European Commission

Market Uptake and Impact of Key Green Aviation Technologies

Final Report

Research and Innovation

Market Uptake and Impact of Key Green Aviation Technologies

European Commission
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EUROPEAN COMMISSION

MARKET UPTAKE AND IMPACT OF KEY GREEN AVIATION TECHNOLOGIES

Final Report

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2023 Directorate-General for Research and Innovation

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EXECUTIVE SUMMARY

Introduction

Steer was appointed by the Directorate-General of Research and Innovation (DG RTD) to undertake an overview of key green aviation technologies and conditions for their market uptake. Steer is being supported in delivery by the Institute of Air Transport and Airport Research of the German Aerospace Centre, DLR.

The study was undertaken in the context of the Clean Aviation Partnership's Strategic Research and Innovation Agenda (SRIA) for the period 2030-2050. The objective of the project is to identify the prerequisites for the market entry of climate-neutral aviation technologies as well as the flanking measures required for this to be successful.

The scope of the study is hydrogen and electrically powered aircraft in the regional and short/medium range categories, taking a holistic view on the technological development and keeping the economic context in mind. The outcome of the study will serve as guidance for the Commission and other actors with regard to further policy or industry initiatives, such as in the context of Horizon Europe or the Alliance Zero Emission Aviation.

Our approach to the study

Our approach to the study includes:

- *a review of the relevant literature covering the Clean Aviation programme and associated initiatives by industry participants, academics and policy makers;*
- *development of a roll-out scenario for hydrogen and electrically powered aircraft based on plausible assumptions rather than a detailed programme of evidence gathering, undertaken to provide a detailed set of assumptions to consider in relation to the technical and policy challenges identified and as a basis for discussion with stakeholders;*
- *a programme of stakeholder consultation including aircraft manufacturers, airlines and airports and their respective representatives, financiers, regulatory authorities and hydrogen fuel experts;*
- *a review of technical challenges covering the broad range of pre-requisites for achieving a roll-out of the technology, from clean fuel production and distribution, airport infrastructure, aircraft production and operational procedures, based on the assumed roll-out scenario; and*
- *consideration of the range of policy options and challenges, in the context of the assumed roll-out scenario, with both an internal European focus and also a review of the challenges to the coordination and cooperation needed internationally.*

Roll-out scenario assumptions

We have developed a roll-out assumption for hydrogen from 2035 and electrically powered aircraft from 2030, based on the considerations set out below. For the purpose of developing the roll-out scenario, it has been assumed that the technical and policy challenges outlined in the sections below can be overcome.

Aircraft technology

In the category of small commuter aircraft, we have chosen a hybrid electric concept with a conventional kerosene-powered gas turbine as range extender (under 19 seats). For regional aircraft, a design of hydrogen fuel cells providing energy for multiple electric motors with propellers is considered to be the most plausible concept (40 to 100 seats). In the segment of short and medium range aircraft, we have assumed an aircraft family with a turbofan propulsion system, using hydrogen for direct combustion (160 to 250 seats). Both hydrogen-powered designs would use liquid hydrogen as fuel.

Aircraft economics – cost of fuel

The economics of hydrogen aircraft will be a key issue for the diffusion of this technology. In this regard, fuel costs are an important element. On short- and medium-range flights, the main focus of this study, fuel costs typically make up between 20% and 30% of total airline operating costs. We find that the price of hydrogen per megajoule (MJ, the most suitable metric) will be on a competitive level with 100% fossil fuel or a blend of fossil and drop-in SAF fuel around the timeframe when hydrogen aircraft are about to be introduced, i.e. 2035 (assuming Fit-for-55 package measures on carbon pricing, taxes and blending mandates are in place). E-Fuels will remain costlier than hydrogen, as hydrogen is an intermediary step, but further energy-intensive processes (carbon capturing, FT-synthesis, refining of eCrude) need to be applied for the production of eFuels. In a European context advanced biofuels are also expected to be more expensive than hydrogen, although in the US and other countries with more land available and potential government subsidy, biofuel prices may be lower.

Underlying traffic forecast

Our forecast of aviation demand is conducted based on an econometric approach, driven by projections of economic growth and prices faced by consumers (air fares). The forecast was developed in a broader context than this study, and no specific assumptions have been made in respect of the technologies likely to be in use over the forecast period (e.g. hydrogen-powered aircraft). It is broadly consistent with previous studies conducted by or on behalf of the European Commission, such as the impact assessments of the Fit-for-55-package with the model PRIMES-TREMOVE.

Aircraft retirement and replacement cycle

The retirement of existing aircraft in airlines' fleets will play an important role in determining the rate of market diffusion of green aircraft, as new aircraft are brought in to replace older ones as well as meeting market growth. Based on historical data, on average 50% of narrowbody jet aircraft are retired before reaching the age of 25 years (the "half-life"). In our model, we assume that policy measures will be implemented in such a way as to accelerate the uptake of green aviation technologies. The consequence of such measures will be that conventional aircraft can be expected to be retired at a younger age than was the case historically, with the half-life shortened to 18 years. We retain a 25 year half-life as a sensitivity.

Airport prioritisation

The roll-out of clean aviation at airports depends on the introduction of the appropriate infrastructure such as hydrogen fuel storage and refuelling equipment. Assuming successful roll-out of the aircraft, it is likely that all significant airports will, in time, install this *equipment. However, the timescales for roll-out will vary, with priority being given to airports with the following characteristics:*

- *airport size – focus on the largest airports based on forecast 2040 passenger volumes;*
- *traffic structure – priority for airports with the highest share of flights under 800 Nm (allowing for out-and-back flights on one tank of fuel);*
- *"macro-logistics" – with favourable access to hydrogen supply and /or green energy; and*
- *"micro-factors" – with no on-site space constraints and commitment to promote hydrogen projects.*

Modelled results of the roll-out scenario

Our modelled results imply that 1,885 hydrogen fuel cell and 5,795 hydrogen turbofan aircraft would be rolled out globally by 2040, out of a total of 9,914 new aircraft by that date. The corresponding numbers within Europe (EU/EEA/CH/UK), would be 375 hydrogen fuel cell and 1,093 hydrogen turbofan aircraft. For battery/hybrid aircraft, which are assumed to have an earlier entry into service of 2030, we forecast that the number of aircraft operating in the year 2035 would be 134 worldwide, of which 29 are expected to operate in EU/EEA/CH/UK.

We estimate that approximately 14 million flights will be hydrogen powered in 2040, out of 45 million total flights globally, reaching 32 million hydrogen-powered flights out of 50 million by 2050. On a global scale, we expect a trajectory of hydrogen demand of 2.6 Mt in the year 2035, increasing to 15.9 Mt in the year 2040, 27.0 Mt in the year 2045 and 36.8 Mt in the year 2050. This can be compared with the estimate of 42 Mt of hydrogen fuel set out in the Hydrogen Powered Aviation (McKinsey study for CleanSky 2/FCH, May 2020).

Stakeholder comments

Steer and DLR undertook a programme of industry consultation across a wide range of stakeholders, with inputs from 25 organisations. Interviews were held with aircraft manufacturers, airlines and airport companies (and their representative bodies), as well as with hydrogen fuel experts, financiers and regulatory authorities.

Aircraft manufacturers and representatives

Steer and DLR spoke to a range of aircraft manufacturers and their representatives. All of the organisations considered that hydrogen-powered aviation was technically feasible and indeed most were involved in developing equipment to facilitate it. There was a consensus that entry into service (EIS) was feasible by 2035, although this would require a strong effort to deliver and was not certain. Finance was needed, in particular, to overcome the so-called "valley of death" between Technical Readiness Level (TRL) 6 at the end of the development phase and TRL 9, corresponding to EIS, at the end of the deployment phase. The certification of hydrogen aircraft was considered to represent a significant barrier to the roll-out of such aircraft.

Airlines and representatives

A number of common themes were identified, but there were also differences in perspective between full-service and low cost carriers. There was a consensus that hydrogen-powered aircraft were likely to be developed and enter airline fleets, but disagreement over the urgency and likely timescales for this, with low-cost carriers considering that hydrogen-powered flight was likely in the 2030s, whereas full-service carriers expected the next generation of aircraft to be powered by hydrocarbons and had a greater emphasis on the use of drop-in SAFs.

Given the additional difficulties of operating hydrogen aircraft (new technology, split fleet, availability of fuel), it was essential that airlines had certainty that hydrogen fuel would have "parity with SAFs" in terms of cost. Any solution supporting the adoption of hydrogen aircraft needed to work at a global level and not just within Europe, in order to make such an aircraft viable.

Airports and representatives

The importance of narrowbody hydrogen-powered aircraft being able to fit within current ICAO Code-C aircraft dimensions was emphasised. There was a consensus across airports who took part in consultation that electrically powered aircraft would be small, with some mentioning 10 seats as the maximum size, although one airport thought that up to 50 seats might be possible.

Most airports considered that supply of hydrogen to airports would need to be by pipeline, which would need to be built in cooperation with other hydrogen users. Storage of hydrogen at airports was not mentioned as a major concern, although some airports did not consider that they had sufficient space on site. Refuelling aircraft was noted as the most serious concern by a number of airports. Refuelling by truck/bowser on the apron was considered feasible, but there were doubts about the ease, feasibility and cost of an on-airport pipeline network to supply liquid hydrogen to airport stands.

It was widely considered that public subsidies and other support would be needed in order to facilitate the development of the necessary infrastructure, particularly in the initial phases of roll-out. However, it was considered necessary in the longer run for the new infrastructure to be profitable for airports. There was a general consensus that additional charges for the use of infrastructure supporting hydrogen and electrical aircraft would not be appropriate, because the objective was to encourage the transition to these new technologies.

Hydrogen fuel experts

Steer spoke to organisations specialising into the technology and economics of alternative fuels including hydrogen and into cryogenic infrastructure.

They provided some key parameters concerning clean hydrogen production methods, hydrogen transportation, boil-off of liquid hydrogen, the demand for electricity for hydrogen production and liquefaction and power generation capacity requirements.

They also explained key points relevant to handling liquid hydrogen (LH2), which needs to be stored at below -253°C and is liquefied through cycles of compression. Pipeline/hydrant systems for airports should be possible, but the distances on airports are above those typically used at present (e.g. 300m). High levels of compression through multiple *compressors would be required, which would be expensive. Delivering the fuel to the aircraft can be achieved with vacuum-insulated couplings. Venting of hydrogen may be necessary but should be minimised given that hydrogen is a greenhouse gas in its own right.*

Financiers

In relation to decarbonising aviation, financiers interviewed recognised three different strands of technological development: battery-powered flight for short flights with small aircraft (including eVTOLs), hydrogen-powered flight for short/medium haul commercial services and drop-in SAFs powering long-haul and potentially also short and medium haul flights. They considered that of the three technologies hydrogen had "the most to prove", given its current low technological level of development and the need for a wide range of supporting infrastructure (green hydrogen production, distribution and deployment at airports as well as development of new aircraft types and operational processes). They also anticipated that (fossil) kerosene fuel will still have a role to play in aviation for a significant period up to and beyond 2050.

They considered that hydrogen has a significant role to play in decarbonising aviation. However, it was noted that the technology is currently at a very early stage, and hence EIS in 2035 appears optimistic, with 2040 being more likely. The impact of hydrogen-powered flight will be limited by 2050, with only 12% of flying fuelled by hydrogen in that year. They also noted that safety risks needed to be added to the potential barriers to roll-out of the technology. In particular, it was important to demonstrate safe operation, and to avoid any major incidents, during the development of the new technology.

In relation to the likely availability of capital to invest in hydrogen aircraft, they noted that there is very strong pressure from investors in the aircraft leasing industry to move towards sustainable activities, and that in future it may be difficult to raise funds for investment in aircraft not meeting the criteria set out in the EU's Sustainable Taxonomy as applied to aviation.

Regulatory authorities

Steer spoke to the European Union Aviation Safety Agency (EASA) and the United States Government's Federal Aviation Administration (FAA).

Technical challenges

Green hydrogen production and distribution

There are significant challenges that exist in the production and supply of green hydrogen across Europe, including for the purposes of aviation fuel. These challenges include:

- *green hydrogen production and costs;*
- *the different uses of green hydrogen for aviation and other industries; and*
- *distribution mechanisms for hydrogen across Europe.*

There is a major challenge in scaling up production of green hydrogen to deliver the required quantities of hydrogen by 2050 for which there are many competing demands. In 2050 it is estimated that aviation would represent only 8% of total hydrogen demand. This *competition for resource, with potential supply bottlenecks and resultant scarcity pricing may present an important barrier to the successful role out of green hydrogen in aviation.*

Green hydrogen would need to be distributed to airports, as well as other users, from its production sites. As these sites are likely to be located near coasts, where green sources of electrical power such as wind turbines and solar are plentiful, the transport distances may be significant, so that a pipeline network for distribution of hydrogen will need to be constructed.

In addition, since commercial hydrogen-powered aircraft will require liquid hydrogen as fuel, it will be necessary to liquefy the gaseous hydrogen at or close to the airport. Liquefaction requires specialised equipment and consumes significant amounts of electrical power, which will need to be provided.

Airport infrastructure

The use of both hydrogen and electrically powered aircraft will require major changes to airport infrastructure. Unlike drop-in SAFs (biofuels or electrofuels, which are hydrocarbons similar to fossil-kerosene), hydrogen cannot be combined with existing aviation fuel, so it will require completely separate transportation and storage infrastructure facilities. Similarly, electric aircraft will require either rapid charging electric connections at aircraft stands or facilities for swapping batteries during aircraft turnarounds.

Safety issues from handling LH2 must also be considered due to its flammability and also due to the cryogenic cold temperatures required to keep it in its liquid form (below -253 °C).

In addition to storage facilities, aircraft refuelling requires that liquid hydrogen is supplied to aircraft, either through bowser trucks or a hydrant system, in either case using cryogenic temperatures. Significant new equipment and infrastructure will be required to deliver this.

Aircraft operations

New safety procedures will need to be established to mitigate the risks of frostbite and hypothermia amongst ground crew and also to mitigate the risk of fire due to the flammability of hydrogen. Maintenance and repair of hydrogen aircraft will require different procedures from those for conventional aircraft. On the proposed hydrogen turbine aircraft, the majority of components on the aircraft remain the same as those on a conventional turbine aircraft.

The new technology aircraft will be required to be certified for safety, as will airport infrastructure and procedures such as refuelling. Staff will need to be trained to operate the new equipment.

Policy options

In assessing the potential policy options to consider in relation to hydrogen-powered aircraft, we developed a "problem tree", linking general and specific objectives to identified problems and underlying "problem drivers". The problems needing to be overcome to facilitate the roll-out of hydrogen aircraft were:

- *There is a significant risk that sufficient hydrogen will not be available, due to the levels of green power and electrolysis equipment needed, as well as competing demand for green hydrogen from other industries.*

- *The economics of hydrogen-powered flight may not be sufficiently attractive:*
  - *to encourage manufacturers to develop the new-technology aircraft; or*
  - *to incentivise and support financing for airlines to buy/lease and operate such aircraft.*
- *There may be insufficient incentives for airports to develop the necessary infrastructure, in particular fuel supply, to support hydrogen-powered aircraft (because there may be insufficient demand from airlines and/or because the costs of doing so are too high).*
- *There may not be sufficiently well-developed safety certification procedures in place to give comfort to investors, airlines, airports, fuel suppliers, ground handlers and/or passengers who might consider supporting or using the aircraft.*

The drivers underlying these problems are found in the following areas:

- *green electricity capacity availability;*
- *green hydrogen, specifically issues around its:*
  - *production,*
  - *transport, and*
  - *liquefaction;*
- *competing fuels and their costs relative to hydrogen (i.e. conventional fossil kerosene and sustainable aviation fuels (SAFs) from both biofuel and e-fuel sources);*
- *development of hydrogen-powered aircraft technology;*
- *installation of airport infrastructure to support hydrogen-powered aircraft; and*
- *safety and certification.*

A range of potential policy interventions to address each of these problems has been identified, which may require EU action on green electricity and hydrogen electrolysis capacity, support for a gaseous hydrogen pipeline network in Europe and for the power supply and equipment needed for hydrogen liquefaction at or near to airports. Consistent policies will be required to ensure that hydrogen fuel is competitive with alternatives, in particular fossil kerosene and drop in biofuel and e-fuel SAFs. Support may be required for the development of aircraft technology and airport infrastructure. New certification and operating standards will need to be developed. At the international level, cooperation with other jurisdictions will be required through ICAO and bilaterally.

Conclusions

This study has reviewed the relevant literature and received inputs from a wide range of industry stakeholders. A roll-out scenario for hydrogen-powered and electrically powered aircraft has been developed and assessed in the context of the literature and stakeholder comments. This assessment indicates that the scenario is, in principle, feasible in the sense that there are no insurmountable technical barriers to the roll-out of such aircraft.

> *However, there are very significant obstacles to be overcome in achieving such a roll-out. These obstacles are highly challenging in a European context, while the roll-out appears close to unachievable at a global level within the timescales being considered*

(EIS of hydrogen-powered aircraft in 2035, significant ramp-up by 2040 and further rapid growth to 2050).

In Europe, the barriers are technical and financial. They include the production and transport to airports of sufficient quantities of green hydrogen, the technical development of new aircraft technology and the investment in the new airport infrastructure required. It is likely that significant public sector financial support will be needed to facilitate this in the early stages of roll-out.

Looking beyond Europe, there are national plans in several key jurisdictions for the development of green hydrogen supplies for a variety of industrial processes, but none of these specifically address the use of hydrogen in aviation. Where plans for aviation decarbonisation exist, they are generally focused on the introduction of drop-in SAFs, rather than hydrogen However, some industry initiatives and policy developments indicate a growing interest in the use of hydrogen, and green aviation technology development continues even where national hydrogen aviation policies are not defined.

In the US in particular, policy on aviation decarbonisation is firmly based on the use of SAFs, for which major tax incentives have been introduced. The significant use of hydrogen as aviation fuel is seen as a long-term option, i.e. beyond 2050 (except for GA and other small aircraft). This position is reflected in a recent ICAO report on emissions reduction and the focus on biofuels seems likely to be replicated in most other jurisdictions outside Europe.

There is therefore a risk that the opportunities for hydrogen aircraft development may need to be focused almost exclusively in Europe during an initial roll-out, implying a smaller commercial market and a need for greater public sector support than would otherwise be the case. While in the long run, assuming that hydrogen aircraft are adopted more widely at a later stage in other parts of the world, this is likely to provide Europe with a competitive advantage in the technology for hydrogen-powered flight, it could make barriers to hydrogen-powered aircraft significantly more challenging for the European aviation industry in the short and medium term. A more restricted geographical roll-out would also result in the environmental benefits envisaged being delayed and reduced.

1. Introduction

1.1. Background

1.1 Steer was appointed by the Directorate-General of Research and Innovation (DG RTD) to undertake an overview of key green aviation technologies and conditions for their market uptake (specific contract RTD/2021/SC/020 under framework contract MOVE/E1/2018-217).

1.2 Steer was supported in delivery by our partner, the Institute of Air Transport and Airport Research of the Deutsches Zentrum für Luft- und Raumfahrt (the German Aerospace Centre, DLR). DLR is the Federal Republic of Germany's research centre for aeronautics and space which conducts research and development activities in the fields of aeronautics, space, energy, transport, security and digitalisation.

1.2. Objectives

1.3 The study was undertaken in the context of the Clean Aviation Partnership's Strategic Research and Innovation Agenda (SRIA) for the period 2030-2050[1]. The objective of the project is to identify the prerequisites for the market entry of climate-neutral aviation technologies as well as the flanking measures required for this to be successful. Market penetration of climate-neutral technologies (alongside other measures such as sustainable aviation fuels (SAFs), operational efficiency improvements and so-called market-based measures) should be sufficiently high to allow for aviation to achieve its climate mitigation pathway.

1.4 As set out in the Terms of Reference (ToR), the scope of the study is hydrogen and electrically powered aircraft in the regional and short/medium range categories, taking a holistic view on the technological development and keeping the economic context in mind. As a priority, the study will consider the requirements for the entry into market of zero- or low-emission aircraft in the regional and medium-range market segment. It is assumed that these aircraft will be hydrogen-powered. The study will also consider the prerequisites of fully electric aircraft, in particular for short-range missions.

1.5 The outcome of the study will serve as guidance for the Commission and other actors with regard to further policy or industry initiatives, such as in the context of Horizon Europe or the Alliance for Zero Emission Aviation.

1.3. This report

1.6 This document represents the Final Report for the study.

1.7 The remainder of this report sets out:

- Chapter 2: Our approach to the study;

[1] https://www.clean-aviation.eu/clean-aviation/strategic-rationale-for-clean-aviation/strategic-research-and-innovation-agenda-sria

- Chapter 3: Roll-out scenario – assumptions;
- Chapter 4: Roll-out scenario – results;
- Chapter 5: Stakeholder comments
- Chapter 6: Technical challenges
- Chapter 7: European and global legislation and policy;
- Chapter 8: Policy options; and
- Chapter 9: Conclusions.

2. Our approach to the study

2.1. Introduction

2.1 As noted in Chapter 1, the objective of the project is to identify the prerequisites for the market entry of climate-neutral aviation technologies as well as the flanking measures required for this to be successful, focusing on hydrogen and electrically powered aircraft in the regional and short/medium range categories.

2.2 The underlying basis of the study is the Clean Aviation programme, so that the analysis undertaken needs to be consistent with this. The study also needs to take into account the policy background, including the Green Deal and Fit for 55. The main objective is climate neutrality, but there is also the need for the EU aviation industry to remain competitive internationally. Given this requirement, it is essential not just to consider the EU market, but also look at what is happening in third country markets, especially the US and China.

2.3 The scope of the study goes beyond aircraft manufacture, also considering what needs to be undertaken by other industry participants, including airports and fuel suppliers. These stakeholders need to be presented with detailed proposals to consider for the new technology aircraft in order to help identify relevant and credible solutions.

2.2. Methodology

2.4 Consistent with meeting these objectives, we have adopted an approach which includes:

- a review of the relevant literature covering the Clean Aviation programme and associated initiatives by industry participants, academics and policy makers;
- development of a roll-out scenario for hydrogen and electrically powered aircraft based on plausible assumptions rather than a detailed programme of evidence gathering, undertaken to provide a detailed set of assumptions to consider in relation to the technical and policy challenges identified and as a basis for discussion with stakeholders;
- a programme of stakeholder consultation including aircraft manufacturers, airlines and airports and their respective representatives, financiers, regulatory authorities and hydrogen fuel experts;
- a review of technical challenges covering the broad range of pre-requisites for achieving a roll-out of the technology, from clean fuel production and distribution, airport infrastructure, aircraft production and operational procedures, based on the assumed roll-out scenario; and
- consideration of the range of policy options and challenges, in the context of the assumed roll-out scenario, with both an internal European focus and also a review of the challenges to the coordination and cooperation needed internationally.

2.5 The different elements of this approach are described below.

Desktop research

2.6 We have reviewed a wide range of sources as part of our desktop review. These include:

- The European Green Deal (Communication from the Commission, December 2019);
- Fit for 55 package, COM/2021/550 final (Communication from the Commission, July 2021);
- SAF Regulation proposal (Communication from the Commission, July 2021);
- The proposed European Partnership for Clean Aviation (Strategic Research and Innovation Agenda (SRIA) Roadmap, July 2020);
- Clean Hydrogen for Europe Strategic Research and Innovation Agenda (SRIA, October 2020);
- Hydrogen Powered Aviation (McKinsey study for CleanSky 2 / FCH, May 2020);
- Waypoint 2050 (Air Transport Action Group, ATAG, 2021);
- Destination 2050 – a route to net zero European aviation (A4E, ACI Europe, ASD, era, CANSO, February 2021);
- Performance analysis of evolutionary hydrogen-powered aircraft (ICCT, January 2022);
- Integration of hydrogen aircraft into the air transport system (Airports Council International / Aerospace Technology Institute, 2021);
- Determining the lowest-cost hydrogen delivery method (University of California Davis Working Paper, 2008);
- Liquid Hydrogen Fuelled Aircraft – System Analysis (Report from the Project "CRYOPLANE", Airbus, 2003);
- Shell Hydrogen Study – Energy of the Future? Sustainable mobility with fuel cell and H2 (Shell/Wuppertal Institute, 2017);
- Green Hydrogen Cost Reduction (IRENA, 2020);
- Hydrogen: A renewable energy perspective (International Renewable Energy Agency (IRENA), 2019);
- Hydrogen (International Energy Agency (IEA), 2021, https://www.iea.org/reports/hydrogen);
- Hydrogen from renewable power: Technology outlook for the energy transition (IRENA, 2018);
- Clean Hydrogen Monitor 2020 (Hydrogen Europe, 2020);
- Global hydrogen demand by sector in the Net Zero Scenario, 2020-2030, (IEA, 2021);
- How a dedicated hydrogen infrastructure can be created (European Hydrogen Backbone, 2020);
- Global Hydrogen Review 2021 (IEA, 2021);

- Innovation Driving Sustainable Aviation (ICAO, November 2021);
- Renewable Energy Prospects for the European Union (IRENA, 2018);
- Gas Decarbonisation Pathways 2020-2050. (Navigant, 2020. Gas for Climate); and
- Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance (R Folkson, 2014).

Development of the roll-out scenario

2.7 In relation to development of a scenario for the rollout of hydrogen and electrically powered aircraft, we noted the need to be as aligned as possible to the assumptions set out in the Strategic Research and Innovation Agenda (SRIA) of the Clean Aviation programme in Horizon Europe and with consistent underlying assumptions in terms of the economic parameters and traffic forecast. The Commission has confirmed that the focus should be on the first five years from entry into service (EIS), starting in 2035 for hydrogen aircraft but somewhat earlier for electric aircraft. As requested, we have developed the scenario to be as specific as possible, setting out:

- the types of routes where the hydrogen / electric aircraft will operate;
- which airports will be used;
- the volumes of green fuels required at those airports; and
- which airlines are likely to adopt the aircraft into their fleets.

2.8 The detailed assumptions for the roll-out scenario were discussed and agreed with the Commission and are described in Chapter 3. The results are described in Chapter 4. While it was not possible to validate the results of the scenario in detail, the volumes of hydrogen flights and fuel usage were checked with the four airport companies interviewed in respect of their respective airports.

Stakeholder consultation

2.9 We identified a number of stakeholders to consult with from each of the categories set out in paragraph 2.4 above. Although we were not able to arrange an interview in all cases, we did receive a response from multiple stakeholders in each category, with a total of 19 interviews undertaken and, in addition, written responses from a further seven airport companies. The interviews held and/or written responses received are set out in the table below.

Table 2.1: Stakeholder list for consultation

Category	Organisation	Status
Aircraft manufacturers and representatives	Advisory Council for Aviation Research in Europe (ACARE)	Interview completed
	Airbus	Interview completed

Category	Organisation	Status
	ZeroAvia	Interview completed
	Wright Electric	Interview completed
	Bauhaus Luftfahrt	Interview completed
Airlines and representatives	Airlines for Europe (A4E) / easyJet / KLM	Interview completed
	easyJet	Interview completed
	Lufthansa	Interview completed
Airports and representatives	ACI-Europe	Interview completed
	Groupe ADP: Aéroports de Paris	Interview completed
	Budapest Airport	Interview completed
	Eindhoven Airport	Written response / Interview completed
	Hamburg Airport	Interview completed
	Aeroporti di Roma	Written response
	Cologne-Bonn Airport	Written response
	FRAPORT (Frankfurt Airport)	Written response
	Ljubljana Airport	Written response
	Munich Airport	Written response
	SAVE S.p.A. (Venice Airport)	Written response
	Swedavia	Written response
Financiers	European Investment Bank (EIB)	Interview completed
	Aircraft Leasing Ireland	Interview completed
Authorities	European Union Aviation Safety Agency (EASA)	Interview completed
	Federal Aviation Administration (FAA)	Interview completed
Hydrogen fuel experts	Institute of Environmental Technology and Energy Economics, Hamburg Technical University (TUHH)	Interview completed
	Demaco	Interview completed

2.10 The stakeholder consultation results are set out in Chapter 5.

Technical challenges

2.11 Based on a review of the literature, stakeholder responses and taking into account the results of the roll-out scenario described in Chapter 3 and Chapter 4, we identified the technical challenges related to:

- the production and supply of hydrogen;
- airport infrastructure; and
- aircraft operations.

2.12 These are discussed in Chapter 6.

Policy options and conclusions

2.13 We have reviewed EU policy and legislation on aviation decarbonisation and hydrogen production and usage, and compared this with corresponding policy and legislation in other jurisdictions (including the USA, the UK, Canada, China, Japan and Australia, as well as at international level (through the International Civil Aviation Organization, ICAO). This is set out in Chapter 7.

2.14 In Chapter 8, we set out an analysis of the objectives, problems, problem drivers and potential policy options. We set out our conclusions in Chapter 9.

3. Roll-out scenario - assumptions

3.1 The development of a roll-out scenario for hydrogen and electrically powered aircraft (whose results are presented in Chapter 4 below) has been based on many assumptions. As there are many unknowns in this emerging area of aviation, it was particularly important to transparently present, in this chapter, the assumptions used that feed into the modelling of the roll-out scenario. These assumptions were discussed and agreed with the European Commission. Where technical and policy challenges exist and may slow-down or stop the roll-out, (technical challenges are set out in Chapter 6 and the policy issues identified are set out in Chapter 7), the roll-out scenario was projected on the assumption that these challenges can and would be overcome in time.

3.1. Selection of new technology aircraft

3.1 A decisive factor in the uptake of new technology aircraft and, subsequently, energy demand and airport infrastructure requirements are the characteristics of new aircraft, including modified (retrofitted) ones. Based on an extensive literature review and in coordination with the client, we have defined three groups of aircraft, which are assumed to enter the fleet in future, as shown in Table 3.1.

Table 3.1: Green technology aircraft in roll-out scenario (Source: DLR analysis)

Aircraft family	Seats	Aircraft in uptake of green aviation Technologies Scenario	Entry into service	Max. range	Cruise speed	Design mission payload
Commuter	19	Hybrid electric E19 + Gas Turbine Range Extender and/or retrofitted hydrogen-electric aircraft	2030	700 Nm	<215 Knots	1,805 kg
Regional	40	Hydrogen Fuel Cell Electric Regional Turboprop	2035	1,000 Nm	Mach 0.55	3,800 kg
	70	Hydrogen Fuel Cell Electric Regional Turboprop	2035	1,000 Nm	Mach 0.55	6,650 kg
	100	Hydrogen Fuel Cell Electric Regional Turboprop	2035	1,000 Nm	Mach 0.55	9,500 kg
Short/ medium range	160	Hydrogen Direct Combustion Turbofan	2035	2,000 Nm	Mach 0.78	15,200 kg
	200	Hydrogen Direct Combustion Turbofan	2035	2,000 Nm	Mach 0.78	19,000 kg
	250	Hydrogen Direct Combustion Turbofan	2035	2,000 Nm	Mach 0.78	23,750 kg

3.3 In the category of small commuter aircraft, we have chosen a hybrid electric concept with a conventional kerosene-powered gas turbine as range extender. We refrained from using aircraft concepts with batteries as the only energy carrier. Such concepts remain questionable in terms of plausibility for scheduled passenger operations under Instrument Flight Rules (IFR), which require extensive reserves (among others providing enough fuel reserves to fly to an alternative airport and an additional 45 minutes flying time at cruise speed). In the current regulatory framework, it is doubtful whether purely battery-electric aircraft can operate on commercially relevant distances given these requirements. The hybrid-electric concept allows for a fully electrically operated flight on distances of less than 135 Nm, while giving airlines flexibility to operate longer missions of up to 700 Nm and fulfilling IFR reserve requirements.

3.4 An alternative or additional/parallel approach for a 19-seater could follow a (green) hydrogen-electric concept where a hydrogen-electric powertrain, (initially retrofitted to existing aircraft) replaces traditional engines on fixed wing aircraft, to simplify regulatory issues and reduce time to market. Bottled gaseous hydrogen could be taken onboard as fuel in place of liquid hydrogen, if appropriate.

3.5 For regional aircraft, a concept of hydrogen fuel cells providing energy for multiple electric motors with propellers is considered to be the most plausible concept. This concept allows for very high degrees of efficiency in the powertrain and aerodynamics, which will also allow operating on short runways with distributed propulsion and lower noise emissions. In order to cover a range of different requirements in terms of passenger demand, the basic aircraft design with 70 seats was up- and downscaled to accommodate 40 and 100 passengers, respectively.

3.6 In the segment of short and medium range aircraft, we have assumed an aircraft family with a turbofan propulsion system, using hydrogen for direct combustion. While this concept is less energy efficient than turboprop/open rotor propulsion, it will have similar characteristics in terms of cruise speed and cabin noise levels as conventional aircraft. This could be, particularly for longer missions, a key factor for the acceptance of passengers and airlines. In order to cover different requirements in terms of demand and capacity, we also assumed a family concept, comparable to the current Airbus A320 family. We have assumed aircraft sizes of 160, 200 and 250 seats. The latter, being slightly larger than an Airbus A321, will accommodate larger passenger volumes expected in the long run on a variety of short- and medium haul routes.

3.7 Consistent with the assumptions of the Clean Aviation programme, the assumed entry into service is 2035.

3.2. Cost of hydrogen fuel

3.8 The economics of hydrogen aircraft will be a key issue for the diffusion of this technology. In this regard, fuel costs are an important element. On short- and medium-range flights, the main focus of this study, fuel costs typically make up between 20% and 30% of total airline operating costs, with a lower share on shorter routes and a higher share on longer routes. For example, in 2019, e.g. easyJet's fuel costs were 24% of total operating costs[2].

3.9 A cost comparison of different potential aircraft fuels can provide a valuable insight into the likely costs of hydrogen. Given that the energy density of hydrogen and kerosene (or drop-in SAFs) are very different, this comparison is best made in terms of the cost per unit of energy, rather than per unit mass or volume (i.e. in € per MJ), given that the energy consumption of a direct combustion hydrogen aircraft is likely to be similar to aircraft powered with kerosene.

3.10 Projections for the costs of fossil kerosene, drop-in sustainable aviation fuels (SAFs) and hydrogen as aviation fuel are shown in the chart below. These are shown in real price terms, and no particular trend in the price of untaxed fossil fuel has been assumed given the very large uncertainties that have applied to this historically (with

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2 https://corporate.easyjet.com/~/media/Files/E/Easyjet/pdf/investors/results-centre/2019/eas040-annual-report-2019-web.pdf, p.130

crude oil prices now similar to those of 10 years ago, but having been significantly lower, and highly volatile, in between).

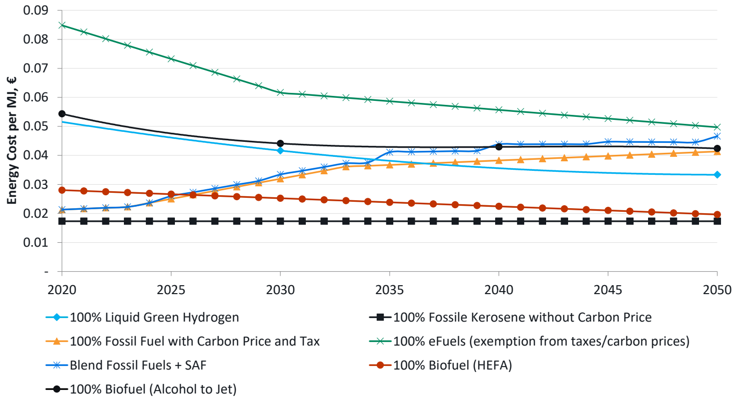

Figure 3.1: Comparison of expected price development per energy unit (MJ) of different energy carriers **(Source: DLR analysis)**

3.11 As shown in Figure 3.1, we find that the cost for liquid green hydrogen will decrease in the long run from currently 0.053 €/MJ to 0.033 €/MJ in the year 2050. This is in line with assumptions of Prognos and Greenpeace (as quoted by a study for the German Bundestag[3]) under conservative assumptions and includes already an additional cost of 0.0083 € /MJ (€1 per kg of hydrogen) for the liquefaction of hydrogen on site of the airport in order to make it useable for aviation.

3.12 The price development of sustainable aviation fuels in the graph is taken from the Global Alliance Powerfuels study “Powerfuels in Aviation”[4]. We focus on eFuels, as the availability of biomass feedstock may be limited in order to fulfil future aviation fuel demand. This is particularly true for HEFA[5] based biofuels for which only waste cooking oil is environmentally viable, considering the negative carbon impact of palm oil plantations.

3.13 For biofuels sourced via alcohol to jet (from feedstock such as corn) processes are shown to approach 0.02 €/MJ of the cost of green hydrogen by 2050. However, it should be noted that this price is based on a European production perspective. In a US context, with more land available for corn production (and potential government subsidy support, as described in paragraph 7.46 below), the prices may be significantly lower.

3.14 For fossil fuel kerosene, we have assumed the spot price of April 2022 (€742 per tonne of Jet A-1 fuel), which is, in the long-term comparison, relatively high.

3.15 For carbon pricing and taxation measures, we assume an increase in the carbon price from around 50 €/t CO_2 today to 180 €/t CO_2 in the year 2050 (which may be

3 https://www.bundestag.de/resource/blob/691748/01a954b2b2d7c70259b19662ae37a575/WD-5-029-20-pdf-data.pdf

4 https://www.powerfuels.org/fileadmin/dena/Publikationen/PDFs/2019/Powerfuels_in_Aviation_GAP.pdf

5 Hydroprocessed Fatty Acid Esters and Free Fatty Acid. See bio-fuel information on EASA website: https://www.easa.europa.eu/eaer/topics/sustainable-aviation-fuels/bio-based-aviation-fuels

conservative), assuming that the allowances in the EU ETS will be reduced further and carbon pricing is likely to be prioritized by a number of legislations worldwide. Additionally, we assume a taxation of fossil fuel by the rates proposed in the Fit-for-55 package (increase from 0 to 10.75 €/GJ in the year 2033), which will be applicable for intra-EU traffic.

3.16 We find that the price of hydrogen per MJ will be on a competitive level with 100% fossil fuel or a blend of fossil and drop-in SAF fuel (according to the blending quota proposed in the Fit-for-55 package) around the timeframe when hydrogen aircraft are about to be introduced, i.e. 2035. E-Fuels will remain costlier than hydrogen, as hydrogen is an intermediary step, while further energy-intensive processes (carbon capturing, FT-synthesis, refining of eCrude) need to be applied for the production of eFuels.

3.17 While hydrogen aviation fuel will therefore be more expensive than today's price of Jet-A1 kerosene aviation fuel, it may be competitive with both fossil fuels and drop-in SAFs by 2035, on the assumption that the political objectives of a decarbonisation of aviation are implemented through measures such as those in Fit-for-55, or equivalents in other jurisdictions.

3.18 However, measures to encourage SAF production in other jurisdictions have the potential to undercut the cost of hydrogen-powered aircraft operation, particularly given that drop-in SAFs avoid additional costs related to the development of hydrogen aircraft technology and hydrogen-transport and storage infrastructure.

3.3. Traffic growth assumptions

3.19 Our forecast of aviation demand is based on an econometric approach, which relies on external input data driving air transport development. Key input sources are the forecasts on the development of GDP/capita and population, provided by IHS Markit and the United Nations. The forecast was developed in a broader context than this study, and no specific assumptions have been made in respect of the technologies likely to be in use over the forecast period (e.g. hydrogen-powered aircraft). We have chosen to use DLR's "low" traffic scenario, which assumes a lower rate of economic growth than in "high" forecast.

3.20 Economic growth, in terms of real incomes per capita, is a main driver of aviation demand. For Europe, the long-term (pre-COVID) economic forecast used in the air transport forecast assumes a growth in real GDP per capita of 1.5 % per year in the timeframe 2020-2025, 1.46% p.a. in 2026-2030, 1.39% p.a. in 2031-2035 and 1.45% p.a. for the period after the year 2035. Based on empirical data, an income elasticity of 1.3 has been applied to convert growth in economic activity to traffic (passenger) growth.

3.21 Historically, we can observe a relatively constant decline in real ticket prices. On the basis of empirical data analysis from 2002 to 2019, DLR researchers have estimated a decline in real air fares of 1.5% per year. This was realised despite a substantial increase in real oil prices from an average of 38 USD in 2002 to 65 USD per barrel in 2019 in real terms[6], a real increase of 71%. This was achieved through efficiency

6 Year 2000 prices. Source: US Energy Information Administration

gains on a wide variety of factors influencing energy consumption per passenger kilometre (flight efficiency gains, higher load factors, more efficient aircraft, larger aircraft), as well as success in driving down the non-fuel component of operating costs.

