

Analysing the costs of hydrogen aircraft



Analysing the costs of hydrogen aircraft

Prepared by:

Steer
14-21 Rushworth Street
London SE1 0RB

+44 20 7910 5000
www.steergroup.com

Steer has prepared this material for Transport & Environment. This material may only be used within the context and scope for which Steer has prepared it and may not be relied upon in part or whole by any third party or be used for any other purpose. Any person choosing to use any part of this material without the express and written permission of Steer shall be deemed to confirm their agreement to indemnify Steer for all loss or damage resulting therefrom. Steer has prepared this material using professional practices and procedures using information available to it at the time and as such any new information could alter the validity of the results and conclusions made.

This study has been supported by the European Climate Foundation. Responsibility for the information and views set out in this study lie with the authors. The European Climate Foundation cannot be held responsible for any use which may be made of the information contained or expressed therein.

Prepared for:

Transport & Environment
Square de Meeus 18,
1050 Brussels
Belgium

Supported by:

European Climate Foundation
Riviermarkt 5
2513 AM The Hague
The Netherlands

Our ref: 24135101

Contents

Executive Summary	i
Hydrogen aircraft	i
Hydrogen fuel supply chain	i
Cost quantification	iii
Policy support	iv
1 Introduction.....	1
Background.....	1
Our Approach	1
This Report	1
2 Hydrogen aircraft.....	3
Aircraft technology development	3
Aircraft uptake.....	6
3 Hydrogen fuel supply chain	10
Fuel production	10
Fuel distribution	13
Airport infrastructure	15
4 Cost quantification.....	18
Approach	18
Fuel production	19
Fuel distribution	21
Airport infrastructure	22
Aircraft.....	23
Overall Costs.....	25
5 Policy Support.....	33
Hydrogen fuel supply.....	33
Hydrogen aircraft and infrastructure	36

Figures

Figure 1: Projected intra-European hydrogen aviation fuel demand range (2035-2050).....	ii
Figure 2: Total costs (2025-2050, EU Reference Scenario).....	iii
Figure 3: Unit costs (2035-2050, EU Reference Scenario).....	iv
Figure 2.1: Aviation specific hydrogen demand timeline with key milestones.....	4
Figure 2.2: Maximum range of first-generation hydrogen aircraft (3,700km).....	5
Figure 2.3: Airports in scope of assessment.....	7
Figure 2.4: Projected intra-European traffic range (2019-2050).....	7
Figure 2.5: Intra- European hydrogen aircraft RPKs (EU Reference Scenario, 2035-2050).....	8
Figure 2.6: Hydrogen aircraft in operation on intra-European routes (EU Reference Scenario, 2035-2050).....	9
Figure 3.1: Projected intra-European hydrogen fuel demand range (2035-2050).....	10
Figure 3.2: Hydrogen production cost (€ ₂₀₂₀ /kg) 2035-2050.....	11
Figure 3.3: Locations of airports and hydrogen production sites.....	12
Figure 3.4: European hydrogen backbone (2040), envisaged within the European Hydrogen Background initiative.....	14
Figure 3.5: Liquefied and gaseous distribution example – Nantes airport.....	15
Figure 3.6: Hydrogen airport distribution methods.....	15
Figure 3.7: Rollout of hydrogen airport infrastructure (2035-2050).....	17
Figure 4.1: Depiction of in-scope costs (EU Reference Scenario, 2025-2050).....	19
Figure 4.2: Unit production costs 2035-2050 (All scenarios).....	20
Figure 4.3: Production sites’ share of production (All scenarios, 2035-2050).....	20
Figure 4.4: Hydrogen production costs (2025-2050, EU Reference Scenario).....	21
Figure 4.5: Hydrogen distribution costs (2025-2050, EU Reference Scenario).....	22
Figure 4.6: Share of hydrogen distribution streams (2035-2050, EU Reference Scenario).....	22
Figure 4.7: Airport infrastructure costs (2025-2050, EU Reference Scenario).....	23
Figure 4.8: Total costs (2025-2050, EU Reference Scenario).....	26
Figure 4.9: Total cost distribution (2025-2050, EU Reference Scenario).....	26
Figure 4.10: Projected total cost scenario range (2025-2050).....	27
Figure 4.11: Cost and traffic scenario range (2025-2050).....	28
Figure 4.12: Unit costs (2035-2050, EU Reference Scenario).....	29

Figure 4.13: Hydrogen cost vs. kerosene and SAFs (EU Reference Scenario & Baseline Cost Scenario, 2035-2050)..... 30

Figure 4.14: Breakdown of typical airline operating costs 30

Figure 4.15: Breakdown of flight operation cost increases (2050) 31

Figure 4.16: Total change in flight operation costs with alternative fuels (2050)..... 32

Figure 5.1: Projected hydrogen demand (2020-2030) 34

Tables

Table 4.1: Typical aircraft maintenance schedule 24

Table 4.2: Total costs (2025-2050, EU Reference Scenario)..... 25

Table 4.3: Changes to airline operating costs..... 31

Appendices

A Modelling Assumptions

Executive Summary

Steer was appointed by Transport & Environment and the European Climate Foundation to undertake a study to provide a quantification of the costs associated with the development, deployment and operation of hydrogen-powered aircraft and supporting infrastructure within Europe, based on current aircraft and supporting infrastructure rollout ambitions. Steer was supported by the Institute of Environmental Technology and Energy Economics at Hamburg University of Technology (TUHH) and airport cost consultants Doig + Smith.

Hydrogen aircraft

Aircraft development

Airbus has an ambition to develop the world's first commercial clean-sheet-designed hydrogen aircraft by 2035, which is in line with wider industry projections and ambitions and with the date we have assumed for the introduction of commercial hydrogen aircraft within our assessment. Airbus' first-generation hydrogen aircraft include a regional aircraft type design, capable of operating routes of up to 1,000 nautical miles (1,850km), and a short-medium range (SMR) aircraft type design, capable of operating routes of up to 2,000 nautical miles (3,700km). Although this is significantly shorter than the range of the Airbus' current conventional SMR aircraft, first generation SMR hydrogen aircraft will be able to operate the vast majority of intra-European routes.

Traffic projections

As part of our assessment, we have used two traffic scenarios as upper and lower bounds for the level of projected traffic to 2050:

- a baseline traffic scenario, which assumes traffic growth in line with the EU Reference Scenario¹ projections over the period between 2019 and 2050; and
- a 'capped' traffic scenario, which assumes, through the use of market-based demand management measures, traffic does not recover to above pre-COVID (2019) levels throughout the period.

Within our assessment the volume of revenue passenger kilometres (RPKs) operated by hydrogen aircraft is driven primarily by the availability of hydrogen infrastructure at airports, which is rolled out progressively across the largest 100 European airports throughout the assessment period.

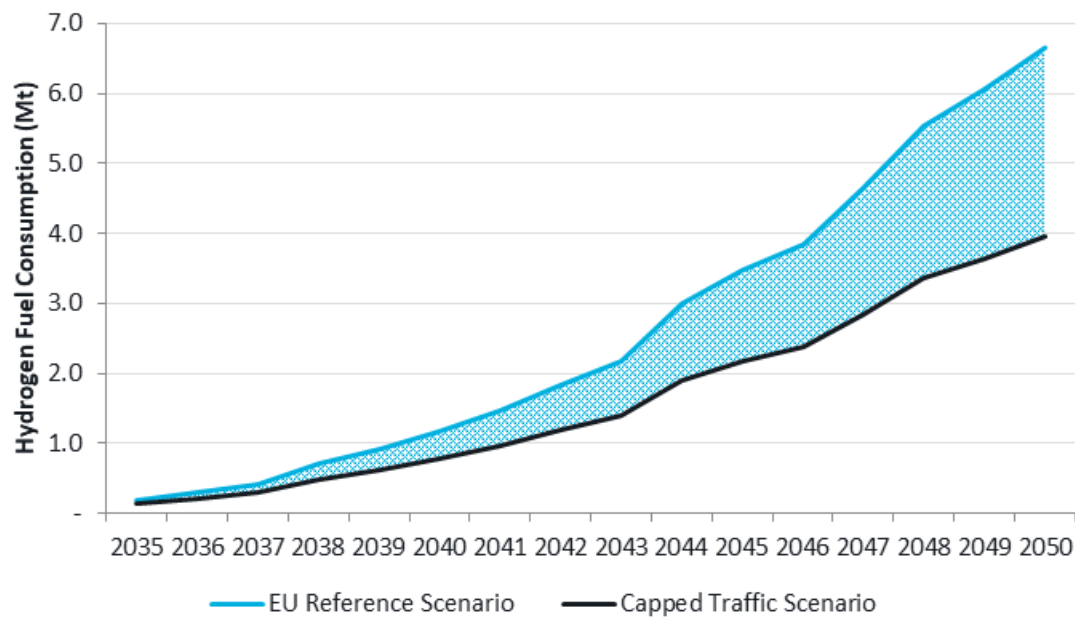
Hydrogen aircraft are projected to account for 65% of intra-European traffic by 2050; assuming the current level of ATMs operated per aircraft remains constant, a European hydrogen aircraft fleet of around 100 aircraft would be required to operate the projected traffic in 2035, growing to over 3,500 aircraft by 2050.

Hydrogen fuel supply chain

Hydrogen production

The level of hydrogen fuel demand, and therefore the required level of production across the two traffic scenarios, is shown in Figure 1 below.

¹ [EU Reference Scenario 2020](#)

Figure 1: Projected intra-European hydrogen aviation fuel demand range (2035-2050)

Source: EU Reference Scenario, T&E, Steer Analysis

While there are several industrial methods of hydrogen production, many of these produce greenhouse gas emissions as part of the production process. Our assessment assumes all hydrogen produced for aviation fuel is “green” hydrogen, that is, using water electrolysis powered by renewable energy. For green hydrogen to be as price competitive as possible, it needs to be produced in locations with the most favourable renewable energy producing conditions. Within Europe, the most favourable locations are around the North Sea coast (using mostly wind power) and in Southern Europe (using mostly solar photovoltaic (PV) power).

