27], [12]

7.1 Estimating capital costs: gaseous

Gaseous hydrogen storage: The total capital cost of gaseous hydrogen storage will depend on the pressure, size (or capacity) and quantity of tanks required. Unit costs for gaseous hydrogen storage are generally expressed as cost per tonne or kilogram of hydrogen. Future capital costs have been projected considering a learning rate of 10%.

The total (uninstalled) capital costs can be calculated as:

$$Total\ H2\ Storage\ CAPEX\ (£) \\ = Number\ of\ tanks\ *\ Cost\ per\ tank$$

Indirect cost factors

- Installation cost: 30%
- Engineering service a 1% of CAPEX
- Project contingency:

Total indirect costs add capital costs.

Type 4 storage tanks (High Pressure)

Scenario	Units	Current	2035	2050
Low	£k/tonne	650	550	400
Central	£k/tonne	1,500	1,200	900
High	£k/tonne	3,000	2,500	1,850

Source references: [12], [29], [30], [31], [32] , [33] , [34], [35]

drogen storage

capital costs can be

$(£)$
$Cost\ per\ tonne$

% of CAPEX [17]

e and licensing cost:

y: 15% of CAPEX

d up to 46% of direct

Case Study:

- Quantity of vertical tanks: 1
- Quantity of horizontal tanks: 6
- Quantity of hydrogen storage: 407t
- Starting operating year of vertical tank: 2027
- End of life vertical tank: 2057
- Starting operating year of horizontal tanks: 2040-50
- End of life horizontal tanks: 2070-80

$$LH2\ Storage\ Direct\ CAPEX\ (£) \\ = 407\ tonnes * 50{,}000\left(\frac{£}{tonne}\right) =$$

$$£20.5M^{*}$$

$$LH2\ Storage\ Indirect\ CAPEX\ (£) = £20.5M * 46\% =$$

$$£9.5M$$

$$LH2\ Storage\ Total\ CAPEX\ (£) = £20.5M + £9.5M =$$

£30M (Central demand scenario, central cost scenario)

* For simplicity, all tanks have been costed as per the 2050 price. In practice the tanks will be purchased before this date at a different price.

n stations

capital costs can be

(£)
ost per station

% of CAPEX [17]

e and licensing cost:

y: 15% of CAPEX

d up to 46% of direct

Case Study:

- Quantity of hydrogen stations required: 5
- Number of LH_2 station replacements during the period
- 2027-2050 due to their end-of-life: 4
- Total number of LH_2 stations: 9

$$LH2\ Stations\ Direct\ CAPEX\,(£) = 9\ stations * 1{,}500{,}000\left(\frac{£}{station}\right) = £13.5M\ *$$

$$LH2\ Stations\ Indirect\ CAPEX\,(£) = £13.5M * 46\% = £6.5M$$

$$LH2\ Stations\ Total\ CAPEX\,(£) = £13.5M + £6.5M = £20M$$ (Central demand scenario, central cost scenario)

* For simplicity, all 9 stations have been priced as per the 2050 price. In reality, the stations will be purchased before this date at a different price and later replaced at their end-of-life.

7.1 Estimating capital costs: refuellin

Dispenser vehicle and refuelling trucks: Hydrogen dispenser vehicles do not currently exist and therefore data on potential costs is very limited. Costs below are based on current jet fuel hydrant dispenser vehicles introducing a scaling factor of between 1.5 and 3. For refuelling trucks, costs presented in this report consider the truck and the trailer (liquid or gaseous). Future capital costs have been projected considering a learning rate of 10%. The total capital costs for refuelling and dispenser vehicles can be obtained by multiplying the unit costs by the total number of vehicles required.

$$Total\ vehicles\ (dispenser, refuelling) CAPEX\ (£) = Number\ of\ vehicles (dispenser, refuelling) * Cost\ per\ vehicle\ (dispenser, refuelling)$$

Indirect cost factors

- Installation cost: Not applicable
- Engineering service and licensing cost: 1% of CAPEX
- Project contingency: 15% of CAPEX

Total indirect costs add up to 16% of direct capital costs.