3.22 A comparable relative increase in energy costs can be expected for the timeframe from now up to 2035/2040 due to a combination of carbon pricing for conventional fuels and the introduction of more expensive alternatives such as hydrogen. Despite the different drivers of fuel price increases, the economic impacts are likely to be similar to those seen in the past from rising oil prices. We therefore anticipate that, over the forecast period to 2050, air ticket prices will continue to decline gradually, as increasing competition and further efficiency gains in airline and aircraft operations are realised. However, as these efficiency gains are increasingly harder to realise over time, a decreasing rate of ticket price decline is applied in the model.

3.23 The selection of DLR's "low" traffic forecast means that conservative assumptions are being made about GDP per capita growth. As GDP per capita growth is a strong driver of demand, this means that the traffic forecast is robust to the risk of higher fuel costs preventing air ticket prices from falling as fast as has been seen historically, which would tend to decrease growth arising from a price elasticity effect. Overall, we therefore consider that the traffic forecast adopted is reasonable. See Table 3.2 below with a comparison of traffic growth in DLR's "low" traffic forecast with other European and global aviation market benchmarks.

Table 3.2: Traffic forecast growth comparison (Source: DLR, Primes-Tremove, Airbus GMF 2021-2040, Boeing CMO 2021, ATAG Waypoint 2050)

Traffic forecast	Focus	2019-2030	2030-2040	2019-2040
DLR Capacity Constrained Forecast, Low	Intra-Europe	1.4%	2.0%	1.7%
Primes-Tremove Baseline Scenario	Intra-Europe	-	1.6%	-
Airbus GMF 2021-2040	Intra-Europe	1.1%	2.3%	1.7%
Boeing CMO 2021	Intra-Europe	3.4%	3.2%	3.3%
ATAG Waypoint 2050, Low	Global	0.6%	2.8%	-
ATAG Waypoint 2050, Central	Global	3.1%	3.2%	-
ATAG Waypoint 2050, High	Global	3.7%	3.4%	-

3.24 Assuming that air transport in Europe will have recovered from the most severe impacts of the COVID-19 pandemic in 2023, the long-term average annual growth rate (CAGR) of passenger traffic within the EU is forecasted to be 1.9% p.a, and 1.7% over the period 2019-2040. This medium-term projection is in-line with the Airbus Global Market Forecast 2021-2040. Comparisons to other global aviation benchmarks show that the DLR forecast is more conservative over the period of interest in this study.

3.25 By working with DLR's low forecast, which provides a self-consistent and detailed traffic forecast by aircraft type and airport-pairs served, we are able to support the modelling requirements for the study in terms of aircraft fleet, destinations served and hydrogen fuel requirements.

3.4. Aircraft progression through airline fleets / retirement

3.26 The retirement of existing aircraft in airlines' fleets will play an important role in determining the rate of market diffusion of green aircraft, as new aircraft are brought in to replace older ones as well as meeting market growth. Based on historical data, on average 50% of narrowbody jet aircraft will be retired before reaching the age of 25 years (the "half-life").

3.27 On the basis that policy efforts will continue to strive for a substantial reduction in aviation climate impacts, including through carbon pricing, taxation and other measures on fossil fuels, we have assumed for the purpose of developing the roll-out scenario that, following entry into service of the new aircraft types, airlines will adopt and utilise "green" aircraft whenever these are suitable for their requirements (in terms of size, range, etc.). Our assumption for the purpose of developing the roll-out scenario is that this airline behaviour will occur globally, based on policy measures adopted across the majority of key aviation jurisdictions worldwide. This is supported by the analysis of fuel costs above (Figure 3.1), which demonstrate that hydrogen fuel will be competitive with alternative fuels (whether fossil kerosene or drop-in SAFs).

3.28 In our model, we further assume that these policy measures will be implemented in such a way as to accelerate the uptake of green aviation technologies. Among these are carbon pricing, financial incentives for the retirement of conventional aircraft and investment into "green" aircraft and others. The consequence of such measures will be that conventional aircraft can be expected to be retired at a younger age than was the case historically. This is supported by stakeholder comments that the finance community is positive about supporting aviation technology which can be classified as sustainable or "green" (see Chapter 5)

3.29 In order to reflect these measures in the model we have assumed that the half-life of aircraft that could be replaced by green technology aircraft will be shortened to 18 years. The survival/retirement of aircraft is shown in the following figure. The model applied is a logistic regression of aircraft survival depending on aircraft age. The methodology is similar to the one used in the ICAO CAEP[7] fleet modelling/forecasting.

[7] The International Civil Aviation Organisation's Committee on Aviation Environmental Protection

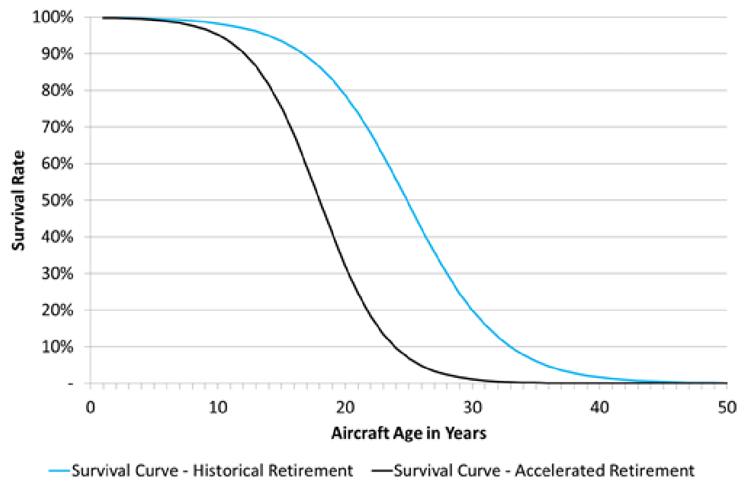

Figure 3.2: Aircraft Survival Curves – historical vs. accelerated retirement (Source: DLR analysis)

3.30 This assumption is based on a balance between the anticipated impacts of policy measures favouring faster adoption of "green" aircraft and the negative impacts on airline economics of faster fleet turn-over, given the need to finance new aircraft and the likely fall in the value of second-hand conventional aircraft due to policy measures disadvantaging their use. The reduced aircraft half-life leads to forecasts of hydrogen fuel usage consistent with those of other studies, as noted below and therefore implies that those other studies must have implicitly adopted similar assumptions on fleet churn.

3.31 By adopting this optimistic assumption on green aircraft adoption by airlines, the model estimates an upper bound on the effective rate of green aircraft market diffusion, and subsequently, on the level of flying by such hydrogen and electrically powered aircraft. Clearly it is possible that this upper bound will not be achieved due to failures to adopt such policy measures consistently around the world, but for the purpose of this study, where the objective is to identify barriers to adoption as well as ways to overcome them, it is an appropriate assumption.

3.32 As a sensitivity to this accelerated rate of aircraft churn, we also consider the results of the roll-out modelling under the assumption that there is no acceleration of aircraft fleet churn, so that the aircraft "half-life" remains at 25 years, as seen historically. Full results for this 25-year half-life assumption are provided in Appendix A.

3.5. Airport roll-out assumptions

3.33 One key question in the course of the introduction of aircraft using alternative energy carriers will be which airports will be the frontrunners in the introduction. Our focus is on Europe, but for the purposes of the roll-out scenario we have assumed that equivalent results will be obtained in most major global aviation markets.

Our approach

3.34 Focusing on Europe, we have developed an approach to identify which airports are likely to have the highest priority in adopting a capability to serve hydrogen aircraft. This is likely to limit the initial roll-out geographically, although we anticipate that, in the event of a successful roll-out of hydrogen-powered aircraft at the “pioneering” airports, in due course most significant European airports would adopt the necessary technology.

3.35 However, the need for supporting infrastructure may be made less acute as, potentially, not all airports accommodating hydrogen-powered aircraft will be required to provide hydrogen fuel facilities in the first phase of rollout. We assume that the range of hydrogen aircraft will be sufficient to operate flights from the base airport (where maintenance, logistics and refuelling infrastructure will be provided) to a destination and back with the hydrogen taken on board at the home base. This practice is known as “tankering” and is relatively common today for conventional kerosene-burning aircraft, for both commercial (e.g. fuel price differentials) and operational reasons (faster turnarounds). We note that there was support for this approach from some of the airlines interviewed in the stakeholder consultation (see Chapter 5 below). This tankering will take place alongside conventional full-range routes between airports where both airports have supporting hydrogen infrastructure.

3.36 On this basis the fuel cell regional aircraft will have an operational range in the order of 400 nautical miles (Nm) and the short-/medium-haul turbofan aircraft of 800 Nm plus IFR reserves (which are, in the optimistic case, only relevant to be on board at the end of the return leg), assuming that the total range for individual missions including IFR reserves are 1,000 Nm and 2,000 Nm, respectively. IFR reserves are mandated by EASA and mean that an aircraft must retain sufficient fuel for diversions in case it cannot land at its targeted destination airport, effectively reducing the range.

3.37 This range will cover large parts of geographical Europe from bases in West/Central Europe like Amsterdam, Brussels, Frankfurt, Munich or Vienna (see Figure 3.3 for an example showing the range of hydrogen aircraft based at Frankfurt). Under this scenario, the total demand of hydrogen would remain relatively high, but infrastructure requirements will initially be limited to those airports only where hydrogen aircraft are expected to be based.

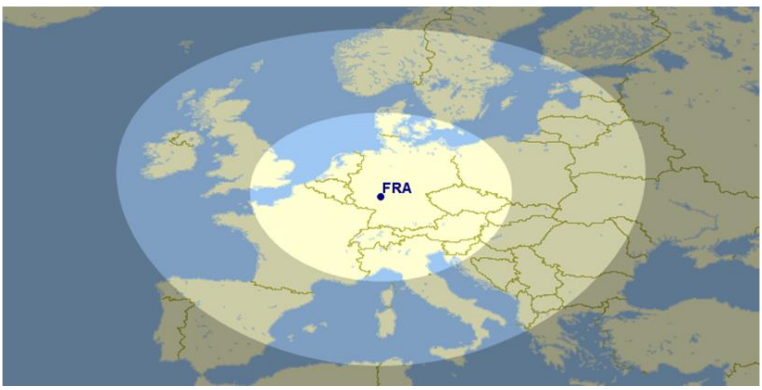

Figure 3.3: Operational range of hydrogen aircraft based at Frankfurt, refuelling at home base only (ranges of 400 Nm and 800 Nm) (Source: www.gcmap.com)

Further assumptions

3.38 We have assumed that hydrogen is expected to be available in large quantities and at commercially viable prices throughout Europe by the time hydrogen aircraft will enter service. This is based on anticipated demand and supply networks being developed for use in a wide range of industries such as the petrochemical, steel and energy industries as well as other transport modes. On this assumption, most airports could be connected by pipeline or trucks to future hydrogen transmission/distribution systems. So even when airports do not expect a very high level of hydrogen demand, it is expected that small quantities of hydrogen for occasional services with hydrogen aircraft would be provided by trucks or with small scale, mobile facilities wherever required. The challenges relating to these assumptions are discussed below in Chapter 6.

3.39 We do not assume a selective preference for hydrogen aircraft by particular airlines or airline business models because, in order for hydrogen aircraft to become widely available and commercially successful, they will need to have operational and commercial characteristics which make them suitable for use by network, low cost and holiday charter carriers alike. In particular, aircraft productivity/utilisation should be similar to that of conventional aircraft (ideally with minimum scheduled turnaround times of 25 minutes and annual utilisation of short/medium haul aircraft exceeding 3,500 flight hours per year).

3.40 To achieve a widespread acceptance of hydrogen aircraft ahead of the commercial entry into service, reliability, safety and competitiveness must be high. Any operational uncertainties concerning the deployment need to be resolved ahead of the entry into service of commercial aircraft. The level of maturity of entry into service must be high, most probably requiring an extensive phase of testing and demonstration ahead of the commercial application, as emphasised by ACARE.

Rest of the world

3.41 For the rest of the world, although we assume that the same considerations would apply, we have not undertaken a similar geographical analysis of the likely drivers of roll-out to individual airports.

Prioritisation of airports for roll-out

3.42 For the identification of the most promising early adopter airports, a scoring model has been developed, based on four categories. In each category, the attractiveness of each airport has been rated on a scale from 1 to 10 points. The points in each of the four categories have been multiplied to calculate an overall "hydrogen attractiveness score"

3.43 The four categories are as follows:

- airport size;
- traffic structure;
- "macro-logistics", i.e. access to green electricity, proximitiy to petrochemical or steel industries; and
- "micro-factors", i.e. airport space constraints and/or commitment to future hydrogen usage.

Airport size

3.44 It is assumed that larger airports are better suited for hydrogen introduction, e.g. a better business case for hydrogen suppliers, scale effects driving down prices, more based aircraft that form a demand base etc. Based on 2040 projected departing passengers from each airport the scoring is as follows:

- Airports exceeding 50m departing passengers: 10 points
- Airports serving 25m-50m departing passengers: 9 points
- Airports serving 15m-25m departing passengers: 8 points
- Airports serving 10m-15m departing passengers: 7 points
- Airports serving 7.5m-10m departing passengers: 6 points.
- Airports serving 5m-7.5m departing passengers: 5 points.
- Airports serving 2.5m-5m departing passengers: 4 points.
- Airports serving 1m-2.5m departing passengers: 3 points.
- Airports serving 0.5m-1m departing passengers: 2 points.
- Airports serving less than 0.5m departing passengers: 1 point.

Traffic structure

3.4 Airports with a traffic structure largely compatible with the range of hydrogen-powered aircraft are preferred for basing hydrogen aircraft. In the initial phase, when hydrogen is not available at all airports, airports with a high share of flights <800 Nm are preferred, as hydrogen aircraft could be refuelled at the home base, including the fuel required for the return flight to the base. Hence, hydrogen aircraft based at these airports could operate both the outbound and inbound flight legs, irrespective of the availability of hydrogen at the destination airport. Based on the 2040 share of flights <800 Nm, the scores are set as follows:

- Greater than 90%: 10 points
- 80-90%: 9 points
- 70-80%: 8 points
- 60-70%: 7 points
- 50-60%: 6 points
- 40-50%: 5 points
- 30-40%: 4 points
- 20-30%: 3 points
- 10-20%: 2 points
- Less than 10%: 1 point.

Macro-logistics

3.46 Airports with favourable access to green electricity or hydrogen directly are preferred for the introduction of hydrogen-powered aircraft at an early stage. Proximity to wind power (on- and offshore) as well as the potential for photovoltaic electricity production, and other electrical sources considered green/renewable by the EU taxonomy, are favourable conditions for the introduction of hydrogen at airports. Also, the proximity to petrochemical or steel industries as major future users of hydrogen could be favourable, as aviation can benefit from hydrogen infrastructure (such as pipelines) in these industries. Proximity to a harbour is also considered favourable, as green hydrogen could be imported more easily (provided that a terminal will be built). Airports located on small islands get a one-point penalty, as it is more difficult to integrate these airports into larger hydrogen infrastructures (e.g. connection to pipelines). The scoring also considers aspirational goals of national and regional government/authorities to introduce renewable energies and hydrogen. These considerations lead to the following scores:

- Closest proximity to macro-factors above: 9-10 points
- Close proximity to macro-factors above: 7-8 points
- Medium proximity to macro-factors above: 5-6 points
- Further proximity to macro-factors above: 3-4 points
- No proximity to macro-factors above: 1-2 points.

Micro-factors

3.47 It can be expected that airports will require relatively large amount of space for hydrogen storage and liquefaction. Hence, airports without space constraints are more favourable for the introduction of hydrogen. We assume that smaller airports have less space constraints, hence score higher than larger airports. Factors such as the commitment of airport management to promote hydrogen projects are also considered, fed from stakeholder consultation activities. This leads to the following scores:

- No space constraints, high commitment: 10 points
- No space constraints, low commitment: 9 points
- Minor space constraints, high commitment: 8 points
- Minor space constraints, low commitment: 7 points
- Medium space constraints, high commitment: 6 points
- Medium space constraints, low commitment: 5 points
- High space constraints, high commitment: 4 points
- High space constraints, low commitment: 3 points
- Very high space constraints (e.g. city airport), high commitment: 2 points
- Very high space constraints (e.g. city airport), low commitment: 1 point.

3.48 In cases where airports are given an equal score it is assumed larger airports (measured by forecast flight movements in 2040) are more likely to adopt hydrogen than smaller airports. Based on this, the 50 airports most likely to adopt infrastructure to support hydrogen-powered flight in the early years would be as shown in the table below.

Table 3.3: Early-adopter airport ranking (Source: DLR analysis)

Rank	Early-adopter Airport	Country	Departing flights by 2040	"Score"
1	Copenhagen	Denmark	153,616	5040
2	Oslo	Norway	142,342	5040
3	Amsterdam	Netherlands	285,256	4800
4	Paris - Charles de Gaulle	France	282,329	4410
5	Stockholm - Arlanda	Sweden	134,784	4032
6	Edinburgh	United Kingdom	68,373	3969
7	Hamburg	Germany	87,230	3920
8	Glasgow	United Kingdom	51,611	3888
9	Stavanger	Norway	29,288	3600
10	Berlin	Germany	161,607	3528
11	Vienna	Austria	136,681	3456
12	Bergen	Norway	42,356	3240
13	Trondheim	Norway	32,202	3240
14	London - Stansted	United Kingdom	93,822	3072
15	Rome - Fiumicino	Italy	190,584	3024
16	Torp	Norway	11,062	3000
17	Aalborg	Denmark	8,982	3000
18	Lyon	France	61,752	2880
19	Billund	Denmark	16,761	2700
20	Marseille	France	47,523	2700
21	Toulouse	France	46,868	2700
22	Athens	Greece	99,535	2688
23	Paris - Orly	France	149,062	2592
24	Stuttgart	Germany	60,325	2592
25	Bari	Italy	18,594	2560
26	Nice	France	72,357	2520
27	Aberdeen	United Kingdom	28,546	2400
28	Helsinki	Finland	97,002	2352
29	Milan - Malpensa	Italy	89,721	2352
30	Barcelona	Spain	182,558	2304
31	Brussels	Belgium	126,437	2304
32	Cologne/Bonn	Germany	55,638	2304
33	Gothenburg	Sweden	36,384	2304
34	Valencia	Spain	28,785	2304
35	Dublin	Ireland	124,571	2304
36	Madrid	Spain	227,958	2268
37	Bergamo	Italy	40,829	2268
38	London - Gatwick	United Kingdom	171,761	2268
39	Frankfurt	Germany	280,438	2240
40	Bologna	Italy	35,722	2160
41	Basel	Switzerland	33,871	2160
42	Bodø	Norway	21,577	2160
43	Tromsø	Norway	19,617	2160

Rank	Early-adopter Airport	Country	Departing flights by 2040	"Score"
44	Malmö	Sweden	11,783	2160
45	Girona	Spain	5,431	2160
46	Rygge	Norway	4,876	2160
47	London - Luton	United Kingdom	60,822	2016
48	Budapest	Hungary	52,400	2016
49	Sevilla	Spain	19,944	2016
50	Eindhoven	Netherlands	17,726	2016

3.49 The list has a strong focus on particular geographies, with Nordic countries accounting for 14 out of the top 50 airports, of which eight are in Norway. Other countries which feature significantly include France, the United Kingdom, Germany, Italy and Spain.

Estimating hydrogen demand

3.50 The demand for hydrogen at the airports in question will depend strongly on the number of hydrogen aircraft being based there. Hence, the quantity of hydrogen to be provided can be derived as a function of aircraft based there. When we assume that hydrogen aircraft will be as productive as conventional aircraft, an annual utilisation of 1,600 flights over an average of 800 Nm can be assumed for the hydrogen-powered short- and medium haul turbofan aircraft. At an average consumption of 1.5 tonnes hydrogen per flight, this equals a hydrogen demand of 2,400 tonnes per aircraft per year. This would also equal the demand of hydrogen required at the home base, in case the aircraft will be refuelled only there for both the out- and inbound flights.

3.51 Fuel cell-powered regional aircraft can be estimated to be operated for 2,000 flights annually over an average distance of 400 Nm. This would result in an annual hydrogen requirement of around 600 tonnes per aircraft.

3.52 The total amount of hydrogen required will highly depend on assumptions on the number of aircraft being based at each airport. As at least some economies of scale in terms of crew base, maintenance and spare part management as well as reserve capacities should be realised, it is reasonable to assume that a fleet size of five aircraft per base is a lower threshold for continuous and stable operations, at least in the roll-out phase.

3.53 Hence, the initial demand for hydrogen per airport can be estimated at around 10,000 tonnes per year in the roll-out phase, for the supply of five short- and medium haul aircraft with re-fuelling at the home base only. For five fuel-cell powered regional aircraft, the hydrogen requirement would amount to 3,000 tonnes per year.

3.54 Due to its special characteristics (e.g. high share of charter/non-scheduled operations, flights over short distances, operation as PSO services), the potentials of hydrogen in regional aviation are to be explored further.

3.6. Potential early roll-out for commuter and regional operations

3.55 It is likely that smaller regional aircraft powered by “green” technologies (fully or hybrid electric, hydrogen fuel cells) will become available in the market before such technologies diffuse into aircraft with a higher number of seats (e.g. Airbus A320 family). Hence, especially for a very early stage of introduction of green aircraft, a look at the regional aircraft market and potential clusters for the introduction of aircraft types with alternative propulsion technologies is helpful. This analysis has been undertaken independently from the fleet/forecasting model discussed above.

3.56 Overall, the regional aviation market is heterogenous with aircraft types ranging from around five seats for small commuter operations up to larger turboprops close to 80 seats, operated on high-frequency, high-demand short-haul routes. To cover the full range of regional aviation, we have analysed in the following paragraphs the market covering small turboprop aircraft from such as the Pilatus PC-12 or the Socata TBM 700 (typically 5-9 seats) up to the ATR72 and deHavilland Dash 8 (up to 75 seats). While the market of aircraft with less than 80 seats is only a fraction of the European traffic and fuel consumption, it may be a likely segment for the early adoption of new technologies and serve as a platform for gaining knowledge of green aircraft deployment at a very early stage of roll-out.

3.57 A high share of operations with commuter and regional aircraft take place outside the scheduled passenger services uploaded to global reservation systems. For this reason, we analysed EUROCONTROL flight data in order to identify the European “centres of gravity” in regional aviation. We identified aircraft ranging from 2 tonnes to 30 tonnes maximum take-off mass (MTOM), excluding business jets, conducting flights under instrument flight rules (IFR) as passenger and/or cargo services. This reflects services being operated with aircraft as small as a Cessna Caravan (9 passengers) up to aircraft the size of a de Havilland Dash8-Q300 with up to 75 passengers.

3.58 In total, more than 1.2 million IFR flights in commuter/regional aviation were operated in Europe in 2019, out of a total of more than 11 million flights in EUROCONTROL airspace. We identified several clusters where commuter/regional aviation is concentrated (see Figure 3.4 below).

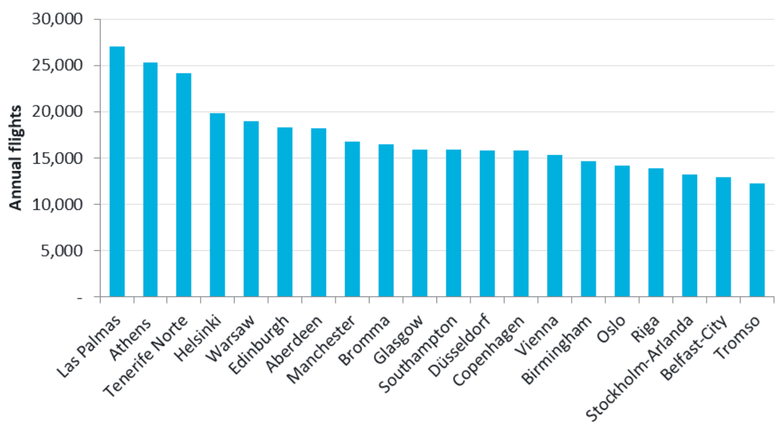

Figure 3.4: Annual flights in commuter/regional aviation (passenger and cargo) from European airports (2019) (Source: DLR analysis)

3.59 These centres of gravity could be well suited for the early introduction of hydrogen and/or battery-electric aviation. Firstly, the airports on the Canary Islands feature a high density of regional aircraft flights, with Las Palmas leading with more than 27,000 annual flights, followed by Tenerife North (24,100 flights). They are currently operated by ATR 72 aircraft seating around 72-74 passengers, a category of aircraft which is envisaged to be powered by hydrogen (either fuel cells with electric motors or direct combustion in turboprop engines) in various concepts and studies, such as the Airbus ZEROe Turboprop study.

3.60 Secondly, various European hubs, particularly smaller ones operate regional services to nearby destinations, such as Athens (25,300 flights), Helsinki (19,800 flights), Warsaw (18,900 flights) and Düsseldorf (15,800 flights).

3.61 Finally, with some overlap with the second category, are regional domestic services with smaller aircraft (under 50 seats). This includes 100,000 annual flights in 2019 (UK / Channel Islands), with Edinburgh (18,300 flights), Aberdeen (18,200 flights) and Manchester (16,800 flights) being the most prominent, followed by France (86,000 flights), Germany (36,000 flights), Sweden (32,000 flights), Greece (27,000 flights) and Norway (26,000 flights).

4. Roll-out scenario - results

4.1. Introduction

4.1 This chapter presents the modelled results of the roll-out of hydrogen and electrically powered aircraft based on the assumptions set out in Chapter 3 above. It includes assumptions on early aircraft retirement and the exclusive adoption of hydrogen aircraft by airlines for all airport pairs with suitable distance, where either conventional aircraft need to be replaced due to retirement or new traffic has to be accommodated due to demand growth.

4.2 We assume that entry into service of battery/hybrid electric aircraft will be in 2030 and of hydrogen aircraft (including both fuel cell electric and hydrogen direct combustion) will be in 2035. It is possible that General Aviation (GA) and small commuter aircraft (less than 19 seats) could be operating earlier than that, following the approach being pioneered by some "disruptor" Original Equipment Manufacturers (OEMs) to retrofit existing aircraft for use with gaseous hydrogen-powered fuel cells, but this has not been modelled as it is likely that converted aircraft will play only a limited role in global and European aviation.

4.3 The results are based on an assumption of aircraft fleet replacement with an aircraft "half-life" of 18 years, i.e. accelerated from the historical situation in which half of aircraft are retired after 25 years. The corresponding results under the 25-year half-life assumption are shown in Appendix A.

4.4 The results in the following sections (Hydrogen aircraft roll-out, Battery/hybrid aircraft roll-out, Quantum of clean flying and Volume of hydrogen fuel required) do not assume any restrictions relating to airport infrastructure and therefore represent an upper bound of the level of hydrogen-powered flying. From paragraph 4.32, in the Results by airport section, we consider the impact of hydrogen-related infrastructure being limited to a subset of airports in Europe, restricting the amount of hydrogen-powered activity by 2040. It is assumed that these restrictions cease to apply be 2050 (i.e. all significant airports will be able to provide hydrogen fuel to meet market demand). This exercise has not been extended to the rest of the world as there has not been sufficient information to prioritise airport adoption outside Europe.

4.5 These results were used as background information during stakeholder consultations

4.2. Hydrogen aircraft roll-out

4.6 Aircraft in the category of larger short-medium range aircraft are shown to have the highest potential in Figure 4.1, largely driven by aviation growth and an accelerated retirement of conventional aircraft.

4.7 The number of hydrogen aircraft required on a global scale will have substantial implications for planning of production capacities. We estimate that in 2035, approximately 325 fuel-cell-powered regional aircraft will be required and approximately 950 short-/medium range turbofan aircraft.

4.8 If we focus only on traffic departing from or arriving at airports located in Europe (defined as the EU, EEA, Switzerland and the UK), aircraft numbers are considerably smaller, as seen in Figure 4.2. In 2035, we estimate a potential of approximately 66 fuel-cell powered regional aircraft and 174 turbofan aircraft powered with liquid hydrogen. Given that a production ramp-up has to take place, and that based on historical performance with new technology this is likely to challenge both the Original Equipment Manufacturers (OEMs) and their suppliers, these figures seem to be plausible orders of magnitude for the introduction in the first year, if rollout is initially limited to Europe.

4.9 For the year 2040, we expect a total of 375 fuel-cell powered regional aircraft and 1,093 liquid hydrogen short-medium range turbofan aircraft operating flights to and from airports in the EU, EEA, Switzerland and UK.

4.10 The calculations on the number of aircraft required to operate hydrogen-powered service assume that hydrogen-powered aircraft will be as productive as conventional aircraft in terms of annual utilisation. A key factor in this regard could be ground handling/processing times, particularly the refuelling process. Longer refuelling procedures may severely impede aircraft productivity. This could result in a considerably larger number of aircraft required to accommodate demand.

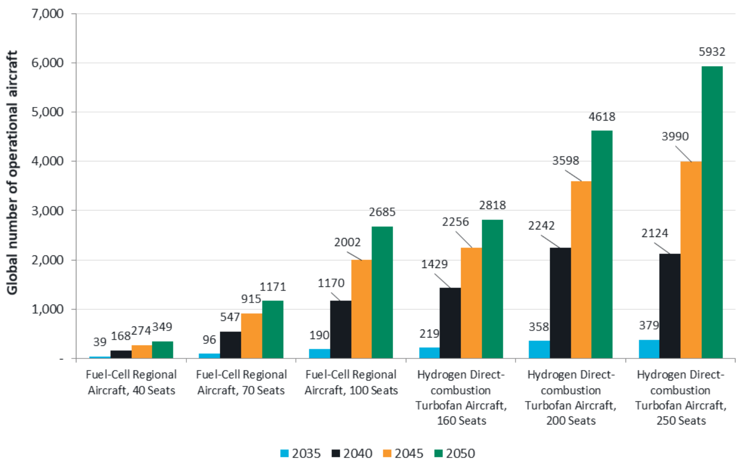

Figure 4.1: Global operational fleet of hydrogen-powered aircraft 2035-2050 (Source: DLR analysis)

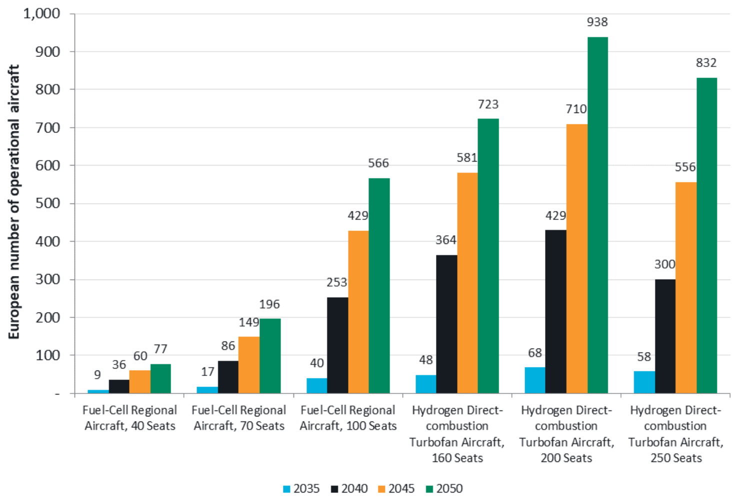

Figure 4.2: European operational fleet of hydrogen-powered aircraft 2035-2050 (Source: DLR analysis)

4.11 The analysis shows that a particular large market will be in the short/medium haul aircraft segment, with aircraft sizes tending towards the higher end of today's Airbus A320 family.

4.12 The high rate of introduction of hydrogen-powered aircraft corresponds to the traffic growth assumptions and a relatively high rate of aircraft retirements (see Figure 4.3 and Figure 4.4 below). On a global level, we expect an annual retirement of more than 200 turboprop aircraft in 2035. With the more widespread availability of fuel-cell powered regional aircraft this is expected to reach almost 300 aircraft globally per year in the timeframe 2036-2040. This compares to a retirement rate of only about 100 turboprop aircraft per year in the more recent past. Regional jet retirement is expected to be in the order of around 200 aircraft per year in the timeframe 2035-2040. This compares to around 120 annual retirements currently in this market segment.

4.13 In the narrowbody jet category, we expect an annual retirement rate of around 800 aircraft globally. Today, around 300 narrowbody aircraft are retired every year. The general increase in retirements in our model occurs because we have assumed an accelerated retirement (see from paragraph 3.26 above). In any case, retirements are expected to rise in the long-term, particularly in the case of the global turboprop fleet, which has a relatively high average age. These factors can be considered as positive framework conditions for the introduction of "green" aircraft technologies, as the market will demand a high number of new aircraft in the medium and long term. Particularly in the regional aircraft segment, where new developments have occurred only slowly over the past decades, a high potential for the modernisation of aircraft fleets and the introduction of "green" technology can be expected.

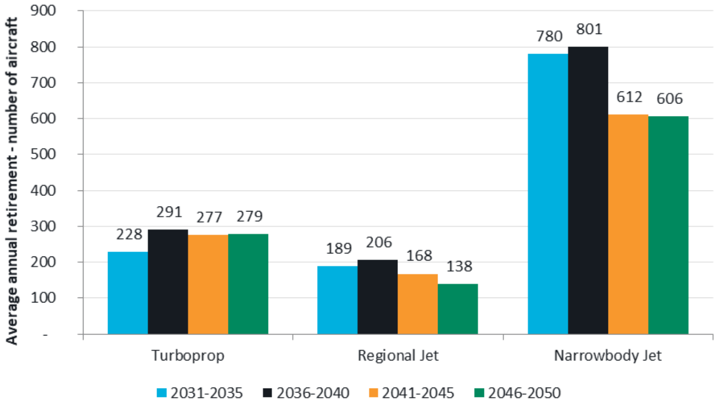

Figure 4.3: Expected future global annual aircraft retirement 2035-2050 (Source: DLR analysis)

4.14 Similar trends as described above are seen within the rate of retirement of European aircraft, seen in Figure 4.4 below.

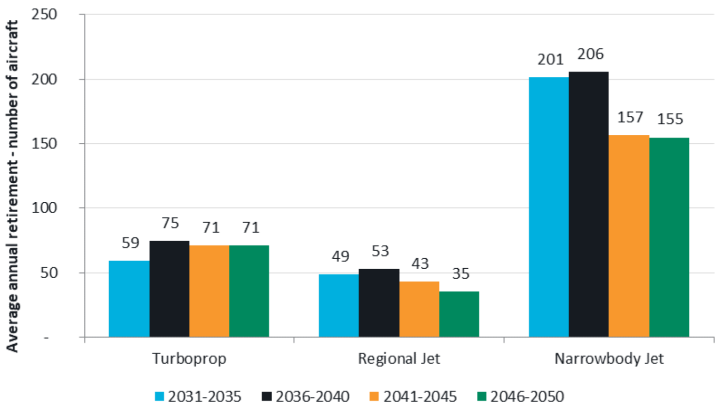

Figure 4.4: Expected future European annual aircraft retirement 2035-2050 (Source: DLR analysis)

4.3. Battery/hybrid aircraft roll-out

4.15 According to our assumptions, battery-electric/hybrid aircraft are expected to be introduced only in the category of commuter aircraft with 19 seats. This market segment has had – at least in scheduled passenger aviation – only a very small share in global demand. In our model, which covers scheduled passenger air transport only, this is also reflected by comparably low numbers of aircraft in this segment on a global scale. In the first year of introduction (2030), we expect a demand for the scheduled passenger segment for 26 aircraft globally. The number of aircraft operating globally by the year 2035 is expected to increase to 134, of which 29 are expected to operate in EU/EEA/CH/UK. We are aware of retrofit-concepts for hydrogen-electric 19-seater aircraft, as proposed by, e.g. Zeroavia, which may become operational even earlier. If this concept turns out to be successful, EIS may be shifted forward. However, given the small scale of the fleets in question, this issue can be regarded as relatively minor.

4.16 Concerning the operational deployment, commuter aircraft have the potential to become pioneering applications for both battery/hybrid-electric or hydrogen flying. These aircraft operate only on short distances and the network structures often resemble small hub-and-spoke networks with a central node.

4.17 In Europe, a particular demand can be expected for regional aviation in Norway. A promising example of this commuter network application is shown in Figure 4.5. The network in the forecast for 2035 consists of 7 destinations with distances of less than 105 Nm and a total forecast of 1,702 flights annually.

Figure 4.5: Forecast of the 19-seat commuter route network in Norway in the year 2035 (Source: DLR analysis)

4.4. Quantum of clean flying

4.18 Under the above-mentioned assumptions, we expect that in 2035 approximately 2.6 million flights could be conducted with hydrogen-powered aircraft, out of a total of approximately 43 million flights worldwide, with the number of flights by hydrogen-powered aircraft increasing to 14 million in the year 2040.7

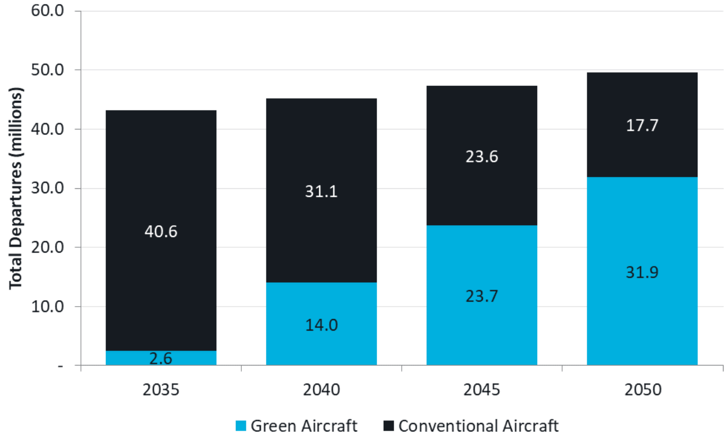

Figure 4.6: Global aircraft departures (green and conventional aircraft) (Source: DLR analysis)

4.19 For all departures from airports in Europe (EU/EEA/CH/UK), we expect 0.47 million flights by hydrogen-powered aircraft in 2035 and an increase of this figure to more than 2.6 million in 2040. In 2045, more than half of global flights could be operated by hydrogen-powered aircraft, both on a global and European scale.

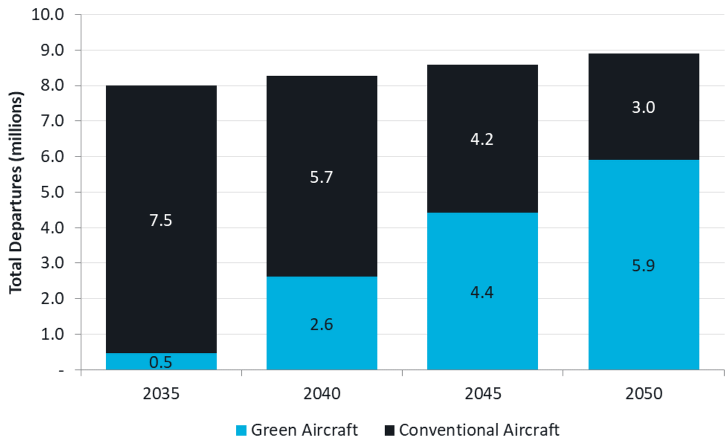

Figure 4.7: European airport aircraft departures from EU/EEA/CH/UK to all destinations (green and conventional aircraft) (Source: DLR analysis)

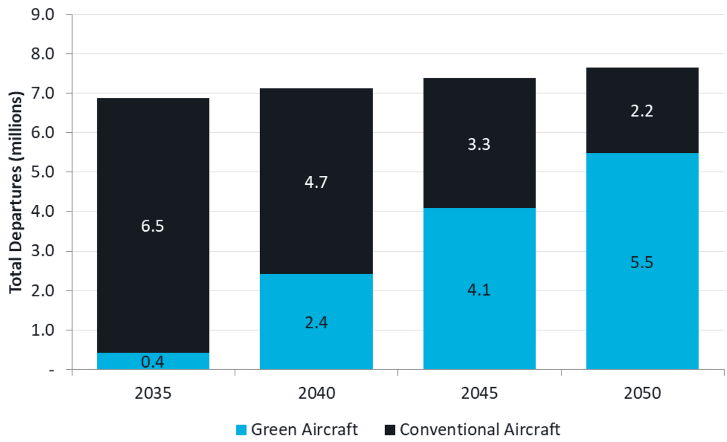

Figure 4.8: Intra-Europe aircraft departures within/between EU/EEA/CH/UK (green and conventional aircraft) (Source: DLR analysis)

4.20 In terms of flight kilometres (i.e. the total distance of all aircraft flown) and passenger kilometres, the uptake of hydrogen aircraft is less pronounced due to the predominance of long-haul flying in these indicators.