Hydrogen distribution

The electrolysis process produces hydrogen in gaseous form, which, in order to be used as aviation fuel for regional and SMR aircraft, must be converted into liquid hydrogen, which must then be stored at cryogenic temperatures (below -253°C). The location of the liquefaction process determines the method of transportation, with two feasible options:

- In gaseous (CGH₂) form via pipeline, which means liquefaction takes place at or close to the airport after transportation; or
- In liquid (LH₂) form via trucks and ships, which means liquefaction takes place at or close to the production site prior to transportation.

While transport of hydrogen in liquid form via truck is feasible for low volumes of fuel, once fuel demand reaches a certain threshold level, a pipeline is likely to be necessary for inland airports. Therefore, we have assumed that most airports are initially supplied using a combination of cryogenic trucks and (where necessary) ships with liquefaction taking place prior to transportation at the production facility. Once fuel demand reaches a certain threshold, supply switches to gaseous pipeline supply with liquefaction taking place close to or at the airport.

Airport infrastructure

The use of hydrogen aircraft will require major changes to airport infrastructure. As hydrogen cannot be combined with existing aviation fuel it will require separate transportation and storage infrastructure facilities. All airports will require cryogenic storage, distribution and fuelling facilities. In addition, where hydrogen is delivered in gaseous form on-site liquefaction facilities will be required.

We have assumed that at airports with a relatively low levels of hydrogen flights in the initial years, liquid hydrogen fuel is distributed to aircraft by bowzers. For larger airports where fuel demand is above a certain threshold, on-airport distribution switches to pipeline and hydrant supply of liquid hydrogen. Pipeline and hydrant capacity is added incrementally at the airport in order to meet the fuel demand.

Cost quantification

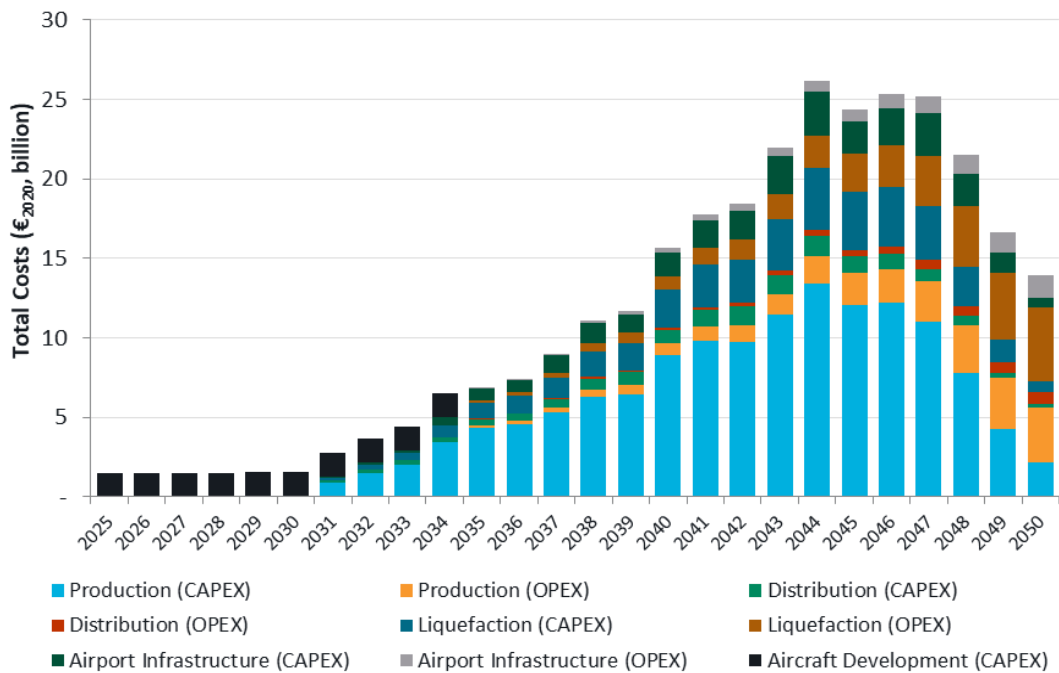
Total costs

The cost projections include operating expenditure (opex), which is incurred every year once the relevant asset or infrastructure is operational, and capital expenditure (capex), which is incurred as upfront investment costs while the relevant asset or infrastructure is being constructed. The cost projections below include upfront capex required to meet demand to 2050 only.

Only incremental costs that would not be incurred in a ‘baseline’ or ‘do nothing’ scenario (i.e. without hydrogen aircraft) are included. In addition to the costs for the hydrogen production, distribution and airport infrastructure requirements described above, aircraft development costs are included (assumed to be €15 billion over a 10-year period).

Total projected costs over the period are €299 billion, equivalent to €126 billion in 2020 present value terms.

Figure 2: Total costs (2025-2050, EU Reference Scenario)

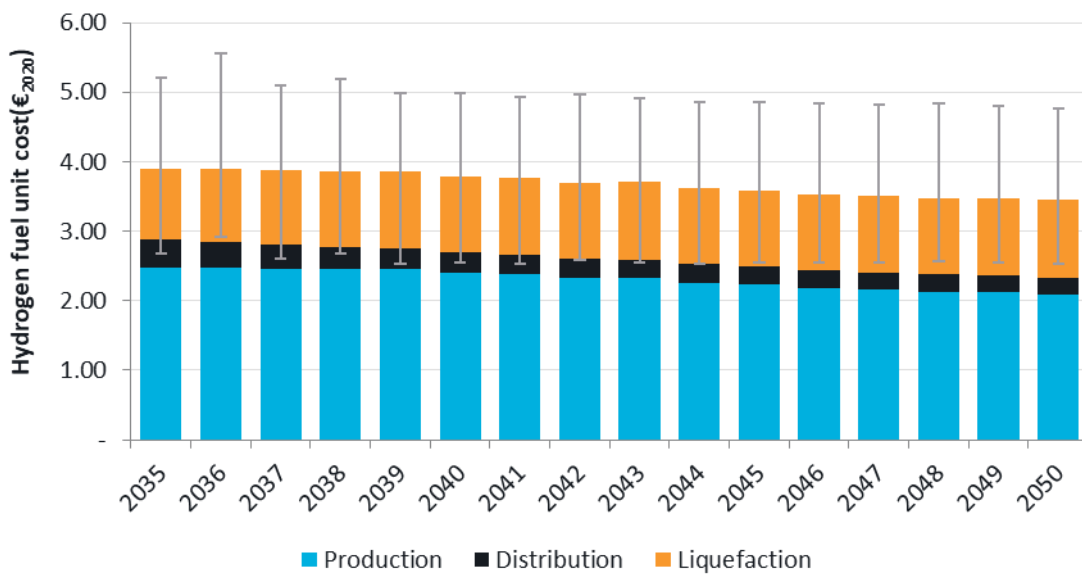


Source: TUHH, Doig + Smith, Steer analysis.

Unit costs

Unit hydrogen costs (€/kg) have been calculated using total hydrogen demand, opex and an equivalent annual cost (EAC) value for capex. Unit hydrogen fuel costs, comprising production, distribution and liquefaction costs (i.e., the costs that would be charged to airlines as fuel costs) are shown in the figure below. Costs fall from €3.90 per kg in 2035 to €3.45 per kg in 2050, driven by a combination of falling production costs and greater utilisation of gaseous (versus liquefied) distribution and liquefaction infrastructure. The unit costs are based on TUHH's baseline cost scenario (which uses central estimates for the economic, financial and technical model inputs), with the progressive and conservative scenarios (which account for the range of model input estimates) shown as a range above and below the baseline costs.

Figure 3: Unit costs (2035-2050, EU Reference Scenario)



Source: TUHH, Doig + Smith, Steer analysis.

Policy support

Hydrogen fuel supply

Many of the challenges associated with the hydrogen fuel supply chain stem from the fact that, based on current trajectories, projected renewable energy and hydrogen production capacity will not be sufficient to produce the quantity of hydrogen required to meet net zero targets by 2050. It is also difficult to envisage that the aviation sector alone will be able to fund or finance the cost of the fuel supply infrastructure required to accommodate hydrogen aircraft. Instead, it seems likely that the wider hydrogen ecosystem will need to develop for the aviation industry to be able to utilise the necessary infrastructure, for example by being supplied with green hydrogen from general (as opposed dedicated) production facilities or by utilising already established distribution networks used by other transport modes and industries.

Therefore, in order to increase green hydrogen production and distribution capacity, potential policies that could be enacted at a national or EU level to increase supply capacity include:

- direct financial support, in form of grants or cheap loans to finance technology research and the construction of fuel production infrastructure;

- indirect financial support, such as tax breaks or subsidies, which would incentivise investment in infrastructure; and/or
- supply-side measures, such as usage mandates or floor prices, which would provide more certainty to suppliers to invest in capacity.

While there is some uncertainty around the level of investment required, the magnitude of the costs mean that, within Europe, significant support may be required from the EU, which has the means and resources to lend to fund large-scale infrastructure projects through the European Investment Bank (EIB) and to issue collective debt. The EU can also enact Europe-wide legislation to incentivise investment in infrastructure, which would be less effective at a national level.