Hydrogen dispenser

Scenario	Units	Curre
Low	£/unit	225,0
Central	£/unit	300,0
High	£/unit	450,0

Source references: [39], [45

Liquid trailer + Truck

Scenario	Units	Curre
Low	£/unit	600,0
Central	£/unit	800,0
High	£/unit	1,200,

Source references: [14], [22

Gaseous trailer + Truck

Scenario	Units	Curre
Low	£/unit	600,0
Central	£/unit	800,0
High	£/unit	1,200,0

Source references: [14], [22

system

ts provided are
ic tank capital

he tanks will
pacity) and
. The unit
e relates
tank. For a
mated that
e required.
been projected
e of 10%.

ded in the

d licensing

5% of CAPEX
o to 16% of

Pipelines

Scenario	Units	Current	2035	2050
Low	£/m	5,000	4,000	3,000
Central	£/m	10,000	8,000	6,000
High	£/m	15,000	12,500	9,500

Source references: [39], consultant estimate for pipes between 300-400mm diameter

Transfer tanks

Scenario	Units	Current	2035	2050
Low	£/tank	250,000	200,000	150,000
Central	£/tank	400,000	325,000	250,000
High	£/tank	500,000	400,000	325,000

Consultant estimate

Case Study:

- A hydrant system is not required for the case study airport pre-2050.

7.2 Estimating fixed operational cost

ii

The next step is to **estimate the OPEX costs**. These consist of tw

- **Fixed OPEX:** These do not change with increases/decreases direct CAPEX.
- **Variable OPEX:** Consists mainly of power purchase costs, cos costs of refuelling vehicles, etc.

OPEX costs should be discounted in line with national discount Treasury Green Book guidance [17]. Costs, especially OPEX costs simplicity, the suggested approach is to increase OPEX costs in

OPEX should not be adjusted for optimism bias. Instead, it is rec factors and / or inflation rates. This table presents typical range

Fixed operating costs as a percentage of direct CAPEX

Asset	Units	High
Electrolyser	%	8.0%
Liquid Hydrogen Storage	%	5.0%
Gaseous Hydrogen Storage	%	5.0%
Liquefier	%	8.0%
Refuelling Stations	%	5.0%
Refuelling Vehicle	%	30.0
Hydrant System	%	10.0

osts

consumption parameters for all hydrogen technology presented in ogen production or flow (kgH2 / hr).

Expected Electricity Consumption	Sources
46 kWh/kg	[22], [51], [52]
6.7 – 7.5 kWh/kg	[22], [39], [53], [54]

e for the electrolysis process. Current electrolysers require a water ed.

nsumption	Sources
H_2O/kg	[56]

s a guideline only.

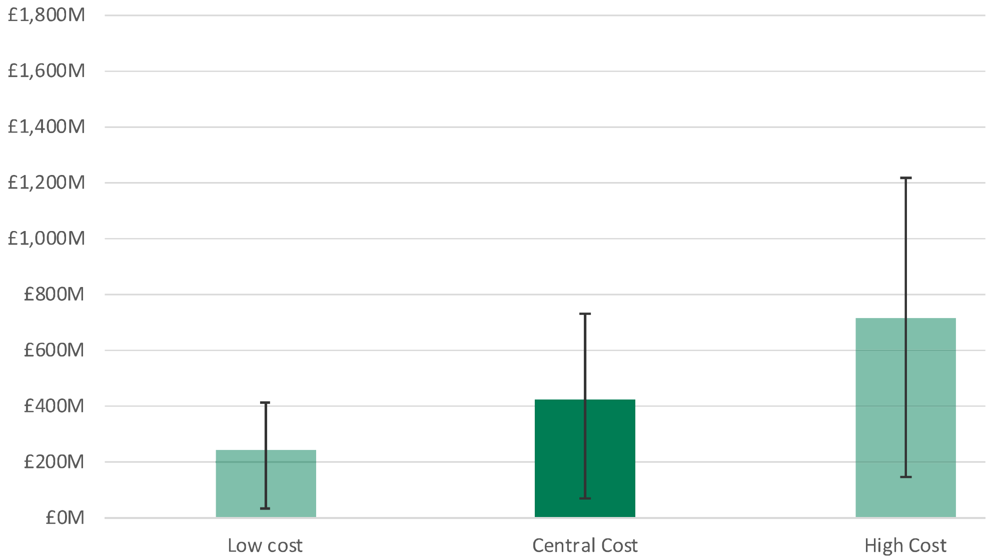
Value	Sources
20 – 40	[23], [50]
400 – 500	[36], [57]
130 – 200	[50]

of liquid and/or gaseous hydrogen to the airport.

7.2 Rough order of magnitude costs f

The graph below presents the rough order of magnitude capital costs projected for the case study airport for the period 2025-2050. The central hydrogen demand scenario with central costs forecast a total CAPEX of £426m. For the central demand case, an optimism bias factor of 56% has been considered. These costs include both direct and indirect costs. Variations on the demand and/or cost of the equipment will have a significant impact on the cost estimations. The high demand and high cost scenario projects a total capital cost of over £1,200m, almost three times the central-central scenario, while the low demand and low cost scenario has a capital cost of £36m. This low demand scenario considers that liquefaction on site will not be required pre-2050, reducing the capital costs significantly.