Table 4.1: Total traffic operated by hydrogen/hybrid-electric aircraft, 2035-2050 (Source: DLR analysis)

Indicator/Geographical coverage	2035	2040	2045	2050
Global air transport system				
Total Departures (millions)	2.6	14.0	23.7	31.9
Flight Kilometers (billions)	2.3	13.5	22.7	30.6
Passenger Kilometers (billions)	376	2277	3929	5405
Departing flights from EU, EEA, CH and UK				
Total Departures (millions)	0.5	2.6	4.4	5.9
Flight Kilometers (billions)	0.4	2.2	3.7	4.9
Passenger Kilometers (billions)	58	357	611	835
Flights within and between EU, EEA, CH and UK				
Total Departures (millions)	0.4	2.4	4.1	5.5
Flight Kilometers (billions)	0.3	1.9	3.2	4.3
Passenger Kilometers (billions)	50	307	525	718

4.21 In the longer term, adoption rates could rise quickly. For intra-European traffic, we expect a potential of more than 70% in terms of departures in 2050, corresponding to more than half of the passenger-kilometres flown. Hence, hydrogen-aircraft could make up the majority share of flight operations at European airports and on intra-European routes within less than two decades.

Table 4.2: Share of traffic operated by hydrogen/hybrid-electric aircraft, 2035-2050 (Source: DLR analysis)

Indicator/Geographical coverage	2035	2040	2045	2050
Global air transport system				
Share of Departures	5.9%	31.1%	50.1%	64.3%
Share of Flight Kilometers	3.8%	21.5%	34.5%	44.3%
Share of Passenger Kilometers	3.2%	17.0%	26.3%	32.9%
Departing flights from EU, EEA, CH and UK				
Share of Departures	5.8%	31.7%	51.4%	66.4%
Share of Flight Kilometers	3.4%	19.6%	31.6%	40.6%
Share of Passenger Kilometers	2.6%	14.1%	22.1%	27.8%
Flights within and between EU, EEA, CH and UK				
Share of Departures	6.2%	34.0%	55.4%	71.7%
Share of Flight Kilometers	5.1%	29.4%	47.7%	61.8%
Share of Passenger Kilometers	4.7%	25.9%	40.8%	51.7%

4.22 A key objective in the transition to green technologies in aviation is the reduction in carbon dioxide emissions. Although restricted only to consideration of short-haul flying, the impact of the introduction of hydrogen aircraft on emissions is significant in this scenario. Figure 4.9 below compares CO2 emissions in a scenario including the roll-out of hydrogen aircraft (i.e. the emissions from the residual conventional aircraft) with a situation where all demand is met through conventional aircraft (no hydrogen aircraft roll-out). By 2050, an ambitious global introduction of hydrogen aircraft has the potential to reduce CO2 emissions by 340 Mt per year. Already in the year 2040, hydrogen aircraft have a global CO2 reduction potential of 147 Mt.

4.23 Note that this comparison looks at the emissions in flight, so does not consider the reductions in lifecycle emissions which might be achieved through the use of Sustainable Aviation Fuel (SAF) by conventional aircraft.

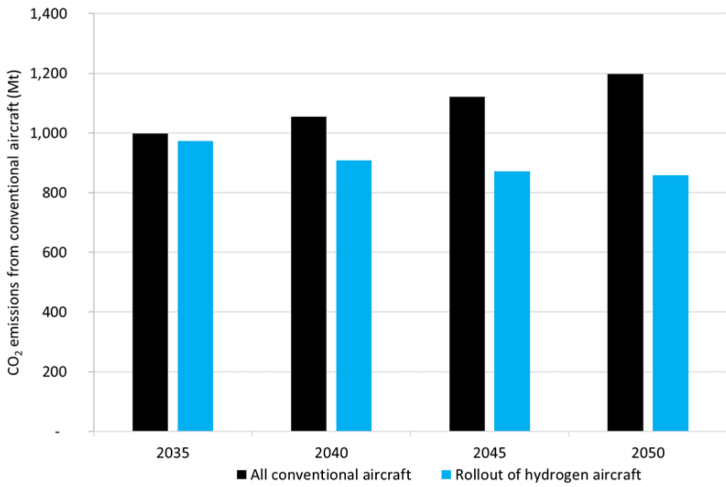

Figure 4.9: Global CO2 reduction potential through the introduction of hydrogen aircraft (Source: DLR analysis)

4.24 For intra-European traffic (within EU/EEA/CH/UK), the CO2 reduction potential also very high, with a reduction of 21.8 Mt in 2040, reaching 59.3 Mt in 2050.

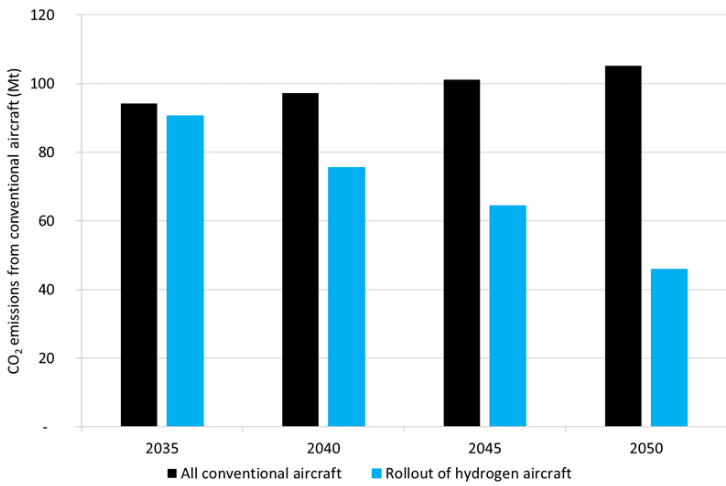

Figure 4.10: CO2 reduction potential for intra-European flights through the introduction of hydrogen aircraft (Source: DLR analysis)

4.25 The results show that the introduction of hydrogen-powered aircraft can have a substantial impact on CO2 reduction. This becomes particularly important with a view on entry-into service of aircraft with “green” technologies and the cumulative emissions of aviation. The earlier an entry of service can be realised, the more CO2 can be reduced in the long-run.

4.5. Volume of hydrogen fuel required

4.26 The volume of hydrogen required for aviation purposes (not including any bottled, gaseous hydrogen for 19-seaters) will steeply increase over the introduction phase between entry of service of hydrogen aircraft in 2035 and 2040. This is largely determined by the retirement of conventional aircraft and traffic growth to be expected.

4.27 The calculation of hydrogen demand is conducted using a bottom-up approach. DLR has created, on the basis of aircraft preliminary design, the concepts for families of fuel-cell powered regional aircraft and turbofan short-/medium-haul aircraft set out in Table 3.1 above. Simulation tools were used to create a set of around 20 exemplary missions of various distances for each aircraft, in order to calculate hydrogen consumption (including IFR reserves and allowances for vertical/horizontal flight inefficiency).

4.28 Based on these results and interpolations between the data points, it has been possible to calculate hydrogen fuel consumption for any flight mission within the maximum range of each aircraft - see Figure 4.11 below for an illustration of hydrogen consumption per nautical mile flown. Since the DLR traffic forecast/fleet model operates at the level of projected flights between all airport pairs and the market diffusion is to be assumed based on aircraft retirement/traffic growth, hydrogen aircraft will be allocated over time to all routes within the maximum aircraft range, wherever required. Total hydrogen demand is then calculated as the sum of hydrogen consumed on each mission multiplied by the number of annual flights projected for each airport pair.

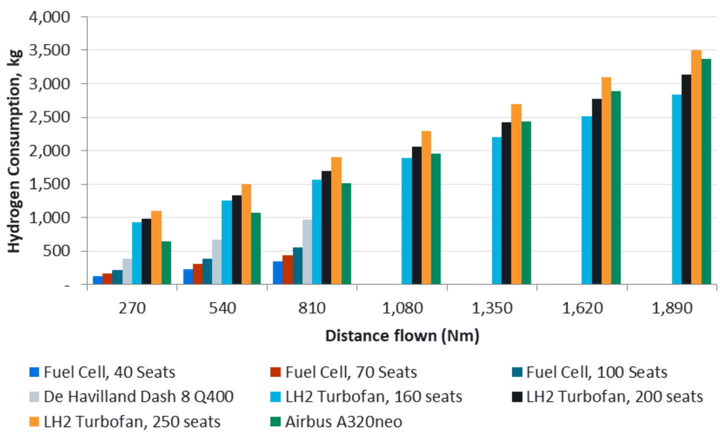

Figure 4.11: Hydrogen aircraft fuel consumption across flight lengths (Source: DLR analysis)

4.29 On a global scale, we expect a trajectory of hydrogen demand of 2.6 Mt in the year 2035, increasing to 15.9 Mt in the year 2040, 27.0 Mt in the year 2045 and 36.8 Mt in the year 2050. This can be compared with the estimate of 42 Mt of hydrogen fuel set out in the Hydrogen Powered Aviation (McKinsey study for CleanSky 2/FCH, May 2020). This is shown in the figure below, split by world region, including the EEA+ (lowest part of each bar).

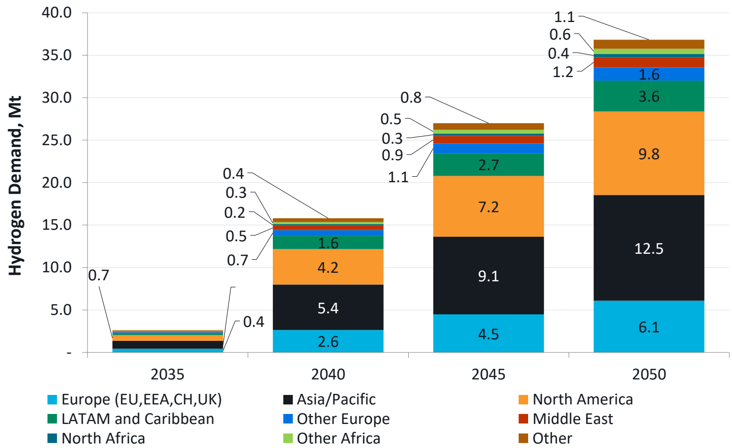

Figure 4.12: Global hydrogen demand development (Source: DLR analysis)

4.30 In the first year following the entry into service (2035), at EU airports a demand for hydrogen of less than 340,000 tonnes is expected. This will quickly evolve in the introductory phase to more than 2 million tonnes in the year 2040.

4.31 If the introduction of hydrogen aircraft takes place also on a global scale, substantial potentials for hydrogen-powered aviation emerge. Particularly in Asia (mainly because of the expected demand growth) and in North America (because of the route structures and aircraft categories utilized), a substantial potential for the use of hydrogen-powered aircraft exists.

The chart below shows the split of aviation hydrogen demand by global region, in 2040.

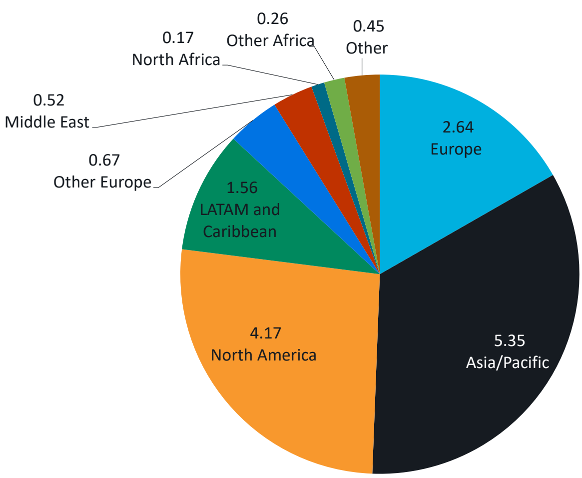

Figure 4.13: Global hydrogen demand in 2040 (tonnes) (Source: DLR analysis)

4.6. Results by airport

4.32 As noted in paragraph 4.4, the results presented so far in this report have not considered the potential impact of restrictions on the availability of hydrogen fuel at European airports. We have assumed that, given the significant infrastructure requirements at airports (discussed in Chapter 6 below), it is likely that in the initial years of roll-out only some airports will be able to provide hydrogen fuel. We consider a reasonable estimate is that, after five years from roll-out starting in 2035, i.e. 2040, that around 50 airports in Europe will have this infrastructure, corresponding to the list set out in Table 3.3 above.

4.33 The impact that this will have on hydrogen aircraft, flights operated and hydrogen used will then depend on whether it is assumed that fuel tankering is possible. Tankering allows aircraft to fly to airports without hydrogen fuel over a shorter range, carrying sufficient fuel for the return journey. The benefit of tankering is that it provides airlines with more flexibility of their choice of routes to serve with hydrogen aircraft as they only need to ensure that supply is available on one airport of the route, versus two where tankering is not possible. Tankering therefore drives the demand up for hydrogen by allowing significantly more airports to be served by hydrogen aircraft during the roll-out period. The impact of the restricted set of airports in 2040, with and without tankering, is shown in the chart below.

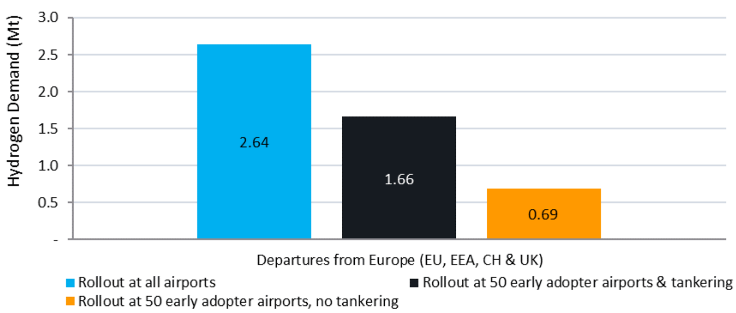

Figure 4.14: Impact of airport restrictions with and without tankering for departures from Europe (EU, EEA, CH & UK) in 2040 (Source: DLR analysis)

4.34 It is not assumed that there will be any significant impact of airport fuel availability restrictions by 2050.

4.35 The following table shows results of the roll-out of hydrogen to European airports by 2040, with Table 4.3 showing results for airports identified as priority airports in the early phases of hydrogen aviation roll-out in 2040, matching the early-adopter airport list shown in Table 3.3 above.

Table 4.3: Top 50 early hydrogen supporting airports key results in 2040 (Source: DLR analysis. Note: Liquefaction energy requirement calculated using an energy efficiency of 7.4kWh per kg of liquid hydrogen produced.)

Rank	Airport	Country	Departing flights in 2040	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
1	Copenhagen	DK	153,616	27	53,145	54,248	401
2	Oslo	NO	142,342	26	53,048	54,248	401
3	Amsterdam	NL	285,256	46	86,700	92,179	682
4	Paris - CDG	FR	282,329	44	79,778	95,885	710
5	Stockholm - Arlanda	SE	134,784	25	47,083	48,338	358
6	Edinburgh	UK	68,373	11	21,506	18,499	137
7	Hamburg	DE	87,230	16	30,791	30,392	225
8	Glasgow	UK	51,611	7	14,298	10,090	75
9	Stavanger	NO	29,288	5	11,867	7,086	52
10	Berlin	DE	161,607	28	53,887	62,758	464
11	Vienna	AT	136,681	25	45,756	47,918	355
12	Bergen	NO	42,356	7	16,295	10,493	78
13	Trondheim	NO	32,202	6	12,383	7,783	58
14	London - Stansted	UK	93,822	12	22,252	31,976	237
15	Rome-Fiumicino	IT	190,584	35	66,951	80,096	593
16	Torp	NO	11,062	2	3,561	1,955	14
17	Aalborg	DK	8,982	1	3,234	2,113	16
18	Lyon	FR	61,752	12	22,053	17,338	128
19	Billund	DK	16,761	3	5,267	3,587	27
20	Marseille	FR	47,523	9	16,847	16,941	125
21	Toulouse	FR	46,868	9	17,392	15,079	112
22	Athens	EL	99,535	16	28,839	36,634	271
23	Paris - Orly	FR	149,062	27	50,086	59,163	438
24	Stuttgart	DE	60,325	10	20,266	18,737	139
25	Bari	IT	18,594	3	5,788	6,404	47
26	Nice	FR	72,357	12	22,635	24,881	184
27	Aberdeen	UK	28,546	5	9,631	4,673	35
28	Helsinki	FI	97,002	18	31,498	34,921	258
29	Milan - Malpensa	IT	89,721	14	23,034	27,074	200
30	Barcelona	ES	182,558	31	58,156	80,290	594
31	Brussels	BE	126,437	26	43,333	47,879	354
32	Cologne/Bonn	DE	55,638	9	18,387	21,528	159
33	Gothenburg	SE	36,384	7	12,998	10,579	78
34	Valencia	ES	28,785	4	7,681	7,750	57
35	Dublin	IE	124,571	18	36,546	42,324	313
36	Madrid	ES	227,958	39	68,885	86,582	641
37	Bergamo	IT	40,829	5	9,893	14,461	107
38	London - Gatwick	UK	171,761	28	49,654	72,386	536
39	Frankfurt	DE	280,438	44	85,092	89,372	661
40	Bologna	IT	35,722	6	11,299	13,214	98
41	Basel	CH	33,871	6	10,849	10,835	80
42	Bodø	NO	21,577	3	6,917	2,966	22
43	Tromsø	NO	19,617	3	6,890	4,232	31
44	Malmö	SE	11,783	2	4,195	3,177	24
45	Girona	ES	5,431	1	1,304	1,959	14
46	Rygge	NO	4,876	1	1,733	2,935	22
47	London - Luton	UK	60,822	10	17,110	27,922	207
48	Budapest	HU	52,400	8	13,464	18,410	136
49	Sevilla	ES	19,944	3	4,631	6,086	45
50	Eindhoven	NL	17,726	2	3,970	6,284	47

4.36 Based on this, we have assumed that all large and medium sized airports will adopt a hydrogen capability, including all major European airports. In other words, if demand in the early years is suppressed at such airports due to failure to be early adopters, we assume that these airports will "catch up" on the level of hydrogen flying supported. On this basis, Table 4.4 below highlights the key results from the roll-out scenario for airports which have the largest demand for hydrogen in 2050. Some of the prioritised airports in 2040 shown in Table 4.3 above are no longer in the top 50 airports in this table, as they are overtaken by larger airports by 2050, although they do appear further down the list of airports.

Table 4.4: Top 50 largest European airports for hydrogen demand in 2050. (Source: DLR analysis. Note: Liquefaction energy requirement calculated using an energy efficiency of 7.4kWh per kg of liquid hydrogen produced.)

Rank	Airport	Country	Departing flights in 2050	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
1	London - Heathrow	UK	357,085	97	181,041	236,126	1,747
2	Paris - CDG	FR	308,594	99	181,442	223,118	1,651
3	Amsterdam	NL	312,501	106	201,024	218,998	1,621
4	Madrid	DE	306,871	98	191,104	206,747	1,530
5	Frankfurt	ES	248,487	91	160,575	206,354	1,527
6	Barcelona	ES	197,769	71	133,679	187,828	1,390
7	Munich	DE	256,281	97	183,773	182,718	1,352
8	Rome-Fiumicino	IT	204,533	78	148,367	181,732	1,345
9	London - Gatwick	UK	190,308	64	114,597	168,686	1,248
10	Berlin	DE	172,262	62	121,920	142,481	1,054
11	Paris - Orly	FR	161,217	60	113,353	135,905	1,006
12	Copenhagen	DK	167,004	63	121,978	127,307	942
13	Oslo	NO	155,747	58	119,931	124,709	923
14	Lisbon	PT	118,345	52	81,099	117,919	873
15	Vienna	AT	147,137	59	107,809	114,240	845
16	Stockholm - Arlanda	SE	146,306	57	107,345	113,563	840
17	Brussels	BE	136,273	58	98,101	111,383	824
18	Zurich	CH	155,078	52	102,514	101,959	754
19	Dublin	IE	133,834	43	86,717	100,734	745
20	Athens	EL	106,516	40	73,586	91,087	674
21	Düsseldorf	DE	136,716	50	93,270	86,566	641
22	Helsinki	FI	105,916	43	74,707	82,889	613
23	Palma de Mallorca	ES	109,993	33	65,246	80,820	598
24	Geneva	CH	97,893	40	74,214	78,229	579
25	Hamburg	IT	93,583	33	58,377	70,107	519
26	Malaga	DE	93,239	36	69,105	69,695	516
27	London - Stansted	ES	69,791	26	38,562	69,146	512
28	Milan - Malpensa	UK	99,720	24	46,040	65,899	488
29	London - Luton	UK	65,267	23	38,620	63,459	470
30	Nice	UK	119,246	31	60,463	59,493	440
31	Manchester	CZ	75,125	28	52,197	58,240	431
32	Bucharest - Otopeni	FR	78,368	27	51,847	58,235	431
33	Prague	RO	68,184	26	42,954	57,016	422
34	Warsaw	PL	91,372	42	67,266	49,563	367
35	Milan - Linate	DE	58,951	20	40,859	48,572	359
36	Cologne/Bonn	IT	64,154	28	54,053	47,295	350
37	Alicante	ES	51,510	17	27,466	45,830	339
38	Edinburgh	UK	74,789	26	50,929	43,848	324
39	Stuttgart	IT	51,021	20	37,856	43,596	323
40	Venice	DE	63,906	23	46,055	43,175	319
41	Budapest	FR	65,544	26	50,257	41,259	305
42	Lyon	HU	56,912	17	30,667	40,859	302
43	Marseille	FR	50,293	19	37,323	37,941	281

Rank	Airport	Country	Departing flights in 2050	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
44	Toulouse	PT	47,325	18	31,903	35,830	265
45	Porto	FR	49,694	20	38,823	35,327	261
46	Bergamo	IT	35,277	13	25,660	31,948	236
47	Catania	IT	41,689	11	21,590	31,581	234
48	Bologna	IT	37,761	14	25,807	30,287	224
49	Birmingham	UK	66,274	21	39,814	29,964	222
50	Faro	PT	29,029	11	15,243	29,797	220

4.7. Sensitivity tests

4.37 Forecast future hydrogen demand depends to a large extent on the assumptions going into the model. The presented figures reflect optimistic assumptions in terms of retirement of conventional aircraft, range capabilities of hydrogen aircraft (1,000 Nm for fuel cell regional aircraft and 2,000 Nm for turbofan short-/medium range aircraft, production rates of hydrogen aircraft and the acceptance of such aircraft by airlines and passengers. Moreover, we assume under optimistic assumptions, that neither aircraft production rates nor airport infrastructure limitations constrain the rate of adoption of hydrogen aircraft into the active fleet.

Aircraft range

4.38 Sensitivity in terms of aircraft range: In the current environment, it is not yet exactly known which range capabilities hydrogen-powered aircraft will be optimized for. Here, a trade-off between economic parameters (basically direct operating costs (DOC) and costs per ASK, respectively) and the operational flexibility airlines demand exists. Technically, limited floor space inside the fuselage is likely to be allocated for tank or passenger space. An optimization for shorter ranges will probably allow a higher usable share of passenger space. The following figure indicates that from a hydrogen demand perspective a deviation from our assumption of 2,000 Nm (3,700 km) range for the short-/medium haul turbofan aircraft to e.g. 1,500 Nm (2,780 km) will only have a minor impact on global hydrogen demand, declining from 15.9 Mt to 14.7 Mt. Hence, a 25% reduction in individual aircraft range would only result in a reduction of 7.5% in hydrogen demand. From this analysis it can be seen that most of the hydrogen aircraft in the model operate on routes of considerably shorter distances than the design range of the aircraft.

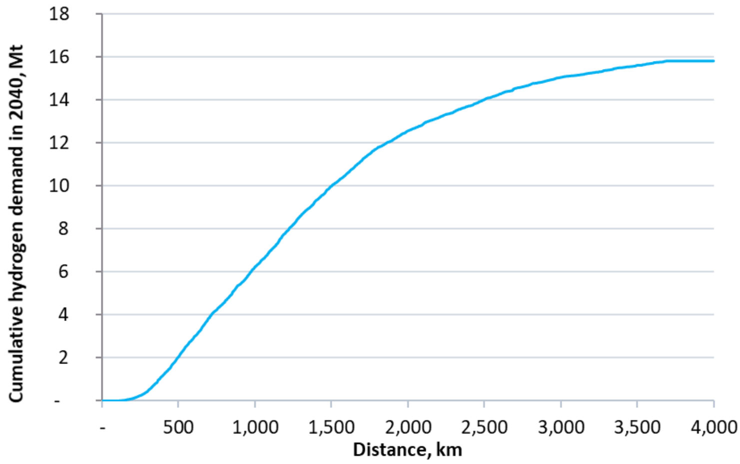

Figure 4.15: Global cumulative hydrogen demand by flight distance (2040) (Source: DLR analysis)

Rate of retirement of existing aircraft

4.39 One of the key assumptions in the market diffusion modelling is an accelerated retirement with a half-life of narrowbody and regional jets as well as turboprop aircraft of 18 years, which is a considerable reduction on the historical half-life e.g. for narrowbody jets of 25 years. The charts below show the impact on the total hydrogen aircraft required, hydrogen aircraft departures and consequent hydrogen demand in 2035 through to 2050 in the case where the half-life remains at 25 years, instead of the assumed 18 years in our base case.

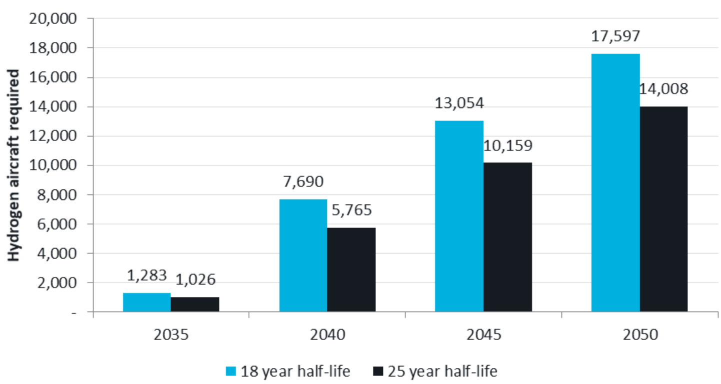

Figure 4.16: Total hydrogen aircraft required globally under respective aircraft retirement scenarios (Source: DLR analysis)

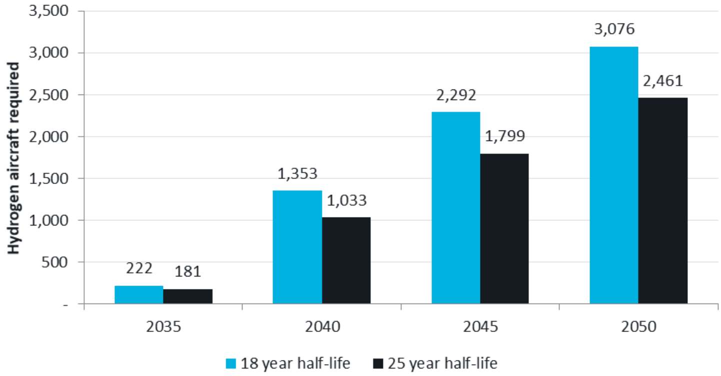

Figure 4.17: Total hydrogen aircraft required in Europe (EU, EEA, CH & UK) under respective aircraft retirement scenarios (Source: DLR analysis)

4.40 Figure 4.16 shows that global hydrogen aircraft would be reduced from 7,690 to 5,765 in 2040 if the aircraft retirement half-life remained at 25 years instead of accelerating to 18 years. By 2050, the number of hydrogen aircraft would reduce from 17,597 to 14,000. Figure 4.17 shows that if the half-life remained at 25 years rather than 18 years the number of European hydrogen aircraft required will reduce to 2,461 rather than 3,076.

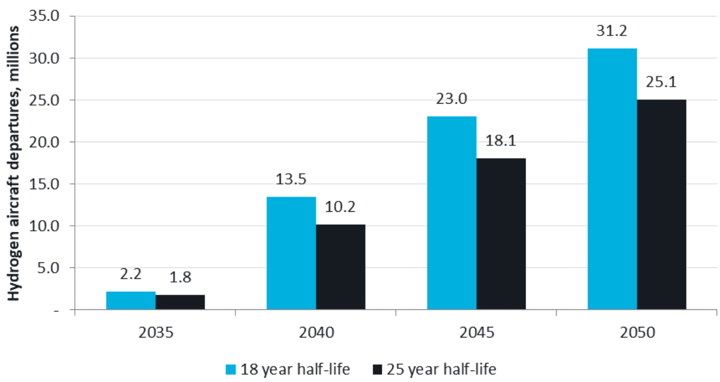

Figure 4.18: Total hydrogen aircraft departures globally respective aircraft retirement scenarios (Source: DLR analysis)

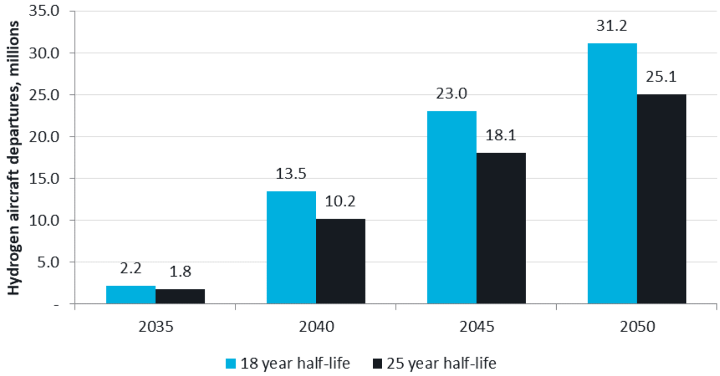

Figure 4.19: Total hydrogen aircraft departures in Europe (EU, EEA, CH & UK) for respective aircraft retirement scenarios (Source: DLR analysis)

4.41 Figure 4.18 shows that global hydrogen aircraft departures would be reduced from 13.5 million to 10.2 million in 2040 if the aircraft retirement half-life remained at 25 years instead of accelerating to 18 years. By 2050, the number of hydrogen aircraft departures would reduce from 31.2 million to 25.1 million. Similarly in Europe, the number for hydrogen aircraft departures would reduce to 4.7 million from 5.8 million as shown in Figure 4.19.

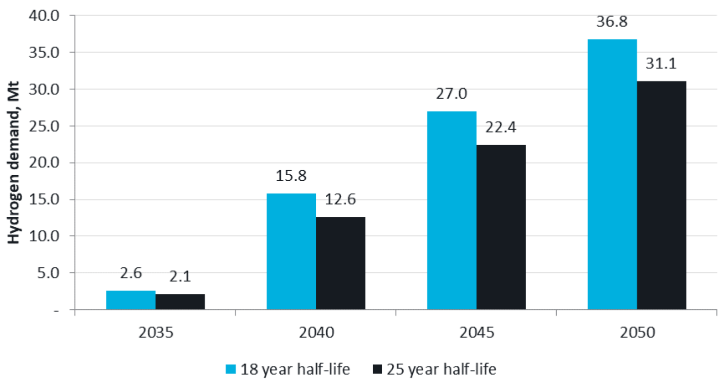

Figure 4.20: Total hydrogen demand globally required under respective aircraft retirement scenarios (Source: DLR analysis)

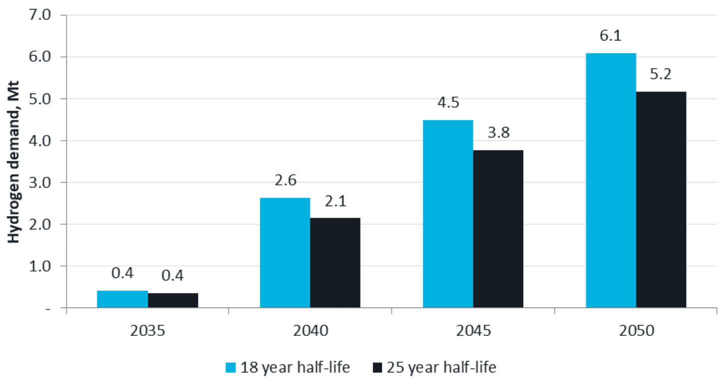

Figure 4.21: Total hydrogen demand in Europe (EU, EEA, CH & UK) under respective aircraft retirement scenarios (Source: DLR analysis)

4.42 Figure 4.20 shows that the global hydrogen aviation fuel demand would be reduced from 15.Mt to 12.6Mt in 2040 if the aircraft retirement half-life remained at 25 years instead of accelerating to 18 years. By 2050, the global hydrogen aviation fuel demand would reduce from 36.8Mt to 31.1Mt. Figure 4.21 shows that a reduction from 6.1Mt to 5.2Mt in European hydrogen aviation fuel demand would be seen in 2050 if a 25-year retirement half-life is seen instead of an 18-year half life.

4.43 A complete set of scenario projections for the 25-aircraft “half-life” assumption are shown in Appendix A.

Traffic growth

4.44 Traffic growth is another factor contributing to the market diffusion of hydrogen aircraft. The higher the growth rate, the more new aircraft will be demanded by airlines to accommodate future traffic. In order to evaluate the sensitivity of traffic growth we have undertaken a model run with traffic volumes (passengers and flights) held constant beyond the year 2035. All other factors remain unchanged in comparison to the main model run.

Table 4.5: Global hydrogen demand in relation to changes in traffic growth assumptions (Source: DLR analysis)

Year	Hydrogen demand, traffic growth beyond 2035 (Mt)	Hydrogen demand, no traffic growth beyond 2035 (Mt)	Absolute difference in Mt	Relative difference in %
2035	2.6	2.6	-0.0	-0%
2040	15.8	12.6	-3.2	-20.3%
2045	27.0	21.6	-5.4	-20.0%
2050	36.8	29.6	-7.2	-19.6%

4.45 While hydrogen demand still increases over time under the assumption that traffic will not grow beyond 2035, it is 20% below the scenario with an average traffic growth of 2.1 % for extra-EU traffic and 1.7% for intra-EU traffic in the timeframe between 2035 and 2050. The increase in hydrogen demand is driven by the replacement of conventional aircraft only. We can conclude from this sensitivity analysis that traffic growth is another powerful driver for the market diffusion of "green" aviation technologies. However, even when traffic growth comes to a virtual standstill (which might be the case because of a substantial cost increase leading to higher air fares), the replacement of conventional aircraft can be sufficient to support the business case for hydrogen aircraft.

Airport infrastructure availability

4.46 The following figure shows global cumulative hydrogen demand by airport in 2040. As with many other indicators in air transport (flight movements, passengers, kerosene demand), we expect to see also with hydrogen a relatively high level of concentration. 20% of hydrogen demand is consumed at 23 airports (0.8% of all airports), 50 % of hydrogen is consumed at only 89 airports (3% of all airports).

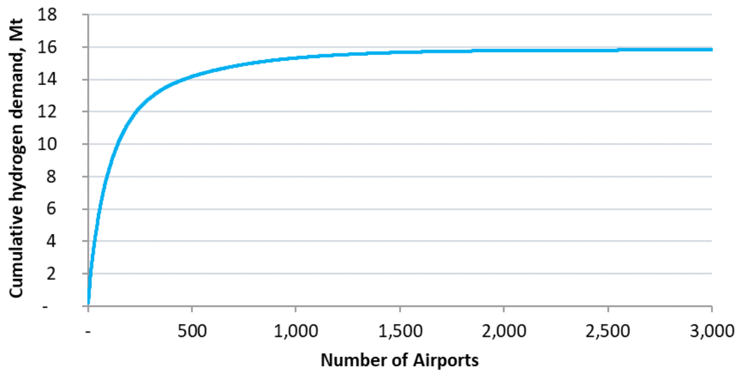

Figure 4.22: Global cumulative hydrogen demand by airport (2040) (Source: DLR analysis)

4.47 Similar levels of cumulative hydrogen demand is seen across European airports, as illustrated in Figure 4.23, with the 21 largest hydrogen consuming airports reaching over 50% of total European demand in 2040.

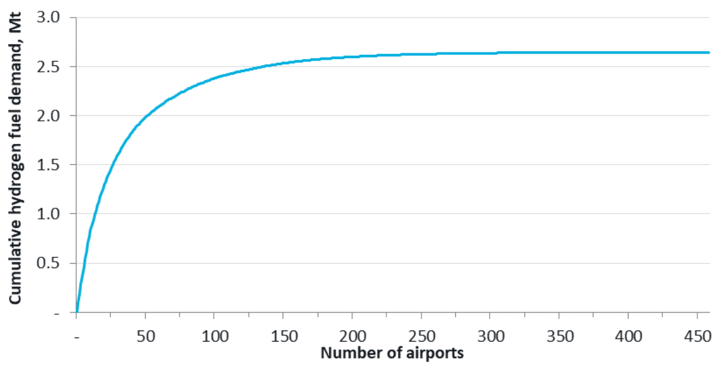

Figure 4.23: European cumulative hydrogen demand by airport (2040) (Source: DLR analysis)

4.48 The policy implications of this findings are important especially for the early phase of market introduction of hydrogen aircraft. At the immediate start, potentially not all airports need to be equipped with hydrogen infrastructure. A core set of airports would be sufficient to provide an extensive market coverage.

4.49 The level of equipage with hydrogen infrastructure is less problematic, if it is operationally possible to fly the outward and inward flight leg with hydrogen taken on board at the home base. This effect could result in both a shift of hydrogen demand in geographical terms to fewer airports (with subsequent higher demand at the respective airports) in contrast to the model results, which do not consider tankering and a change in route allocation. With tankering, operational range for individual missions would be reduced by more than 50 % (short/medium range jets from 2,000 Nm to ~800 Nm, fuel cell regional aircraft from 1,000 Nm to ~400 Nm), when considering the tank capacity, energy demand profiles (two takeoffs and landings on one refueling level) and the IFR requirements to be fulfilled also at the end of the second flight leg.

The non-availability of hydrogen at airports further away from home bases could lead to a concentration of aircraft allocation to short haul routes, allowing for out- and inbound legs to be operated on one tank contents. This, however, is not expected to significantly reduce overall hydrogen demand, as shown in Figure 4.15 above, as most of the hydrogen is consumed on relatively short flights.

5. Stakeholder comments

5.1. Introduction

5.1 This chapter sets out the results of our engagement with stakeholders, summarising stakeholder views for each category of stakeholder, namely:

- aircraft manufacturers and representatives;
- airlines and representatives;
- airports and representatives;
- financiers;
- regulatory authorities; and
- hydrogen fuel experts.

5.2 We identify where, within each category, there was consensus and where there was disagreement. To preserve stakeholders' confidentiality, we have not identified individual stakeholders. More detail on the questionnaires put to stakeholders and on the responses provided by individual stakeholders can be found in Steer's Stakeholder Report.

5.2. Aircraft manufacturers and representatives

Introduction

5.3 Steer and DLR spoke to a range of aircraft manufacturers clean aviation start-ups, aviation research institute as well as the Advisory Council of Aeronautics Research in Europe (ACARE).

5.4 While each organisation had its own particular focus and perspective, a number of common themes emerged from the interviews. These are set out below.

Feasibility of and timescales for hydrogen-powered aviation

5.5 All of the organisations considered that hydrogen-powered aviation was technically feasible and indeed most were involved in developing equipment to facilitate it. There was a consensus that entry into service (EIS) was feasible by 2035, although this would require a strong effort to deliver and was not certain. A 10-year development programme, somewhat longer than the typical 6- to 8-year programmes for new aircraft development, was considered credible (implying that aircraft development would need to start in 2025 to achieve EIS in 2035).

Aircraft characteristics

5.6 Two different propulsion systems are being considered for hydrogen-powered aviation. These are hydrogen fuel cells powering electric motors and hydrogen combustion in a turbofan engine. The former is the "cleaner" solution, producing only water as a by-product, while the latter is likely also to produce NOx emissions, though at a lower level than emissions from turbofans burning conventional aviation fuel.

5.7 The fuel cell solution is better suited to smaller, slower and shorter-range aircraft as sufficiently powerful electric motors are not yet available to power aircraft equivalent to an A320 or 737. However, the start-up manufacturers were confident that fuel cell could be scaled up over time to be used in A320/737-sized aircraft. A 2MW fuel cell was considered possible by 2026 and a 10MW fuel cell was considered possible by 2035.

5.8 For small aircraft under 50 seats, it is possible to use pressurised gaseous hydrogen as the fuel source. For larger aircraft, liquid hydrogen would need to be used. One manufacturer is also looking at aluminium fuel cells as a power source, rather than hydrogen fuel cells.