Hydrogen aircraft and infrastructure

As with fuel supply infrastructure, many of the challenges associated with airport infrastructure are driven by the magnitude of the costs and uncertainty for airports and airlines whether the other party will also invest in hydrogen equipment or infrastructure. Therefore, in order to address this, potential policies that could be enacted at a national or EU level to increase supply capacity include:

- direct financial support, in form of grants or cheap loans to finance technology research (e.g., decentralised liquefaction facilities) and the construction of airport infrastructure;
- indirect financial support, such as tax breaks or subsidies, which would incentivise investment in infrastructure; and/or
- supply-side measures, such as airline fuel usage or airport fuel supply mandates (as has been proposed by the ReFuelEU initiative for sustainable aviation fuels (SAFs)), which would provide more certainty for other investors.

The other major area where policy support could be provided is on the demand side with respect to the price competitiveness of hydrogen aircraft versus those powered by other fuels (including conventional fossil kerosene and SAFs) using carbon pricing or taxes on kerosene.

1 Introduction

Background

- 1.1 Steer was appointed by Transport & Environment and the European Climate Foundation to undertake a study to provide a quantification of the costs associated with the development, deployment and operation of hydrogen-powered aircraft and supporting infrastructure within Europe, based on current aircraft and supporting infrastructure rollout ambitions.
- 1.2 The study has been undertaken in the context of an increasing need for the aviation industry to decarbonise. One potential option for decarbonisation is hydrogen-powered aircraft; there have been a number of recent studies on the feasibility and timeframe for introducing hydrogen-powered aircraft, and a number of hydrogen aircraft and infrastructure projects are underway within the industry.
- 1.3 The work has been undertaken by Steer, supported by our partners the Institute of Environmental Technology and Energy Economics at Hamburg University of Technology (TUHH) and airport cost consultants Doig + Smith.
- 1.4 This document is the Final Report for the study.

Our Approach

- 1.5 While there is general agreement on the technical feasibility of developing hydrogen aircraft technology, there are uncertainties around the practical and commercial feasibility of adopting hydrogen technology within the aviation industry at a large scale, and the timeframe in which this can be achieved.
- 1.6 The focus of this study is not the feasibility of using hydrogen aircraft technology, but rather a quantification of the costs of the aviation industry adopting the technology within a timeframe consistent with industry projections and ambitions. These costs have been quantified within an assessment period up to 2050, consistent with the European Green Deal and the Paris Agreement's net-zero target.
- 1.7 To undertake this assessment, we have drawn upon hydrogen production and distribution understanding provided by TUHH (experts in the costs of alternative fuels), airport infrastructure understanding from Doig + Smith (airport costing experts), undertaken a review of the available literature and interviews and consulted industry stakeholders. Steer has full responsibility for the outputs – further information on our approach and data sources is provided in Appendix A.

This Report

- 1.8 The remainder of this report is structured as follows:
 - Chapter 2 gives an overview of hydrogen aircraft technology and sets out our aircraft rollout projections;

- Chapter 3 provides a description of the hydrogen fuel supply chain and some of the assumptions used within our study;
- Chapter 4 provides a quantification of the costs of developing and rolling out hydrogen aircraft and supporting technology; and
- Chapter 5 sets out potential policy support options that could be adopted to facilitate the uptake of hydrogen aircraft technology.

2 Hydrogen aircraft

2.1 This chapter sets out:

- a description of first-generation hydrogen aircraft, the expected date of their entry into commercial service and the markets in which they will operate; and
- a projection of the uptake rate of hydrogen aircraft and the level of traffic operated by these aircraft within our assessment period.

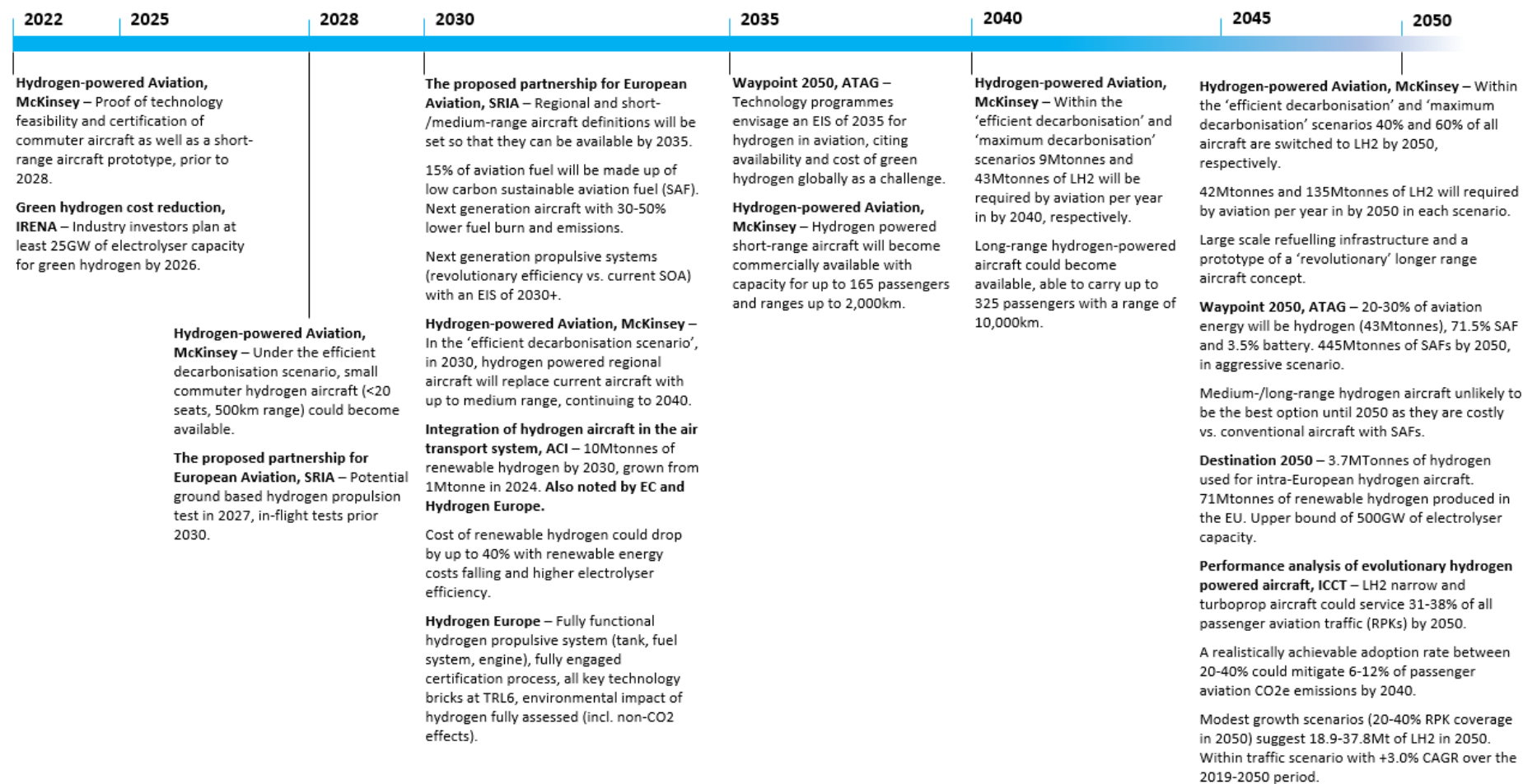
Aircraft technology development

Development timeframe

- 2.2 Airbus, one of world's two major aircraft manufacturers and the only major manufacturer based on Europe, has an ambition to develop the world's first commercial clean-sheet-designed hydrogen aircraft by 2035 through its ZEROe² concept aircraft. Figure 2.1 below summarises wider industry projections and ambitions for the roll out and uptake of hydrogen aircraft, which are contained within a number of recent industry reports and studies.
- 2.3 The EU's Clean Sky 2 initiative report, produced by McKinsey, envisages small hydrogen aircraft entering service in 2028 at the earliest, with prototype small and medium range aircraft also being produced from this date; commercial small and medium range aircraft are expected to enter service from 2030 and 2035 respectively. The EU's Strategic research and innovation agenda (SRIA) initiative also envisages that next-generation propulsion technologies will be available from 2030, including hydrogen propulsion on smaller aircraft.
- 2.4 The Air Transport Action Group's (ATAG) Waypoint 2050 envisages a slightly later entry into service (EIS) of 2035 for hydrogen aircraft, with the EU's SRIA initiative also expecting next-generation propulsion technologies, including hydrogen, to be available for regional and short-medium range (SMR) aircraft by 2035. Airbus's ambition date of 2035 therefore appears in line with projections and ambitions of the wider industry.

² ZEROe, Airbus

Figure 2.1: Aviation specific hydrogen demand timeline with key milestones



Sources: McKinsey & Clean Sky 2 (2020), Hydrogen-powered aviation, A fact-based study of hydrogen technology, economics, and climate impact by 2050. SRIA (2020), The proposed partnership for European Aviation. ACI (2021), Integration of hydrogen aircraft in the air transport system. Hydrogen Europe. ATAG (2021), Waypoint 2050. Destination 2050 (2021). ICCT (2022), Performance analysis of evolutionary hydrogen aircraft

Aircraft range

- 2.5 When consulted as part of this study, Airbus stated that first generation hydrogen aircraft will have airframes similar to current aircraft, though the propulsion systems will need to be redesigned for hydrogen combustion. The use of hydrogen fuel, as opposed to kerosene, will mean hydrogen aircraft will be required to carry a larger volume of fuel for an equivalent flight because, while hydrogen has a high energy gravimetric density (megajoule per kilogram (MJ/kg)), it has a low volumetric density (megajoule per litre (MJ/L)), which means four times the volume of hydrogen compared to kerosene is required to produce the same amount of energy³.
- 2.6 The requirement to carry four times the volume of fuel for first generation hydrogen aircraft will mean that their range is more limited compared to equivalent kerosene-powered aircraft. Airbus' first-generation hydrogen aircraft include a regional aircraft type design, capable of operating routes of up to 1,000 nautical miles (1,850km), and a SMR aircraft type design, capable of operating routes of up to 2,000 nautical miles (3,700km), but currently no long-range aircraft type design. Figure 2.2 shows the maximum range of first-generation SMR hydrogen aircraft operating from Frankfurt (FRA) and Tenerife South (TFS) airports, assuming hydrogen refuelling is available at both the origin and destination airports.