RoM CAPEX (2025 – 2050)

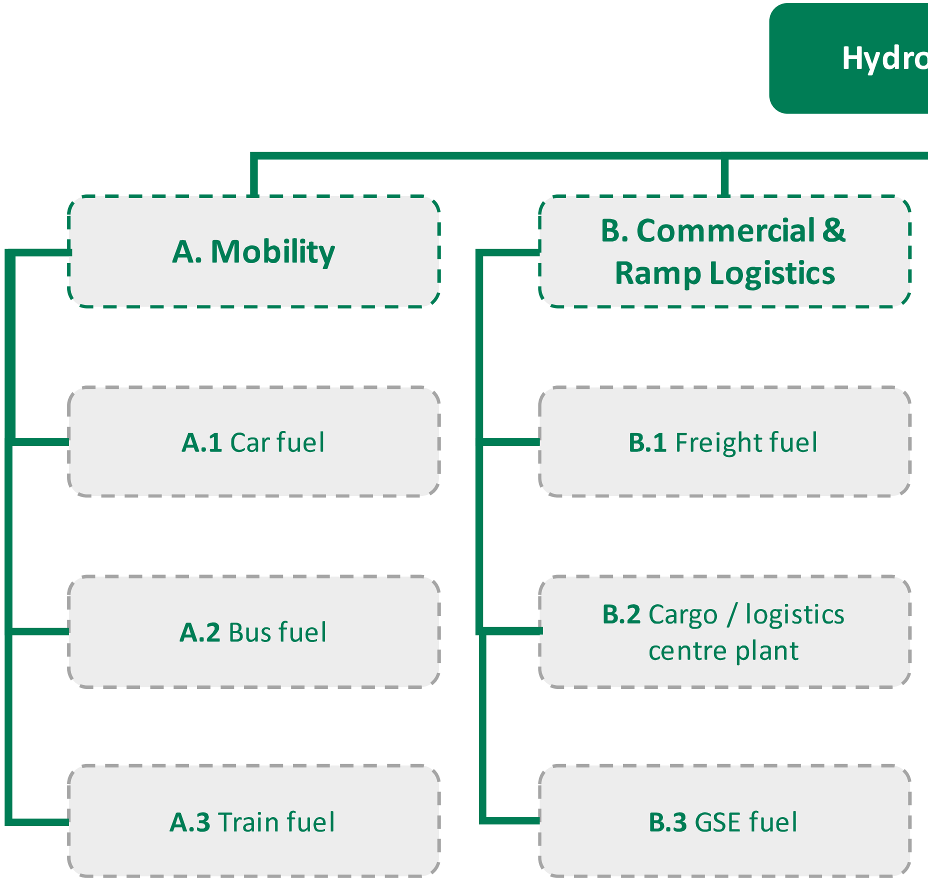


* Error bars represent variations on CAPEX due to the low and high hydrogen demand scenarios

rces and application uses for

As well as the opportunity to utilise surplus hydrogen for other purposes, if an airport has invested heavily in infrastructure for its own aeronautical hydrogen use, it could also increase supply and storage capability specifically to generate income through onward supply to other users. Alternatively, the airport could generate revenue from leasing the hydrogen facilities and site to a third-party operator.

This section of the report looks to identify, at a high level, how the excess hydrogen could be utilised within or adjacent to an airport environment. The main benefits as well as limitations are also identified.



This section does not recommend or consider the viabili potential for airports, based on use cases considered by extent of green hydrogen availability and use, all option ultimately viable or not.

erations for non-aeronautical

Potential revenue stream (R)	Benefits	
e and landside service hydrogen vehicles (U) e emergency service hydrogen vehicles (U) e hydrogen fuel station for airport (U) and 3rd e hydrogen fuel station for public and rental	• Reduction on airfield pollutants / contaminants that could otherwise enter watercourses. • Refuelling times for hydrogen vehicles range between 3 to 5 minutes, which presents a significant benefit in an operational environment when compared with electric vehicle (EV) charging [59]. This could be particularly relevant for emergency service vehicles. • The range of hydrogen cars are approx. 400 miles [62], similar to diesel / petrol cars and currently higher than a comparable EV.	• Hydrogen ve in the produ • Refuelling co prices decre fuel cell elec • Refuelling ti which may re • Cost of fuel vehicle. • Airports and readily availa towards EVs to transition
e and landside hydrogen buses vehicles (U) e hydrogen fuel station for airport buses (U) e hydrogen fuel station for hotels, local and	• Benefits as above • Buses using hydrogen fuel cells are already on the market. For example, Caetano Buses (owners of Cobus – supplier of airport buses) have an H2 city bus on the market [60]. Also, TfL already operates 20 hydrogen buses, meaning that there could be demand for hydrogen refuelling for local public buses [61].	• Constraints • Hydrogen po in. Demand routes to air vehicle coul • Smaller airp hydrogen re periods. • Airside bus