Barriers to development – finance

5.9 There was a range of views on the ease with which finance could be raised to develop hydrogen-powered flight. Manufacturers indicated that there was a lot of interest from investors and creditors. However, there was also a consensus that public funding would be required to support the development of commercial hydrogen-powered aircraft.

5.10 One stakeholder indicated that there was a risk of market failure, with aircraft manufacturers, airlines and airports all unenthusiastic to act as a "first mover". Without available airport and fuelling infrastructure, airlines would be unwilling to purchase hydrogen aircraft while without airline purchases, airports would be unwilling to invest in infrastructure. Without certainty on airline orders, aircraft manufacturers would be unwilling to invest in aircraft development. It was felt likely that government intervention would be needed to help pay for the relevant transformation costs.

5.11 Such finance was needed, in particular, to overcome the so-called "valley of death" between Technical Readiness Level (TRL) 6 at the end of the development phase and TRL 9, corresponding to EIS, at the end of the deployment phase. It was noted that funding would need to be compatible with WTO rules, which make grant funding difficult beyond TRL 6 (the level currently targeted by the Clean Aviation Joint Undertaking).

Barriers to development – certification

5.12 The certification of hydrogen aircraft was considered to represent a significant barrier to the roll-out of such aircraft. One manufacturer said that, while investors had confidence in the market and the technology for hydrogen-powered aircraft, they were worried about the risks arising from the certification of the new technology. Another stakeholder highlighted the need to accelerate work on proving the safety of aircraft and airport systems for hydrogen, as well as processes to ensure that certification did not become a bottleneck in the roll-out.

Airport infrastructure

5.13 A number of comments were made about the airport infrastructure required to support hydrogen flying. For small aircraft, using gaseous hydrogen, fuel availability was not considered to present a significant challenge.

5.14 For larger aircraft, requiring liquid hydrogen fuel, there is a need for supplies of liquid hydrogen to be available at the airports used. The means of transport of hydrogen fuel was mentioned, with one respondent comparing the costs of trucking liquid hydrogen fuel with providing green electricity to the airport site in order to liquefy hydrogen arriving by gas pipeline.

5.15 It was mentioned that "clustering" of airports with hydrogen fuel might be needed during the initial roll-out, to provide a viable set of destinations. Some stakeholders considered that fuel tankering would be a viable option, particularly as the tankered fuel is relatively light (given the high gravimetric energy density of hydrogen). Tankering would widen the range of available routes without requiring hydrogen fuel to be available at both ends of the route during the initial roll-out.

5.3. Airlines and representatives

Introduction

5.16 Steer and DLR spoke to some European full-service and low-cost carriers and representatives.

5.17 A number of common themes were identified, but there were also differences in perspective between the full-service low-cost carriers.

Benefits of hydrogen-powered aircraft

5.18 There was a consensus that hydrogen-powered aircraft were likely to be developed and enter airline fleets, but disagreement over the urgency and likely timescales for this. While a low-cost carrier's view was that only zero-emission flying would be acceptable by the mid-2030s, the full-service carriers were more sceptical, considering that hydrogen-powered aircraft would not be a major part of aviation decarbonisation in the medium term [assumed to mean before 2050]. It was considered likely that the next generation of aircraft (beyond the A320-neo / 737-MAX families) would also be powered by hydrocarbons.

5.19 A full-service carrier was supportive of the use of (drop-in, hydrocarbon) SAFs, which were considered to be "almost as good" in environmental benefit terms as hydrogen, while being able to support all parts of the fleet (i.e. long-haul as well as short-haul aircraft). Therefore, the key priority was to ensure a good supply of SAFs, which would be likely to include power-to-liquid (synthetic hydrocarbon) fuels as well as biofuels. Public policy should be focused on ensuring a good supply of SAFs at acceptable prices.

Barriers to adoption of hydrogen-powered aircraft

Fuel price

5.20 The most important barrier to the adoption of hydrogen-powered aircraft was the underlying economics. While it was agreed that carbon pricing applying to kerosene would be likely to enable hydrogen fuel to be competitive (at least within Europe where ETS applies), there was strong concern about how hydrogen fuel would compete with SAFs, which would not be subject to the ETS.

5.21 Given the additional difficulties of operating hydrogen aircraft (new technology, split fleet, availability of fuel), it was essential that airlines had certainty that hydrogen fuel would have "parity with SAFs" in terms of cost. A European airline considered that, although generating emissions would be unacceptable to the public by the 2030s, this did not mean that passengers would be willing to pay more to fly on hydrogen-powered aircraft, so public policy needed to ensure that prices were equivalent.

Aircraft acquisition

5.22 Airlines were generally cautious about being a "first mover" in adopting new hydrogen aircraft technology and there was a "chicken-and-egg" problem about purchasing aircraft when insufficient airports had the infrastructure to support them (and recognition of a similar problem for airports).

5.23 Therefore, it was felt that government/public sector support was likely to be needed to support aircraft development and also likely for the purchase of the initial batch of aircraft. One option could be for the public sector to purchase aircraft and then lease out to airlines at advantageous rates to encourage adoption of hydrogen aircraft.

5.24 Any solution supporting the adoption of hydrogen aircraft needed to work at a global level and not just within Europe, in order to make such an aircraft viable.

Technical and operational issues

5.25 It was generally agreed that there were no "show-stopper" technical issues which would prevent the roll-out of hydrogen aircraft.

5.26 Aircraft safety and certification were non-negotiable, but considered largely to be the concern of the manufacturers rather than airlines.

5.27 Aircraft turnaround processes and timings were important, with airlines noting that refuelling at aircraft stands (rather than remotely on the airfield) was required to give confidence to passengers about safety and to keep turnaround times short. However, there was not complete consensus about this, with one airline stating that longer turnarounds could be acceptable as part of a wider package.

5.28 Aircraft performance in terms of handling characteristics and airport approach speed was important, as if the approach speed was significantly different from that of conventional aircraft, it would cause airport slot capacity problems.

5.29 There were differing views about fuel tankering, with some airlines considering that tankering was an acceptable way of widening the airports accessible to hydrogen-powered aircraft while another was concerned about the risk of aircraft being diverted and then stuck on the ground without fuel.

5.30 For full-service carriers, adoption of hydrogen aircraft necessarily implies a split fleet, since long-haul hydrogen-powered aircraft are not likely to be available in the medium term. Although not ideal, it was considered that this could be managed, but the sub-fleet size would need to be at least 10 aircraft to be viable.

Public policy

5.31 There was a consensus that public policy measures and incentives were needed to support the development and then roll-out of hydrogen-powered aircraft. As noted above, these would include parity of pricing and availability of hydrogen fuel and public support for aircraft development and acquisition.

5.32 In addition, it was suggested that incentives could be introduced for hydrogen-powered aircraft through reduced airport and en route charges for such aircraft, which would require policy interventions.

5.33 To support the availability of hydrogen at airports, it was suggested that airports not be made responsible for ensuring the environmental sustainability of hydrogen fuel. This should be dealt with as part of wider environmental policy, both in relation to hydrogen production (whether sufficiently "green") as well as liquefaction of hydrogen at airports if supplied in by pipeline in gaseous form [as is anticipated to be likely]. It was considered that, while airports should ideally use green electricity to power the hydrogen liquefaction process, this should be the responsibility of the national grid in the relevant country.

5.4. Airports and representatives

Introduction

5.34 Steer and DLR held interviews with four airports and received written inputs from a further six, facilitated by airport representatives. These are summarised below.

Understanding of the capabilities of hydrogen and electrically powered aircraft

5.35 There was a consensus among the airports that hydrogen aircraft would be likely to be narrowbodies with up to about 200 seats operating on short/medium-haul routes. One airport also mentioned a separate category of smaller aircraft with under 100 seats. While some airports considered that the Airbus target of entry into service in 2035 was realistic, another commented that it was unlikely before 2040. The importance of narrowbody hydrogen-powered aircraft being able to fit within current ICAO Code-C aircraft dimensions was emphasised (and with length limited to a maximum of 35m), door positions and other dimensions as similar as possible to those of existing aircraft such as the A320.

5.36 There was also a consensus that electrically powered aircraft would be small, with some mentioning 10 seats as the maximum size, although one airport thought that up to 50 seats might be possible. Flying range was expected to short, with figures of 160 Nm and 270 Nm being mentioned.

Technical pre-requisites to support hydrogen-powered or electrically powered aircraft

5.37 Most airports considered that supply of hydrogen to airports would need to be by pipeline, although trucks and ships were also mentioned. One airport noted that hydrogen pipelines would need to built in cooperation with other hydrogen users. Another airport mentioned the possibility, as an alternative to a pipeline, of producing hydrogen locally through electrolysis, although recognising the very high electricity usage involved. It was noted that hydrogen production was an issue of national or EU-level policy rather than specifically for airports.

5.38 Storage of hydrogen at the airports was not mentioned as a major concern, although some airports did not consider that they had sufficient space to store the tanks on site and might need to use nearby, or underground, facilities, subject to safety rules allowing this.

5.39 Refuelling aircraft was noted as the most serious concern by a number of airports. Refuelling by truck/bowser on the apron was considered feasible, but there were doubts about the ease, feasibility and cost of an on-airport pipeline network to supply liquid hydrogen to airport stands. It was considered likely that not all aircraft stands would be able to have a pipeline/hydrant system installed. There were also concerns about whether the rapid turnarounds required by short-haul carriers (especially low-cost carriers) would be feasible and whether refuelling at the aircraft stand with passengers on board would be possible.

5.40 There was a divergence of views between airports, with some smaller and medium-sized airports considering that it would be possible to rely on trucks/bowsers for refuelling, while larger airports considered that it would be necessary to install pipelines and hydrants to supply liquid hydrogen to avoid congestion. It was cautioned that airport pavements would need to be able to cope with the presence of cryogenic pipelines and that asphalt pavement might not be able to withstand the low temperatures without degradation. However, concrete pavements would be able to handle this.

5.41 For electrically powered aircraft, the options of rapid charging and battery swapping were mentioned. Rapid charging could require upgrades to infrastructure, while battery swapping could lead to issues of safety and responsibility if aircraft from different companies re-used batteries.

5.42 One airport noted the very significant increase in electricity supply required to support the liquefaction of hydrogen, noting its concern that the electricity grid in its region was already at maximum capacity and might not be able to support the additional power transmission required.

Commercial and financing pre-requisites to support hydrogen-powered or electrically powered aircraft

5.43 There was a general consensus that additional charges for the use of infrastructure supporting hydrogen and electrical aircraft would not be appropriate, because the objective was to encourage the transition to these new technologies. Some airports suggested that there should be discounts for such aircraft, despite the additional infrastructure costs involved.

5.44 It was widely considered that public subsidies and other support would be needed in order to facilitate the development of the necessary infrastructure, particularly in the initial phases of roll-out. However, it was considered necessary in the longer run for the new infrastructure to be profitable for airports.

5.45 There was less concern with regard to specific infrastructure for hydrogen fuel handling, as it was assumed that this would be built and maintained by third parties (e.g. fuel companies) rather than by the airports themselves.

5.46 Some public sector support for electrical airport charging infrastructure was thought more likely to necessary, as this was more likely to be developed by the airports directly.

5.47 Acceptability of the new technology to the flying public was considered to be an obvious necessity, but such acceptability was not considered likely to be a barrier and indeed as the need for decarbonisation became more widely understood, would be seen to be a necessity.

Public policy / regulatory measures required

5.48 Consistent with the comments above, most airports considered that financial support from the public sector were a necessity for the roll-out of hydrogen aircraft to take place.

5.49 In addition, most also considered that carbon pricing, with the effect of making conventional flight powered by fossil fuels more expensive, was essential in order to provide the incentives to make the transition happen. One airport expressed a preference for the use of carbon prices, rather than fuel taxes, as the mechanism for making conventional flight more expensive.

5.50 Most airports recognised the need for suitable safety procedures and certification and some emphasised the need for international coordination, e.g. through ICAO, in order to facilitate a uniform and efficient approach. Training and certification for personnel was also recognised, particularly in relation to staff undertaking aircraft refuelling.

Individual airport comments on fuel usage and other issues

5.51 Steer provided estimates of the projected hydrogen fuel usage (tonnes) in 2035, 2040, 2045 and 2050, based on the DLR/Steer roll-out scenario, to each of the four airport companies with which interviews were held. In addition, estimates of likely fuel storage for liquid hydrogen (in m3) and electricity requirements for the liquefaction of gaseous hydrogen before storage (in TWh). The purpose was to gauge the reaction of each airport to these estimates and whether they considered them to be realistic or plausible in terms of order of magnitude.

5.52 Comments were received from three of the airports, indicating that the DLR/Steer annual hydrogen fuel usage forecasts were broadly consistent with their own projections (or in one case potentially lower than their own forecast). One airport considered that the electricity requirement for hydrogen liquefaction might be overstated, while another noted that it did not have sufficient storage on site to meet the requirements estimated by DLR/Steer, but would need to look for additional storage off-site.

5.53 One airport noted the importance of access to hydrogen supply and stated that it is engaged with a project to develop a gaseous hydrogen pipeline. However, it also noted the constraint on the electrical power grid in its region which might prevent it from acquiring sufficient power to liquefy the hydrogen arriving at the airport in gaseous form.

5.5. Hydrogen fuel experts

Introduction

5.54 Steer spoke to the Institute Environmental Technology and Energy Economics at Hamburg Technical University (TUHH), researchers into the technology and economics of alternative fuels including hydrogen. In addition, Steer spoke to a company specialising in cryogenic infrastructure.

5.55 The purpose was to understand the issues of producing and transporting green hydrogen fuel to airports, storing it at airports and handling liquid hydrogen fuel and supplying this to aircraft.

Institute of Environmental Technology and Energy Economics at Hamburg Technical University

5.56 TUHH provided some key parameters concerning the following aspects of hydrogen production and handling:

- clean hydrogen production methods;
- hydrogen transportation;
- boil-off of liquid hydrogen;
- demand for electricity for hydrogen production and liquefaction;
- power generation capacity requirements.

Production

5.57 Green hydrogen is produced by water electrolysis using renewable electricity. The main energy sources are expected to be photovoltaic and wind power, but in some locations hydro power and concentrated solar power might also play an important role. Another option is “turquoise hydrogen”, which is a relatively clean alternative using methane gas as an input and storing the carbon as a solid, although leakage of methane gas means that there will be some greenhouse gas impacts.

5.58 Power-to-liquid (PtL) fuels, a subset of broader Sustainable Aviation Fuels (SAFs), require more hydrogen in the production process than would be required if a solely hydrogen energy system was utilised due to additional losses in the production process. There are also more significant non-CO2 effects with the combustion of PtL fuels relative to direct hydrogen use in aviation.

Transportation

5.59 Pipelines for gaseous hydrogen and to some extent transport of liquid hydrogen in cryogenic-capable vehicles are likely to be the cheapest methods for transporting hydrogen over long distances over land, noting that if hydrogen is transported via gaseous pipeline there will be large green energy requirements at the airport in-order to liquefy the hydrogen for use in aircraft. On water, ships carrying liquid hydrogen are the cheapest option.

5.60 For transportation by pipeline, converting natural gas pipeline infrastructure is technically feasible. However, there are several considerations to be aware of, such as: the pipeline will likely need to continue to be used for natural gas necessitating dual use or parallel infrastructure, the number of compressors and extraction points will differ for hydrogen compared to existing natural gas infrastructure and the quality of hydrogen in a dual use system may not be suitable for some end uses without subsequent purification processes.

5.61 The main challenge for transporting liquid hydrogen is to avoid boil-off losses (discussed below). Estimates for the maximum trucking storage are around 4 to 5 tonnes of liquid hydrogen per truck.

5.62 Alternative means of transport of hydrogen in compounds such as ammonia and liquid organic hydrogen carriers (LOHC) are feasible, but need significant additional energy to release the hydrogen from the organic states (cracking), higher than that required for the liquefaction of hydrogen. The purity of the hydrogen stored in compounds can also be an issue.

Boil-off of liquid hydrogen

5.63 The rate of “boil-off” of liquid hydrogen varies enormously depending on size (and shape) of the storage vessel, the quality of insulation, the level to which the vessel is filled and frequency of emptying / refilling. In NASA’s large-scale facilities, 0.1% boil-off per day has been reported, whereas at a smaller scale (e.g. a cryogenic-storage truck) losses can be up to 5%. The estimate reported by Steer of 1% a day for spherical tanks as might be used at airports is credible. It is reasonable to assume only minimal boil-off from aircraft liquid hydrogen tanks in normal operation, including tankering of fuel.

Electricity demand

5.64 There are significant green energy requirements for both production and liquefaction of green hydrogen. Production energy requirements are expected to be around 50kWh in 2030, falling to 47kWh/kg of hydrogen by 2050 with liquefaction energy requirements ranging between 6 and 10kWh/kg of hydrogen (7.4kWh is a practical mid-point estimate for liquefaction energy requirements).

5.65 The levels of electricity energy required are highly significant compared to the energy content of hydrogen, which is 33.3 kWh/kg (equal to 120MJ/kg). In particular, liquefaction, at 7.4kWh/kg is equivalent to 22% of the energy content.

Power generation capacity requirements

5.66 Energy requirements for hydrogen production and liquefaction can be calculated using the parameters quoted above for production (47kWh/kg) and liquefaction (7.4 kWh/kg) for the long term. In order to estimate the level of power output required to supply the energy required (e.g. to liquefy gaseous hydrogen at a particular airport), it is necessary to consider the “full-load hours” available in a year for the relevant power source.

5.67 While there are 8,760 hours in a year (24 x 365), the full-load hours from renewable sources of electricity are significantly less, ranging between 3,000 and 5,000 hours per year, with 4,000 hours being a reasonable figure. Higher “full-load hours” would be available from sources such as nuclear power (which does not generate CO2 emissions) or indeed from fossil fuel sources such as coal and gas, but these latter two would of course not be “green”.

Cryogenics supplier

5.68 The supplier explained the key points relevant to handling liquid hydrogen (LH2). LH2 needs to be stored at below -253□C and is liquefied through cycles of compression. This is done industrially by companies such as Air Liquide and Linde.

5.69 For the distribution of LH2, closed loop systems are appropriate to avoid boil-off losses. Insulation is the most important factor. Pipelines need to be vacuum sealed with an inner and outer tube (approximately 5cm and 7cm respectively), with insulation against radiation and minimal connections between the inner and outer tubes.

5.70 Storage of LH2 is most efficient in spherical containers to minimise boil-off losses, which can be kept to 1% per day. In practice, other shapes such as cylindrical tanks can be used, with correspondingly higher boil-off rates (e.g. 1.5% per day).

5.71 Pipeline/hydrant systems for airports should be possible, but the distances are above those typically used at present (e.g. 300m). High levels of compression through multiple compressors would be required, using a closed loop system to minimise boil off and recompression of the gaseous hydrogen back into the storage. This would be expensive.

5.72 Delivering the fuel to the aircraft can be achieved with vacuum-insulated couplings (a “Johnston coupling”). These can support ground handling processes and the necessary flow rates. Maintenance and longevity of the equipment would be non-trivial to avoid build-up of ice and liquid contaminants such as liquid oxygen.

5.73 Venting of hydrogen may be necessary but should be minimised given that hydrogen is a greenhouse gas in its own right.

5.6. Financiers

Introduction

5.74 Steer spoke to the European Investment Bank (EIB) and an association of aircraft lessors.

5.75 The focus of the discussions was the expected level of interest in and barriers to the funding of hydrogen-powered aviation. The views of the two organisations differed in a number of areas, but there was consensus that commercial hydrogen-powered flight would not be rolled out quickly and that its contribution to aviation decarbonisation would be, at best, relatively modest by 2050.

EIB comments

5.76 The EIB noted that it has not yet received any requests for funding relating to hydrogen-powered aviation (or indeed to any other hydrogen-related infrastructure). It considered that any funding over the next five to eight years would be likely to relate only to financing research, rather than the development or roll-out of commercially viable products.

5.77 In relation to decarbonising aviation, the EIB recognised three different strands of technological development:

- battery-powered flight for short flights with small aircraft (including eVTOLs);
- hydrogen-powered flight for short/medium haul commercial services; and / or
- drop-in SAFs powering long-haul and potentially also short and medium haul flights.

5.78 Of these, the first is currently under development and it is anticipated that viable equipment will be in service within a few years. Commercial funding is available for these aircraft. Drop-in SAFs are well understood and are expected to be the only option for long-haul flight for a long time (decades) and can also be used for short-haul conventional aircraft. The EIB considered that the aviation industry is currently mainly focused on the production and deployment of SAFs rather than the other technologies.

5.79 The EIB considered that of the three technologies hydrogen had “the most to prove”, given its current low technological level of development and the need for a wide range of supporting infrastructure (green hydrogen production, distribution and deployment at airports as well as development of new aircraft types and operational processes).

5.80 The EIB also anticipates that (fossil) kerosene fuel will still have a role to play in aviation for a significant period up to and beyond 2050. Given the need for decarbonisation, this implies that it is likely to be necessary to fund direct decarbonisation technology, through carbon capture from the atmosphere.

5.81 It was noted that in its appraisal work, the EIB needed to use a projected carbon price consistent with remaining within the 1.5C global heating target, which was at the level of €800 per tonne of CO2. Despite this high price feeding through to consumers, its analysis still showed a continuing expansion of the industry, indicating the willingness of consumers to pay to fly.

5.82 Consistent with this, it is likely that investments can be funded, including in hydrogen aircraft and supporting infrastructure, once these have been demonstrated to be viable. Although the EIB would not consider becoming an aircraft lessor in its own right, it would be willing to fund aircraft lessors, or other financial vehicles, as part of supporting the roll-out of hydrogen-powered aircraft to airlines.

5.83 This could also apply to airports requiring support to fund related infrastructure, although the EIB considered that airports would be the “last to invest” in the hydrogen-powered flight ecosystem, but would do so once it was clear that there was a suitable level of demand from airlines.

Aircraft lessor association comments

5.84 The aircraft lessor association considered that hydrogen has a significant role to play in decarbonising aviation. However, it noted that:

- the technology is currently at a very early stage;
- EIS in 2035 appears optimistic, with 2040 being more likely; and
- the impact of hydrogen-powered flight will be limited by 2050, with only 12% of flying fuelled by hydrogen in that year.

5.85 The lessor association also noted that safety risks needed to be added to the potential barriers to roll-out of the technology. In particular, it was important to demonstrate safe operation, and to avoid any major incidents, during the development of the new technology.

5.86 In relation to the likely availability of capital to invest in hydrogen aircraft, ALI noted that there is very strong pressure from investors in the aircraft leasing industry to move towards sustainable activities, and that in future it may be difficult to raise funds for investment in aircraft not meeting the criteria set out in the EU's Sustainable Taxonomy as it will apply to aviation.

5.87 As evidence for this, it was noted that its members have already invested in over 1,000 eVTOL aircraft, despite this being a new and unproven technology. This reflected a strong desire to invest in sustainable technology.

5.88 More generally the association noted that lessors have historically had a positive attitude to financing projects with new technology risks, for example the 747 when first developed, the original A320 (first fly-by-wire aircraft) and the geared turbofan engine. The fact that the focus of hydrogen aircraft was in the size range of short-haul narrowbody aircraft would reduce the commercial risk, as these are the most widely used class of aircraft.

5.89 Based on this, it was felt that the leasing industry would be keen to invest in hydrogen aircraft once the technology was proven. However, it should be expected that the initial roll-out is likely to be relatively slow (< 100 aircraft p.a.).

5.90 On policy issues towards sustainable aviation, it was noted that the EU approach tended to be based on the "stick" (e.g. blending mandates, fuel taxes), whereas the US approach tended to be based more on the "carrot" (e.g. subsidies for sustainable aviation fuels, SAFs). As a result, most SAF manufacturing is in the US and not in Europe. It was also noted that Europe has used the carrot approach in the past, e.g. in relation to wind turbines in Germany, which was successful.

5.7. Authorities

Introduction

5.91 Steer spoke to the European Union Aviation Safety Agency (EASA) and the United States Government's Federal Aviation Administration (FAA).

5.92 The focus of the discussions with EASA was the requirements for the regulatory approval of hydrogen-powered aircraft. EASA provided a referral to the FAA, where the conversation focused on the potential for hydrogen-powered aircraft in supporting the decarbonisation of aviation.

5.93 Therefore, while complementary, the discussions with EASA and with the FAA followed somewhat different agendas.

EASA

5.94 The purpose of the discussion was to gain an understanding of EASA's views on the likely roll-out of hydrogen and electrically powered aircraft as well as processes which would be required for safety certification.

5.95 In relation to earliest possible timescales for the roll-out of new technology aircraft, EASA's understanding was as follows:

- Small electric aircraft – 2027
- 19-seater aircraft using gaseous hydrogen – late 2027/28
- Regional aircraft powered by gaseous hydrogen (very short range) – 2029/30
- Regional aircraft powered by liquid hydrogen (<1000 nm range) – 2035
- Narrowbody aircraft powered by liquid hydrogen (<2000 nm range) – 2038
- Intercontinental aircraft powered by liquid hydrogen – 2040s or later.

5.96 The certification process for hydrogen-powered aircraft would, in principle, not be very different from that for conventional aircraft, using the standard certification specifications (CS-25 for Large Aeroplanes and CS-23 for Commuter Aeroplanes). These specifications are more based on performance requirements than on specific technological requirements, but nevertheless it can be expected that some changes would be required.

5.97 "Special conditions" would be used to cover the gap between the existing requirements and additional requirements for hydrogen aircraft and the certification specifications would be updated in due course. Work has been undertaken on the likely requirements by the FAA's Airworthiness Rulemaking Committee (ARC), to which EASA contributed[8]. The powerplants / engines would need to go through their own certification process according to the certification specification for engines (CS-E).

5.98 The original equipment manufacturers (OEMs) also need to be certified by being given a Design Organisation Approval (DOA) certificate. Existing OEMs such as Airbus already have these approvals, although they would need to be updated to cover the new risk areas inherent in the design of hydrogen aircraft. New manufacturers entering the market would need to obtain a DOA as part of the development process.

5.99 In terms of resourcing, EASA has limitations on the resources it can deploy and the challenge would be to identify suitably qualified engineers with the necessary competencies able to review manufacturers' plans for the new technologies. It would

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8 https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/Energy%20Supply%20Device%20ARC%20Recommendation%20Report.pdf

be expected that the organisation might need another 10 to 20 staff above the 230 to 250 currently there.

5.100 Looking beyond Europe, while EASA is responsible for the certification of aircraft produced by European manufacturers, these certifications would need to be validated by the competent authorities when adopted by airlines based in other jurisdictions. Thus, for example, for US airlines to purchase an aircraft manufactured in Europe, an FAA validation is needed. It will be important to work with other safety regulators to avoid unnecessary duplication of effort in certifying the new technology aircraft.

5.101 At the international level, ICAO Annex 8, covering airworthiness standards, is unlikely to need to be updated. However, ICAO's involvement would be required in relation to environmental standards, particularly for non-CO2 emissions such as NOx and H2O. The former is a by-product of combustion of engines using hydrogen and the latter – water vapour – is a by-product of all hydrogen usage (whether by combustion or fuel cell). The importance of limits on these emissions is still subject to significant research and may become a political issue.

5.102 In relation to the certification of other elements of a hydrogen ecosystem beyond the aircraft itself, maintenance and crew procedures can be covered by rules relating to training. Rules may be required in relation to aircraft refuelling, including what can be done at stands close to terminal gates and firefighting. In principle, refuelling at aircraft stands should be possible, but likely to require bespoke equipment and procedures which will need to be refined.

5.103 Storage of hydrogen fuel at airports may be beyond EASA's remit and covered, rather, by national regulations. This would also be the case for production and transportation of the fuel to the airport. However, there may be a need for EASA to be involved in certifying the purity of liquid hydrogen as aircraft fuel.

5.104 More generally, it was perceived that the availability of green hydrogen could be the biggest bottleneck for achieving hydrogen-powered aviation.

FAA

5.105 Steer held an interview with a senior environmental advisor at the FAA. The advisor made it clear that he did not speak for the US Government.

5.106 In the United States' 2021 Aviation Climate Action Plan[9], released at the COP 26 conference in autumn 2021 the FAA sets out a "big picture" view of the potential for the use of hydrogen for the decarbonisation of aviation:

- It is relatively easy to design an aircraft powered by hydrogen fuel (noting that all but the smallest aircraft would require to store fuel in liquid hydrogen form).
- However, to create the infrastructure needed to support hydrogen-powered flight, including the production, distribution and liquefaction of hydrogen is very difficult.
- Further, to provide this infrastructure economically is "nearly impossible".

[9] https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

5.107 It was noted that this has been recognised internationally, with little likelihood of significant use of hydrogen fuel before 2050. This is set out in the International Civil Aviation Organisation (ICAO) report "on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO2 emission reductions"[10], published in March 2022.

5.108 The difficulties with the use of hydrogen fuel for aviation stem from difficulties with distribution of the fuel to airports, particularly given the need for hydrogen to be in liquid form to have sufficient volumetric energy density to power the aircraft over a significant distance, as described below.

- It is not technically possible to pump liquid hydrogen over long distances (i.e. from production site to airports) due to the equipment and energy needed for the cryogenic temperatures required to be maintained and problems such as boil-off losses.
- While hydrogen can be pumped through pipelines in gaseous form, the aviation industry would not be able to afford to pay for the pipeline infrastructure required to be constructed.
- The gaseous hydrogen would then need to be compressed/liquefied at or near the airport. However, this liquefaction would require very large levels of electrical power input. For example, to liquefy sufficient hydrogen to replace the aviation fuel currently used by Charles-de-Gaulle airport would require a power supply greater than that of the largest current existing nuclear power station.

5.109 More generally, while there are expected to be multiple applications of hydrogen by a range of industries as part of moves to decarbonise society, aviation is unique in requiring the hydrogen in liquid form. This implies that aviation would need to pay a premium over other users for hydrogen.

5.110 It was noted that the United States has a different appetite for regulation compared with European countries. There is no federal Emissions Trading Scheme (ETS) in the US and the country does not mandate climate reduction. Instead, the approach has been to incentivise decarbonisation through tax incentives. These are extensive, but quite complicated. In addition, some States, particularly California, have developed additional incentive mechanisms.

5.111 The US approach to decarbonise aviation is set out in the Aviation Climate Action Plan, with specific measures set out in President Biden's plan to advance "the Future of Sustainable Fuels in American Aviation"[11], published in September 2021. This plan focuses on expanding the use of SAFs, particularly biofuels, with a "new Sustainable Aviation Fuel Grand Challenge to inspire the dramatic increase in the production of sustainable aviation fuels to at least 3 billion gallons per year by 2030"[12].

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[10] https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf

[11] https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

[12] This corresponds to 9 million tonnes of aviation fuel, or 11% of US aviation fuel consumption in 2019.

5.112 In relation to the certification of hydrogen aircraft, reference was made to the report by the FAA's Airworthiness Rulemaking Committee (ARC) – see footnote 8 above.

6. Technical challenges

6.1. Introduction

6.1 This chapter considers the technical challenges facing the roll-out of hydrogen and electrically powered aircraft described in Chapter 4, taking into account our desktop research and comments by stakeholders. The key challenges relate to:

- green hydrogen production and distribution (getting hydrogen to airports);
- airport infrastructure (on-airport storage and refuelling facilities); and
- aircraft operations (ground handling, maintenance, training and certification).

6.2 These are discussed in the sections below.

6.2. Green hydrogen production and distribution

6.3 This section identifies the challenges that exist in the production and supply of green hydrogen across Europe, including for the purposes of aviation fuel. There are likely to be significant competing requirements for green hydrogen, potentially creating bottlenecks in supply and increasing costs, though also allowing some co-funding of infrastructure. Physical distribution networks for hydrogen will need to be created to support all these needs. In addition, aviation's use of hydrogen requires the fuel to held in liquefied form (except for very small aircraft), so that liquefaction of hydrogen is a particular, aviation-specific requirement.

6.4 These challenges are described below. While some of these challenges go beyond those specific to the aviation industry, it is important to understand the context in which hydrogen-powered flight would take place, in particular the current scarcity of "green" hydrogen and competition for such hydrogen supplies from other industries. The challenges feed into the "problem tree" (Figure 8.1) in Chapter 8 Policy options, where they are discussed from paragraph 8.8.

Green hydrogen production

Forms of commercial and industrial hydrogen

6.5 There are several industrial methods of hydrogen production, which have been labelled with colours (grey, blue, turquoise, green) to indicate the level of carbon emissions involved. In decreasing order of carbon emissions, these methods include:

- Grey hydrogen – synthesised from a natural gas base13 through the 'steam reforming' process.
- Blue hydrogen – involves production from natural gas, but is combined with carbon capture, utilisation and storage (CCUS) to become a carbon neutral source of hydrogen.

[13] IRENA (2019), Hydrogen: A renewable energy perspective, International Renewable Energy Agency

- Turquoise hydrogen – similarly to blue hydrogen, the production process for turquoise hydrogen stems from natural gas, but uses ‘methane pyrolysis’ to produce hydrogen and a solid carbon by-product called “carbon black”.
- Green hydrogen – produced by the process of electrolysis of water using renewable energy14. As a result, no carbon emissions are released either through the production of electricity or as a result of electrolysis process itself.

6.6 The environmental benefits of green hydrogen relative to the other current and future hydrogen production methods are clear, with no carbon emission emitted throughout the production phases. It can be considered fully renewable, since there are no limits in principle to the feedstock (electricity and water). The barriers that could hinder the production of green hydrogen are principally in the areas of availability of green electricity and availability of sufficient electrolyser capacity for production of hydrogen from the water feedstock.

6.7 However, barriers remain to successful implementation of all green hydrogen alternatives namely: cost of natural gas (blue, turquoise), scale and cost of carbon capture, usage and storage (blue), scale and cost of green power and electricity (green), and electrolyser cost (green). The remaining portions of this section will focus only on the barriers associated to the production of green hydrogen.

Sources of green power and electricity

6.8 Renewable and green sources are tending towards becoming the cheapest source of electricity and the share of renewable energy electricity consumption across the EU has grown to 37.5% in 2020 from 23.3% in 2011[15]. The sources of renewable electricity generated in the EU in 2020 were principally wind power (36% of the total), hydro (33%) and solar (14%). In some Member States, such as Austria and Sweden, more than 70% of electricity consumed was generated from renewable sources.

6.9 Although there have been increases in green electricity capacity and reduction in green electricity generation unit costs, there remains a significant challenge in bridging the gap between current capacity and cost levels and those required to satisfy energy targets. Analysis from IRENA suggests that the cumulative investment cost for additional renewable energy generation across the EU could reach €393billion (USD 433billion[16]) by 2030, to achieve a 34% share for renewable energy. This is significantly larger than the investment costs associated with distributing hydrogen across Europe, discussed later, which amounts to tens of billions of Euros.

6.10 Ensuring that further green electricity generation capacity is added at the required levels to satisfy the energy requirements of electrolysers across Europe, as well as other industries, will be key to meet the needs of future European green hydrogen consumers.

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14 IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency

15 Eurostat, NRG_IND_REN

16 IRENA (2018), Renewable Energy Prospects for the European Union

Electrolysis

6.11 Electrolysis is the process which produces hydrogen from water using electricity. It has the potential to generate hydrogen without any carbon emissions if green electricity is used. In the cases where green electricity is not used, at the average grid carbon intensity of France (50-70gCO2/kWh[17]) an electrolyser produces hydrogen at 2.6-3.6gCO2/gH2 which is a similar level to a natural gas steam reformer with a carbon capture rate of 60-70%[18].

6.12 Electrolysers are a mature technology having been used in industrial processes, such as the chlor-alkali process, for a long time. However, dedicated hydrogen production via electrolysis is a tiny fraction of the total hydrogen produced globally every year (30kt per year or 0.03% of total hydrogen produced). Europe currently has approximately 40% of global electrolyser capacity with 300MW in total[19].

6.13 There is therefore a major challenge in scaling up production of green hydrogen to deliver the required quantities of hydrogen by 2050 and in parallel significantly bring down investment and operating costs. Technological innovation will be necessary to improve the efficiency and lifespan of electrolysers, primarily through the use of new catalysts and configurations as well as through likely standardisation as a result of mass production[20].

6.14 Electrolysis capacity is already growing rapidly, with the both the IEA[21] and IRENA noting that a large number of projects are planned or have recently become operational, with capacity potentially breaking the 1GW barrier in 2022 (equivalent to roughly 170kt of green hydrogen). This has the potential to reach between 54GW and 91GW by 2030 leading to production of between 4.9Mt and 8.3Mt of green hydrogen. However, this level of capacity falls well short of goals set to reach a net zero emissions by 2050 which requires 850GW of capacity by 2030 and output of 80Mt of green hydrogen. Therefore, significant further effort is required to encourage further capacity generation.

Aviation and other uses for green hydrogen across Europe

Green hydrogen required for aviation

6.15 Green hydrogen is seen as a potential alternative or complement to the use of drop-in sustainable aviation fuels (SAFs) in the decarbonising of the EU and global aviation sector[22]. The use of hydrogen in aviation to tackle carbon emissions was analysed by in a report by McKinsey undertaken for Clean Sky 2, which estimated that with aviation traffic volume growth of between 3-4% per annum (p.a.) and absent any mitigations from the use of hydrogen, carbon emissions will more than double by

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[17] European Environment Agency, https://www.eea.europa.eu/data-and-maps

[18] IEA (2021), Hydrogen, IEA, Paris https://www.iea.org/reports/hydrogen

[19] Ibid

[20] IRENA (2020), Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal, International Renewable Energy Agency

[21] IEA (2021), Hydrogen, IEA, Paris https://www.iea.org/reports/hydrogen

[22] Drop-in SAFs are manufactured hydrocarbon chains chemically similar to kerosene derived from fossil fuel sources (usually crude oil). They can be “dropped in” to existing aircraft and airport fuel facilities.

2050[23] even assuming an emissions efficiency improvement of 2% p.a. To avoid this, McKinsey considered different scenarios for the use of hydrogen-powered aircraft. In its more conservative scenario, a global demand for hydrogen for aviation of 42Mt by 2050, which is similar to the level estimated using our model, described in Chapter 4 above.

6.16 Note that while hydrogen is also a feedstock within the production of some SAFs such as those based off hydroprocessed esters and fatty acids (HEFA)[24] as well as electrofuels, this is not included in the hydrogen usage estimate above. The figure below provides an overview of the various different forecasts for hydrogen usage for aviation found in the literature.

23 McKinsey & Clean Sky 2. Hydrogen-powered aviation, A fact-based study of hydrogen technology, economics, and climate impact by 2050

24 ICAO, Sustainable Aviation Fuels Guide

2022

Hydrogen-powered Aviation, McKinsey – Proof of technology feasibility and certification of commuter aircraft as well as a short-range aircraft prototype, prior to 2028.

2025

2028

Hydrogen-powered Aviation, McKinsey – Within the 'maximum decarbonisation scenario', in 2028, hydrogen aircraft will replace current aircraft with up to medium-range, continuing to 2038.

Scaling up of R&I activities, with focuses on safe and efficient refuelling.

The proposed partnership for European Aviation, SRIA – Potential ground based hydrogen propulsion test in 2027, in-flight tests prior 2030.

2030

The proposed partnership for European Aviation, SRIA – Regional and short-/medium-range aircraft definitions will be set so that they can be available by 2035.

15% of aviation fuel will be made up of low carbon sustainable aviation fuel (SAF). Next generation aircraft with 30-50% lower fuel burn and emissions.

Next generation propulsive systems (revolutionary efficiency vs. current SOA) with an EIS of 2030+.

Hydrogen-powered Aviation, McKinsey – Within the 'efficient decarbonisation scenario', in 2030, hydrogen aircraft will replace current aircraft with up to medium range, continuing to 2040.

Integration of hydrogen aircraft in the air transport system, ACI – 10Mtonnes of renewable hydrogen by 2030, grown from 1Mtonne in 2024. **Also noted by EC and Hydrogen Europe.**

Cost of renewable hydrogen could drop by up to 40% with renewable energy costs falling and higher electrolyser efficiency.

Hydrogen Europe – Fully functional hydrogen propulsive system (tank, fuel system, engine), fully engaged certification process, all key technology bricks at TRL6, environmental impact of hydrogen fully assessed (incl. non-CO2 effects).