Figure 2.2: Maximum range of first-generation hydrogen aircraft (3,700km)



Source: www.gcmap.com

³ 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/L (= 120 x 0.071) for liquid hydrogen vs 34.7 MJ/L 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.

- 2.7 The maximum range of first-generation SMR hydrogen aircraft of 3,700km is significantly shorter than the range of the Airbus' current SMR aircraft, the A320neo, which has a range of around 6,000km. This means first-generation SMR hydrogen aircraft will be able to operate all intra-European routes from central Europe, while intra-European routes from airports in Europe's periphery are slightly more limited. In spite of this, first generation SMR hydrogen aircraft will be able to operate the vast majority of intra-European routes currently operated by conventional SMR aircraft.
- 2.8 While relative fuel energy density can be used to calculate how much hydrogen fuel is required to generate the same amount of energy as kerosene, the exact energy requirement of hydrogen aircraft, relative to conventional aircraft, is less certain. An aircraft's energy requirement is determined by its design (through its mass and aerodynamics); some elements of hydrogen aircraft design will likely reduce the energy requirements (lighter fuel) and others will increase it (larger and heavier fuel systems). Given first generation SMR hydrogen aircraft are in the very early stages of development, it is unclear what the exact energy requirement will be relative to conventional aircraft.
- 2.9 Projections of hydrogen aircraft's energy requirements are also mixed, with some studies projecting a slightly increased energy requirement relative to conventional aircraft and others projecting a slightly lower requirement. For example, the ICCT⁴ projects a +5% increase in MJ/RPK energy requirement for narrow-body aircraft, whereas McKinsey/Clean Sky 2⁵ projects a -4% reduction for aircraft with a range of up to 2,000km and a +22% increase for aircraft with a range of up to 7,000km. Given these uncertainties, within our assessment, we have assumed that first generation hydrogen aircraft with a range of 3,700km have the same energy requirements as the equivalent conventional aircraft when they enter service in 2035, which we consider to be a reasonable approximation.

Aircraft uptake

- 2.10 The uptake of hydrogen aircraft will be driven by a number of factors, though significant determinants will be:
- the level of projected traffic growth, which will drive overall demand for aircraft;
 - fleet turnover projections, which will drive the rate at which hydrogen aircraft replace older technology; and
 - the availability of hydrogen infrastructure at airports, which is necessary for aircraft to operate.
- 2.11 Traffic and fleet turnover projections are discussed below; airport infrastructure rollout projections are set out in the following chapter.

Traffic projections

- 2.12 The scope of the traffic projections and our analysis is limited to routes under 3,700km (the maximum range of the first generation SMR hydrogen aircraft) between the 100 largest airports in Europe⁶, which represents 74% of intra-European traffic and 99% of the traffic

⁴ ICCT (2022)

⁵ McKinsey & Clean Sky 2 (2020)

⁶ Europe here defined as EU27, EEA (Iceland, Liechtenstein and Norway), Switzerland and the UK

between the 100 airports. This is the scope of all references to ‘intra-European’ traffic, hydrogen fuel demand and airport infrastructure in the remainder of this report.

Figure 2.3: Airports in scope of assessment

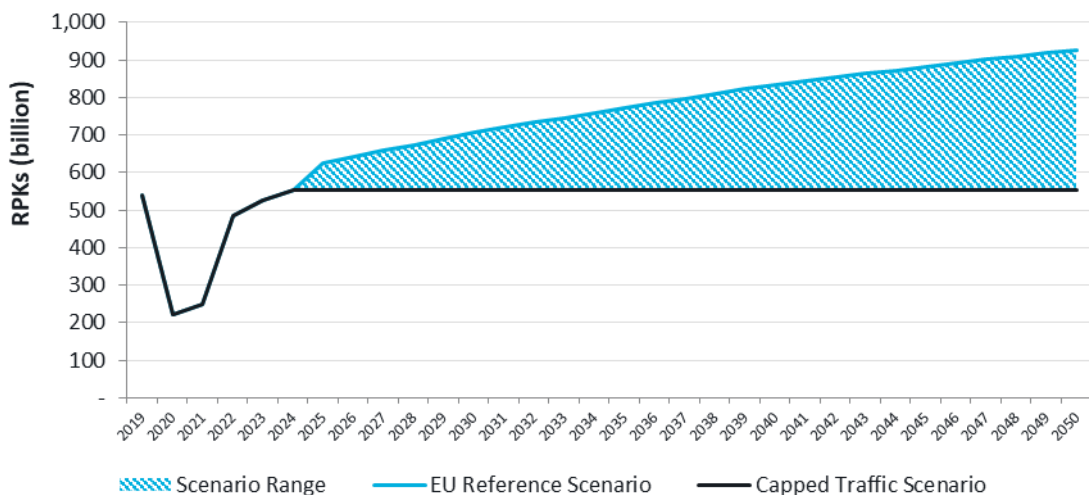


Source: www.gcmap.com

2.13 The traffic scenarios used within our assessment are shown in Figure 2.4; we have used two traffic scenarios as upper and lower bounds for the level of projected traffic to 2050:

- a baseline traffic scenario, which assumes traffic growth in line with the EU Reference Scenario⁷ projections over the period between 2019 and 2050; and
- a ‘capped’ traffic scenario, which assumes, through the use of market-based demand management measures, traffic does not recover to above pre-COVID (2019) levels throughout the period.

Figure 2.4: Projected intra-European traffic range (2019-2050)

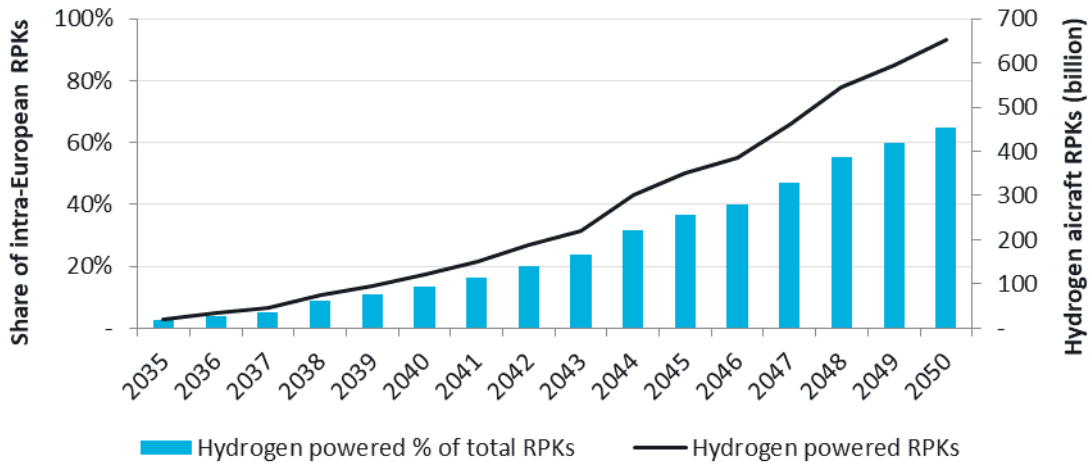


Source: EU Reference Scenario, T&E

⁷ [EU Reference Scenario 2020](#)

- 2.14 Within our assessment the volume of revenue passenger kilometres (RPKs) operated by hydrogen aircraft is driven primarily by the availability of hydrogen infrastructure at airports, which is rolled out progressively across the largest 100 European airports throughout the assessment period. As hydrogen infrastructure becomes available at different-sized airports each year, the increase in overall hydrogen-powered RPKs varies from year to year. More detailed airport infrastructure rollout projections are set out in the following chapter.
- 2.15 The volume of RPKs projected to be operated by hydrogen aircraft under the EU Reference Scenario, and share of total RPKs this represents, is shown in Figure 2.5.

Figure 2.5: Intra- European hydrogen aircraft RPKs (EU Reference Scenario, 2035-2050)



Source: EU Reference Scenario, Steer analysis

- 2.16 Hydrogen aircraft are projected to account for 65% of intra-European RPK traffic by 2050, which is broadly in line with wider industry projections; the maximum decarbonisation within the McKinsey/Clean Sky 2 study⁸ envisages close to 60% of aircraft being hydrogen-powered by 2050.