erations for non-aeronautical

tential revenue stream (R)	Benefits	
nce train journeys (R) n infrastructure and operations - e.g., logistic operations, etc. (R)	• Hydrogen could have uses in rail stations, such as for power backup, maintenance and operational vehicles, etc.	• The use of hydrogen fuelled tr it is stated that this would only when compared with electrific lines will be electrified, with or train journeys will be small, an • Very small airports may not ha all airports.
drogen fuel stations for cargo companies' erating at the airport site (R)	• Same benefits to A.1 (i.e., less pollutants and lower refuelling times, and longer range than EVs). The latter being especially relevant to haulage firms. • Potential for high hydrogen demand due to large volumes of freight movements around an airport site.	• With current hydrogen retail p niche situations in which BEVs [65]. • Heavy-duty commercial fuel-c to purchase EVs (when applica greater refuelling infrastructur • Adoption of FCEVs may vary be challenging.
drogen fuel stations to refuel cargo s) (R)	• Reduced equipment downtime compared with electric charging. • No harmful pollutants released from hydrogen fuel-cell equipment. Relevant for confined space working environments. • Hydrogen forklifts, automated guided vehicles and other material handling vehicles are already in the market [63].	• Cost of hydrogen equipment is companies may be the only bu until prices are reduced in the

erations for non-aeronautical

tential revenue stream (R)	Benefits	
drogen fuel stations for airport (U) and 3rd), including bowsers	- Ramp operations would benefit from the quick refuelling times of hydrogen when compared with EV equivalents. This is especially relevant for larger airports, where there are higher volumes of operations and a limited amount of time when EV charging can take place without taking required units out of service. - Risk of running out of power is reduced. - The greater range of hydrogen vehicles compared to EVs would allow agents to operate equipment for longer. - Reduction on airfield pollutants / contaminants that could enter watercourses.	- Electric GSE vehicles are read look to reduce their environme If airports invest in EV infrastru or uptake could be delayed 10- - In some cases, GSE is owned a a number of airports. It is likely transportation and maintenan - There is a large variety of equi reasonable degree of scale ca as forklifts, cars, buses and sta upgrades to specialist GSE, wi loaders, pushback tugs).
ncillary facilities and water heating (U), natural gas. nd water heating within airport vicinity (R)	- A hydrogen boiler reduces emissions, with water as the only by-product. - A hydrogen / oxygen boiler could utilise some of the by-product oxygen created from the electrolysis process – if done at or nearby the airport site. - Hydrogen Technologies (HTI) have created a Hydrogen / Oxygen commercial boiler that could be utilised within an airport environment.	- Initial industry research sugge hydrogen boilers are less effic - If hydrogen were used, a const to ensure the boilers meet der

erations for non-aeronautical

tential revenue stream (R)	Benefits	
ower on-site backup generators (U) s to be used to power their backup	- Hydrogen backup generators can operate at low ambient temperatures, last longer and produce lower emissions than other fuel alternatives. They can also be scaled up or down to meet the power requirements of different applications [66]. - The hydrogen itself can be stored for extended periods, especially relevant on those areas where access for resupply is limited.	- Hydrogen fuel cells are still mo diesel generators and lead-aci manufacturing technologies ca - Availability of hydrogen and hy limit the use of hydrogen fuel c - The size of existing fuel cell ge of the airport or airfield. To dat prototypes of up to 3MW being
hub networks for industrial use (R)	- Connection to a wider network may provide resilience, as hydrogen could also be drawn from the network if required. - No requirement to provide additional refuelling facilities.	- The current proposed hydroge cover the whole of the UK. The networks across the UK may b
as grid to be used as part of the blending	- Hydrogen can be blended with natural gas and used in domestic boilers.	- Initial industry research sugge domestic heating. Electricity c hydrogen through electrolysis, where losses would be experie - Many airports are connected t generation facilities. Opportun or potentially upgrade to a 100 rather than undertaken locally

gen.energy.
amlibraries/
eling-station-cost.
ext=Across%20
0new,capital%20
0million).