2035

Hydrogen-powered Aviation, McKinsey – Within the 'efficient decarbonisation scenario', in 2030, hydrogen aircraft will replace current aircraft with up to medium-range, continuing to 2040.

Longer range aircraft prototype, safe and efficient airport refuelling setup.

Waypoint 2050, ATAG – Technology programmes envisage an EIS of 2035 for hydrogen in aviation, citing availability and cost of green hydrogen globally as a challenge.

2040

Hydrogen-powered Aviation, McKinsey – Within the 'efficient decarbonisation' and 'maximum decarbonisation' scenarios 9Mtonnes and 43Mtonnes of LH2 will be required by aviation per year in by 2040, respectively.

2045

2050

Hydrogen-powered Aviation, McKinsey – Within the 'efficient decarbonisation' and 'maximum decarbonisation' scenarios 40% and 60% of all aircraft are switched to LH2 by 2050, respectively.

42Mtonnes and 135Mtonnes of LH2 will required by aviation per year in by 2050 in each scenario.

Large scale refuelling infrastructure and a prototype of a 'revolutionary' longer range aircraft concept.

Waypoint 2050, ATAG – 20-30% of aviation energy will be hydrogen (43Mtonnes), 71.5% SAF,3.5% battery. 445Mtonnes of SAFs by 2050, in aggressive scenario.

Destination 2050 – 3.7MTonnes of hydrogen used for intra-European hydrogen aircraft. 71Mtonnes of renewable hydrogen produced in the EU.

Performance analysis of evolutionary hydrogen powered aircraft, ICCT – LH2 narrow and turboprop aircraft could service 31-38% of all passenger aviation traffic (RPKs) by 2050.

A realistically achievable adoption rate between 20-40% could mitigate 6-12% of passenger aviation CO2e emissions by 2040.

Modest growth scenarios (20-40% RPK coverage in 2050) suggest 18.9-37.8Mt of LH2 in 2050. Within traffic scenario with +3.0% CAGR over the '19-'50 period.

Figure 6.1: Aviation specific hydrogen demand timeline with key milestones (Sources: McKinsey & Clean Sky 2. Hydrogen-powered aviation, A fact-based study of hydrogen technology, economics, and climate impact by 2050. SRIA, The proposed partnership for European Aviation. ACI, Integration of hydrogen aircraft in the air transport system. Hydrogen Europe. ATAG, Waypoint 2050. Destination 2050. ICCT, Performance analysis of evolutionary hydrogen aircraft.)

Other uses for hydrogen in Europe

6.17 In 2018 the total demand in Europe for hydrogen was estimated at 8.3Mt[25]. The largest share of this demand come from industries (46%, principally ammonia, methanol and other chemicals) and refineries (45%). As part of the Fit for 55 package, the European Commission proposed a modification of the Renewable Energy Directive to include a 50% renewable hydrogen consumption across all industries currently using hydrogen, by 2030[26]. However, it should be noted that transport uses made up of less than 0.1% of the total hydrogen demand in Europe in 2018 (hence not shown in the figure), although this is increasing rapidly.

6.18 In order to reach net zero emissions, the future demand for green hydrogen is expected to increase rapidly with the IEA estimating a total hydrogen demand of 211Mt[27] by 2030 globally (9.1% CAGR) with significant increases across industry applications, transport, power, and grid injection. The only notable decline is seen in the refining industry, which is consistent with a higher uptake of green energy. This breakdown of future global industry demand is displayed in Figure 6.2, for the IEA Net Zero Scenario. Within the EU, proposed annual hydrogen demand is expected to be equivalent to 1,130 TWh[28] (28.7Mt) of energy by 2040.

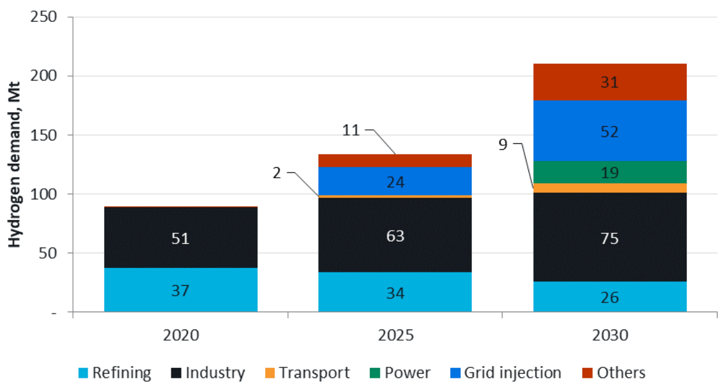

Figure 6.2: Global estimated hydrogen demand segregated by industry uses (Source: Steer analysis of IEA data for their Net Zero Scenario[29])

Summary

6.19 Based on analysis by IEA, global aviation is estimated to demand 40Mt of hydrogen in 2050. In comparison, across all industries within a net zero scenario, hydrogen

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[25] Hydrogen Europe, Clean Hydrogen Monitor 2020

[26] Fit for 55 package, COM/2021/550 final

[27] Ibid

[28] Navigant, 2020. Gas for Climate. Gas Decarbonisation Pathways 2020-2050. https://gasforclimate2050.eu/publications

[29] IEA, Global hydrogen demand by sector in the Net Zero Scenario, 2020-2030, IEA, Paris https://www.iea.org/data-and-statistics/charts/global-hydrogen-demand-by-sector-in-the-net-zero-scenario-2020-2030

demand is estimated at 528Mt of which transport uses 106Mt[30]. Hence, aviation would represent only 8% of total hydrogen demand, as many other industries are more energy intensive than aviation and may therefore have stronger demand for green hydrogen. This competition for resource, with potential supply bottlenecks and resultant scarcity pricing may present an important large barrier to the successful role out of green hydrogen in aviation.

Distribution of hydrogen in Europe

6.20 There are a number of ways that hydrogen can be distributed across Europe. In future, distances for the transport of hydrogen are likely to be longer than at present, because green hydrogen production is expected to be concentrated in locations with high availability of green electricity (for example, near coastal areas with significant wind power generation), in contrast to the production of hydrogen from fossil fuel sources, which can be located near to current use by industrial consumers. Potential methods of distribution include:

- Gaseous pipeline supply – This involves connecting hydrogen production centres and consumers directly using pipeline infrastructure to deliver gaseous hydrogen. This is similar to current methods of distributing natural gas across Europe.
- Road/waterway supply – This method delivers liquid hydrogen by trucks and ships, directly from the production site to the consumer or port.

6.21 Based on consultation with stakeholders and a review of the literature, liquid pipeline supply is not considered feasible over long distances due to the pumping, cooling and insulation infrastructure required.

6.22 The likely most cost-effective way to distribute large quantities of hydrogen across long distances in Europe is through a network of pipelines for hydrogen gas[31]. This is due to the relative costs of electrolysis, transportation and liquefaction, with the case for the gaseous pipelines strengthened by the fact that there is significant pipeline infrastructure already in place across Europe, currently used for the transport of natural gas, which can be repurposed as the demand for natural gas (a hydrocarbon generating greenhouse gas emissions) reduces and the demand for green hydrogen increases.

6.23 As an illustration of a potential solution to green hydrogen across Europe, an initiative has been developed by Guidehous to develop a European Hydrogen Backbone[32] as a potential solution for the future distribution of green hydrogen across Europe. This initiative includes a future roadmap of the development of a European hydrogen pipeline based on using existing natural gas pipelines as well as additional new hydrogen pipeline infrastructure. This infrastructure will be used by both low carbon hydrogen (blue) and green hydrogen, with the former initially being available whilst green renewable electricity is scaled up across Europe.

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[30] IEA (2021), Net Zero by 2050, IEA, Paris https://www.iea.org/reports/net-zero-by-2050

[31] ACI Report – Based on NASA Study

[32] European Hydrogen Backbone (2020), How a dedicated hydrogen infrastructure can be created.

6.24 By 2040 a core European hydrogen backbone would be developed. This connects most western European countries as well as crucial extensions to central and eastern European countries, totally 22,900km in length. The backbone will also allow for large quantities of hydrogen to be imported from Northern Africa, the North Sea region as well as eastern Europe by 2050 as natural gas imports are replaced. Based off EHB analysis, this backbone would be comprised of 75% re-purposed natural gas pipelines and 25% additional hydrogen pipeline infrastructure with a theoretical capacity to meet the annual 1,130TWh[33] hydrogen demand in Europe by 2040. The scale and extend of this hydrogen backbone can be seen in Figure 6.3.

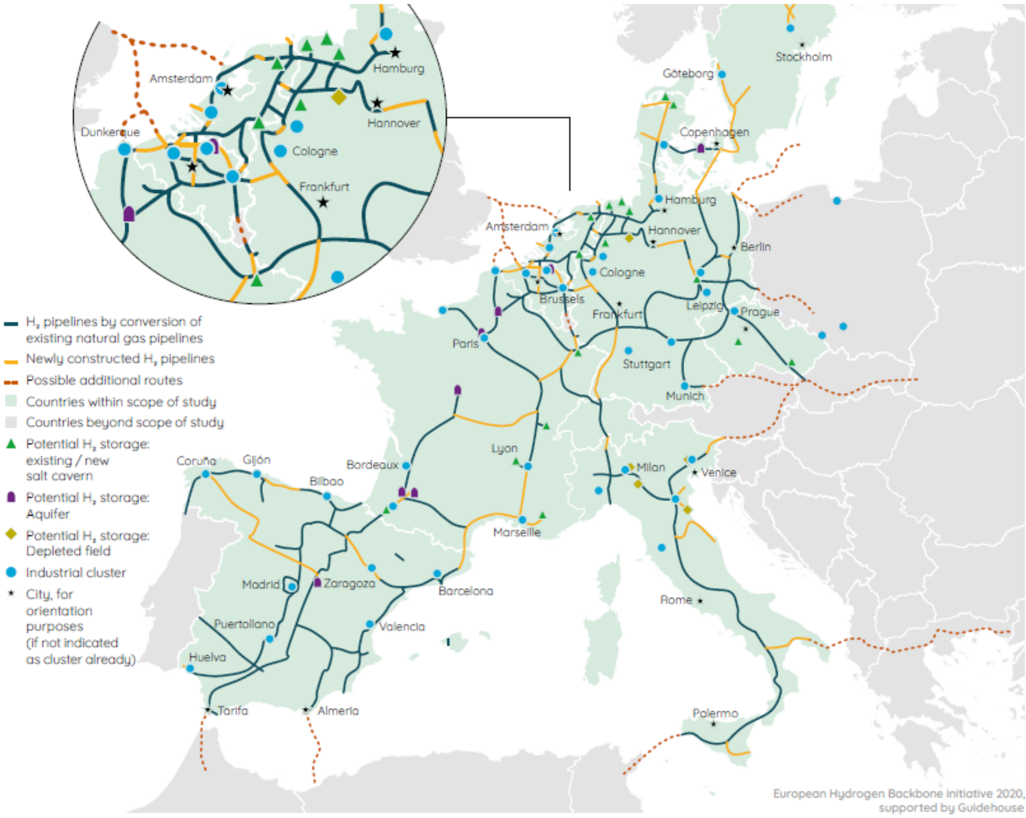

Figure 6.3: European hydrogen backbone, envisaged within the European Hydrogen Background project (Source: European Hydrogen Backbone Initiative[34] (reproduced with permission))

6.25 The investment costs of developing the backbone described in this section range from €27-€64billion, covering the full capital cost of building and retrofitting existing natural gas pipelines. The repurposing of the natural gas pipeline infrastructure is crucial in reducing the investment cost with this 75% of the backbone requiring 50% of the investment.

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[33] Navigant, 2020. Gas for Climate. Gas Decarbonisation Pathways 2020-2050. https://gasforclimate2050.eu/publications

[34] European Hydrogen Backbone (2020), How a dedicated hydrogen infrastructure can be created.

6.26 A further example of hydrogen pipeline being considered is the Delta Corridor project, connecting the port of Rotterdam with the German Rhineland region[35]. As explained to us in the stakeholder consultation process, Eindhoven Airport is participating in this project in order to help it secure supplies of hydrogen fuel.

Inbound supply of hydrogen fuel to airports

6.27 A further challenge remains for aviation, namely distributing green hydrogen away from central infrastructure used for all industries onward to particular airports.

6.28 Different mechanisms are potentially available for the supply of hydrogen to airports for use as fuel, noting that for aviation an additional step is required compared with for other industries, as the vast majority of hydrogen-powered aircraft fuel will need to be in the form of liquid hydrogen (LH2), due to its higher density compared to gaseous hydrogen. The figure below shows three potential distribution mechanisms:

1. No distribution to airport: green hydrogen generated and liquefied on airport site.

2. Hydrogen produced remotely and transported to the airport by gaseous pipeline, with liquefaction on site.

3. Hydrogen produced and liquefied remotely, with transport in liquid form to the airport (by ship, truck or, potentially, pipeline), noting that LH2 has to be kept at cryogenic temperatures due to its very low boiling point (-253 °C).

6.29 These mechanisms are illustrated in the figure below.

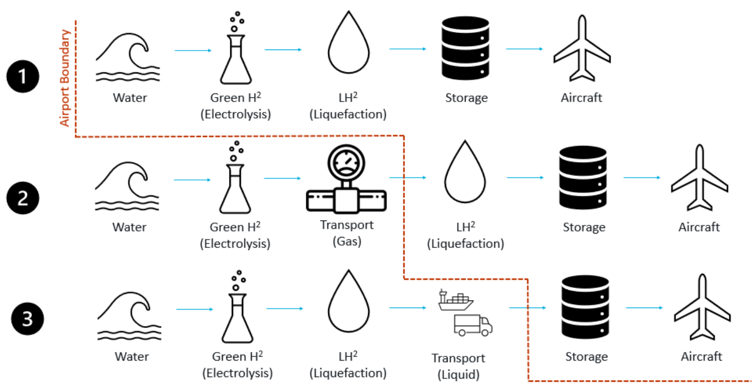

Figure 6.4: Green hydrogen production and distribution methods (Source: Steer. Note: Green electricity is needed in to produce green hydrogen via electrolysis.)

6.30 Supplying airports with liquified hydrogen via pipeline is not seen as economically viable[36] due to the boiling point of hydrogen (-253°C) will require extensive cooling of

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[35] https://www.portofrotterdam.com/sites/default/files/2021-06/202104id-095_delta_corridor_en.pdf

[36] ACI Report – Based on NASA Study

the pipeline. Supplying airports with liquid hydrogen via truck, following centralised liquification or import via ship, will likely be more suitable for lower quantities of airport hydrogen demand. Lower infrastructure investment costs may be needed with this distribution method, however managing large scale operation of trucks across the network, and at airport sites, to cater for large volumes may encourage airports to invest in dedicated hydrogen pipeline infrastructure. As previously mentioned, the likelihood that aviation is the only industry requiring liquified hydrogen may also result in gaseous pipeline infrastructure dominating the future distribution and supply system to minimise additional infrastructure costs for aviation and to make it possible tap into a larger distribution network

6.31 However, combining both gaseous and liquid hydrogen distribution streams would add inefficiencies related to the supply of hydrogen with the associated energy and financial costs of additional cycles of liquefaction.

6.32 Addressing this challenge will require, investments from airports and energy providers on re-purposing current inbound infrastructure or building new hydrogen dedicated infrastructure which in turn will rely on relative certainty of future use of hydrogen by airlines. This may lead to liquid hydrogen trucks being the initial inbound delivery method to allow proof of hydrogen aircraft and dual fuel airline business models. The lack of certainty of roll-out of hydrogen aircraft is in itself an additional challenge.

Liquefaction

6.33 Liquefaction of hydrogen will be required for the majority of uses of hydrogen in aviation due to the volume and structural weight requirements of aircraft. Liquefaction can either take place centrally or at the airport. Liquefaction is an energy-intensive process, and it is estimated that energy input of between 6- and 10 kWh/kg is required to convert gaseous H2 to liquid H2 (LH2), although the minimum theoretical energy required to liquefy hydrogen is 3.3kWh/kg[37], indicating that there is potential for the current rate to be improved. It is hoped that increased demand and future opportunities to integrate liquefaction with other processes will reduce this energy requirement. The cost of hydrogen liquefaction is of course in addition to the cost of production and transport of the hydrogen.

6.34 The costs of carbon neutral energy per kWh have reduced significantly in recent years to levels which are competitive against fossil fuel generated energy. Table 6.1 below presents the typical cost of liquefaction associated with a typical hydrogen aircraft fuel load (3 tonnes) assuming 7.4kWh/kg energy requirement for a series of energy sources. At 2021 prices, the cost of liquefaction is highly variable dependent on the source of energy used, ranging from €1,110 to €2,664 per aircraft fuel tank. This gives rise to potentially large differences in cost depending on the location of liquefaction and sources of energy available. If the average EU energy cost in H1 2021 is used this increases costs further to €4,884 per tank, in addition to the cost of production and transport of the hydrogen fuel. This can be compared with the costs of the same energy content of Jet A1, which would equate to around €9,880[38], which is an all-in price, including production and transport to the airport. These additional

[37] US Department of Energy (https://www.hydrogen.energy.gov/pdfs/9013_energy_requirements_for_hydrogen_gas_compression.pdf)

[38] 360,000 MJ = 42,420L LH2 ~ 10,400L Jet A1 – Assumes Jet A1 cost of €0.95 per litre (11 March 2022)

costs will need to be assumed by fuel suppliers at airports which make use of gaseous hydrogen supply and decentralised liquefaction (on-airport) and as a result are an additional challenge to be overcome to ensure widespread green hydrogen use in aviation.

Table 6.1: Estimated costs of liquefaction (Source: EnergyPost, Steer analysis)

Source	Energy Price per kWh[39]	Cost of Liquefaction
Photovoltaic (2021)	€0.05	€ 1,110
Onshore Wind (2021)	€0.05	€ 1,110
Concentrated Solar (2021)	€0.08	€ 1,776
Offshore Wind (2021)	€0.12	€ 2,664
EU Average H1 (2021)	€0.22	€ 4,884

6.35 The availability of sufficient electrical power to support the liquefaction also needs to be considered, as the electrical input can be material in relation to existing grid capacity. As noted in Chapter 5, an airport explained that there was not additional power available in the grid in its region. Even where such limits do not apply, significant additional electrical generating capacity is likely to be needed, potentially requiring additional power stations and electrical transmission infrastructure.

6.3. Airport infrastructure

6.36 The use of both hydrogen and electrically powered aircraft will require major changes to airport infrastructure. Unlike drop-in SAFs (biofuels or electrofuels, which are hydrocarbons similar to fossil-kerosene), hydrogen cannot be combined with existing aviation fuel, so it will require completely separate transportation and storage infrastructure facilities. Similarly, electric aircraft will require either rapid charging electric connections at aircraft stands or facilities for swapping batteries during aircraft turnarounds. The challenges involved feed into the "problem tree" (Figure 8.1) in Chapter 8 Policy options, where they are discussed from paragraph 8.22.

6.37 The options for refuelling hydrogen aircraft must also be considered. It is anticipated that aircraft will store hydrogen in liquid form (LH2), as this is its most dense state, however it should be noted that in this state it remains four times less dense in energy per unit volume than kerosene. Safety issues borne from handling LH2 must also be considered due to its flammability and also due to the temperatures required to keep it in its liquid form.

6.38 The section below primarily focus on the introduction of LH2 facilities at airports.

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[39] Energy Post (https://energypost.eu/5-charts-show-the-rapid-fall-in-costs-of-renewable-energy/#:~:text=For%20the%20first%20time%2C%20the,in%20comfortably%20within%20that%20range.)

Supply (on-airport)

6.39 The form of hydrogen supplied to an airport, as discussed in the section above, will determine the range of facilities maintained by an airport to ensure that LH2 is available for fuelling aircraft. These correspond to three primary pathways, each with differing infrastructural requirements and suitability of application illustrated in Figure 6.4 above. The relevant facilities are outlined in Table 6.2 below.

Table 6.2: Summary of on-airport facilities required (Source: Steer)

Pathway	Supply to airport	Facilities required	Airport requirements Suitability	Other considerations
Pathway 1	None	Hydrogen production, Liquefaction, Storage	Large Spatial requirement for all facilities Carbon neutral energy source for all processes	Requires further investigation as to the suitability of this application to smaller airports in the case that it is more cost effective than the construction of gaseous pipeline or LH_2 deliveries.
Pathway 2	Hydrogen pipeline (Gas)	Liquefaction, Storage	Spatial requirement for all facilities Carbon neutral energy source for all processes	Construction of a new pipeline to the airport will only be viable provided there is sufficient consumption to warrant this. Currently only major/large airports maintain pipeline access for Jet A1 fuel.
Pathway 3	Road/ Waterway Transportation (LH_2)	Storage	Increase fuel farm spatial requirement Some carbon neutral energy required to maintain required temperatures; lack of liquefaction plant on site will require continued cooling of storage	The impact of additional traffic to/from the airport resulting from these deliveries will need to be considered owing to LH_2's low volumetric density; four times the volume of hydrogen fuel is required per flight.

6.40 The pathway selected for an airport will be dependent on numerous factors and the following considerations need to be accounted for at each airport:

- spatial restrictions;
- access to carbon neutral energy; and
- volume of hydrogen required and viability of delivery method.

6.41 Under all pathways, the new on-airport infrastructure required is significant, but greatest in Pathway 1 and least in Pathway 3.

6.42 Airports consulted with had considered all of these different pathways for hydrogen supply. Most considered that pipeline supply was the most feasible option, but smaller airports were considering the possibility of using supply of liquid hydrogen by truck, while larger airports have also looked at the potential to produce hydrogen on site, while recognising the very large electrical power supply that this would require.

Storage

Volumetric density

6.43 The properties of LH2 are highly challenging. Firstly, while LH2 has a high energy gravimetric density (MJ/kg) it has a low volumetric density (MJ/litre), such that four times the volume of LH2 compared to kerosene is required to produce the same amount of energy[40]. This implies that:

- airport fuel farms for LH2 require four times the volume as corresponding existing fuel farms storing Jet A-1 (kerosene) fuel; and
- four times the volume of fuel needs to be transferred into aircraft.

6.44 The impact of these properties on required fuel storage has been estimated for a selection of European airports for which information is publicly available, Athens (ATH), Dublin (DUB), Frankfurt (FRA) and London Heathrow (LHR), in Table 6.3 below. Fuel storage capability at each of the airports, as well as the proportion of capacity and fuel consumption required by flights which have the potential to use LH2 technology, have been included. We note that airports typically store 3-3.5 days' fuel demand, but that the storage capability at Athens and Frankfurt seems to exceed this considerably.

6.45 Due to the higher proportions of short-haul traffic at Athens and Dublin airports, the storage requirements for LH2 at these airports will require the volume of storage to be expanded from current levels by 200% and 130% respectively. Meanwhile, at Frankfurt and London Heathrow the requirements are proportionally smaller owing to higher proportions of long-haul traffic, which cannot feasibly switch to LH2 fuel.

Table 6.3: Theoretical Hydrogen Storage Requirement (2019 Traffic) (Source: OAG, IATA, Fraport, Dublin Airport, Steer analysis)

	Current			Hydrogen Scenario			Ratio of required to current storage
	Conventional fuel storage capacity (m^3)	In scope		Storage requirement (m^3)			
Airport		% of seats	% of fuel	Conventional Fuel	LH_2	Total	
ATH	30,000	91%	68%	9,706	81,177	90,883	3.0

[40] The gravimetric energy density of hydrogen is 120 MJ/kg (vs 43 MJ/kg for Aviation Jet A-1 kerosene), so the mass/weight of hydrogen burned to generate the same energy is approximately one third of that of kerosene (=43/120). However, liquid hydrogen has a volumetric density of only 71 kg/m3 (vs 804 kg/m3 for Jet A-1), so the energy stored on a volumetric basis is 8.5 MJ/litre (= 120 x 0.071) for liquid hydrogen vs 34.7 MJ/litre for Jet A-1 (=43 x 0.804), i.e. the energy density per litre of liquid hydrogen is only 24.5% (=8.5/34.7) of that of kerosene, so approximately 4x the storage volume is required for liquid hydrogen to produce the same energy output.

Airport	Current			Hydrogen Scenario			Ratio of required to current storage
	Conventional fuel storage capacity (m³)	In scope		Storage requirement (m³)			
		% of seats	% of fuel	Conventional Fuel	LH_2	Total	
DUB	15,000	80%	43%	8,619	25,525	34,144	2.3
FRA	186,000	66%	20%	148,420	150,320	298,740	1.6
LHR	52,000	48%	12%	45,807	24,773	70,580	1.4

Cryogenic requirement

6.47 To remain a liquid, LH2 must be stored below its boiling point of -253°C, which presents further challenges. Storage tanks in the airport fuel farm will need to be kept at -253°C, which is feasible, but requires special tanks and continuous use of power to maintain the cryogenic temperatures. Even when stored properly, LH2 will warm and vaporise slowly and the gas generated must be used or vented off. Boil off rates of less than 1% per day can be achieved[41], however condensing evaporated hydrogen is usually not an economical option unless a liquefaction plant is also present on site.

6.48 Due to the requirement to store the fuel at -253°C, the most thermally efficient storage vessel to maintain these temperatures would be a sphere, which in terms of footprint would also require more area than a typical kerosene storage tank for a similar quantity. Within the confines of the same dimensions (radius and height) a cylindrical tank can hold 50% more volume than a spherical tank.

6.49 Where possible, the number and capacity of airport storage tanks has been sourced and a suitable set of dimensions for these tanks has been assumed. These dimensions have been used as a limiting factor in the calculation of LH2 storage tanks, since airports are required to abide by 'obstacles limitation surface layout' parameters, which limit the height of airport buildings and facilities near runways. It has been assumed that the LH2 storage will be in a similar location on the airport to current conventional fuel storage. Underground storage has not been considered and would be challenging given the large volumes of space required.

6.50 The table below (Table 6.4) shows the current fuel storage and estimated footprint at the four airports.

Table 6.4: Current fuel storage footprint requirement (2019 Traffic) (Source: OAG, IATA, Fraport, Dublin Airport, Steer assumptions and analysis)

Airport	Jet A1 Storage capacity (m³)	Tanks	Average Capacity per Tank (m³)	Assumed Diameter (m)	Assumed Height (m)	Current Footprint (m²)
ATH	30,000	5	6,000	20	20	1939

[41] H2tools.org, Handling Cryogenic Liquid

Airport	Jet A1 Storage capacity (m³)	Tanks	Average Capacity per Tank (m³)	Assumed Diameter (m)	Assumed Height (m)	Current Footprint (m²)
DUB	15,000	3	5,000	19	19	1030
FRA	186,000	10	18,600	29	29	8247
LHR	52,000	8 (estimated)	6,283	20	20	3310

6.51 Applying the same logic to the hydrogen scenario (and taking account of apparent height restrictions impacting the maximum volume of individual fuel tanks), the footprint under the hydrogen scenario, allowing for storage of the hydrogen fuel and residual needs for conventional fuel, is shown in Table 6.5 below.

Table 6.5: Hydrogen Scenario: potential fuel storage footprint requirement (2019 Traffic) (Source: Steer assumptions and analysis)

Airport	Conventional Fuel Requirement		Hydrogen Requirement			Footprint for conventional + hydrogen fuel (m²)	Ratio of required to current footprint
	Storage requirement (m³)	Tanks	Storage requirement (m³)	Max volume of sphere[42]	Tanks		
ATH	9,706	2	81,177	4,000	21	8,921	4.6
DUB	8,619	2	25,525	3,334	8	3,435	3.3
FRA	148,420	8	150,320	12,399	13	17,318	2.1
LHR	45,807	8	24,773	4,189	6	5,600	1.7

6.52 The additional footprint required for hydrogen fuel storage is therefore significant.

6.53 Additionally, we note that LH2 tank sizes typically range from 1.5m³ to 75m³[43]. This is considerably smaller than the volumes derived in the analysis above and this will require further research and development. Currently NASA own the largest cryogenic storage tank (3,800m³, corresponding to a sphere of diameter of 19m), whilst Kawasaki, in Japan, completed designs for a 10,000m³ tank in December 2020 and hopes to achieve a boil-off rate of less than 0.1% per day[44].

On-apron supply

Current procedures

6.54 Currently fuel is supplied to the aircraft stand from the fuel storage area via bowser (fuel tanker vehicle) or via a system of pipelines under the airfield which feed fuel hydrants at each aircraft stand (fuel hydrant system). Fuel hydrant systems are more

[42] Max volume of sphere within current height limitations, affecting number of tanks required

[43] R Folkson, Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance, 2014

[44] https://global.kawasaki.com/en/corp/newsroom/news/detail/?f=20201224_8018

common at larger airports and are often installed as part of new infrastructural works. For example, at Dublin airport, a fuel hydrant system was installed as part of the Terminal 2 project, however Terminal 1 flights remain dependent on refuelling via bowser (refuelling tanker vehicle). Terminal 1 generally handles short-haul flights, whilst long-haul flights are concentrated in Terminal 2.

6.55 There are advantages and disadvantages associated with each method; whilst the use of bowsers required less capex expenditure and potentially lower maintenance and operating costs, extensive use of bowsers, especially at congested airports, has the potential to generate considerable vehicle congestion of the on apron.

Bowsers (refuelling tanker vehicles)

6.56 Where bowsers are commonly used for refuelling, or could be considered, there is risk of considerable additional vehicle congestion on the apron, owing to the fact that the volume of hydrogen required to be delivered to the aircraft will be four times higher than using kerosene owing to its low volumetric energy density. It is estimated that a typical short haul flight operated by the 200 seat turbofan aircraft would require one tonne (equivalent to $14m^3$) of liquid hydrogen per refuel. A typical airport bowser contains capacity up to $40m^3$ of conventional fuel; with the requirement for a LH2 bowser to be thermally isolated and insulated it is estimated that the maximum practical capacity would be around $30m^3$, which is sufficient for two aircraft refuels.

Hydrants

6.57 At airports where under-apron pipelines and stand hydrants are currently used, these are operated at ambient temperatures and are capable of transporting one fuel type only. As hydrogen cannot be combined with existing aviation fuel, this would require the installation of a dedicated hydrogen hydrant system in parallel to the conventional system at many large airports. This will be a significant undertaking both in terms of cost and disruption.

6.58 It is not yet clear whether it is technically feasible to maintain corresponding pipelines for LH2 at -253°C, given that materials become brittle at such temperatures, and the long-thin nature of pipes means that the surface area to volume ratio is high, requiring more energy to maintain the cryogenic temperatures. The cryogenic equipment provider consulted with stated that vacuum insulation technology employed in storage tanks is also suitable for transfer lines[45], however the applicability of this at scale remains to be determined.

Options

6.59 A summary of re-fuelling options is presented in Table 6.6 below together with relative advantages and shortcomings. In addition to established bowser and hydrant methods, the option to refuel aircraft at a dedicated hydrogen refuelling area and at dedicated hydrogen gates has also been included. Due to the increased operational complexity involved with these two options, the traditional bowser and hydrant methods appear to be favourable, however the impact of increased vehicular activity and the practicality of laying an (extensive) thermally isolated hydrant system under an operational needs to be considered.

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45 https://demaco-cryogenics.com/products/vacuum-insulated-transfer-lines/

6.60 The table shows different options for fuel supply in each of the columns, considering the relevant issues for each aspect of the process/infrastructure. A RAG (Red/Amber/Green) coding has been applied, with Red representing the most challenging issues.

Table 6.6: Summary of potential options (Source: Steer analysis)

	Bowser	Hybrid	Hydrant	
		Dedicated refuelling area	Dedicated gates	Full Dual fuelling capability
Airport Suitability	*Low traffic volumes*	*Low traffic volumes*	*Airports with regular, non-variable flows*[46]	*High traffic volumes*
Disruption	*None*	*Small*	*Some*	*High*
Location and length of system	Fuel farm and associated parking only	Can locate near fuel farm to minimise fuel transportation distance	Pipeline to a designated area of the airport requires and network of pipes at stands focussed on hydrogen aircraft usage	Requires duplication of current hydrant system with thermally isolated system, which requires further investigation /development
Space requirement	Hydrogen Fuel farm only	Hydrogen Fuel Farm and additional fuelling spaces	Hydrogen Fuel farm and some additional gates	Hydrogen Fuel farm only
Airport Operations	Increased on-airport movements by aircraft vehicles	Increased on-airport movements by aircraft	Increased operational complexity for airports, sufficient gates for peak requirements of both conventional and hydrogen aircraft must be made available	No change
Airline operations	No change	Increased turnaround times	No change (provided sufficient capacity is available to cater to operations)	No Change

Aircraft fuelling systems

6.62 Whichever method is used, a connector pipe into the aircraft will be required. This process needs to be done while maintaining the temperature below -253°C and without any safety risk, as discussed in the ACI/ATI report[47].

Practicality

6.63 Until this point, the LH2 will have been stored and transported in heavily insulated containers and systems. The availability of technology to maintain this thermal distancing during refuelling is unclear to stop LH2 boiling at point of contact. Currently

46 Airports where traffic demands are consistent throughout the day, ie. predominantly short-haul and gates are not used for short and long haul aircraft types depending on passenger flows throughout the day. Could be applied well at low cost piers, or piers with Code C/D aircraft size stands only.

47 Ibid. Table 4, page 13

LH2 filling systems are available, however these are more suited to smaller scale applications, such as in laboratories, and permit the filling of open or closed dewars (cannisters), which allow the LH2 to be carried elsewhere. Information regarding losses due to boiling and/or the application of these methods on a larger scale do not appear to be developed.

6.64 A purge system (possibly using helium) may also be required to expel air and nitrogen from the system before fuelling can commence.

Safety requirements

6.65 The low temperatures associated with LH2 could cause severe frostbite and/or hypothermia for ground staff handling the equipment at airports.

6.66 There is also an increased risk of fire as hydrogen requires weaker sparks to ignite compared with kerosene. If a LH2 leak or spill were to occurs, a hydrogen gas cloud can flow horizontally for some distance or even downward until the gas warms. The warmed gas will mix with air, creating flammable clouds that, if ignited, will result in explosions or fires. This risk may require stringent measures to be taken on the apron to further reduce the risk of sparks, including:

- use of electric vehicles around the aircraft only; and
- requirement for passengers to not use electric devices while boarding the aircraft.

6.67 Other considerations to recognise include[48]:

- condensed air on uninsulated LH2 equipment (potentially at the refuelling point to the aircraft) could result in oxygen enrichment and explosive conditions near a LH2 system;
- the required separation distances for LH2 facilities are generally larger than required for gas systems[49];
- ice formation from condensing atmospheric moisture on the outside of valves can prevent the valves from being operated; and
- ice formation on the inside of vent lines can block the vent flow, resulting in equipment failure by overpressure.

Conclusion on airport infrastructure challenges

6.68 Based on the analysis presented here, there are therefore very significant requirements for new infrastructure at airports planning to handle hydrogen or electrically powered aircraft. Assuming that these technical challenges can be met, the airports concerned will need to deal with additional commercial and operational challenges. They will need to:

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48 https://h2tools.org/bestpractices/handling-cryogenic-liquid

49 NFPA 2.

- make very significant financial investment in the new equipment and infrastructure;
- endure a high level of disruption while the new infrastructure is installed;
- continue to maintain and operate the existing infrastructure for conventionally powered aircraft; and
- potentially adopt new operational procedures for handling the new technology aircraft.

6.4. Aircraft operations

6.69 This section considers a number of aspects of hydrogen aircraft operations which would need to be successfully managed in order to these aircraft to be rolled out successfully. They include groundhandling and in particular aircraft turnarounds, which are commercially crucial to airlines, since they affect the utilisation of highly expensive aircraft assets, as well as maintenance and repair of aircraft, training of crew and engineering staff and the certification of aircraft. In addition, the measures needed to allow airlines sufficient operational flexibility to operate in a commercially viable manner, are considered.

Groundhandling and turnarounds

6.70 Due to the low volumetric density of hydrogen, the quantity of fuel required to be loaded onto an aircraft during a turnaround will increase by a factor of approximately four compared to aircraft using conventional fuel (or SAFs), for a given flown distance.

6.71 Commercial aircraft are typically refuelled at a rate of 300 Gallons (1,136 litres) per Minute (GPM) per fuel intake. Short haul aircraft typically have one fuel intake, whilst wide-bodied aircraft (predominantly operating longer sectors) can have two or more fuel intakes to accelerate refuelling times. If LH2 were to be loaded onto aircraft at the same rate (300GPM) and in the same fashion, the time taken to refuel an aircraft at this rate would be around 30 minutes. Whilst it typically takes 20 minutes to fully fuel an A320/737 aircraft today, this figure is reduced when a full tank-load is not required, as is often the case with such aircraft using conventional fuel. With more typical fuel loads, the fuelling time may be as low as around 10 minutes.

6.72 However, aircraft using hydrogen fuel, with higher volumes and a shorter operating range, may take longer to refuel. Designing aircraft with addition fuel inlets could help to reduce this re-fuelling time.

6.73 Other differentiators could also include the location of the on-airport fuel supply and whether any other procedures are required during the connecting process[50]:

- If hydrogen aircraft can be refuelled on stand in the same manner as conventional aircraft are today, this would necessitate no major change in turnaround times due to fuelling. However, if it is required that hydrogen aircraft refuel at a site away from the main terminal, either for safety reasons or due to

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[50] Insertion on fuel pump into the aircraft.

practicalities around transferring fuel from the fuel farm to the airport, then this would incur significant time penalties and would not be possible within typical short-haul airline turnarounds of 25-60 minutes.

- If additional steps are required during the connecting process to evacuate heat and/or ensure sufficient levels of insulation are provided across the connection to prevent hydrogen boiling then this may require additional time.

6.74 New safety procedures will need to be established to mitigate the risks of frostbite and hypothermia amongst ground crew and also to mitigate the risk of fire due to the flammability of hydrogen. These factors were discussed in the section from paragraph 6.65 above.

6.75 As noted above, airports consulted with considered aircraft refuelling to be one of the biggest challenges they would face in supporting hydrogen-powered aircraft. They recognised the need for aircraft turnarounds to take a similar time as with conventional aircraft and that refuelling processes would need to support this.

Maintenance and repair

6.76 Table 6.7 below shows the typical maintenance schedule for a commercial aircraft.

Table 6.7: Typical aircraft maintenance schedule (Source: National Aviation Academy)

Check type	Activity	Frequency
Line maintenance	Inspection of wheels, break and fluid levels (oils and hydraulics)	Daily
A	General inspection of the interior and exterior for evidence of damage, corrosion, missing parts,	Every 400-600 flight hours or 200-300 flights (variable by aircraft type)
B	A-check plus fluid servicing and lubrication as well as an open inspection of the panels and cowlings	6-8 months
C	A/B plus detailed examination of structures (load-bearing components on the fuselage and wings) and functions for corrosion and damage. Calibration of flight controls and testing of systems.	20-24 months
D	Comprehensive inspection of the entire aircraft	6-10 years

6.77 Currently no information could be found supporting whether these procedures will remain suitable for hydrogen aircraft and no information stating specific maintenance and repair considerations could be located.

6.78 On the proposed hydrogen turbine aircraft, the majority of components on the aircraft remain the same as those on a conventional turbine aircraft. The fuel system is the primary difference and may warrant additional procedures owing to:

- the critical nature of the tank cooling system to keep the fuel in liquid form and to prevent it from boiling and having to be ejected due to pressure increases;

- the ability for the reinforced and thermally efficient fuel tank and on-board systems to withstand repeated take-offs and landings, which is currently unproven; and
- issues with materials becoming brittle due the low temperatures involved.

6.79 It was mentioned by one stakeholder that maintenance requirements on hydrogen fuel cell aircraft may even decrease due to the lower temperatures involved in comparison to combustion in turbofan aircraft.

Training and certification

Certification

6.80 An enhanced certification programme is likely to be required to assess the impacts of the new fuel type on aircraft handling and maintenance.

Air crew

6.81 No information is currently available stating whether hydrogen aircraft will have any particularly different handling characteristics. It is likely that flight crew will be trained to fly on these aircraft in a similar manner to obtaining a new type-rating on conventional aircraft. This would include training on any new systems incorporated into the aircraft.

Ground staff

6.82 Advanced training for ground and maintenance staff to safely handle hydrogen aircraft from both a low-temperature and fire risk perspective. Enhanced maintenance training programmes may have to be developed depending on the maintenance requirements of the aircraft.

Operational flexibility

Availability of fuel

6.83 During the roll-out phase, hydrogen facilities will only be available at selected airports, which will impact airline operational flexibility as aircraft will be restricted to a selected number of routes only. This may reduce operational efficiency and result in increased operational costs for airlines. Where aircraft are required to make an unscheduled stop, there is no guarantee that hydrogen fuel will be available and it may need to be transported by lorry.