Fleet projection

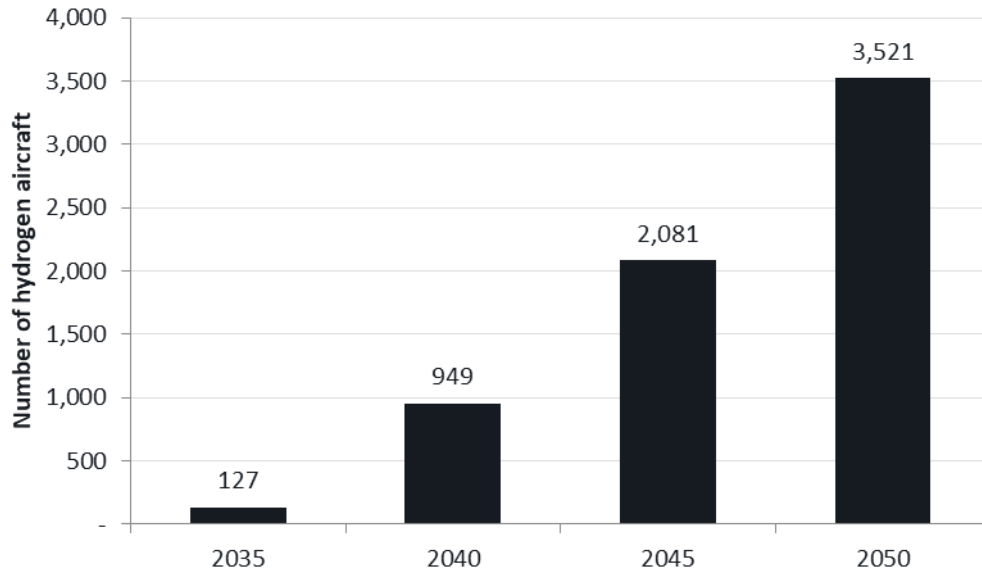
- 2.17 An estimate of the number of hydrogen aircraft required to operate this level of traffic throughout the assessment period is shown in Figure 2.6. This has been calculated by assuming the aircraft operate 4 ATMs per day in 2035, based on a lower bound figure⁹ for intra-European narrow body aircraft, and that aircraft deliveries increase at a constant rate throughout the assessment period. A European hydrogen aircraft fleet of around 100 aircraft would be required to operate the projected RPKs in 2035, growing to over 3,500 aircraft by 2050.
- 2.18 Assuming 65% of aircraft replacements are met by hydrogen aircraft from 2035 (and a market growth projection of 1.2% CAGR), an average aircraft retirement age of 18 years would be required to reach 65% market penetration by 2050. This would represent a reduction from the

⁸ McKinsey & Clean Sky 2 (2020)

⁹ [Eurocontrol](#)

current average of between 20 to 25 years¹⁰ and would need to be incentivised through market-based measures. While there may be some variability in the rate at which aircraft are delivered from year to year, the number of aircraft required in 2035 and 2050 imply an accelerating rate of aircraft deliveries (increasing by around 12 aircraft each year), rising from 127 deliveries in 2035 to around 313 in 2050.

Figure 2.6: Hydrogen aircraft in operation on intra-European routes (EU Reference Scenario, 2035-2050)



Source: Oliver Wyman¹¹, Steer analysis

¹⁰ Destination 2050 (2021)

¹¹ Oliver Wyman Global Fleet & MRO Market Forecast 2022-2032 (Western Europe SMR aircraft)

3 Hydrogen fuel supply chain

3.1 This chapter sets out:

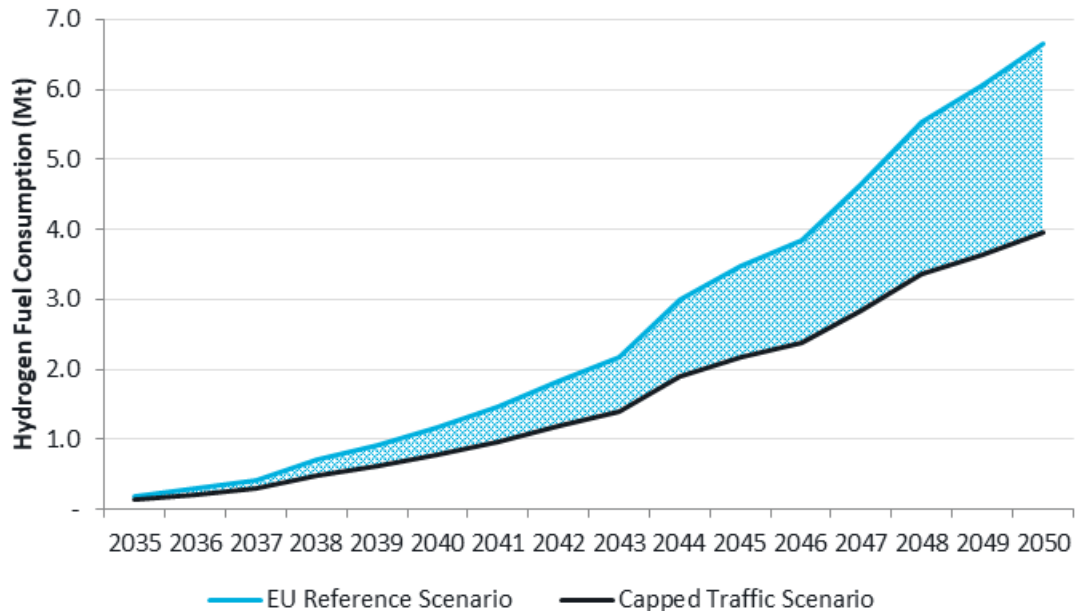
- a description of the hydrogen production process and the projected level of fuel production required;
- an overview of the different means of transporting and distributing hydrogen fuel; and
- a description of the airport infrastructure required to accommodate hydrogen aircraft and fuel supply, and the projected roll out of this infrastructure across European airports.

Fuel production

Production volume

3.2 The level of traffic (described in Chapter 2) and distance flown by hydrogen aircraft have been used to estimate the total energy consumption and fuel demand requirement across the assessment period, based on the energy requirement, fuel density and volume assumptions set out from paragraph 2.5. The level of hydrogen fuel demand, and therefore the required level of production across the two traffic scenarios, is shown in Figure 3.1.

Figure 3.1: Projected intra-European hydrogen fuel demand range (2035-2050)



Source: EU Reference Scenario, T&E, Steer Analysis

Production locations

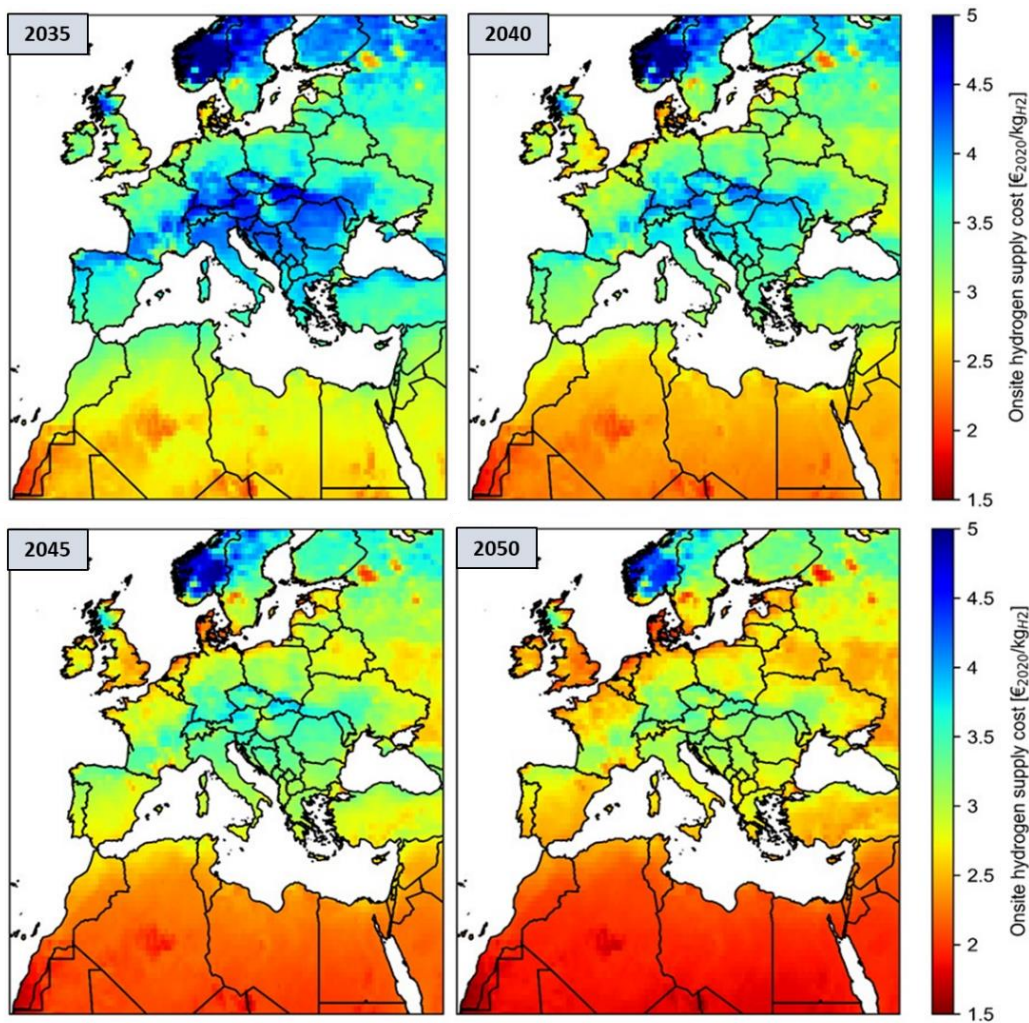
3.3 There are currently several industrial methods of hydrogen production, although many of these produce emissions as part of the production process. These methods include using coal

(black or brown hydrogen), using natural gas (grey hydrogen), using natural gas with some form of carbon capture (blue and turquoise hydrogen) and using water electrolysis powered by renewable energy (green hydrogen).

3.4 In addition to the hydrogen produced, the only by-product from green hydrogen is oxygen, which means, unlike other production processes, it produces no carbon dioxide or any other greenhouse gas emissions. Given the only feedstocks are water and electricity, green hydrogen is therefore the only fully renewable way of producing hydrogen aviation fuel, provided a sufficient quantity of renewable energy is available. Our assessment therefore assumes all hydrogen produced for aviation fuel is green hydrogen.

3.5 While the cost of renewable energy has come down over time – and is expected to continue to do so – for green hydrogen to be as price competitive as possible, it needs to be produced in locations with the most favourable renewable energy producing conditions. Figure 3.2 shows the projected hydrogen production (including on-site supply) unit costs in euros per kg at 2020 prices (€₂₀₂₀/kg) from 2035 to 2050 across the wider European region. Within Europe, the most favourable locations are around the North Sea coast (using mostly wind power) and in Southern Europe (using mostly solar photovoltaic (PV) power).