eere/fuelcells/

v.gov/eere/fuelcells/
drogen-delivery

geninsight.com/
f-green-hydrogen-
led-in-europe-
hydrogen-

ral.com/c/cp/
elivery-options

org/-/media/Files/
on/2020/Dec/
_cost_2020.pdf

om/1996-

k/government/
book-appraisal-
l-government/

18. 2018 - https://assets.publishing.service.gov.uk/media/5c00053d40f0b65b09a3a827/H2_supply_chain_evidence_-_publication_version.pdf
19. 2020 - https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf
20. 2023 - https://www.energypolicy.columbia.edu/demystifying-electrolyzer-production-costs/
21. 2020 - https://theicct.org/wp-content/uploads/2021/06/final_icct2020_assessment_of-_hydrogen_production_costs-v2.pdf
22. 2015 - https://www.aeh2.org/images/stories/PDF/DOCS_SECTOR/technologyroadmaphydrogenandfuelcells.pdf
23. 2022 - https://assets.kpmg.com/content/dam/kpmg/be/pdf/2022/hydrogen-industry-1.pdf
24. 2020 - https://www.energynetworks.org/assets/images/Resource%20library/FINAL_Hydrogen%20cost%20to%20customer_SENT.pdf
25. 2019 - https://iea.blob.core.windows.net/assets/a02a0c80-77b2-462e-a9d5-1099e0e572ce/IEA-The-Future-of-Hydrogen-Assumptions-Annex.pdf
26. 2021 - https://www.researchgate.net/publication/351611920_Designing_Optimal_Integrated_Electricity_Supply_Configurations_for_Renewable_Hydrogen_Generation_in_Australia
27. 2020 - https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/st001_ahluwalia_2020_o.pdf
28. 2021 - https://www.mdpi.com/1996-1073/14/11/3166
29. 2017 - https://www.energy.gov/sites/prod/files/2017/08/f36/hdtt_roadmap_July2017.pdf
30. 2019 - https://arxiv.org/ftp/arxiv/papers/1910/1910.05632.pdf
31. 2023 - https://www.mdpi.com/1996-1073/16/13/5233#B53-energies-16-05233
32. 2016 - https://www.osti.gov/servlets/purl/1343975
33. 2022 - https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/

review22/st235_
pdf?Status=Mas

34. 2023 - https://ww
science/article/
35. 2016 - https://ww
docs/hydrogenp
review16/pd110_
36. 2017 - https://ww
com/science/ar
S030626191730
37. https://hdsam.e
php?content=pu
38. 2017 - https://ww
science/article/
39. 2022 - https://ww
science/article/
40. 2014 - https://iea
P12_H2_Feb201
GS%20Mz%20G
41. https://pureener
products-pure-e
compressor/
42. 2015 - https://dig
cgi/viewcontent

o.uk/drive/advice/
s/hydrogen-
%20want%20
0back%20
t=Finally%2C%20
%20be,costs%20
%20weight.

ydrogen-refuelling-

bano-zero-
city-gold

co.uk/2021/07/
bus-fleet-hits-the-

/hydrogen-fuel-cell

ower.com/
ons-for-zero-
the-manufacturing-
ile/

gineer.co.uk/
s-uk/

a.org/sites/default/
powered-heavy-

66. 2009 - https://www.nrel.gov/docs/fy09osti/44520.pdf
67. 2023 - https://www.researchgate.net/publication/369591946_Hydrogen_fuel_cells_for_backup_power_applications_Advantages_Challenges_And_case_studies
68. 2022 - https://www.datacenterdynamics.com/en/news/toyota-and-nrel-to-build-1mw-fuel-cell-backup/
69. 2022 - https://www.nationalgas.com/document/139641/download
70. https://www.hynethydrogenpipeline.co.uk/
71. https://h21.green/projects/
72. 2020 - https://www.csiro.au/-/media/Do-Business/Files/Futures/Boeing-Opportunities-for-hydrogen-in-commercial-aviation.pdf
73. 2022 - https://www.nrel.gov/news/program/2022/fast-flow-future-heavy-duty-hydrogen-trucks.html

Visit Connected Places Catapult
website here

Follow us on Twitter
@CPCatapult

Follow us on LinkedIn
Connected Places Catapult

Email us
info@cp.catapult.org.uk

Copyright © 2024 Connected Places Catapult. No part of this report may be reproduced, distributed or communicated to any third party without written consent. Connected Places Catapult does not accept any liability for reliance placed on this report. CPC00665