Operating two distinct aircraft fleets

6.84 Currently it is unclear how much overlap can be achieved with crewing and maintenance processes across the two fleet and the extent to which additional spare components must be stored. The operation of multiple fleets will inevitably increase costs for airlines.

Operating performance

6.85 It is currently assumed that hydrogen aircraft will have similar operating characteristics to their conventional counterparts, however the following factors will need to be evaluated.

- take-off performance, runway length requirements and whether these are more adversely affected by impacted ambient temperature changes;
- noise emissions;
- climb rates and ability to conform with established flight routings (ANSP impact); and
- most efficient cruising altitude (ANSP impact).

7. European and global legislation, policy and trends

7.1. Introduction

7.1 An analysis of European and selected global legislation and policy has been conducted to establish pathways to developing a hydrogen-based aviation market internationally. Trends in the global green aviation industry are also discussed.

7.2. European legislation and policy

Overview

7.2 Hydrogen is not included in the Fit for 55 legislative proposal and the associated ReFuelEU aviation initiative. SAFs represent the current means by which the EC expects to reach its GHG emission targets in 2030 and 2050. Estimated investments faced by the European air transport industry to transition towards carbon neutrality using these measures are already significant.

7.3 Whilst a multitude of legislation concerning the development of the use of green hydrogen in the EU could be found, direct application to the aviation industry was not mentioned. However, the experience and knowledge gained from hydrogen gas grids, fuelling stations and application to the maritime industry could provide a foundation from which they could be adapted for the aviation industry.

7.4 The Clean Aviation Partnership includes the development of 'disruptive technologies to enable hydrogen powered aircraft' as a core theme of the programme, which lasts until 2031. The Clean Aviation Partnership has set earliest entry into service (EIS) targets of 2035 for hybrid-electric regional aircraft as well as ultra-efficient short-medium range commercial aircraft (using current technologies). However, an EIS for a hydrogen-powered aircraft has not been stated, implying that this technology may not be mature until after this date.

Directives

7.5 The Renewable Energy Directive (EU) 2018/2001 sets out legally binding definitions of renewable liquid and gaseous transport fuels of non-biological origin. This includes definitions for renewable hydrogen. This has since been reviewed to aid with consistency with the 'Fit for 55' framework as part of the RefuelEU initiative[51].

7.6 The Alternative Fuels Infrastructure Directive 2014/94/EU establishes a common framework and sets out minimum requirements for the roll-out of alternative fuels infrastructure for Member States. but the proposal omits direct references to hydrogen fuelled aircraft. In July 2021, the proposal for an Alternative Fuels Infrastructure Regulation (AFIR)[52] was presented to the European Commission as

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[51] COM(2021) 561, proposal for a regulation of the European Parliament and of the Council on ensuring a level playing field for sustainable air transport

[52] COM/2021/559 final - Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council

part of the overall set of interlinked policy initiatives under the 'Fit for 55' package. Currently the proposal omits direct references to hydrogen fuelled aircraft.

Fit for 55 and aviation related proposals

7.7 The Fit for 55 legislative proposals cover a wide range of policy areas including climate, energy, transport and taxation, setting out the ways in which the EU will reach its updated 2030 target. The overall objectives of the proposals are to:

- reduce net EU greenhouse gas emissions to 55% below 1990 levels by 2030;
- contribute to the European Green Deal[53] objective of EU-wide climate neutrality by 2050;
- stimulate the creation of green jobs and maintain the EU's record of cutting greenhouse gas emissions while growing its economy; and
- ensure that the transition is fair and leaves no-one behind.

7.8 Three of the proposals are most relevant in the context of aviation:

- A tightening of the existing EU Emissions Trading System (ETS) – phasing out free emission allowances for aviation and aligning with the global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).
- The ReFuelEU Aviation Initiative that will oblige fuel suppliers to blend increasing levels of sustainable aviation fuels (SAFs) in jet fuel taken on-board at EU airports, including synthetic low carbon fuels, known as e-fuels. The targets are provided below:
  - 2% from 2025;
  - 5% from 2030, with a minimum of 0.7% e-kerosene;
  - 20% from 2035, with a minimum of 5% e-kerosene;
  - 32% from 2040, with a minimum of 8% e-kerosene;
  - 38% by 2045; with a minimum of 11% e-kerosene; and
  - 63% by 2050, with a minimum of 28% e-kerosene.
- A revision of the Energy Taxation Directive (ETD) which proposes to align the taxation of energy products with EU energy and climate policies, promoting clean technologies and removing outdated exemptions and reduced rates that currently encourage the use of fossil fuels.

7.9 The direct use of hydrogen as a fuel for aviation is not included in these proposals, implicitly indicating the use of drop-in SAFs with conventional technologies is the primary means by which the aviation industry will achieve its objective of climate neutrality by 2050. Hydrogen, however, is a key element in the production of bio-fuels and is required to upgrade oxygen-rich feedstocks into hydrogen-rich hydrocarbons that are functionally equivalent to fossil-derived jet fuel. The source of hydrogen in

[53] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

this process is also important as it affects the potential life cycle greenhouse gas (GHG) savings from aviation biofuels.

Alternative Fuels Infrastructure Regulation (AFIR)

7.10 As mentioned above, in July 2021, the European Commission presented a proposal for a regulation on the deployment of alternative fuels infrastructure (AFIR)[54]. This would repeal the existing Directive 2014/94/EU of the European Parliament and of the Council on the deployment of alternative fuels infrastructure.

7.11 The proposal does not make a direct reference to the usage of hydrogen fuel within aviation prior to 2030, potentially later for full commercialization. As a consequence the focuses, with respect to aviation, are on delivering fossil gaseous or liquid fuels that are part of a clear decarbonisation pathway. This will involve extensive blending with, or by replacement by, renewable fuels. The Regulation refers to bio-methane, advanced biofuels or renewable and low-carbon synthetic gaseous or liquid fuels as examples of future renewable fuels.

REPowerEU

7.12 The REPowerEU Plan[55] was presented on 18 May 2022 in response to the market disruption experienced globally as a consequence of the Russian invasion of Ukraine with the focuses to 'rapidly reduce dependence on Russian fossil fuels and fast forward the green transition'[56].

7.13 Regarding renewable energy, the Plan proposes to increase the target of renewable energy generation capacities by 5% to 45% by 2030, to a total of 1,236 GW, compared to what was set out in Fit for 55 proposals. Solar and wind energy, particularly offshore, are outlined as technologies to facilitate this.

7.14 With respect to hydrogen, the REPowerEU Plan recognises that renewable hydrogen will be key to replacing natural gas, coal and oil across hard-to-decarbonise industries and transport. To support this the Plan sets a target of 10Mt of domestic renewable hydrogen production and 10Mt of renewable hydrogen imports by 2030. It is noted in the plan that other forms of fossil fuel free hydrogen, such as from nuclear powered electrolysers, will play a role in substituting natural gas. The Plan recognises that accelerated efforts are needed to deploy hydrogen infrastructure for production, import and transportation, with total key hydrogen infrastructure investment estimated as being €28-38 billion for EU internal pipelines and €6-11 billion for storage.

7.15 Three major hydrogen import corridors via the Mediterranean, the North Sea area and Ukraine will be developed, with support from the Commission, to accommodate the import of up to 10Mt of renewable hydrogen.

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[54] COM/2021/559 final - Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU of the European Parliament and of the Council

[55] COM(2020) 230 final – Communication from the Commission to the European Parliament, the Europen Council, the Council, the Europen Economic and Social Committee and the Committee of the Regions, REPowerEU Plan

[56] https://ec.europa.eu/commission/presscorner/detail/en/IP_22_3131

Hydrogen legislation

7.16 The HyLaw project[57] identified more than 50 legislative acts in the wider regulatory area impacting hydrogen development. Deployment to the aviation industry was not directly included, but a number of related areas were identified as being particularly relevant and possibly requiring revision for both direct and indirect applicability to the aviation sector. These include:

- The legal framework surrounding the injection of hydrogen into the gas grid, in particular:
  - permitting requirements;
  - injection limits;
  - payment and remuneration mechanisms;
  - gas quality requirements; and
  - safety and end-user equipment requirements.
- Permitting of Hydrogen Refuelling stations, in particular:
  - stations with on-site production; and
  - stations storing low and medium quantities of hydrogen.
- The introduction of hydrogen and hydrogen-based fuels in the maritime sector, in particular:
  - the type approval of hydrogen and hydrogen-based fuel vessels (ships, boats, utility vessels, etc.);
  - rules for the landing and bunkering (refuelling) of hydrogen; and
  - pn-shore and off-shore refuelling of hydrogen and hydrogen-based fuels vessels.

7.17 The HyLaw project also highlighted that delays caused by lack of experience, administrative maturity or legal clarity are likely, which are also relevant factors to consider in the application to Hydrogen aircraft.

Hydrogen Strategy

7.18 A hydrogen strategy for a climate-neutral Europe[58] was outlined by the European Commission on 8 July 2020. This describes a roadmap to a hydrogen ecosystem in Europe in 2050. The priority of this strategy is to develop renewable hydrogen, via solar and wind energy, as this is in line with the EU's ultimate climate neutrality and zero pollution goals.

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[57] https://www.hylaw.eu/

[58] COM(2020) 301 final, Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions – A hydrogen strategy for a climate-neutral Europe.

7.19 The plan recognises that significant build up of the renewable hydrogen production, distribution and storage ecosystem is required, and as a result highlights that in the short and medium term low carbon forms of hydrogen are required. This will primarily reduce emissions from existing hydrogen production and support any future uptake of renewable hydrogen.

7.20 Landmarks in the roadmap towards 2050 include:

- **2020 – 2024**: Strategic objective to install at least 6 GW of renewable hydrogen electrolysers in the EU and the production of 1 Mt of renewable hydrogen.
- **2024 – 2030**: To increase the EU renewable hydrogen electrolyser capacity to 40 GW by 2030 and to produce 10 Mt of renewable hydrogen annually by the end of the period.
- **2030 – 2050**: Renewable hydrogen technologies should reach maturity and as a result be deployed at a large scale to reach all hard-to-decarbonise sectors, such as aviation. The Commission estimate that up to 25% of renewable electricity will be required by renewable hydrogen production by 2050. Hydrogen synthetic fuels are also highlighted as an alternative fuel for aviation on the road to carbon neutrality.

Trans-European Networks for Energy (TEN-E)

7.21 The Trans-European Networks for Energy (TEN-E) policy is focused on the linking of EU Member State's energy infrastructure. Nine priority corridors and three priority thematic areas are identified with the aim to help EU countries to develop better connected energy networks. The policy also provides funding for new energy infrastructure.

7.22 On 15 December 2020 the European Commission accepted a proposal to revise the rules of the TEN-E Regulation[59], to further contribute to the EU emissions reduction objectives by promoting integration of renewables and new clean energy technologies. The regulation will continue to connect isolated regions to the European energy markets and strengthen existing cross-border interconnections and cooperation between countries.

7.23 The nine priority corridors are as follows[60]:

- Electricity corridors;
  - North Sea offshore grid (NSOG);
  - North-south electricity interconnections in western Europe (NSI West Electricity);
  - North-south electricity interconnections in central eastern and south-eastern Europe (NSI East Electricity);

[59] COM (2020) 824 final, Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on guidelines for trans-European energy infrastructure and repealing Regulation (EU) No 347/2013

[60] https://energy.ec.europa.eu/topics/infrastructure/trans-european-networks-energy_en

- Baltic Energy Market Interconnection Plan in electricity (BEMIP Electricity);

- Gas corridors;
  - North-south gas interconnections in western Europe (NSI West Gas);
  - North-south gas interconnections in central eastern and south-eastern Europe (NSI East Gas);
  - Southern Gas Corridor (SGC);
  - Baltic Energy Market Interconnection Plan in gas (BEMIP Gas);
- Oil corridors;
  - Oil supply connections in central eastern Europe (OSC).

7.24 The three thematic areas are as follows:

- Smart grids development;
- Electricity highways;
- Cross-border carbon dioxide network.

7.25 The Regulation directly states that in order to support decarbonisation needs of the hard-to-abate sectors, TEN-E will include dedicated new and re-purposed hydrogen networks with cross-border relevance. This includes hydrogen transmission pipelines, storage, and electrolyser facilities[61].

The Trans-European Transport Network (TEN-T)

7.26 The Trans-European Transport Network policy[62] has the objective to close gaps, remove bottlenecks and technical barriers in the EU via the implementation and development of a Europe-wide network of railway lines, roads, inland waterways, maritime shipping routes, ports, railroad terminals and airports. This will be addressed via construction of new physical infrastructure as well as application of innovative new technologies and digital solutions across all modes of transport. The TEN-T policy is currently under review following growing transport demand, geo-political developments and evolving transport policy challenges[63].

7.27 The TEN-T is made up of two network 'layers':

- Core Network – comprised of the most important connections and nodes, to be completed by 2030.

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[61] COM(2020) 824 final, Proposal for a REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on guidelines for trans-European energy infrastructure and repealing Regulation (EU) No 347/2013, Pg. 14, 20.

[62] Regulation (EU) No 1315/2013 of the European Parliament and of the Council of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU Text with EEA relevance

[63] https://transport.ec.europa.eu/transport-themes/infrastructure-and-investment/trans-european-transport-network-ten-t/ten-t-review_en

- Comprehensive Network – covers all European regions and is to be completed by 2050.

7.28 With respect to aviation, TEN-T airports must correspond to one of the following categories of connecting points.

1. **International connecting points** – All airports with a total annual traffic no less than:
    i. 5 million passenger movements, or
    ii. 100,000 commercial aircraft movements, or
    iii. 150,000 tonnes of freight throughput, or
    iv. 1 million extra-community passenger movements.

2. **Community connecting points** – All airports with annual traffic volume of:
    i. between 1,000,000 and 4,499,999 passenger movements, or
    ii. between 50,000 and 149,999 tonnes freight throughput, or
    iii. between 500,000 and 899,999 passenger movements, of which at least 30% are non-national, or
    iv. between 300,000 and 899,999 passenger movements, and located off the European mainland at a distance of over 270 Nm from the nearest international connecting point.

3. **Regional connecting points and accessibility points**:
    i. with an annual traffic volume of between 500,000 and 899,999 passenger movements, of which less than 30% are non-national, or
    ii. with an annual traffic volume of between 250,000 and 499,999 passenger movements, or
    iii. with an annual traffic volume of between 10,000 and 49,999 tonnes freight throughput, or
    iv. located on an island of a Member State, or
    v. located in a landlocked area of the Community with commercial services operated by aircraft with a maximum take-off weight in excess of 10 tonnes.

7.29 Any new airport constructed to replace an existing connecting point which cannot be developed further is also considered a TEN-T airport.

Infrastructure and technology development support

Research and Joint Undertakings

7.30 In late February 2021, the European Commission presented its proposal to establish 10 new European Joint Undertakings (JUs) between the EU, Member States and/or industry, including a Clean Aviation JU and a Clean Hydrogen JU. The EU would provide nearly €10 billion of funding that the partners would match with at least an equivalent amount of investment.

7.31 The Clean Aviation JU follows on from the Clean Sky 2 JU and targets research and innovation in the aerospace industry as well as bringing technologies to demonstrator stage. The Clean Aviation JU will run from 2021-2031 and has a budget of €4.1 billion

(€1.7 provided by the EU). The Clean Aviation programme is built on three core areas:

- hybrid electrical regional aircraft;
- ultra-efficient short and medium range aircraft; and
- disruptive technologies to enable hydrogen-powered aircraft.

7.32 The Clean Hydrogen JU focuses on producing, distributing and storing clean hydrogen and on supplying sectors that are hard to decarbonise, such as heavy industries and heavy-duty transport applications. The EC will support the Clean Hydrogen JU with €1 billion for the period 2021-2027, complemented by at least an equivalent amount of private investment.

Role of financing in the EU

7.33 The estimated investments faced by the air transport industry to transition towards SAF and carbon neutral airport facilities are very large. It is estimated that:

- achieving Net Zero CO2 at airport terminals at the top 50 European airports will require €29 billion;
- capex in the range of USD 219 billion to USD 306 billion will be required in Europe to enable SAF production capacity in line with the Net Zero CO2 goal for 2050[64];
- airlines will invest in more fuel-efficient aircraft that will amount for European airlines of around €140-170 billion of investments in new aircraft by 2030[65];
- €12 billion will need to be invested in R&I until 2030, whilst the subsequent development of new aircraft technologies are estimated to cost €15 billion per aircraft type[66]

7.34 The scale of the investments described above are very significant, while investments in hydrogen technologies and associated infrastructure would be additional, implying that they could be highly challenging to deliver.

7.3. International net-zero legislation, policies and positioning

Overview

7.35 The application of net zero targets and legislation to achieve this has been researched for a number of other jurisdictions, including the United Kingdom (UK), United States (US), Canada, Australia, China and Japan. A summary is presented in Table 7.1 below.

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[64] ATAG's Waypoint 2050 study

[65] Airbus, as per stakeholder consultation response

[66] EU Clean Aviation Partnership

7.36 All of the countries, except Australia and China, are proposing to reach net-zero greenhouse gas emission targets by 2050. Of these countries only the US does not (yet) have this target written into law.

7.37 The EU, UK and the US have all developed and published policies and strategies to enable these targets to be achieved. In all jurisdictions the focus of achieving this objective in the aviation industry has been placed on increasing the use of SAFs. In the EU this is achieved with a SAF blending mandate combined with a taxation directive on fossil fuels, while in the US tax credits are to be provided to fuel blenders provided where at least a 50% reduction in lifecycle greenhouse gas emissions can be realised together with grants to assist with the commercialisation of SAF production. The UK is currently consulting on the possibility of introducing a SAFs blending mandate.

7.38 Policies in the US and Canada are targeted on domestic aviation only, with actions regarding international traffic falling back to the ICAO CORSIA scheme. The large size of the domestic markets in these jurisdictions versus those in EU Member States and the UK will influence this policy decision. In the US, the Inflation Reduction Act, although not an aviation specific policy, does give a major boost to clean and green energy production. In the EU and UK Emissions Trading Schemes (ETSs) cover flights both within each jurisdiction and also apply to flights between the EEA and UK. China is also looking to include domestic aviation its carbon trading scheme as part of its 14th Five-Year Plan. All of the countries reviewed have opted into the CORSIA scheme during its voluntary phase (to 2027).

7.39 The table below summarises net zero legislation and its application to hydrogen across the EU, the UK, the US, Canada, Australia, China and Japan. Further detail on policies in the US and China is provided in the sections below the table.

Table 7.1: Summary of legislation and policies in the EU and other jurisdictions (Source: Jurisdiction policies and industry publications)

	EU	UK	USA	Canada	Australia	China	Japan
Comprehensiveness							
Target Net Zero	2050	2050	2050	2050	No target	Before 2060	2050
In law?	Net zero target in law	Net zero target in law	No net zero target	Net zero target in law	No	Target in proposed legislation	Net zero target in law
Coverage	All GHG emissions	All GHG emissions	All GHG emissions	All GHG emissions	N/A	Partial coverage	All GHG emissions
Aviation policies	• Fit for 55 • ReFuelEU	• Net Zero Strategy – Build back Greener • Transport Decarbonisation Strategy • Jet Zero (consultation stage)	• Sustainable Skies Act (SSA) • 'Grand Challenge'	• Clean Fuels (not directly applicable)	None	14th 5-year plan	None
Summary/Notes	• EU-Emission Trading Scheme • SAF blending mandates • Energy Taxation Directive	• Commercialisation of SAFs • SAF blending mandates • UK - ETS	The SSA and Grand Challenge are predominantly aimed at introducing and encouraging take-up of SAFs (tax credits, subsidies and grants), whilst continuing to improve 'current' technologies to further reduce fuel-burn.	The regulations aim to improve production process in the oil and gas sector, foster production of low carbon fuels and enable end-use fuel switching in transport. Whether the standard will be applied to domestic commercial	N/A	Targets to reduce emissions per ton-km, however also acknowledges that the market (and total emissions) will continue to grow in the short term. Lays foundations for the aviation industry to join the Chinese	Japan looks to expand low-emission technologies and restart nuclear plants as part of the Green Transformation (GX) plan (pending). The Japanese government plans to set up a public-private

	EU	UK	USA	Canada	Australia	China	Japan
			SAFs in the US will predominately be based on biofuels. The Inflation Reduction Act includes policy initiatives to encourage the development of green hydrogen and clean energy infrastructure across the US, for the benefit of US industry.	airline jet fuel is still under consideration.		carbon trading scheme	committee to consider specific measures to encourage Japanese companies to make and use these fuels.
Application to International aviation	✓	✓	✗	✗	✗	✗	✗
CORSIA *Voluntary participation pre-2027*	✓	✓	✓	✓	✓	✓	✓
Industry Actions	-	-	Airlines for America (A4A) airlines have pledged to work with government to assist with the 2030 SAF target (3 billion gallons per year)	C-SAF (Canadian council for sustainable fuels): 60 airlines – goal to facilitate production of Canadian, affordable, low-carbon SAF to produce roadmap by Summer 2022			

ICAO report on CO2 aviation emissions reduction goals

7.40 The International Civil Aviation Organization (ICAO) issued its report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO2 emission reduction in March 2022[67]. The report includes the modelling of three 'integrated scenarios', which cover a range of technology readiness/attainability levels as well as levels of aspiration. A summary of the scenarios and outputs (2050) is provided in Table 7.2.

Table 7.2: Summary of results to 2050 (Source: ICAO, Steer analysis)

Scenario		Composition of reduction (versus base)	2050 CO_2 emissions relative to 2019 (and vs Base case)
Base	Frozen technology, operational practice and fuels (2018)	No change	+163%
IS1	High readiness/attainability Low aspiration	Improvement in technology (51%) Operational improvements (10%) Fuels (39%)	+60% (-103pp vs Base)
IS2	Middle readiness/attainability Middle aspiration	Improvement in technology (31%) Operational improvements (9%) Fuels (60%)	-20% (-183pp vs Base)
IS3	Low readiness/attainability High aspiration	Improvement in technology (24%) Operational improvements (13%) Fuels (63%)	-66% (-209pp vs Base)

7.41 The scenarios show that there is scope for substantial CO2 reductions. However, none of the scenarios reach zero CO2 emissions in 2050 due to consideration of fuels' life cycle emissions, even when conventional fuels are completely replaced with drop-in SAFs and/or hydrogen. Consequently, future demand growth of the industry still has a significant impact on industry emissions.

7.42 Hydrogen is not assumed to have any material impact until after 2050 in any of the scenarios, with drop-in fuels having the largest impact on residual CO2 emissions and driving overall reductions by 2050. Post 2050, hydrogen is only considered in the IS3 scenario owing to the complex nature and high cost associated with implementation. The study mentions that while hydrogen-fuelled aircraft R&D is active and that such aircraft may be technically feasible, many challenges to their introduction reside outside of the aviation industry, whilst costs and commercial viability are major considerations. Challenges highlighted include:

- the readiness of cryogenic hydrogen production infrastructure;

[67] https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf

- the availability of green electricity to produce the hydrogen (life cycle carbon benefits are highly dependent on the method of hydrogen production);
- the need for substantial investments in airport infrastructure; and
- commercial viability and other non-technical attainability challenges.

7.43 Table 7.5 presents the estimated costs (cumulative to 2050) incurred under each scenario. Under IS1, total investment of between €2.4 and €2.8 trillion is required by the industry, increasing to between €5.0 and €6.4 trillion under IS2 where SAFs are more prevalent. Estimates increase considerably under IS3 to between €7.1 and €8.6 trillion, despite the roll-out of hydrogen technologies not becoming prevalent until after 2050.

Table 7.3: Estimated investment required to 2050, € billion (Source: ICAO, Steer analysis)

Investments from	IS1	IS2	IS3
States	€14 - €167	€70 - 809	€70 - €809
Aircraft manufacturers	€140 - €353	€242 - 930	€242 - €930
Fuel suppliers	€1,209	€2,139	€2,976
Airports	€2 - €6	€2 - 6	€93 - €140
ANSP	€10 - €19	€10 - 19	€10 - €19
Operators	€1,023	€2,511	€3,720
Total	**€2,398 – €2,777**	**€4,974 – €6,413**	**€7,111 – €8,593**

Country specific policies

United States

7.44 In May 2021 the United States (US) Congress introduced the **'Sustainable Skies Act'** to boost incentives to use SAFs. This incentive is supplied as a tax credit to fuel blenders, provided at least a 50% reduction in lifecycle greenhouse gas emissions (GHG) is achieved. Credit of US$1.50 to US$2.00 per US gallon is provided dependent on the level of GHG. Additionally, a grant of US$1 billion is to be made available over five years to expand SAF producing facilities in the US.

7.45 In September 2021 the Biden administration set out its **plan to advance the future of sustainable fuels**[68] in US aviation and to permit the US to reach its 2030 climate goals and ultimately a zero-carbon aviation sector by 2050. Currently aviation accounts for 11% of transport related emissions in the United States of America (USA) and without intervention it is expected that this will rise.

68 https://www.whitehouse.gov/briefing-room/statements-releases/2021/09/09/fact-sheet-biden-administration-advances-the-future-of-sustainable-fuels-in-american-aviation/

7.46 This action will be supported with a number of new and ongoing funding opportunities to support sustainable aviation fuel projects and fuel producers (totalling up to US$4.3 billion). These include:

- A 'Grand Challenge' to increase in the production of SAF to three billion gallons per year by 2030 (~10% of demand) and sufficient SAF to meet 100% of demand by 2050 (estimated to be 35 billion gallons per year). This measure will require collaboration of the Department of Energy (DOE), Department of Transportation (DOT) and Department of Agriculture (USDA) and will provide:
  - support to farmers for climate-smart agricultural practices and research[69]; and
  - DOE Loan programmes office offering up to $3.0 billion in loan guarantees for commercial scale SAF projects that utilise innovative technology and reduce greenhouse gas emissions.
- An increase in R&D activities to demonstrate new technologies that can achieve at least a 30% improvement in aircraft fuel efficiency, including:
  - collaboration between NASA and the Federal Aviation Authority (FAA) to accelerate the maturation of aircraft and engine technologies to accelerate fuel burn and CO2 emission reductions;
  - funding of the Continuous Lower Energy, Emissions, and Noise (CLEEN) programme ($100m) to aircraft and engine companies to develop and demonstrate new technologies; and
  - $115m to develop battery technologies for eVTOL and short-range aircraft.
- Efforts to improve air traffic and airport efficiency to reduce fuel use, eliminate lead exposure, and ensure cleaner air in and around airports:
  - grants ($20m) to electrify ground equipment at airports;
  - FAA is launching a new research project to develop a contrail avoidance tool to evaluate and optimise the benefits, costs, and practicality of contrail avoidance to minimise aviation climate impacts; and
  - other investments in research to reduce greenhouse gas emissions.
- 'Demonstration of US leadership both internationally and through the federal example':
  - re-establishment of US credibility through ambitious domestic commitments and realistic action plans for implementing those commitments;
  - demonstration of worldwide leadership on aviation ambition by implementing CORSIA transparently and effectively, and supporting adoption of a long-term aspirational goal for reducing aviation emissions; and
  - engagement with bilateral and regional partners to forge a diverse coalition of States committed to greater ambition and action on aviation.

[69] biomass feedstock genetic development, sustainable crop and forest management at scale, and post-harvest supply chain logistics

7.47 The Aviation Climate Action Plan was published by the Federal Aviation Administration (FAA) in November 2021. It describes the following measures to guide the aviation sector towards achieving net-zero emissions by 2050:

- the development of new, more efficient aircraft and engine technologies;
- improvements in aircraft operations throughout the US airspace system;
- production and use of Sustainable Aviation Fuels (SAF);
- electrification and, potentially hydrogen, as solutions for short-haul aviation;
- advancements in airport operations across the United States;
- international initiatives such as the airplane CO2 standard and the Carbon Offsetting and reduction Scheme for International Aviation (CORSIA); and
- support for research into climate science.

7.48 Whilst electrification and hydrogen are initially mentioned as solutions for short-haul aviation, they are only deemed suitable for small, short-haul haul aircraft, which in the context of this plan refers to general aviation (GA) sized aircraft. The shift of these aircraft types to these technologies would have a small impact on greenhouse gas emissions and thus they are not the focus of the plan. Furthermore, the plan explains that exploration into electric and hydrogen technologies has been conducted by NASA, which again states that these technologies will be applied to 'small aircraft' in the first instance and that the process of technology adoption in the commercial market will take decades.

7.49 Drop-in SAFs are considered in the plan to the be most viable and effective way achieving net-zero emission 2050 in tandem with more efficient aircraft and engine technologies together with operational improvements. The US view therefore appears to take account of the apparently significantly lower projected costs of bio-fuel SAFs (see Figure 3.1 above) and does not appear to accept the limitations on availability or potential negative impacts on food production which are seen in Europe as major concerns. In contrast, the plan states that "While there may be a role for hydrogen on shorter-range flights and more broadly in the years beyond 2050, we do not expect hydrogen-powered aircraft to make a significant contribution toward achieving net-zero aviation emissions by 2050".

7.50 In August 2022, the United States Congress enacted the Inflation Reduction Act (IRA)[70]. This gives a major boost to a wide range of clean energy technologies, including hydrogen, carbon capture, solar and wind power generation as well as electric vehicles. The legislation delivers 'almost $370 billon in energy security and climate change resilience investments'[71]. Regarding the development of clean hydrogen, under the IRA, there is scope to receive a hydrogen production tax credit with a value of up to $3 per kilogram. This tax credit will make the production of clean hydrogen (particularly green hydrogen) cost competitive with current 'grey' hydrogen alternatives and SAFs.

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70 Text - H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022, H.R.5376, 117th Cong. (2022), http://www.congress.gov/

71 World Energy Outlook 2022, International Energy Agency

7.51 With the IRA and other supporting recent legislation like the Infrastructure Investment and Jobs Act (IIJA), the development of clean energy infrastructure and green hydrogen in particular has seen a transformative shift to what had previously been announced at a federal level in the United States.

China

7.52 China has introduced energy intensity and carbon emissions-related targets for the aviation segment in its 14th Five-Year Plan (2021). The aviation market in China is still witnessing rapid expansion (2015-2019 CAGR +11%) and combined with continued use of fossil fuels and available aircraft technologies, energy usage and emissions have continued to rise in recent years.

7.53 The Plan aims to reduce energy and carbon intensity (but not overall emissions), as well as laying the foundations for introducing carbon pricing mechanisms and improving existing emission monitoring and reporting systems. The Plan states that its carbon pricing needs to be market-based and well-coordinated with international stakeholders.

7.54 Table 7.4 outlines key targets set out in the plan. By 2025, China's aviation sector aims to reduce carbon emissions per tonne-km by 4.5%, and energy consumption per person-time in the airport by 10% from 2020 levels. Passenger activity levels are expected to grow significantly, however this is in part due to 2020 representing a low baseline level. Significant expansion of domestic and international connectivity is planned.

Table 7.4: Key targets in the 14th Five-Year Plan for aviation (2021-2025) (Source: Chinese 14th Five Year Plan)

Targets	2020	2025
Carbon emission per tonne-km	0.928	0.886
Energy consumption per airport passenger (kg coal equivalent)	0.948	0.853
Total (billion tonne-km)	79.9	175
Civil Airports	580	770
Countries connected	62	>70

7.55 China's Environment Ministry plans to introduce the aviation sector into the national carbon market by 2025 under the China Certified Emission Reduction Scheme (CCER). CCERs are eligible for offsetting carbon emissions under CORSIA and the inclusion of China's aviation sector in carbon trading and CCERs could potentially open opportunities for a more hybrid carbon market with international participants and cross-border trading.

7.56 As part of the Five-Year plan, China will produce roadmaps to climate neutrality for the aviation section. CO2 emissions are expected to peak in 2030 and carbon neutrality is expected to be reached in 2060. China will work with ICAO to develop standards for decarbonisation technologies in aviation and the country also highlighted the possibility of developing pilot airports in China with near-zero emissions as well as demonstrational projects for sustainable jet fuels.

7.4. Hydrogen legislation and policies in other major jurisdictions

7.57 While hydrogen strategies were found for all the jurisdictions investigated, direct applicability of the strategies to the aviation industry in all jurisdictions was minimal in the short term, with most referring to hydrogen as potentially forming part of a longer-term strategy (post 2050). Table 7.5 below presents a summary of the strategies reviewed.

Table 7.5: Summary of hydrogen strategies in the EU and other jurisdictions

		EU	UK	USA	Canada	Australia	China	Japan
Title		A Hydrogen Strategy for a Climate-Neutral Europe, 2020	UK Hydrogen Strategy, 2021	Hydrogen Program Plan, 2020	Hydrogen Strategy for Canada, 2020	Australia's National Hydrogen Strategy, 2019	Planning for the Hydrogen Energy Industry, 2022	Basic Hydrogen Strategy, 2017
H_2 demand (Mt)	**2019**	9.7 (2%)	0.3-0.8 (10-27TWh)	11	3 (production)	0.5	*Unknown*	0.004
	2030	12-17	0.3-1.2 (10-38TWh)	*Unknown*	*Unknown*	0.2-1.0	*Unknown*	0.3
	2050	31-32[72] (Roadmap - 20-57)	4.5-15 (150-495TWh[73])	20-63[74]	*Unknown*	1.4-20	*Unknown*	5-10
Planned H_2 production method(s)		Electrolysis	'Twin – track' Electrolysis, Fossil with CCUS	Fossil with CCUS, Biogas/waste, Electrolysis	Electrolysis, Fossil with CCUS, Biogas/waste	Electrolysis, Gasification, Steam reforming	*Unknown*	*Unknown*

[72] 13-14% of total energy consumption
[73] 2050 demand - H_2 to grow to 20%-35% of total energy supply by 2050
[74] H_2 to grow from to 14% of total energy supply by 2050 – (63Mt)

Low Carbon H_2 production (Mt)	**2025**	1	0.13 [1 GW]	*Unknown*	0	*Unknown*	200	*Unknown*
	2030	10	0.67 [5 GW]	1.8 [13.5 GW][75]	4	NSW – 0.1	*Unknown*	*Unknown*
	2050	31-32	*Unknown*	*Unknown*	20	*Unknown*	*Unknown*	*Unknown*
Application to aviation		As part of longer term strategy	As part of longer term strategy	Potential application	Potential application	×	*Unknown*	×

75 Not set out in strategy but reference can be found at https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/100521-us-hydrogen-development-must-accelerate-to-meet-2030-net-zero-goals-iea

Notes: - Low Carbon H2 – Low Carbon Hydrogen; Conversion factors 33KWh energy per kg Hydrogen, Full-load power output of power stations 4,380 hours per year (12 hours per day) Source: (EU) A Hydrogen Strategy for a Climate-Neutral Europe, 2020, Hydrogen Roadmap Europe; (UK) UK Hydrogen Strategy, 2021; (US) Hydrogen Program Plan, 2020, Hydrogen Strategy: Enabling a Low-Carbon Economy, (Canada) Hydrogen Strategy for Canada, 2020; (Australia) Australia's National Hydrogen Strategy, 2019, Australian and Global Hydrogen Demand Growth Scenario Analysis; (China) 2019, Medium and Long-Term Planning for the Development of Hydrogen Energy Industry (2021-2035); (Japan) 2022 Basic Hydrogen Strategy, METI, 2017

7.58 Demand for hydrogen is expected to rise in all jurisdictions reviewed as it forms part of their net zero target plans. It is especially applicable for areas of consumption which are either difficult or economically unviable to electrify. The majority of strategies first focus on decarbonising current hydrogen consumption, which is primarily used for industrial purposes (steel and fertilisers) as well as oil refining. Hydrogen has also been ear-marked in strategies for:

- Transport – Predominantly in the context of fuel cell vehicles (with targets for many countries also set in terms of vehicle and filling stations), but also for maritime purposes. Application to aviation as a direct fuel source is referred to a long-term potential option.
- SAFs - Hydrogen is also required in the production of biofuels to increase their hydrogen content.
- Gas networks – Hydrogen can be blended into existing gas networks for building heating purposes. Where economically viable (high-population/usage density) dedicated hydrogen networks could also be developed.
- Power generation – Hydrogen can be stored as a fuel for power generation. Rather than being used as a means for generation in its own right, its application would predominately be to provide power system flexibility (i.e. be used as a back-up) when other systems are not available.

7.59 Canada and Australia place emphasis on becoming hydrogen exporters in their strategies, owing to their abundant supplies of natural resources and (relatively) small populations.

7.60 Most strategies outline plans to develop and demonstrate hydrogen capabilities in the period to 2030 and then scale these up in the period 2030 and 2050 for wider-scale application. The extent of the planned scale-up is currently dependent on technology development in other areas of energy generations and supply and hence relevant targets are primarily presented as ranges. Whilst the EU Hydrogen Strategy for a Climate-Neutral Europe targets that 13 to 14% of total energy consumption is hydrogen-based by 2050 (~31-32Mt of hydrogen), the Hydrogen Roadmap Europe shows a range of 20 to 57Mt, whilst the UK, USA and Australia have published ranges of 4.5Mt to 15Mt, 20Mt to 63Mt and 1.4Mt to 20Mt respectively.

7.61 The strategies also outline expected production plans for low-carbon hydrogen. The processes by which low-carbon hydrogen is produced vary by jurisdiction. The European Union has the only strategy which is totally reliant on green hydrogen to meet demand, whereas other jurisdictions include blue and turquoise hydrogen in their strategies, which are reliant on CCUS (Carbon Capture, Utilisation and Storage).

7.62 The EU, UK, USA, Canada and Australia have each published hydrogen production targets in terms of tonnage/production capacity for 2030 and 2050. In 2030, the combined targets of the EU, UK, USA and New South Wales (Australia) amount to approximately 14 Mt of low-carbon hydrogen being produced. In contrast the IEA estimate that total global hydrogen demand will grow to around 211Mt in 2030 from

88Mt[76] (+123Mt) in 2020 due to significant increases in usage from industry, transport (excluding aviation) and well and injection into power grids.

7.63 While the 14Mt target for the four jurisdictions does not equate to the total low-carbon hydrogen target, the inclusion of the EU and USA represent core global markets and thus this still highlights that there is a large discrepancy in hydrogen demand and the ability to fulfil this with low-carbon hydrogen in the medium term and during the roll-out phase of this study. We have compared hydrogen demand for aviation calculated in the model to the levels of hydrogen expected to be produced by each jurisdiction as per their strategies in Table 7.6. The adoption of the scenario modelled will result in significant proportions of produced hydrogen being used solely for in-scope aviation purposes. In 2050, 15% of hydrogen in the EU would be required for aviation purposes, whilst depending on ultimate output, this has the potential to increase to 45% of production in the US and 57% in Australia. The proportions required in 2040 have the potential to be even higher depending the on the pace of development of hydrogen production and the roll-out of hydrogen aircraft.

Table 7.6: Global hydrogen demand in relation to changes in traffic growth assumptions (Source: DLR, Hydrogen Strategies, Steer analysis)

Region	Hydrogen demand for Aviation (Mt)			Total Hydrogen demand (predicted) (Mt)			In-scope aviation requirement as a proportion of predicted demand		
	2030	2040	2050	2030	2040[77]	2050	2030	2040	2050
EU	-	2.1	4.8	10	*18*	31 - 32	-	*12%*	*15%*
UK	-	0.4	0.8	0.75	*2-3*	4.5 - 15	-	*13 - 20%*	*5 - 17%*
USA	-	3.8	9.1	3	*8-14*	20 - 63	-	*27 - 47%*	*14 - 45%*
Canada	-	0.3	0.8	0	*4*	20	-	*8%*	*4%*
Australia	-	0.3	0.8	0.1	*0.4-1.4*	1.4 - 20	-	*21 - 75%*	*4 - 57%*

7.5. Global green aviation technology trends

7.64 Some relevant industry trends towards green aviation technology and infrastructure development around the world have been identified to complement the legislation and policies discussed above.

Europe

Aircraft technology

7.65 The European aerospace industry has a wide range of OEMs and technology start-ups which are innovating in the area of green aircraft technology, through hydrogen powered (via direct combustion and/or fuel-cell) and electrically powered aircraft.