Figure 3.2: Hydrogen production cost (€₂₀₂₀/kg) 2035-2050



Source: TUHH

3.6 As part of our cost assessment, we have therefore assumed that hydrogen is produced at four coastal production sites:

- Using predominantly solar power:
 - South-eastern Spain – Mediterranean coast
 - Sicily (Italy) – Mediterranean coast
- Using predominantly wind power:
 - Denmark – North Sea coast
 - UK– North Sea coast

3.7 While several locations in North Africa have lower production costs than Southern Europe, given the ongoing issue of European energy security and the perceived need for Europe to produce more of its own energy, we have assumed all locations are located within Europe. The locations of the four production sites are shown in Figure 3.3 – all sites are located on the coast to enable access to water for the production process.

3.8 As shown in Figure 3.2, the exact locations on the Mediterranean coast within southern Europe (for solar) and the North Sea coast (for wind) do not make a significant difference to the costs; unit costs are within an approximately $\pm 10\%$ range across both the North Sea and European Mediterranean coastal regions. The production locations can therefore be taken as representative of the costs that would be incurred even if the precise locations used were different from those selected for the study.

Figure 3.3: Locations of airports and hydrogen production sites



Source: www.gcmap.com, TUHH

Fuel distribution

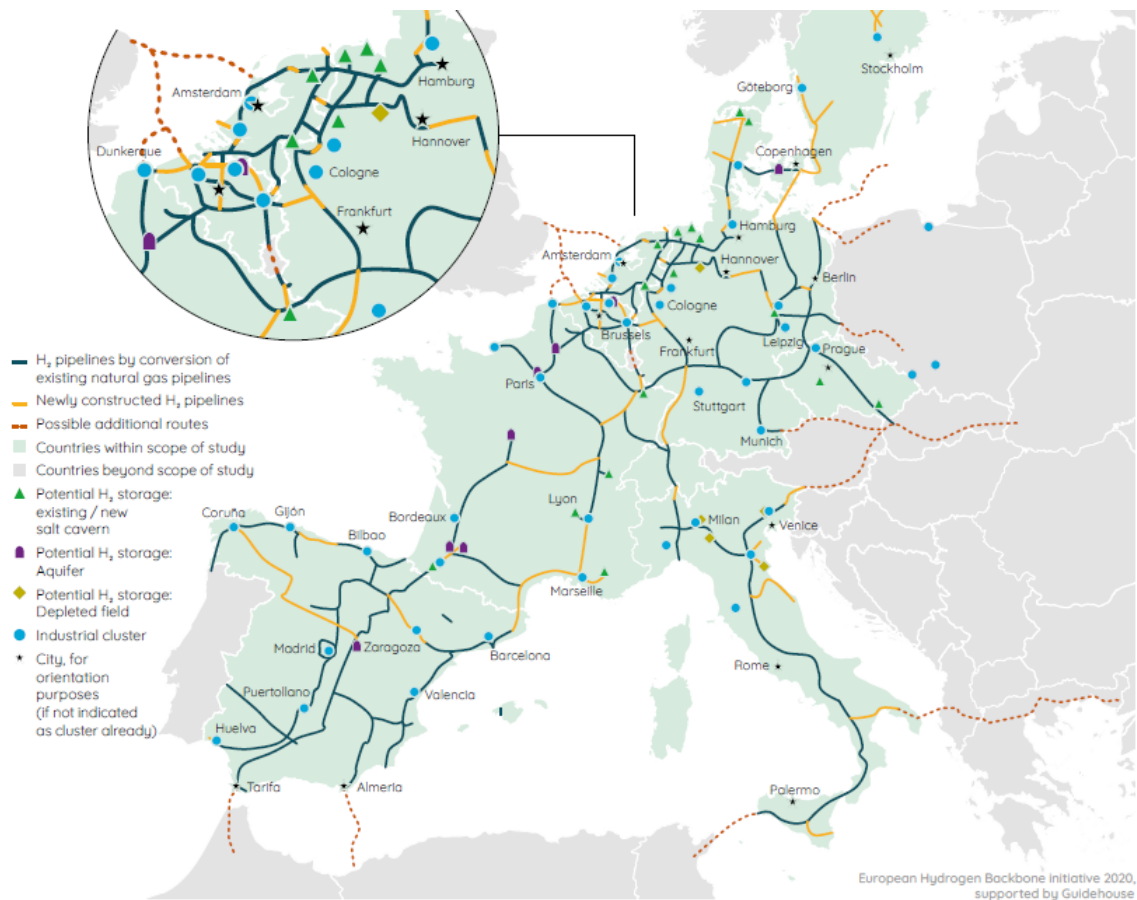
- 3.9 The electrolysis process produces hydrogen in gaseous form, which, in order to be used as aviation fuel, must be converted to liquid through a liquefaction process. Where and when the liquefaction process takes place dictates how the hydrogen is transported. Hydrogen can be transported in a number of ways, though the two methods used within our assessment are:
- **In gaseous (CGH2) form via pipeline**, which means liquefaction takes place at or close to the airport after transportation; or
 - **In liquid (LH2) form via trucks and ships**, which means liquefaction takes place at or close to the production site prior to transportation.
- 3.10 Other methods for transporting hydrogen include in liquid (LH₂) form via pipeline, as liquid ammonia or in liquid organic hydrogen carriers (LOHC); however, none of these methods are considered viable for mass distribution of hydrogen. Given the low boiling point of hydrogen (-253°C), transportation of hydrogen in liquid form will require cryogenic cooling facilities, which for an extensive pipeline network is not considered as economically viable¹². Transportation using LOHC or ammonia (which is also highly toxic) requires transportation of hydrogen with additional chemicals and therefore additional chemical processes to produce sufficiently pure hydrogen fuel.
- 3.11 While transport of hydrogen in liquid form via truck and/or ship is feasible for low volumes of fuel, once fuel demand reaches a certain level, trucks are unlikely to be able to transport the required volumes given the number of vehicles required and the congestion that this would cause, particularly in the vicinity of airports.
- 3.12 As part of our assessment, we have assumed that each airport is supplied by the most suitable of the four hydrogen production sites considered, based on transportation practicality and distribution costs. Most airports¹³ are initially supplied using a combination of cryogenic trucks and (where necessary) ships with liquefaction taking place prior to transportation at the production facility and dedicated cryogenic fuel transfer facilities within the supply chain, including at ports and airports.
- 3.13 Once fuel demand reaches a threshold of 36 tonnes per day, equivalent to approximately 20 hydrogen-powered flights a day, it has been assumed that supply switches to gaseous pipeline supply with liquefaction taking place close to or at the airport. Within our assessment, transportation of gaseous hydrogen is assumed to take place within a network based on repurposing and extending the existing natural gas pipeline network. The European Hydrogen Backbone¹⁴ initiative has set out a roadmap for the development of a European hydrogen pipeline network based on retrofitting existing natural gas pipelines (as use of natural gas is scaled down) combined with additional new hydrogen pipeline infrastructure.
- 3.14 The hydrogen pipeline network envisaged with the report is shown in Figure 3.4.

¹² Integration of Hydrogen Aircraft into the Air Transport System (2021), Airport Council International (ACI) and Aerospace Technology Institute (ATI)

¹³ Larger airports use pipeline distribution from the first year of hydrogen flights as the number of flights is too high to justify use of liquefied distribution.

¹⁴ European Hydrogen Backbone (2020), How a dedicated hydrogen infrastructure can be created.

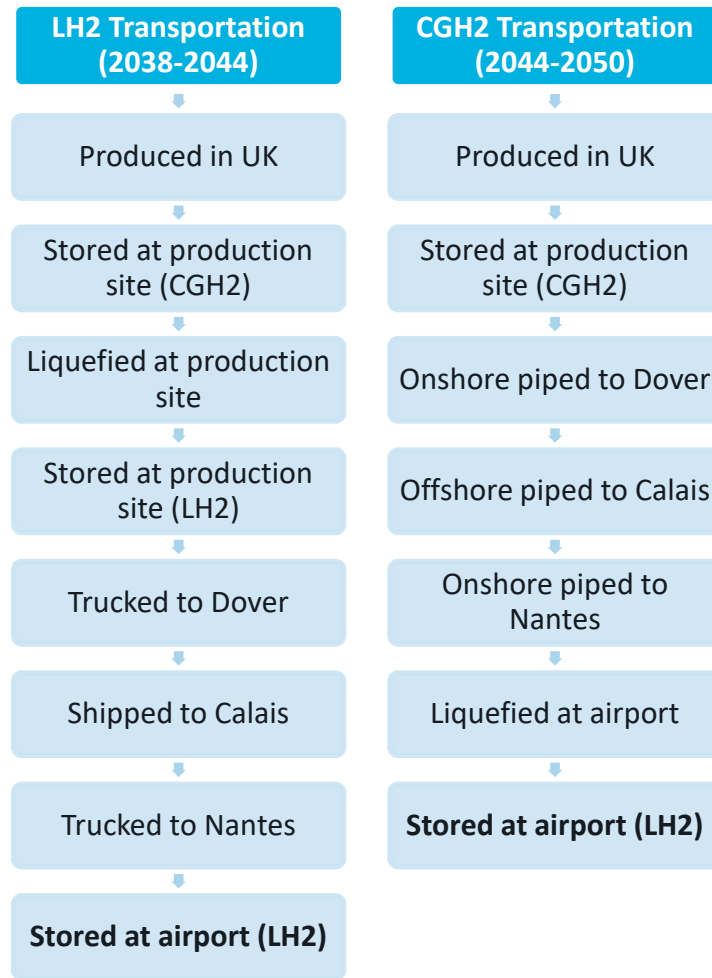
Figure 3.4: European hydrogen backbone (2040), envisaged within the European Hydrogen Background initiative.