[76] Ibid

[77] Estimate based on 2030-2050 CAGR

Well-known examples include the Airbus ZEROe concepts for regional and short-/medium-range missions. These aircraft concepts are estimated to be commercially available by 2035[78] and would serve as replacements to the aircraft in the short-/medium-range narrowbody category which dominates intra-European aircraft traffic. Non-incumbents such as ZeroAvia are aiming to deliver a hydrogen fuel-cell powertrain by 2025 for 9 to 19 seat aircraft[79], suitable for regional aircraft networks. Other European technology start-ups and incumbents are developing powertrain and airframe technologies.

Airport infrastructure

7.66 Partnerships and co-operation across a range of European airports, airlines, and energy/fuel suppliers have been agreed to encourage the sharing of technology, technology requirements and specifications for new generations of aircraft.

7.67 In June 2022, Airbus and Linde signed an MoU to work on the development of hydrogen infrastructure at airports worldwide[80]. This agreement also mentions that Airbus and Linde will analyse the potential of Power-to-Liquid SAFs which are produced from synthetically produced liquid hydrocarbons using renewable electricity.

7.68 Also in June 2022, Air Liquide and Groupe ADP announced "their ambition to create the first joint venture to facilitate the development of hydrogen infrastructure at airports"[81]. The aim of the partnership is to allow airports to consider the following challenges with integrating hydrogen infrastructure[82]:

- estimating hydrogen demand;
- supply chain characteristics;
- scope and installation of infrastructure;
- safety studies;
- cost studies and investment road maps; and
- carbon impact assessments.

7.69 This announcement follows Air Liquide, Airbus, and Groupe ADP conducting a study in 2021 into the configuration of 30 airports worldwide to gain an understanding of the decarbonisation potential of hydrogen at airports worldwide.

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[78] https://www.airbus.com/en/innovation/zero-emission/hydrogen/zeroe. Accessed 25 October 2022.

[79] https://www.zeroavia.com. Accessed 25 October 2022.

[80] https://www.airbus.com/sites/g/files/jlcbta136/files/2022-06/EN_PR_Airbus%20and%20Linde%20to%20cooperate%20on%20hydrogen%20infrastructure%20for%20airports.pdf Accessed 24 October 2022.

[81] https://www.airliquide.com/sites/airliquide.com/files/2022-06/air-liquide-and-groupe-adp-announce-their-ambition-create-first-joint-venture-facilitate-development_62a97f6c50f3e.pdf Accessed 26 October 2022.

[82] Ibid

7.70 In July 2022, easyJet announced that hydrogen aircraft feature in their roadmap to net zero by 2050 and has partnered with Rolls-Royce to accelerate the development of hydrogen aircraft.[83]

North America

OEMs and US airlines

7.71 In August 2022, American Airlines and ZeroAvia (hydrogen-electric powertrain developer) signed a Memorandum of Understanding (MoU) in which the US airline can order up to 100 hydrogen-electric powertrains for use in retro-fitted regional aircraft[84]. Earlier, in 2021, United Airlines and Alaska Air Group also made investments in ZeroAvia as the manufacturer continues to develop zero-emission technology.

7.72 In October 2022, American Airlines made an equity investment in the green hydrogen distribution and storage company Universal Hydrogen[85]. The aims of Universal Hydrogen are to put aviation on the trajectory to meet the Paris Agreement obligations by delivering a conversion kit for regional aircraft that consists of hydrogen fuel cell electric powertrains and modular hydrogen storage capsules. Entry-into-service of a retrofit passenger service making use of this technology is estimated as 2025.

7.73 Based in the US, Wright[86] is developing an electric motor propulsion system that can be utilised on aircraft serving up to 100 passengers on regional range flights. Wright has secured partnerships with airlines as well as maintains strategic collaborations with suppliers and aerospace industry leaders as it continues to develop, with the aim of eliminating all emissions for flights under 700 Nm (1,300 km, 800 miles[87]).

ZeroAvia & Edmonton International Airport (EIA)

7.74 ZeroAvia and Edmonton International Airport (EIA) announced collaboration to explore opportunities to develop hydrogen infrastructure required for delivering zero emission flights as well as decarbonising ground operations[88]. EIA will work with ZeroAvia to develop zero emission infrastructure at both EIA and Villeneuve Airport.

Asia pacific (APAC) developments

Kobe Airport, Japan

7.75 Kawasaki Heavy Ind rolled out a liquid hydrogen terminal in January 2021 with a storage capacity of 2,250m3 in a volume of 2,500m3. The Hydrogen Energy Supply

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[83] https://mediacentre.easyjet.com/story/15532/easyjet-and-rolls-royce-pioneer-hydrogen-engine-combustion-technology-in-h2zero-partnership Accessed 26 October 2022.

[84] https://www.aviationtoday.com/2022/08/05/american-airlines-invests-hydrogen-electric-engine-developer-zeroavia/. Accessed 24 October 2022.

[85] https://hydrogen.aero/american-airlines-makes-equity-investment-in-universal-hydrogen-2/. Accessed 24 October 2022.

[86] https://www.weflywright.com/ Accessed 24 October 2022.

[87] Ibid.

[88] https://www.zeroavia.com/eia-collaboration Accessed 24 October 2022.

Chain (HESC) Project is the first project to deliver clean hydrogen (produced via gasification of Latrobe Valley coal with carbon capture and storage) to a storage facility in Kobe, Japan. The project is led by industry partners from Japan and Australia and is supported by Australian and Japanese Governments, with $AUD 0.5 billion expected to be invested in the HESC Pilot[89].

Airbus and APAC airports – Seoul Incheon, Singapore Changi

7.76 In early 2022, Airbus signed cooperation agreements with Seoul Incheon (Republic of Korea) and Singapore Changi airports[90] in the APAC region to study the development of hydrogen hubs at the two major hub airports. This was signed in conjunction with other industry partners such as industrial gases and engineering company Linde.

Air New Zealand Product Requirement Document

7.77 Similar to the MoU's signed between Airbus and APAC airports, Airbus has also signed an MoU with Air New Zealand (in September 2021) to research how hydrogen-powered aircraft could assist the airline in reaching its net zero goals by 2050[91]. In February 2022, Air New Zealand released a product requirements document (PRD) to outline the specifications and requirements for new generation aircraft, focussing on domestic turboprop aircraft[92].

7.6. Summary

7.78 There is a range of different legislative, policy and industry-driven initiatives relating to the use of hydrogen fuel for aircraft around the world, although the use of drop-in SAFs has generally been given the most emphasis as the means for decarbonising aviation. Europe has shown the strongest policy-led interest in the use of hydrogen, while both ICAO (representing the global view) and the USA have placed emphasis on SAFs as being the primary contributor to achieving net-zero emissions by 2050. In its most ambition scenario, the ICAO report already expects that investments in new fuels and technologies required to 2050 will amount to between €7.1 and €8.6 trillion worldwide, with the proportion of hydrogen aircraft in this scenario being very limited. The cost of hydrogen development is deemed non-competitive with other solutions such as SAFs, which require minimal modifications to be made to both aircraft technologies and airport infrastructure, whilst also facilitating progressive roll-out due to its 'drop-in' qualities. The other jurisdictions reviewed have not yet developed comprehensive strategies detailing how they will reach net-zero emissions in the aviation sector by 2050.

7.79 Nevertheless, recent developments in the US, Japan and the wider APAC region show that there is an increased focus and impetus outside Europe to develop clean energy infrastructure, in which green hydrogen is assumed to play a role. The IRA in the United States and the expected announcements in the Japanese Green

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[89] https://www.hydrogenenergysupplychain.com/resources/faqs/. Accessed 24 October 2022.

[90] https://www.airbus.com/en/newsroom/press-releases/2022-02-airbus-signs-agreement-to-study-hydrogen-hub-in-singapore. Accessed 24 October 2022.

[91] https://www.airnewzealand.co.uk/press-release-2021-airnz-and-airbus-to-research-future-of-hydrogen-powered-aircraft. Accessed 24 October 2022.

[92] https://p-airnz.com/cms/assets/PDFs/2021-air-nz-zero-emissions-aircraft-prd.pdf. Accessed 24 October 2022.

Transformation (GX) plan are examples of policies supporting this point. While there has been historically less ambition for green hydrogen for aviation in hydrogen policies around the world, there are clear examples of industry-led interest in developing its use.

7.80 If the roll-out of hydrogen aircraft globally were to proceed at the rate indicated in our roll-out scenario, the aviation market could consume a considerable proportion of the hydrogen produced in countries such as the US and Australia, or require significant growth in hydrogen production to be implemented by 2050 to ensure there is sufficient supply. It should also be noted that in addition to considering quantities of hydrogen available, global strategies do not currently include factors such as distribution networks to airports and the requirement for liquefaction facilities (and associated energy requirements), which are critical to usage in the aviation sector. However, the most recent policy updates are a step forward to addressing these issues.

7.81 Although there is an increasing interest in the most recent global energy policies and the global aviation industry towards hydrogen technologies, the combination of competing SAFs and the cost of the required technological and infrastructure development may limit the relative impact of hydrogen technologies on achieving net-zero targets in aviation by 2050.

7.82 In the case that a global market approach to hydrogen aircraft and aviation is not achieved, but that hydrogen is still considered within Europe as a contender for meeting net-zero emission targets, development of hydrogen aircraft will likely have to be conducted within Europe for application to the European market only. Due to the high costs of developing new aircraft types, which will likely be increased through a shift to hydrogen technologies, combined with the smaller market potential for the aircraft, costs per aircraft have the potential to be significantly higher than conventional aircraft. This may necessitate financial support being given to aircraft manufacturers and airlines to enable their economic operation.

7.83 There is also the possibility that, while a global roll-out of hydrogen powered aircraft if not achieved, other regions in addition to Europe do adopt the technology, leading to a “patchwork” of hydrogen capability around the world. This would have an intermediate impact on the challenges and costs of roll-out, i.e. less challenging than just for Europe on its own, but more difficult and costly than would be the case with a global roll-out and market.

7.84 In Europe and globally, hydrogen infrastructure both off and on airport will be required to support flying by hydrogen-powered aircraft. This includes green energy supplies to support green hydrogen production by electrolysis, a dedicated hydrogen gas pipeline network and airport storage and refuelling infrastructure. While international synergies are less of an issue for this infrastructure, it is unclear whether this could be developed without significant financial support from the public sector.

8. Policy options

8.1. Introduction

8.1 This chapter examines the policy options which could be considered to address the challenges to the roll-out of hydrogen and electrically powered aircraft which are the subject of this study. We have focused largely on hydrogen aircraft, as our analysis shows that its potential contribution to aviation decarbonisation is very significantly greater than that of electrically powered aircraft, which are likely to be limited to small aircraft flying short distances, whereas hydrogen-powered aircraft have the potential to replace some commercial aviation currently undertaken using conventional narrowbody and regional aircraft.

8.2 Based on our desk-top research, the analysis undertaken to develop a plausible roll-out scenario for hydrogen aircraft and the stakeholder consultation exercise undertaken, we have defined a "problem tree" setting out the challenges to hydrogen-powered flight in a logical framework. This problem tree considers:

- the general objectives for hydrogen-powered flight, which in the context of this study can be regarded as achieving significant commercial rollout of hydrogen-powered aircraft by 2040;
- the specific objectives which need to be achieved in order to deliver the general objectives;
- the key problems identified in the study likely to prevent or retard the roll-out of hydrogen-powered aircraft; and
- the "problem drivers" underlying these identified problems – these are the issues which a successful policy would need to address.

8.2. Problem tree

8.3 The problem tree is set out in Figure 8.1 below.

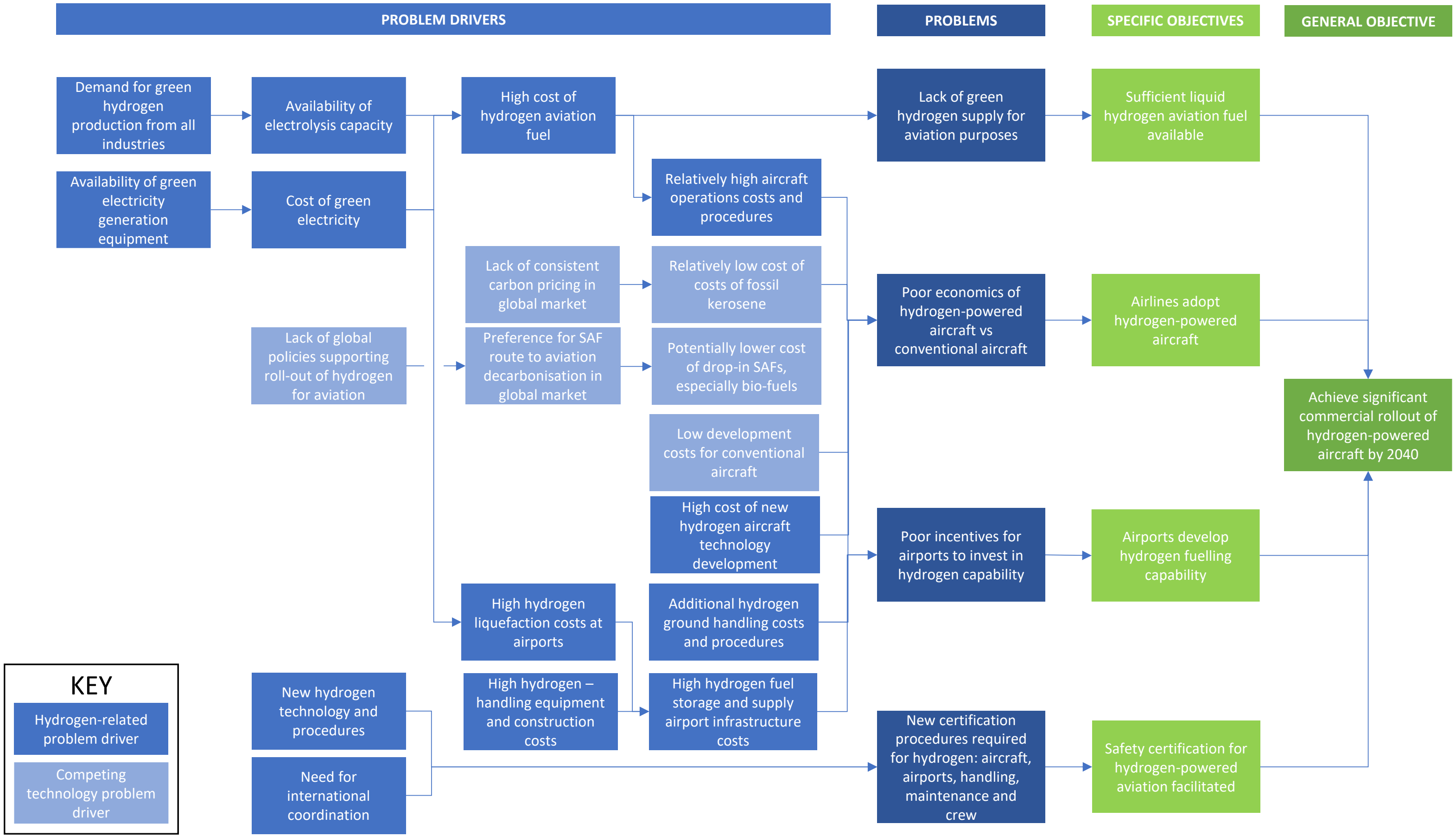

Figure 8.1: Hydrogen-powered flight problem tree (Source: Steer)

8.3. Policy objectives

8.4 As noted above and shown in Figure 8.1, we have defined the general objective as being to achieve significant commercial rollout of hydrogen-powered aircraft by 2040, given the context and objectives of this study set out in paragraph 1.4 above:

- "As a priority, the study will consider the requirements for the entry into market of zero- or low-emission aircraft in the regional and medium-range market segment. It is assumed that these aircraft will be hydrogen powered."

8.5 Based on our analysis, we have broken this general objective down into four specific objectives whose achievement is necessary to deliver the general objective:

- ensuring sufficient availability and supply of green hydrogen as aviation fuel at airports;
- encouraging and facilitating the adoption of hydrogen-powered aircraft by airlines;
- encouraging and facilitating the introduction of the necessary infrastructure at airports to support hydrogen-powered flight; and
- ensuring that all elements of the new technology and processes are safe and that suitable certification processes have been put in place in Europe and worldwide.

8.4. Problems identified

8.6 Corresponding to the specific objectives, we have identified problems which need to be overcome to achieve them, in particular:

- There is a significant risk that sufficient hydrogen will not be available, for the reasons set out in the next section.
- The economics of hydrogen-powered flight may not be sufficiently attractive:
  - to encourage manufacturers to develop the new-technology aircraft; or
  - to incentivise and support financing for airlines to buy/lease and operate such aircraft.
- There may be insufficient incentives for airports to develop the necessary infrastructure, in particular fuel supply, to support hydrogen-powered aircraft (because there may be insufficient demand from airlines and/or because the costs of doing so are too high).
- There may not be sufficiently well-developed safety certification procedures in place to give comfort to investors, airlines, airports, fuel suppliers, ground handlers and/or passengers who might consider supporting or using the aircraft.

8.7 We discuss the problem drivers lying behind these identified problems in the section below.

8.5. Problem drivers

Green electricity

8.8 As shown in Figure 8.1, one of the root causes of the potential non-availability of green hydrogen is the requirement for a very significant expansion in green power generation. This will be needed for replacing non-sustainable power generation as well as providing the power for the production of green hydrogen via electrolysis (see discussion in Chapter 6 from paragraph 6.3). There is clearly a risk that such power generation capacity may be insufficient or too expensive, unless significant policy intervention in the European market is undertaken.

Green hydrogen – production, transport and liquefaction

Production

8.9 As noted from paragraph 6.15 above, potential aviation uses of green hydrogen are likely to be competing with uses by other industries, with aviation forecast to represent only 8% of hydrogen demand by 2050. This could lead to bottlenecks in production, with insufficient electrolysis capacity leading to scarcity pricing and hence uneconomic hydrogen fuel costs.

Transport

8.10 In addition to the production of hydrogen, there is also a need for the hydrogen to be transported to airports, either by tankers or, for larger volumes, by gas pipeline (see from paragraph 6.20 above). There is currently no pipeline network for hydrogen transmission in Europe or elsewhere. There are plans to develop such a network in Europe, which may involve repurposing of existing natural gas pipelines, but it is likely that the costs of such a network, even if borne by multiple industrial users of hydrogen as well as the aviation industry, could be very high, potentially requiring public sector economic support.

Liquefaction

8.11 Whatever the means of transporting hydrogen, it needs to be liquefied before being stored at the airport and then used to refuel aircraft. Liquefaction of hydrogen is highly energy-intensive, around 15% of the energy required for production of green hydrogen by electrolysis, and will require additional electrical power to be available at the location where liquefaction is undertaken (either before transport to the airport or on-site) – see paragraph 6.33 above). There may be barriers to providing sufficient electricity for this (e.g. if the local electrical grid is at capacity) and, in principle, the electricity provided should also be green energy, potentially restricting supply and/or increasing costs.

Implications

8.12 These constraints on the production, transport and liquefaction of hydrogen will contribute to a relatively high cost of hydrogen fuel, increasing airline operating costs when using hydrogen-powered aircraft, as well as imposing significant infrastructure costs and potentially also operating costs on airports. Such high costs will all feed into the prices paid by airline customers, unless mitigated by public subsidy or other policy intervention.

Competing fuels

8.13 In contrast to hydrogen aviation fuel, alternative fuel sources may be significantly cheaper. Policy measures already being developed, such as those in Fit for 55, will impose additional costs on users of fossil fuels, including conventional airliners, through increasing carbon prices and direct measures such as fuel taxes. In addition, Fit for 55 envisages “blending mandates” for fossil kerosene to be combined with “drop-in” sustainable fuels from bio-fuel and, to a lesser extent, electro-fuel sources (see discussion in Chapter 7 from paragraph 7.7). These measures will make alternatives to use of hydrogen fuel more expensive, but there are important risks:

- fossil kerosene fuel may remain cheaper than hydrogen despite the policy measures adopted; and
- drop-in SAFs may remain cheaper than hydrogen despite the policy measures (particularly as it is assumed that carbon pricing and carbon taxes will not apply to SAFs).

8.14 While in a European context, it is potentially under the EU’s control to ensure that alternatives to hydrogen fuel do not under-price it, in a global context this is not the case. Global measures on carbon pricing in aviation (the CORSIA) scheme are relatively weak in terms of the costs imposed on airlines and other measures, such as taxation on fuel for international services are generally ruled out in existing bilateral Air Service Agreements between Member States and third countries or in EU-level Comprehensive Air Transport Agreements (the EU-UK agreement is a notable exception).

8.15 Furthermore, policies in other jurisdictions, and in particular in the US, appear to be strongly oriented towards use of drop-in SAFs as the means to decarbonise aviation, with the US actively encouraging the development of biofuels through subsidies (see from paragraph 7.44 above).

8.16 Consistent with this, while there are industry-led initiatives for hydrogen powered aircraft, there are currently no consistent policy-led interventions favouring the development of hydrogen powered aircraft in other jurisdictions.

8.17 Given these factors, it appears likely that, at a global level, hydrogen fuel may remain uncompetitive with alternatives (whether fossil kerosene or SAFs). If this is the case, any development of hydrogen-powered aircraft and uptake of such aircraft by airlines may be restricted to Europe. This would clearly significantly worsen the economics of such aircraft and reduce the likelihood of their entry into service and deployment.

Aircraft technology

8.18 There are currently no hydrogen-powered commercial aircraft. Different designs are under active consideration by manufacturers and investors, and in particular Airbus has established its ZEROe programme, considering hydrogen-powered flight based on both hydrogen fuel cells and combustion (turbofan). In either case, and as generally acknowledged, for any hydrogen-powered commercial aircraft (above a threshold of 20, possibly up to 50 seats), the hydrogen fuel would need to be stored in liquid form. Therefore, any commercial aircraft powered by hydrogen would need to overcome technical challenges, including:

- storage of liquid hydrogen, with anticipated storage tank volumes approximately four times larger than the equivalent for aircraft using kerosene; and
- development of powertrain technology, whether
  - fuel cell and electric motor technology within strict weight parameters; or
  - gas turbine engine powered by hydrogen starting in a liquid form.

8.19 These technical challenges are considered feasible to be overcome, but are likely to require very significant investment in design, development and testing, expected to be towards or above the upper end of historical aircraft development costs (for example in the range of USD $15 billion to $20 billion).

8.20 It seems likely that financial support for such a large investment programme may be needed by a manufacturer such as Airbus. This is particularly the case if, as seems quite possible, the initial market for hydrogen-powered commercial aircraft is restricted to Europe due to other jurisdictions' preference for following the drop-in SAF route to aviation decarbonisation.

8.21 However, once a successful hydrogen-powered aircraft has been constructed and is on a clear path to successful safety certification, it seems plausible that sufficient finance could be made available without necessarily requiring public support, given the enthusiasm in the financial community to support projects identified as sustainable (i.e. "green").

Airport infrastructure

8.22 The introduction of hydrogen aircraft would require significant investments in airport infrastructure (see discussion in Chapter 6 from paragraph 6.36 above). These would include:

- facilities to accept delivery of hydrogen, whether by truck or pipeline;
  - alternatively, a facility to produce hydrogen through electrolysis of water on-site;
- if arriving by pipeline (assumed to be in gaseous form), a liquefaction facility;
- storage facilities for liquid hydrogen (and a capability to reliquefy hydrogen lost through "boil-off" in the tank or during the aircraft refuelling process;
- facilities for refuelling aircraft with liquid hydrogen: either
  - using bowser/tankers with cryogenic storage; or
  - using a pipeline and hydrant system handling liquid hydrogen, supplied directly to airport stands.

8.23 These facilities are likely to cost significant sums. While generally considered feasible, there is some uncertainty about the use of a pipeline/hydrant system for liquid hydrogen, due to the need to maintain cryogenic temperatures in the pipework, sufficient pumping pressure and a capability to reprocess hydrogen which is boiled off during the process.

8.24 While the ownership of fuel storage and handling facilities may not lie directly with the airport operator, the costs of this infrastructure will fall to airlines operating hydrogen-powered airports and ultimately to their passengers, unless public sector financial support is provided.

8.25 Airports will need to have reasonable certainty that there will be sufficient demand for the use of hydrogen-powered aircraft at their facilities in order to invest in such infrastructure. They will also need certainty in how they can charge customers for the use of the infrastructure under airport charging rules and/or access to public sector financial support.

Safety and certification

8.26 While investors appear to have confidence about the technological capabilities of hydrogen-powered aircraft, there are concerns about the pathway to safety certification (see discussion from paragraph 6.80 above). Without clarity on the likelihood of successful certification of all relevant elements (aircraft technology, maintenance, crew training, hydrogen fuel storage and handling), there may be difficulties in having access to finance for acquiring the aircraft or developing relevant airport facilities.

8.27 It is also important that certification be done on the basis of international agreement and recognition, rather than just by the relevant European authority (EASA), to ensure that such aircraft can be sold and operated outside Europe

8.6. Potential policy interventions

8.28 Considering the problem drivers identified above, a number of different policy interventions could be considered. Given the different expected market conditions and support for hydrogen-powered aviation in Europe and in the rest of the world, as well as the different level of influence of the European authorities within the EU and associated countries compared to that in other jurisdictions, we consider the potential interventions in EU and other jurisdictions separately. These are set out in the Table 8.1 below, following the categorisation in the section above.

Table 8.1: Potential policy interventions (Source: Steer analysis)

Problem category	Potential intervention in EU	Potential intervention elsewhere	Who by	Framework
Green electricity	• European-level plans for development of green electricity power capacity, whether through wind power, photovoltaic or other, and considering both within-EU and imported production (e.g. from North Africa).		European Union	Renewable Energy Directive, REPowerEU Plan, Trans-European Network for Energy (TEN-E)
Green hydrogen - production	• Support for development of electrolysis technology and investment in development and expansion of electrolysis capacity. • Strategy to increase capacity and reduce costs to commercial levels required.	• Promotion of hydrogen technologies worldwide	European Union	EU Hydrogen Strategy and other regulations relating to hydrogen
Green hydrogen - transport	• Support for development of gaseous hydrogen pipeline network in Europe, whether new-build or repurposing existing natural gas pipes. • Develop legal framework surrounding gaseous hydrogen transportation and injection into the grid • Consider whether public sector investment required to kick-start infrastructure development.		European Union	EU Hydrogen Strategey, REPowerEU Plan, Trans-European Network for Energy (TEN-E)
Green hydrogen - liquefaction	• Assessment of impact of liquefaction power requirements on national electricity generation and transmission grids. • Support for potential investment in electricity generation and grids. • Inclusion in the Alternative Fuels Infrastructure Regulation.		European Union	Renewable Energy Directive, Alternative Fuels Infrastructure Regulation
Competing fuels	• Adoption and implementation of Fit for 55 measures on carbon pricing, taxation and blending	• Work in international forums to strengthen CORSIA.	European Union,	European Green Deal / Fit for 55,

Problem category	Potential intervention in EU	Potential intervention elsewhere	Who by	Framework
	mandates. • Apply ReFuelEU Aviation policies on acceptable sources of SAFs, especially biofuels. • Potentially consider carbon pricing or other costs applied to SAFs deemed not meeting criteria as well as to fossil fuels.	• Encourage adoption of equivalent measures to the EU Fit for 55 proposals, including the Energy Taxation Directive, Emissions Trading System (ETS), ReFuelEU Aviation, Renewable Energy Directive and Alternative Fuels Infrastructure Regulation). • Work to remove prohibitions on taxation of fuel and carbon pricing measures in EU-level Comprehensive Air Transport Agreements. • Work to encourage adoption of common policy approaches related to hydrogen aircraft and supporting infrastructure.	ICAO, Bilateral negotiations with third countries	COP26 process
Aircraft technology	• Support development of hydrogen-powered aircraft technology through Clean Aviation JU and similar initiatives. • Consider measures to facilitate Entry into Service of such aircraft without contravening WTO subsidy rules. • Continue to ensure that EASA develops comprehensive certification processes for aircraft manufacture and maintenance, aerodromes, crew	• Participate in ICAO and other international forums to develop multiple approaches to new aircraft technology. • Support discussions at WTO and other forums to allow additional financial support for development and EIS of carbon-neutral technology	European Union, ICAO, WTO	Clean Aviation JU and future initiatives

Problem category	Potential intervention in EU	Potential intervention elsewhere	Who by	Framework
	and engineer training, as well as technology-specific concerns such as refuelling liquid hydrogen tanks.	aircraft, to minimise potential trade disputes.		
Airport infrastructure	• Facilitate development of hydrogen supply pipelines with connections to airports. • Facilitate increase in electrical power supply to airports to support hydrogen liquefaction operations. • Consider public investment in on-airport infrastructure such as hydrogen fuel farms and airport pipeline/hydrant systems. • Consider any changes required to airport charges regulation to allow repayment of infrastructure costs associated with hydrogen-powered aircraft.		European Union	European Green Deal / Fit for 55, Airport Charges Directive, Alternative Fuels Infrastructure Regulation, Trans-European Network for Energy (TEN-E)
Safety and certification	• New certification and operating standards to be developed. • Financial assistance or closer cooperation of authorities and technology developers and manufacturers.	• Continue to work with FAA and other key air safety regulators to agree processes for safety certification, to minimise duplication of effort. • Continue cooperation at ICAO level on relevant environmental standards.	European Union – EASA, FAA, Other safety regulators	EASA Regulations, ICAO Annex 16

9. Conclusions

9.1. Introduction

9.1 This study has reviewed the relevant literature and received inputs from a wide range of industry stakeholders. A roll-out scenario for hydrogen-powered and electrically powered aircraft has been developed and assessed in the context of the literature and stakeholder comments. This assessment indicates that the scenario is, in principle, feasible in the sense that there are no insurmountable technical barriers to the roll-out of such aircraft.

9.2 However, there are very significant obstacles to be overcome in achieving such a roll-out. These obstacles are highly challenging in a European context, while the roll-out appears close to unachievable at a global level within the timescales being considered (which assume EIS of hydrogen-powered aircraft in 2035, significant ramp-up by 2040 and further rapid growth to 2050).

9.3 In Europe, the barriers are technical and financial, while in the rest of the world, in addition to these barriers, there does there appears to be less appetite for pushing forward the use of hydrogen fuel for commercial aircraft, despite a number of industry-led initiatives. Instead, there appears to be a clear preference for the use of drop-in SAFs (i.e. hydrocarbon replacements for conventional fossil kerosene fuel) as the principal path to decarbonise aviation.

9.2. Technical barriers

9.4 The most important barriers to roll-out of hydrogen-powered flight in Europe lie outside of the aviation industry itself. They relate to the production and transport of green hydrogen to airports. Very large investments in sustainable electrical power generation capacity as well as in water electrolysis capacity and in hydrogen pipeline infrastructure will be required. In addition, electrical transmission equipment to supply the power required to liquefy hydrogen on-site at airports will be needed. It seems unlikely that the aviation industry will be able to support such investments and it will need to rely on wider investment for other industries who, however, will also be competing users of the hydrogen produced.

9.5 The direct technical challenges to be addressed within the aviation industry include the development, certification and production of hydrogen-powered aircraft, as well as the on-airport infrastructure required to support them, in particular the handling of hydrogen fuel. Two pathways for hydrogen-powered aircraft appear feasible – regional aircraft using electric motors powered by hydrogen fuel cells (range up to 1,000 Nm) and short haul narrow-body aircraft powered by turbofan engines burning hydrogen (range up to 2,000 Nm). Both aircraft types would store the fuel in liquid hydrogen form, requiring greater volumes than for conventional fuel (about 4x more capacity) in cryogenic tanks (below -253°C). There is a broad consensus about the feasibility of these approaches, which are actively being investigated by Airbus in its ZEROe programme.

9.6 At airports, the technical challenges relate to the liquefaction of hydrogen arriving at the airport in gaseous form, storage of liquid hydrogen in cryogenic tanks and, most critically, the processes for refuelling aircraft safely, while maintaining aircraft turnaround times similar to those of today. Liquefaction of hydrogen is feasible, but will require large quantities of electrical power, which may provide capacity challenges for electricity generation and transmission in the locality. Storage of liquid hydrogen appears feasible, but will require sufficient space for the tanks. Refuelling by bowser tanker appears technically feasible but may lead to unmanageable congestion at larger airports. The alternative is the use of a fixed pipeline/hydrant system pumping liquid hydrogen, which will require enhancement of existing technology and very large levels of investment (and lead to disruption during construction).

9.3. Financial barriers

9.7 The financial challenges relate to the funding of the all the technical issues noted above.

9.8 Funding of sustainable electrical power generating capacity, green hydrogen production electrolysis equipment and long-distance gaseous hydrogen pipelines may need significant public sector support and investment.

9.9 Aircraft manufacturers are likely to need support during the technology development phase of building hydrogen-powered aircraft. Once Technical Readiness Level 6 (TRL 6 – "Technology demonstrated in relevant environment") has been reached, financing to reach Entry into Service (EIS) at TRL 9 may need to be on a commercial basis to conform to WTO rules. However, this is dependent on market confidence in the existence of a sufficiently level of demand, which in turn may depend on global support for hydrogen-powered flight. In the absence of such support, which appears a serious possibility (see below), there may be a need for further public sector support, which may lead to a risk of complaints about unfair subsidies at the WTO.

9.10 Financing of hydrogen aircraft, once developed and certified for safety, appears to be less of a concern, as financiers are keen to support "green" assets, particularly in sectors such as aviation, where there have traditionally not been large sustainable investment opportunities.

9.11 There may also be a need for financial support for the development of the airport infrastructure needed to facilitate hydrogen-powered aircraft. To ensure long-term financial viability of airport operations, it may also be necessary to consider if adaptations of existing rules on airport charging may be needed.

9.4. Prospects for global roll-out of hydrogen aircraft

9.12 Looking beyond Europe, there are national plans in several key jurisdictions for the development of green hydrogen supplies for a variety of industrial processes, but none of these specifically address the use of hydrogen in aviation. Where plans for aviation decarbonisation exist, they are generally focused on the introduction of drop-in SAFs, rather than hydrogen. However, some industry initiatives and policy developments indicate a growing interest in the use of hydrogen, and green aviation technology development continues even where national hydrogen aviation policies are not defined.

9.13 In the US in particular, policy on aviation decarbonisation is firmly based on the use of SAFs, for which major tax incentives have been introduced. The significant use of hydrogen as aviation fuel is seen as a long term option, i.e. beyond 2050 (except for GA and other small aircraft). This position is reflected in a recent ICAO report on emissions reduction and the focus on biofuels seems likely to be replicated in most other jurisdictions outside Europe.

9.14 There is therefore a risk that the opportunities for hydrogen aircraft development may need to be focused almost exclusively in Europe during an initial roll-out, implying a smaller commercial market and a need for greater public sector support than would otherwise be the case. While in the long run, assuming that hydrogen aircraft are adopted more widely at a later stage in other parts of the world, this is likely to provide Europe with a competitive advantage in the technology for hydrogen-powered flight, it could make barriers to hydrogen-powered aircraft significantly more challenging for the European aviation industry in the short and medium term.

9.15 A more restricted geographical roll-out would also result in the environmental benefits envisaged being delayed and reduced.

9.5. Safety certification

9.16 The new technology involved in hydrogen-powered flight (and to a lesser extent, electrically powered flight) will need to be subject to comprehensive safety certification procedures. EASA is well placed to lead on this in a European context and is actively working to provide itself with sufficient capability to do so. Some widening of safety regulation scope may be needed to deal with specific issues relating to the handling of liquid hydrogen fuel.

International cooperation will nevertheless still be needed, both at ICAO and bilaterally with other safety regulators such as the FAA. If hydrogen-powered commercial aircraft are being developed only by European manufacturers, there may be challenges in avoiding duplication of effort in achieving safety certification worldwide.

10. Appendices

10.1. Roll-out scenario projections – Retirement half-life comparison

A.1 Complementing the projections already set out in Chapter 4 (Roll-out scenario – results), this appendix contains the roll-out scenario results for both the 18-year and 25-year half-life scenarios for both global and European geographies.

Operational fleet

Global

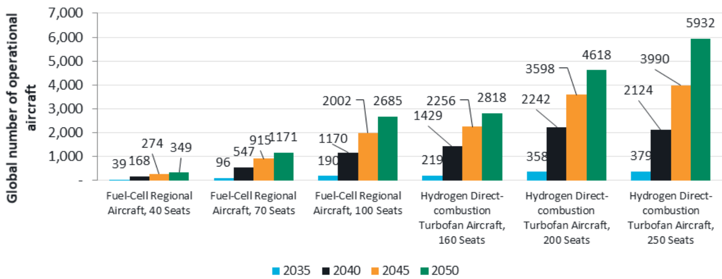

Figure A.1: Global operational fleet, 18-year half-life (Source: DLR analysis)

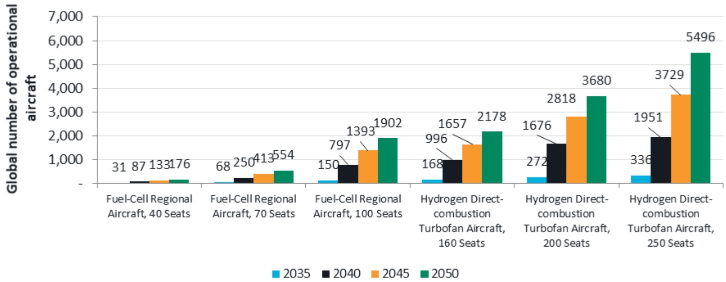

Figure A.2: Global operational fleet, 25-year half-life (Source: DLR analysis)

European (EU, EEA, CH & UK)

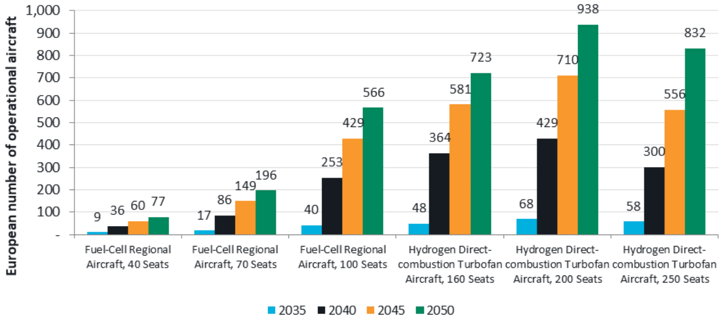

Figure A.3: European (EU, EEA, CH & UK) operational fleet, 18-year half-life (Source: DLR analysis)

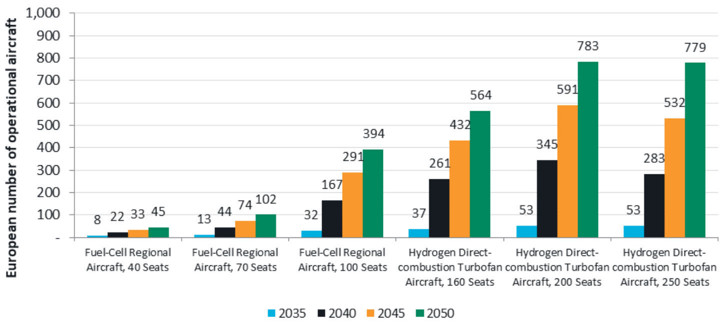

Figure A.4: European (EU, EEA, CH & UK) operational fleet, 25-year half-life (Source: DLR analysis)

Expected future annual aircraft retirement

Global

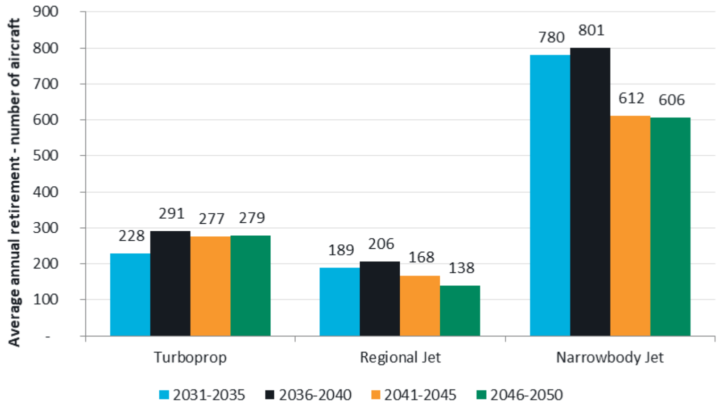

Figure A.5: Global expected average annual retirement, 18-year half-life (Source: DLR analysis)

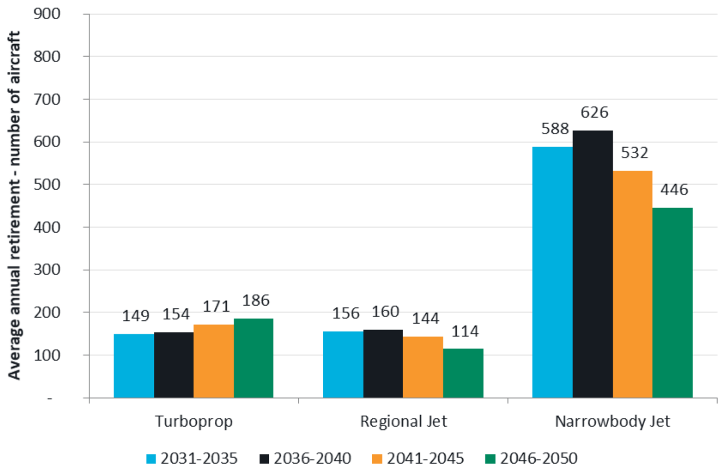

Figure A.6 : Global expected average annual retirement, 25-year half-life (Source: DLR analysis)

European (EU, EEA, CH & UK)

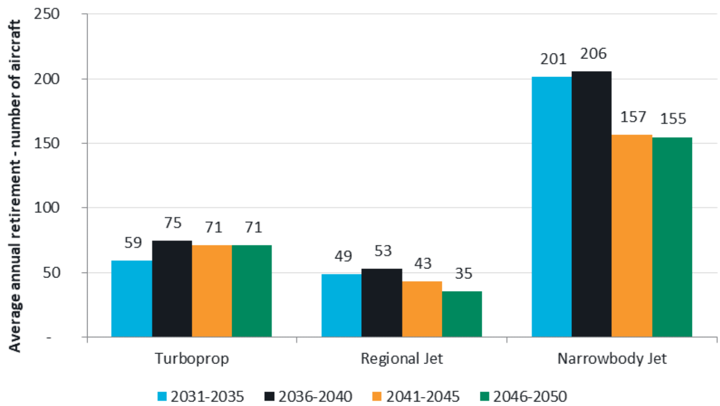

Figure A.7: European (EU, EEA, CH & UK) expected average annual retirement, 18-year half-life. (Source: DLR analysis)

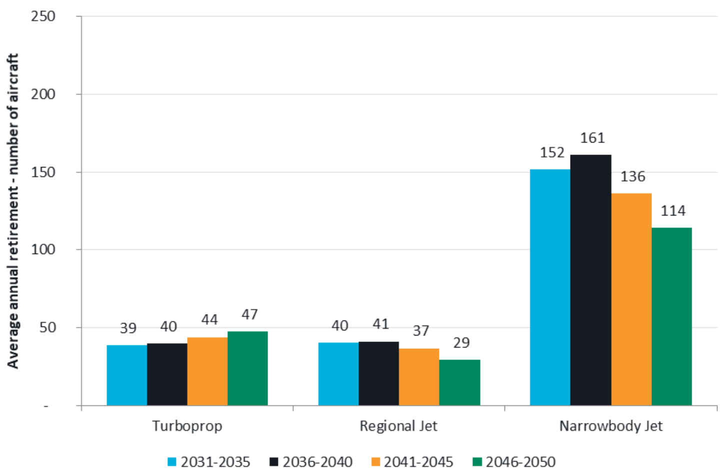

Figure A.8: European (EU, EEA, CH & UK) expected average annual retirement, 25-year half-life. (Source: DLR analysis)

Aircraft departures

Global

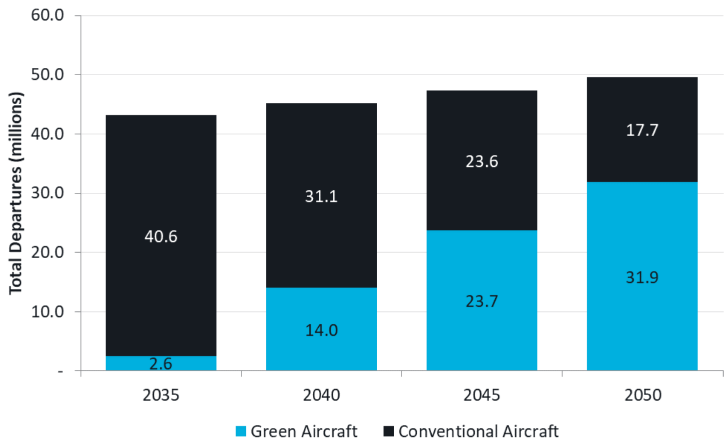

Figure A.9: Global aircraft departures, 18-year half-life (Source: DLR analysis)

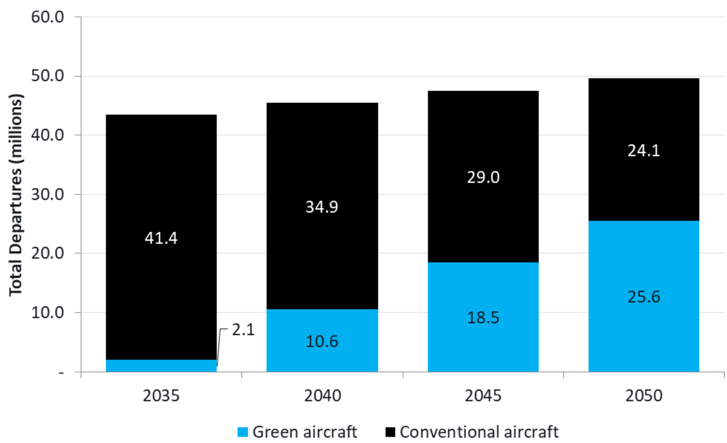

Figure A.10: Global aircraft departures, 25-year half-life (Source: DLR analysis)

European (EU, EEA, CH & UK)

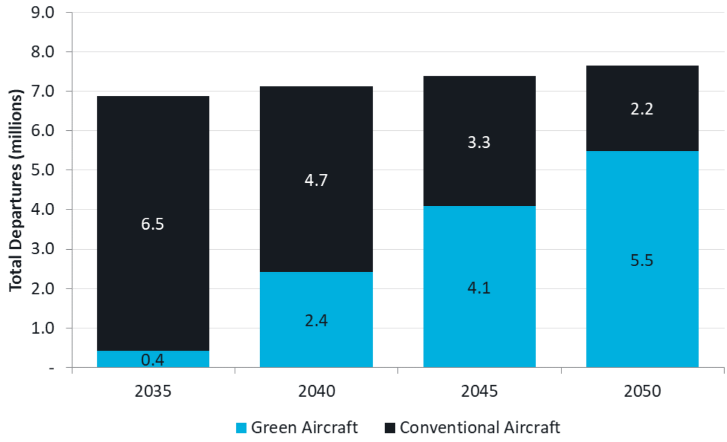

Figure A.11: European (EU, EEA, CH & UK) aircraft departures, 18-year half-life (Source: DLR analysis)

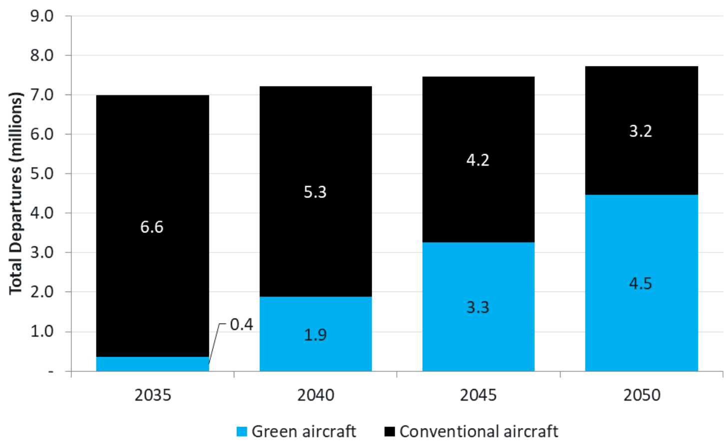

Figure A.12: European (EU, EEA, CH & UK) aircraft departures, 25-year half-life (Source: DLR analysis)

Total traffic operated by hydrogen/hybrid-electric aircraft

Table A.1: Total traffic operated by hydrogen /hybrid-electric aircraft, 2035-2050, 18-year half-life (Source: DLR analysis)

Indicator/Geographical Coverage	2035	2040	2045	2050
Global Air Transport System				
Total Departures (millions)	2.6	14.0	23.7	31.9
Flight Kilometers (billions)	2.3	13.5	22.7	30.6
Passenger Kilometers (billions)	376	2277	3929	5405
Departing flights from EU, EEA, CH and UK				
Total Departures (millions)	0.5	2.6	4.4	5.9
Flight Kilometers (billions)	0.4	2.2	3.7	4.9
Passenger Kilometers (billions)	58	357	611	835
Flights within and between EU, EEA, CH and UK				
Total Departures (millions)	0.4	2.4	4.1	5.5
Flight Kilometers (billions)	0.3	1.9	3.2	4.3
Passenger Kilometers (billions)	50	307	525	718

Table A.2: Share of traffic operated by hydrogen /hybrid-electric aircraft, 2035-2050, 18-year half-life (Source: DLR analysis)

Indicator/Geographical Coverage	2035	2040	2045	2050
Global Air Transport System				
Share of Departures	5.9%	31.1%	50.1%	64.3%
Share of Flight Kilometers	3.8%	21.5%	34.5%	44.3%
Share of Passenger Kilometers	3.2%	17.0%	26.3%	32.9%
Departing flights from EU, EEA, CH and UK				
Share of Departures	5.8%	31.7%	51.4%	66.4%
Share of Flight Kilometers	3.4%	19.6%	31.6%	40.6%
Share of Passenger Kilometers	2.6%	14.1%	22.1%	27.8%
Flights within and between EU, EEA, CH and UK				
Share of Departures	6.2%	34.0%	55.4%	71.7%
Share of Flight Kilometers	5.1%	29.4%	47.7%	61.8%
Share of Passenger Kilometers	4.7%	25.9%	40.8%	51.7%

Table A.3: Total traffic operated by hydrogen /hybrid-electric aircraft, 2035-2050, 25-year half-life (Source: DLR analysis)

Indicator/Geographical Coverage	2035	2040	2045	2050
Global Air Transport System				
Total Departures (millions)	2.1	10.6	18.5	25.6
Flight Kilometers (billions)	1.8	10.4	18.2	25.0
Passenger Kilometers (billions)	307	1821	3270	4566
Departing flights from EU, EEA, CH and UK				
Total Departures (millions)	0.4	2.0	3.5	4.8
Flight Kilometers (billions)	0.3	1.7	3.0	4.1
Passenger Kilometers (billions)	48	290	512	706
Flights within and between EU, EEA, CH and UK				
Total Departures (millions)	42	249	439	606
Flight Kilometers (billions)	0.3	1.9	3.2	4.3
Passenger Kilometers (billions)	50.4	306.7	524.6	717.5

Table A.4: Share of traffic operated by hydrogen /hybrid-electric aircraft, 2035-2050, 25-year half-life (Source: DLR analysis)

Indicator/Geographical Coverage	2035	2040	2045	2050
Global Air Transport System				
Share of Departures	4.8%	23.3%	39.0%	51.5%
Share of Flight Kilometers	3.1%	16.5%	27.6%	36.1%
Share of Passenger Kilometers	2.6%	13.6%	22.0%	27.9%
Departing flights from EU, EEA, CH and UK				
Share of Departures	4.8%	24.2%	40.6%	53.6%
Share of Flight Kilometers	2.8%	15.3%	25.4%	33.2%
Share of Passenger Kilometers	2.1%	11.5%	18.5%	23.5%
Flights within and between EU, EEA, CH and UK				
Share of Departures	5.1%	26.1%	43.8%	57.9%
Share of Flight Kilometers	4.2%	22.8%	38.3%	50.6%
Share of Passenger Kilometers	3.8%	21.0%	34.2%	43.8%

CO2 reduction potential

Global

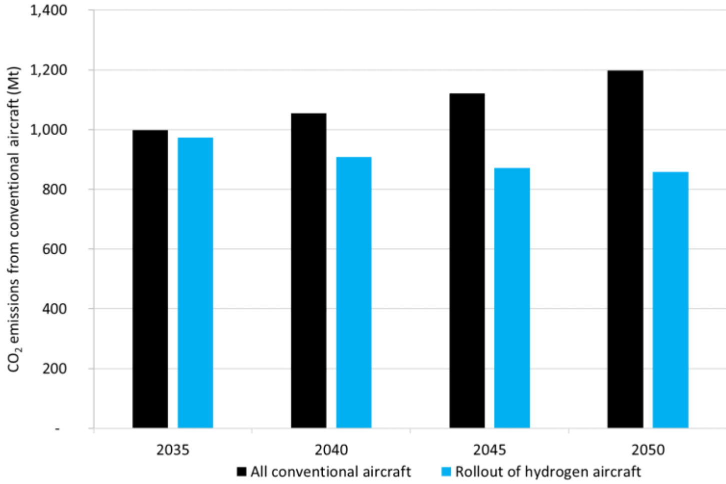

Figure A.13: Global CO2 reduction potential, 18-year half-life (Source: DLR analysis)

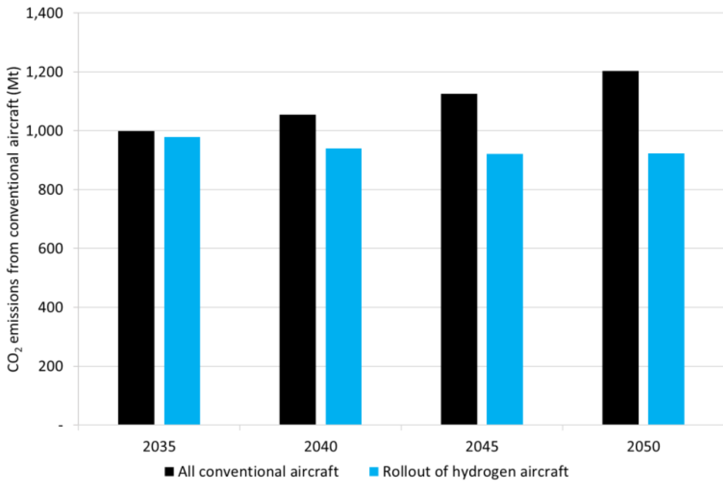

Figure A.14: Global CO2 reduction potential, 25-year half-life (Source: DLR analysis)

European (EU, EEA, CH & UK)

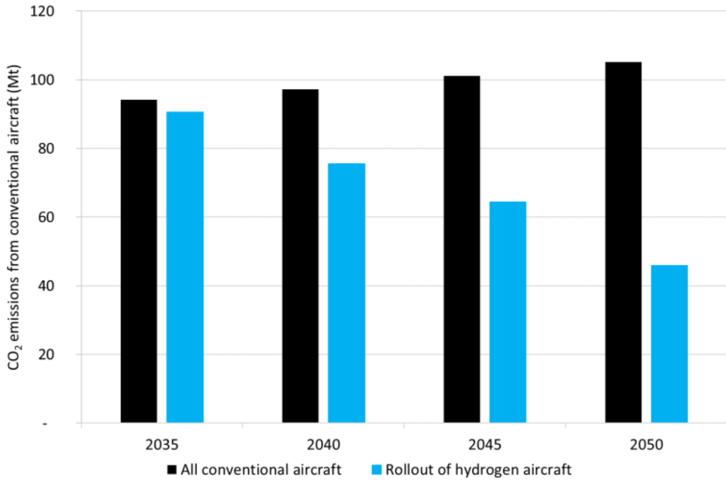

Figure A.15: European (EU, EEA, CH & UK) CO2 reduction potential, 18-year half-life (Source: DLR analysis)

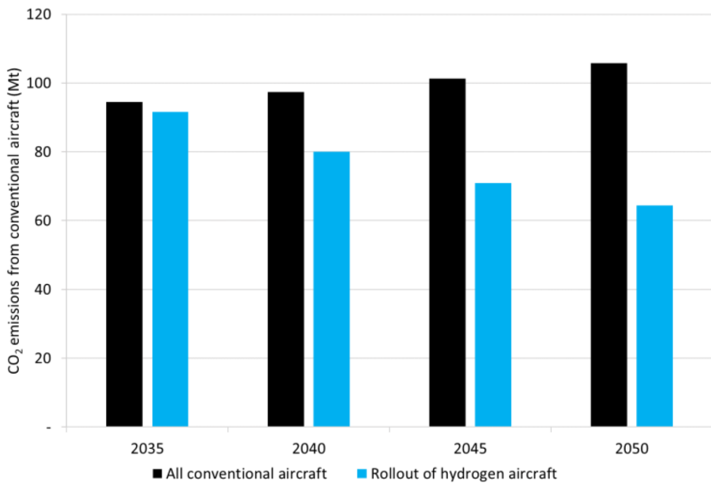

Figure A.16: European (EU**, EEA, CH & UK) CO2 reduction potential, 25-year half-life (Source: DLR analysis)**

Global aviation hydrogen fuel demand

Global

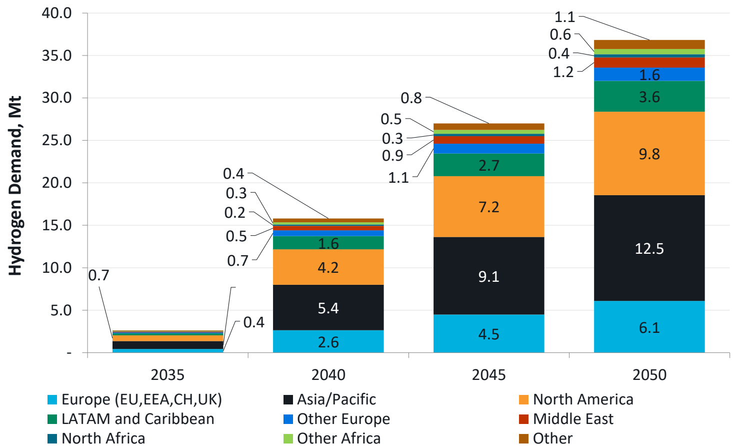

Figure A.17: Global aviation hydrogen fuel demand, 18-year half-life (Source: DLR analysis)

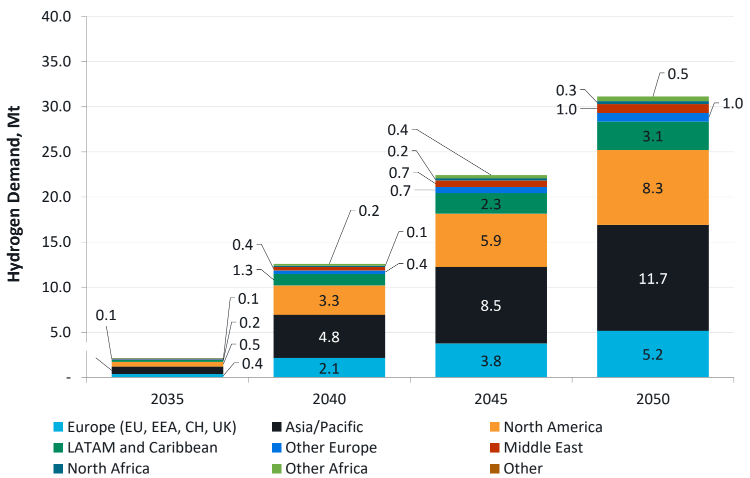

Figure A.18: Global aviation hydrogen fuel demand, 25-year half-life (Source: DLR analysis)

Tankering comparison

European (EU, EEA, CH & UK)

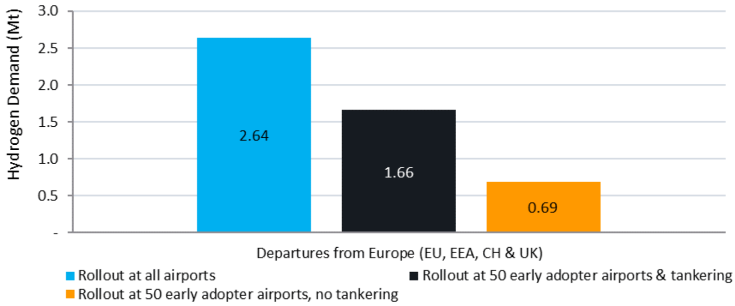

Figure A.19: European (EU, EEA, CH & UK) aviation hydrogen demand tankering sensitivity, 18-year half-life (Source: DLR analysis)

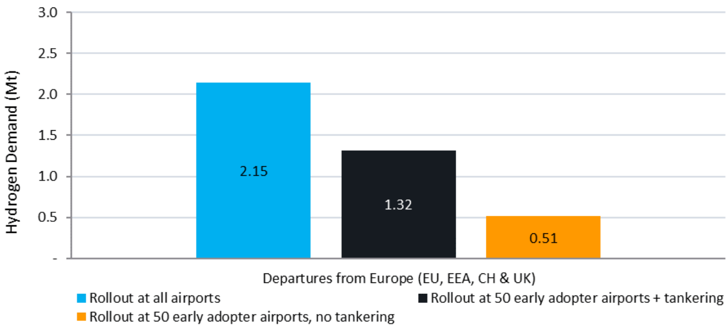

Figure A.20: European (EU, EEA, CH & UK) aviation hydrogen demand tankering sensitivity, 25-year half-life (Source: DLR analysis)

Airport roll-out

Early adopters

A.2 The following tables outline the results for airports identified as priority airports in the early phases of hydrogen aviation roll-out in 2040. The variation between Table A.5 and Table A.6 is a consequence of the differing 18-year and 25-year half-life assumptions.

Table A.5: Top 50 early hydrogen supporting airports key results in 2040, 18-year half-life (Source: DLR analysis)

Rank	Airport	Country	Departing flights in 2040	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
1	Copenhagen	DK	153,616	27	53,145	54,248	401
2	Oslo	NO	142,342	26	53,048	54,248	401
3	Amsterdam	NL	285,256	46	86,700	92,179	682
4	Paris - CDG	FR	282,329	44	79,778	95,885	710
5	Stockholm - Arlanda	SE	134,784	25	47,083	48,338	358
6	Edinburgh	GB	68,373	11	21,506	18,499	137
7	Hamburg	DE	87,230	16	30,791	30,392	225
8	Glasgow	GB	51,611	7	14,298	10,090	75
9	Stavanger	NO	29,288	5	11,867	7,086	52
10	Berlin	DE	161,607	28	53,887	62,758	464
11	Vienna	AT	136,681	25	45,756	47,918	355
12	Bergen	NO	42,356	7	16,295	10,493	78
13	Trondheim	NO	32,202	6	12,383	7,783	58
14	London - Stansted	GB	93,822	12	22,252	31,976	237
15	Rome-Fiumicino	IT	190,584	35	66,951	80,096	593
16	Torp	NO	11,062	2	3,561	1,955	14
17	Aalborg	DK	8,982	1	3,234	2,113	16
18	Lyon	FR	61,752	12	22,053	17,338	128
19	Billund	DK	16,761	3	5,267	3,587	27
20	Marseille	FR	47,523	9	16,847	16,941	125
21	Toulouse	FR	46,868	9	17,392	15,079	112
22	Athens	GR	99,535	16	28,839	36,634	271
23	Paris - Orly	FR	149,062	27	50,086	59,163	438
24	Stuttgart	DE	60,325	10	20,266	18,737	139
25	Bari	IT	18,594	3	5,788	6,404	47
26	Nice	FR	72,357	12	22,635	24,881	184
27	Aberdeen	GB	28,546	5	9,631	4,673	35
28	Helsinki	FI	97,002	18	31,498	34,921	258
29	Milan - Malpensa	IT	89,721	14	23,034	27,074	200
30	Barcelona	ES	182,558	31	58,156	80,290	594
31	Brussels	BE	126,437	26	43,333	47,879	354
32	Cologne/Bonn	DE	55,638	9	18,387	21,528	159
33	Gothenburg	SE	36,384	7	12,998	10,579	78
34	Valencia	ES	28,785	4	7,681	7,750	57
35	Dublin	IE	124,571	18	36,546	42,324	313
36	Madrid	ES	227,958	39	68,885	86,582	641
37	Bergamo	IT	40,829	5	9,893	14,461	107
38	London - Gatwick	GB	171,761	28	49,654	72,386	536
39	Frankfurt	DE	280,438	44	85,092	89,372	661
40	Bologna	IT	35,722	6	11,299	13,214	98
41	Basel	CH	33,871	6	10,849	10,835	80
42	Bodø	NO	21,577	3	6,917	2,966	22
43	Tromsø	NO	19,617	3	6,890	4,232	31
44	Malmö	SE	11,783	2	4,195	3,177	24
45	Girona	ES	5,431	1	1,304	1,959	14

Rank	Airport	Country	Departing flights in 2040	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
46	Rygge	NO	4,876	1	1,733	2,935	22
47	London - Luton	GB	60,822	10	17,110	27,922	207
48	Budapest	HU	52,400	8	13,464	18,410	136
49	Sevilla	ES	19,944	3	4,631	6,086	45
50	Eindhoven	NL	17,726	2	3,970	6,284	47

Table A.6: Top 50 early hydrogen supporting airports key results in 2040, 25-year half-life(Source: DLR analysis)

Rank	City Name	Country	Departing Flights 2040	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
1	Copenhagen	DK	153,906	21	41,129	44,436	329
2	Oslo	NO	143,066	20	41,112	43,993	326
3	Amsterdam	NL	285,843	34	65,098	71,395	528
4	Paris - CDG	FR	283,371	35	63,541	78,957	584
5	Stockholm - Arlanda	SE	134,814	19	36,042	38,313	284
6	Edinburgh	GB	68,621	8	16,742	15,218	113
7	Hamburg	DE	87,576	13	24,288	25,139	186
8	Glasgow	GB	51,704	5	10,925	8,292	61
9	Stavanger	NO	29,330	4	8,938	6,000	44
10	Berlin	DE	163,103	22	42,565	50,570	374
11	Vienna	AT	137,217	19	34,359	37,314	276
12	Bergen	NO	42,433	5	12,066	8,244	61
13	Trondheim	NO	32,396	4	8,932	6,135	45
14	London - Stansted	GB	95,135	10	18,837	27,221	201
15	Rome - Fiumicino	IT	191,021	28	53,020	64,976	481
16	Torp	NO	11,414	1	2,604	1,540	11
17	Aalborg	DK	9,025	1	2,497	1,780	13
18	Lyon	FR	62,383	8	16,331	13,463	100
19	Billund	DK	16,846	2	3,820	2,798	21
20	Marseille	FR	47,692	7	13,225	13,851	102
21	Toulouse	FR	47,259	6	12,988	12,214	90
22	Athens	GR	100,629	12	20,821	28,814	213
23	Paris - Orly	FR	149,882	21	40,412	49,641	367
24	Stuttgart	DE	60,678	8	15,133	14,983	111
25	Bari	IT	18,726	2	4,304	4,910	36
26	Nice	FR	72,673	9	18,401	21,006	155
27	Aberdeen	GB	28,500	4	7,885	4,146	31
28	Helsinki	FI	97,719	14	23,699	27,718	205
29	Milan - Malpensa	IT	93,375	10	16,824	21,178	157
30	Barcelona	ES	182,805	26	48,245	67,671	501
31	Brussels	BE	126,560	20	33,174	38,362	284
32	Cologne/Bonn	DE	55,788	7	14,039	17,186	127
33	Gothenburg	SE	36,714	5	9,104	8,029	59
34	Valencia	ES	29,648	3	6,092	6,582	49
35	Dublin	IE	125,385	14	27,460	33,310	246
36	Madrid	ES	228,535	31	54,155	70,573	522
37	Bergamo	IT	41,704	4	8,211	12,022	89
38	London - Gatwick	GB	171,992	24	42,367	63,291	468
39	Frankfurt	DE	281,382	34	66,365	73,242	542
40	Bologna	IT	35,991	5	8,694	10,562	78
41	Basel	CH	34,425	4	8,171	8,560	63
42	Bodø	NO	21,834	2	5,015	2,435	18
43	Tromsø	NO	19,602	2	5,060	3,406	25
44	Malmö	SE	11,785	1	2,952	2,492	18
45	Girona	ES	5,527	1	1,241	1,873	14

Rank	City Name	Country	Departing Flights 2040	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
46	Rygge	NO	4,875	1	1,635	2,789	21
47	London - Luton	GB	61,252	8	13,883	22,975	170
48	Budapest	HU	52,963	6	10,714	15,076	112
49	Sevilla	ES	20,545	2	3,484	4,767	35
50	Eindhoven	NL	18,265	2	3,320	5,343	40

Largest airports by 2050

A.3 The following tables outline the results for the top 50 airports by total hydrogen aviation fuel demand in 2050, the variation between Table A.7 and Table A.8 is a consequence of the differing 18-year and 25-year half-life assumptions.

Table A.7: Top 50 largest European airports for hydrogen demand in 2050, 18-year half-life(Source: DLR analysis)

Rank	Airport	Country	Departing Flights 2050	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
1	London - Heathrow	GB	357,085	97	181,041	236,126	1,747
2	Paris - CDG	FR	308,594	99	181,442	223,118	1,651
3	Amsterdam	NL	312,501	106	201,024	218,998	1,621
4	Madrid	DE	306,871	98	191,104	206,747	1,530
5	Frankfurt	ES	248,487	91	160,575	206,354	1,527
6	Barcelona	ES	197,769	71	133,679	187,828	1,390
7	Munich	DE	256,281	97	183,773	182,718	1,352
8	Rome-Fiumicino	IT	204,533	78	148,367	181,732	1,345
9	London - Gatwick	GB	190,308	64	114,597	168,686	1,248
10	Berlin	DE	172,262	62	121,920	142,481	1,054
11	Paris - Orly	FR	161,217	60	113,353	135,905	1,006
12	Copenhagen	DK	167,004	63	121,978	127,307	942
13	Oslo	NO	155,747	58	119,931	124,709	923
14	Lisbon	PT	118,345	52	81,099	117,919	873
15	Vienna	AT	147,137	59	107,809	114,240	845
16	Stockholm - Arlanda	SE	146,306	57	107,345	113,563	840
17	Brussels	BE	136,273	58	98,101	111,383	824
18	Zurich	CH	155,078	52	102,514	101,959	754
19	Dublin	IE	133,834	43	86,717	100,734	745
20	Athens	GR	106,516	40	73,586	91,087	674
21	Düsseldorf	DE	136,716	50	93,270	86,566	641
22	Helsinki	FI	105,916	43	74,707	82,889	613
23	Palma de Mallorca	ES	109,993	33	65,246	80,820	598
24	Geneva	CH	97,893	40	74,214	78,229	579
25	Hamburg	IT	93,583	33	58,377	70,107	519
26	Malaga	DE	93,239	36	69,105	69,695	516
27	London - Stansted	ES	69,791	26	38,562	69,146	512
28	Milan - Malpensa	GB	99,720	24	46,040	65,899	488
29	London - Luton	GB	65,267	23	38,620	63,459	470
30	Nice	GB	119,246	31	60,463	59,493	440
31	Manchester	CZ	75,125	28	52,197	58,240	431
32	Bucharest - Otopeni	FR	78,368	27	51,847	58,235	431
33	Prague	RO	68,184	26	42,954	57,016	422
34	Warsaw	PL	91,372	42	67,266	49,563	367
35	Milan - Linate	DE	58,951	20	40,859	48,572	359
36	Cologne/Bonn	IT	64,154	28	54,053	47,295	350
37	Alicante	ES	51,510	17	27,466	45,830	339
38	Edinburgh	GB	74,789	26	50,929	43,848	324

Rank	Airport	Country	Departing Flights 2050	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
39	Stuttgart	IT	51,021	20	37,856	43,596	323
40	Venice	DE	63,906	23	46,055	43,175	319
41	Budapest	FR	65,544	26	50,257	41,259	305
42	Lyon	HU	56,912	17	30,667	40,859	302
43	Marseille	FR	50,293	19	37,323	37,941	281
44	Toulouse	PT	47,325	18	31,903	35,830	265
45	Porto	FR	49,694	20	38,823	35,327	261
46	Bergamo	IT	35,277	13	25,660	31,948	236
47	Catania	IT	41,689	11	21,590	31,581	234
48	Bologna	IT	37,761	14	25,807	30,287	224
49	Birmingham	GB	66,274	21	39,814	29,964	222
50	Faro	PT	29,029	11	15,243	29,797	220

Table A.8: Top 50 largest European airports for hydrogen demand in 2050, 25-year half-life(Source: DLR analysis)

Rank	City Name	Country	Departing Flights 2050	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
1	London - Heathrow	GB	357,229	87	162,316	212,617	1,573
2	Paris - CDG	FR	309,115	83	152,922	193,436	1,431
3	Amsterdam	NL	312,587	86	164,677	186,112	1,377
4	Madrid	ES	248,587	75	133,407	178,581	1,322
5	Frankfurt	DE	307,044	80	157,925	178,228	1,319
6	Barcelona	ES	197,751	61	115,954	164,618	1,218
7	Munich	DE	256,424	78	149,819	157,802	1,168
8	Rome - Fiumicino	IT	204,604	65	123,954	155,516	1,151
9	London - Gatwick	GB	190,328	57	101,161	151,384	1,120
10	Berlin	DE	172,967	51	100,556	119,744	886
11	Paris - Orly	FR	161,155	50	94,123	116,655	863
12	Copenhagen	DK	167,081	51	99,777	109,312	809
13	Oslo	NO	155,872	48	99,126	107,521	796
14	Lisbon	PT	118,922	42	65,288	98,018	725
15	Vienna	AT	147,233	47	86,832	95,747	709
16	Stockholm - Arlanda	SE	146,300	45	87,069	95,605	707
17	Brussels	BE	136,304	46	79,487	94,414	699
18	Zurich	CH	155,374	42	83,893	88,350	654
19	Dublin	IE	133,951	35	70,894	84,752	627
20	Athens	GR	106,669	31	57,342	76,443	566
21	Düsseldorf	DE	136,782	39	73,597	72,482	536
22	Helsinki	FI	106,009	34	59,997	70,176	519
23	Palma de Mallorca	ES	110,125	27	53,202	68,384	506
24	Geneva	CH	97,941	32	61,772	67,876	502
25	Hamburg	DE	93,446	29	56,626	59,799	443
26	Malaga	ES	69,877	21	31,439	57,039	422
27	London-Stansted	GB	100,494	21	39,646	56,742	420
28	Milan-Malpensa	IT	93,991	25	44,126	56,005	414
29	London - Luton	GB	65,367	19	31,718	52,477	388
30	Nice	FR	78,356	22	43,490	50,599	374
31	Manchester	GB	119,364	25	48,844	50,452	373
32	Bucharest - Otopeni	RO	68,286	21	34,858	48,686	360
33	Prague	CZ	75,332	23	41,999	48,254	357
34	Warsaw	PL	91,488	31	51,614	42,620	315
35	Milan - Linate	IT	64,148	22	44,085	40,575	300
36	Cologne/Bonn	DE	58,971	16	33,011	40,179	297
37	Alicante	ES	51,553	14	22,421	38,007	281

Rank	City Name	Country	Departing Flights 2050	Number of based H_2 aircraft	Annual H_2 aircraft departures	Annual H_2 demand (tonnes)	Liquefaction energy req. (GWh)
38	Edinburgh	GB	74,845	21	41,517	37,439	277
39	Stuttgart	DE	64,011	18	36,707	36,571	271
40	Venice	IT	51,097	15	30,156	35,356	262
41	Budapest	HU	56,989	14	25,382	34,623	256
42	Lyon	FR	65,757	20	39,615	34,520	255
43	Marseille	FR	50,409	15	30,670	32,210	238
44	Toulouse	FR	50,005	16	31,300	29,969	222
45	Porto	PT	47,452	14	24,520	29,222	216
46	Bergamo	IT	42,340	9	18,127	26,281	194
47	Catania	IT	35,476	10	20,680	25,936	192
48	Bologna	IT	37,781	11	20,766	25,333	187
49	Birmingham	GB	66,386	17	32,067	25,206	187
50	Faro	PT	29,151	9	12,864	25,186	186

10.2. Glossary

B.1 The table below provides a glossary of key terms used in the report.

Table B.1: Glossary

Acronym	Meaning
A4E	Airlines for Europe
A4A	Airlines for America
ACARE	Advisory Council for Aviation Research in Europe
ACI Europe	Airports Council International – Europe
AFIR	Alternative Fuels Infrastructure Regulation
ANSP	Air navigation service provider
ARC	Air Ruleworthiness Committee
ASD	Aerospace and Defence Industries Association of Europe
ASK	Available seat kilometre
ATAG	Air Transport Action Group
BEMIP	Baltic energy market interconnection plan
CAEP	Committee on Aviation Environmental Protection
CAGR	Compound annual growth rate
CANSO	Civil Air Navigation Services Organisation
CCER	China Certified Emission Reduction Scheme (CCER)
CCUS	Carbon capture utilisation and storage
CH	Switzerland
CMO	Commercial market outlook
Code-C aircraft	Aircraft with a wing span between 24m and a less than 36m, defined by ICAO.
COP26	The 2021 United Nations Climate Change Conference
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CO_2	Carbon dioxide
C-SAF	Canadian council for sustainable fuels
CS-E	Certification Specification for Engines
CS-18	Certification Specification for Commuter Aeroplanes

Acronym	Meaning
CS-25	Certification Specification for Large Aeroplanes
DG RTD	Directorate-General of Research and Innovation
DLR	The Institute of Air Transport and Airport Research of the Deutsches Zentrum für Luft- und Raumfahrt (the German Aerospace Centre)
DOC	Direct operating cost
EC	European Commission
EEA	European Economic Area
EASA	European Aviation Safety Agency
E-fuel	Electro fuel
EHB	European Hydrogen Backbone
EIB	European Investment Bank
EIS	Entry-into-service
EU	European Union
ETS	Emissions trading scheme
ETD	Energy taxation directive
eVTOLs	Electric vertical take-off and landing aircraft
FAA	Federal Aviation Authority
FCH	Fuel Cells and Hydrogen Joint Undertaking
FT-synthesis	Fischer-Tropsch synthesis
GA	General aviation
GDP	Gross domestic product
GHG	Greenhouse gas
GMF	Global market forecast
GPM	Gallons per minute
GW	Gigawatt
GWh	Gigawatthour
H_2	Hydrogen
H_2O	Water
HEFA	Hydroprocessed esters and fatty acids
ICAO	International Civil Aviation Organisation
ICCT	International Council on Clean Transportation
IEA	International Energy Agency
IFR	Instrument flight rules
IRENA	International Renewable Energy Agency
JU	Joint undertaking
kg	Kilogram
kt	Kilotonne
km	Kilometre
kWh	Kilowatthour
LH_2	Liquid hydrogen
LOHC	Liquid organic hydrogen carrier
LTAG	Long-term aspirational goal
MJ	Megajoule
Mt	Megatonne
MTOM	Maximum take-off mass

Acronym	Meaning
NASA	US National Aeronautics and Space Administration
Nm	Nautical mile (1.852 km)
NO_X	Nitrogen oxides
NSI	North-South electricity interconnections
NSOG	North Sea off-shore grid
OEM	Original equipment manufacturer
OSC	Oil supply connections
PSO	Public service obligation
PtL	Power-to-liquid
ReFuelEU	ReFuelEU Aviation initiative: Sustainable aviation fuels and the fit for 55 package
REPowerEU	REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition
RTD	Research and Technology Development
SAF	Sustainable aviation fuel(s)
SGC	Southern Gas Corridor
SRIA	Strategic Research and Innovation Agenda
TEN-E	Trans-European Networks for Energy
TEN-T	Trans-European Networks for Transport
TRL	Technology readiness level
ToR	Terms of Reference
TUHH	Institute of Environmental Technology and Energy Economics, Hamburg Technical University (TUHH)
TW	Terrawatt
TWh	Terrawatthour
UK	United Kingdom
US	United States of America
USD	US Dollar
WTO	World Trade Organisation

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Steer was appointed by the Directorate-General of Research and Innovation (DG RTD) to undertake an overview of key green aviation technologies and conditions for their market uptake. Steer was supported Institute of Air Transport and Airport Research of the German Aerospace Centre, DLR. The study was undertaken in the context of the Clean Aviation Partnership's Strategic Research and Innovation Agenda (SRIA) for the period 2030-2050. The objective was to identify the prerequisites for the market entry of climate-neutral aviation technologies as well as the flanking measures required for this to be successful.
The scope of the study was hydrogen and electrically powered aircraft in the regional and short/medium range categories, taking a holistic view on the technological development and keeping the economic context in mind.
The outcome of the study will serve as guidance for the Commission and other actors with regard to further policy or industry initiatives, such as in the context of Horizon Europe or the Alliance Zero Emission Aviation.

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