Source: European Hydrogen Backbone Initiative (reproduced with permission)

- 3.15 Given the need to keep liquid hydrogen at extremely low temperatures, some evaporation or ‘boil off’ losses are anticipated throughout the distribution process, with greater losses anticipated where hydrogen spends more of the distribution process in liquid form. These boil off losses have been factored into the overall production requirement and cost.
- 3.16 Figure 3.5 provides an illustration of each of the steps within the liquefied (LH₂) and gaseous (CGH₂) distribution processes at Nantes airport, which has its first hydrogen-power flight in 2038 and is supplied with hydrogen fuel produced in the UK.

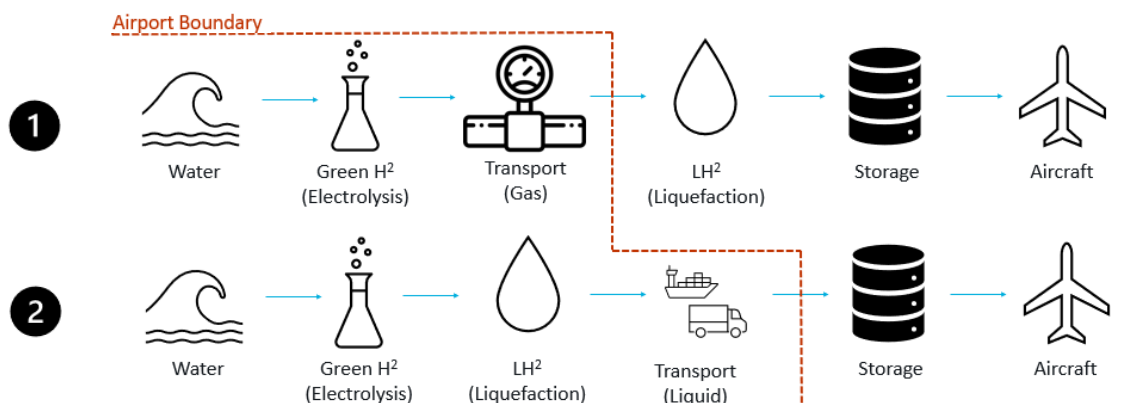
Figure 3.5: Liquefied and gaseous distribution example – Nantes airport



Airport infrastructure

3.17 The use of hydrogen aircraft will require major changes to airport infrastructure. As hydrogen cannot be combined with existing aviation fuel it will require separate transportation and storage infrastructure facilities. Where hydrogen is delivered in liquid form (process 2 in Figure 3.6), airports will require cryogenic storage, distribution and fuelling facilities, and where hydrogen is delivered in gaseous form (process 1 in Figure 3.6), on-site liquefaction facilities.

Figure 3.6: Hydrogen airport distribution methods



Source: Steer

Liquefaction and storage

3.18 For airport storage and liquefaction facilities the following points need to be considered:

- While hydrogen has a high energy gravimetric density (MJ/kg) it has a low volumetric density (MJ/L), such that four times the volume of liquid hydrogen compared to kerosene is required to produce the same amount of energy (see footnote 3 above).
- The relative energy density of hydrogen means airport storage and distribution systems need to be able to handle four times the equivalent amount of kerosene fuel, and sufficient space will be required at the airport for these facilities.
- For cryogenic storage, as well as liquefaction, airports will need access to a large quantity of renewable energy.

3.19 As part of our assessment, we have assumed airport storage facilities are added incrementally in order to accommodate the required level of fuel demand.

Distribution

3.20 Within airports, fuel is currently supplied to aircraft stands 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). Pipelines are used at the vast majority of large European airports, as using bowsters, with resultant airfield congestion, is usually not practical for large volumes of fuel. Whichever method is used, a connector pipe into the aircraft from the hydrant or bowser will be required for refuelling.

3.21 As with liquefaction and storage facilities, airport distribution infrastructure will be required to handle four times the volume of fuel relative to kerosene and will require access to renewable energy to be kept at cryogenic temperatures. In addition, due to its flammability, the temperatures required to keep hydrogen in its liquid form, and the potential for boil-off losses, the aircraft fuelling process is likely to require highly specialised equipment and may require more time than the current refuelling process.

3.22 As part of our assessment, we have assumed that at airports with a relatively low number of hydrogen flights in the initial years, hydrogen fuel is distributed by bowsters. For larger airports where fuel demand is above 36 tonnes per day (equivalent to approximately 20 hydrogen-powered flights a day) in the first year, or once demand reaches this level at smaller airports after a number of years, airport distribution switches to pipeline and hydrant supply (assuming one hydrant per aircraft stand). Pipeline and hydrant capacity is added incrementally at the airport in order to meet the fuel demand.

Rollout

3.23 The point at which airports decide to introduce hydrogen aircraft infrastructure will be largely determined by when they believe there will be sufficient demand from airlines to justify their investment. There is likely to be a dialogue between airlines planning on ordering hydrogen-powered aircraft and airports considering investing in the necessary infrastructure, as both parties will want to be assured that their respective investments are worthwhile.

3.24 The long development, testing and production time required to deliver hydrogen aircraft, means there should be sufficient time for airports to make these adjustments, in cooperation with the airlines and other stakeholders, on the assumption that they are willing (incentivised) and able (with access to hydrogen supply and suitable infrastructure) to do so. Factors influencing airports' decision to invest in the required infrastructure will include:

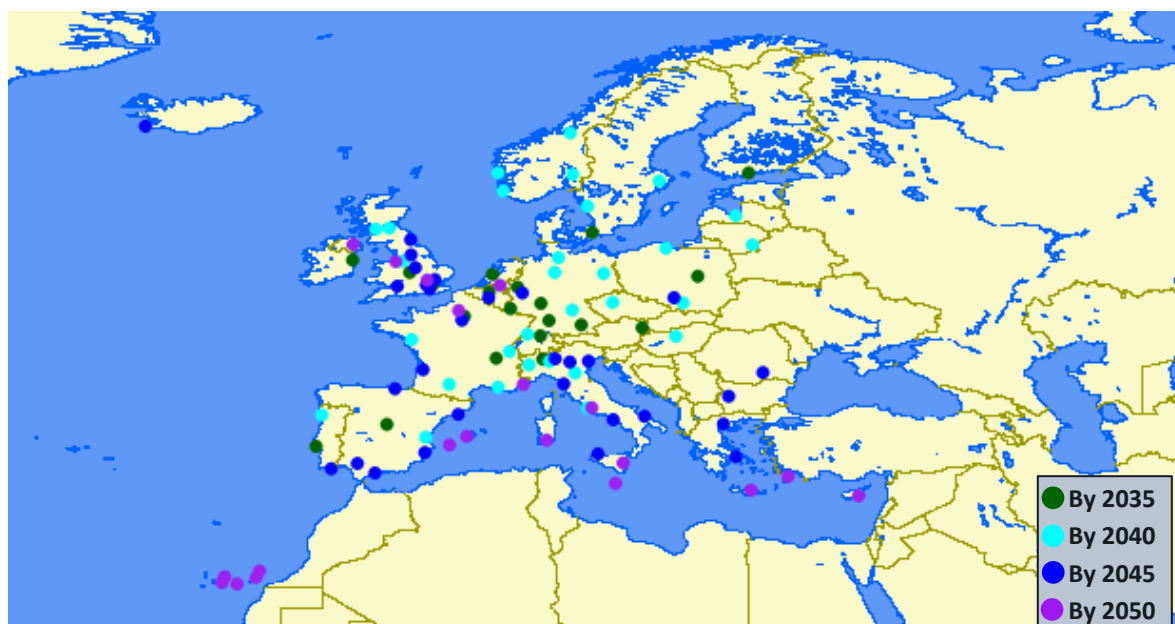
- access to sufficient quantities of green hydrogen through established production facilities and established distribution networks;
- an innovation-friendly business climate at the airport, with cooperation between airport operators, airlines and other stakeholders;
- absence of spatial or other constraints limiting the build-up of hydrogen-related facilities (storage, liquefaction, distribution on the apron); and
- the presence of based aircraft by an early adopter of hydrogen aircraft in order to have a viable business case for building up the infrastructure.

3.25 As part of our assessment, we have assumed there are no constraints on airports' ability to construct hydrogen infrastructure and that they have access to sufficient quantities of fuel. Rather than projecting the precise year hydrogen infrastructure will be available at each airport, the timing of when airports invest in infrastructure is based on a systematic approach and is driven by the level of demand from airlines. The first airports to invest in hydrogen infrastructure are those with the highest proportion of traffic on routes that can be operated by first-generation hydrogen aircraft (i.e., intra-European routes under 3,700km) in 2035.

3.26 Based on this approach, we have therefore assumed that hydrogen infrastructure will be available at 20 airports in 2035 (shown in Figure 3.7), with the remainder of the airports adding infrastructure incrementally throughout the assessment period based on the level of traffic that can be operated by hydrogen aircraft at each airport. 20% of in-scope flights at each airport with hydrogen infrastructure are assumed to be operated by hydrogen aircraft in the first year of operations, rising to 65% and above after 10 years.

3.27 As part of our assessment, we have assumed that airport hydrogen infrastructure is not a constraint on initial green aircraft rollout and uptake (or a disincentive for airlines to purchase hydrogen aircraft). We have also assumed that airport infrastructure is required at both origin and destination airports for hydrogen-powered flights to be able to operate.

Figure 3.7: Rollout of hydrogen airport infrastructure (2035-2050)



Source: www.gcmap.com

4 Cost quantification

4.1 This chapter sets out:

- the high-level approach used to quantify costs;
- a quantification of the costs associated with aircraft development and each stage in the hydrogen fuel supply chain;
- projected unit (€/kg) hydrogen fuel costs compared to projected kerosene costs; and
- the impact of the costs on airline operating costs and passenger airfares.

Approach

Presentation of costs

4.2 The cost projections below include operating expenditure (opex), which is incurred every year once the relevant asset or infrastructure is operational, and capital expenditure (capex), which is incurred as upfront investment costs while the relevant asset or infrastructure is being constructed. All total cost projections below include upfront capex.

4.3 While some costs are incurred prior to 2035, when the first hydrogen-powered flights are assumed to take place, all costs presented below are those required to meet demand between 2035 and 2050. All costs are presented in 2020 prices and present value figures have been calculated using the European Commission's social discount rate of 4%.

Costs in scope

4.4 In order to quantify the costs associated with the development, deployment and operation of hydrogen aircraft, it is important to include only incremental costs that would not be incurred in a 'baseline' or 'do nothing' scenario where hydrogen aircraft are not developed.

4.5 The scope of our cost projection therefore covers:

- The construction and operation of the production and distribution infrastructure required to meet the demand for hydrogen aviation fuel, quantified using the baseline cost scenario with a cost-minimising optimisation model developed by TUHH – more details are provided within TUHH's recently published papers¹⁵¹⁶.
- The construction and operation of any additional airport infrastructure required to accommodate hydrogen aircraft, quantified using inputs provided by Doing + Smith combined with inputs from TUHH's optimisation model.

¹⁵ Sens, Piguel, Neuling, Timmerberg, Wilbrand and Kaltschmitt (2022), [Cost minimized hydrogen from solar and wind – Production and supply in the European catchment area](#)

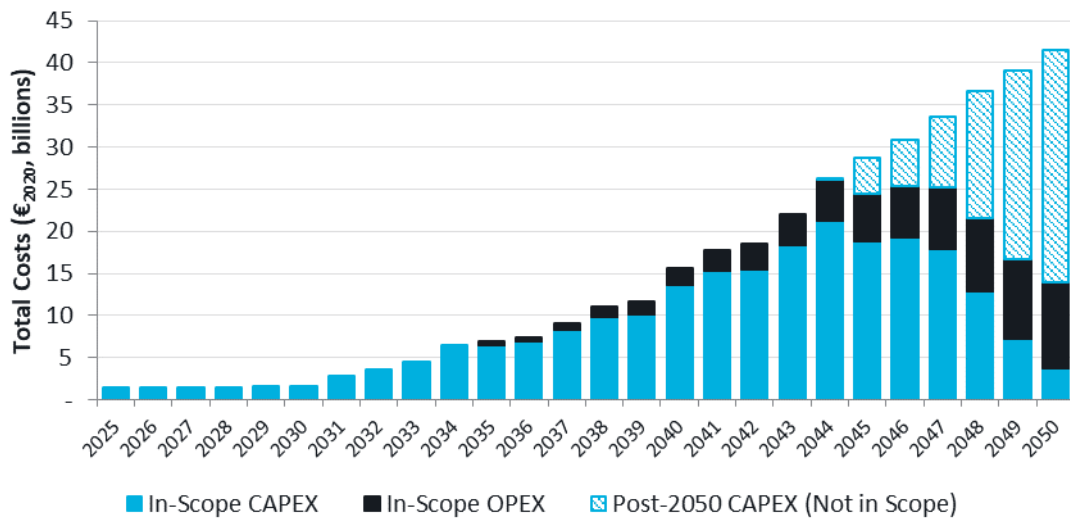
¹⁶ Sens, Neuling, Wilbrand, Kaltschmitt (2022), [Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 – A techno-economic well-to-tank assessment of various supply chains](#)

- The development of a short to medium range (SMR) hydrogen aircraft model and any incremental operating costs for airlines, quantified based on a review of the literature and stakeholder interviews.

4.6 Each of these costs are described in more detail in the remainder of this chapter, with more detailed assumptions provided in Appendix A. It should be noted that the production and distribution costs have been projected based only on the fuel demand from the aviation sector, i.e., not accounting for the impact of the infrastructure being used to provide hydrogen fuel to other sectors and industries.

4.7 The scope of our cost projections includes only those costs incurred to meet hydrogen aircraft and fuel demand within our assessment period, i.e., up to 2050. While capex costs will continue to be incurred to meet post-2050 demand prior to 2050, these are not included in our cost projections below. Therefore, as depicted in Figure 4.1, only costs required to meet fuel demand up to 2050 are included in our projections.

Figure 4.1: Depiction of in-scope costs (EU Reference Scenario, 2025-2050)



Source: TUHH, D+S, Steer analysis.

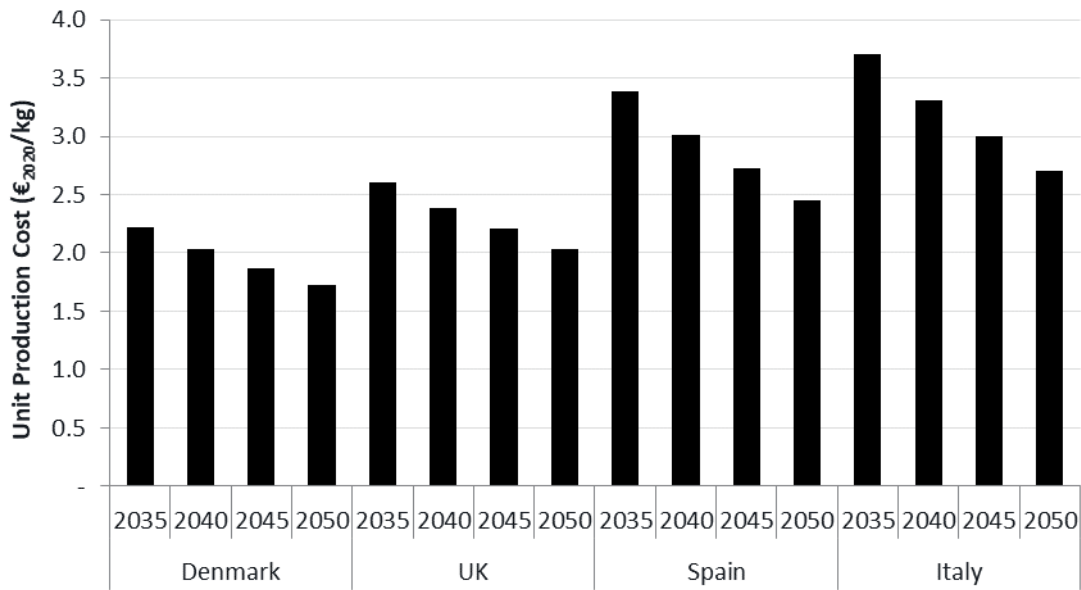
Fuel production

4.8 Fuel production costs include:

- electrolysis of water to produce hydrogen;
- on-site storage of hydrogen prior to distribution;
- renewable energy required to power the electrolysis process; and
- additional production required to account for boil-off losses throughout the supply chain.

4.9 The unit production costs at each of the four production sites selected for our assessment across the assessment period are shown in Figure 4.2. At all four production locations, unit costs are projected to reduce over time, driven by productivity improvements as the volume of production increases and the technologies become more established.

Figure 4.2: Unit production costs 2035-2050 (All scenarios)

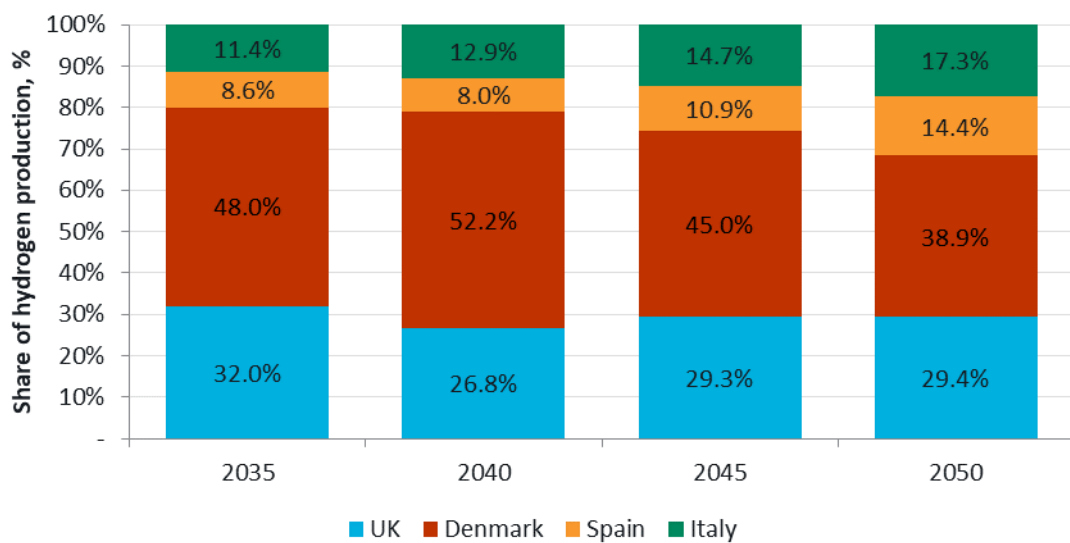


Source: TUHH

4.10 Unit production costs are lower in Denmark and the UK, which use a higher proportion of wind energy, than in Spain and Italy, which use a higher proportion of solar PV energy. It should be noted that there is the potential to utilise more favourable solar PV production locations in North Africa; however, only production locations within Europe have been used given the aforementioned need for European energy security.

4.11 The share of total hydrogen production across the four sites, throughout the assessment period, is shown in Figure 4.3. Given their proximity (and lower distribution costs) to a greater number of airports, Denmark and the UK account for the majority of production throughout the period.

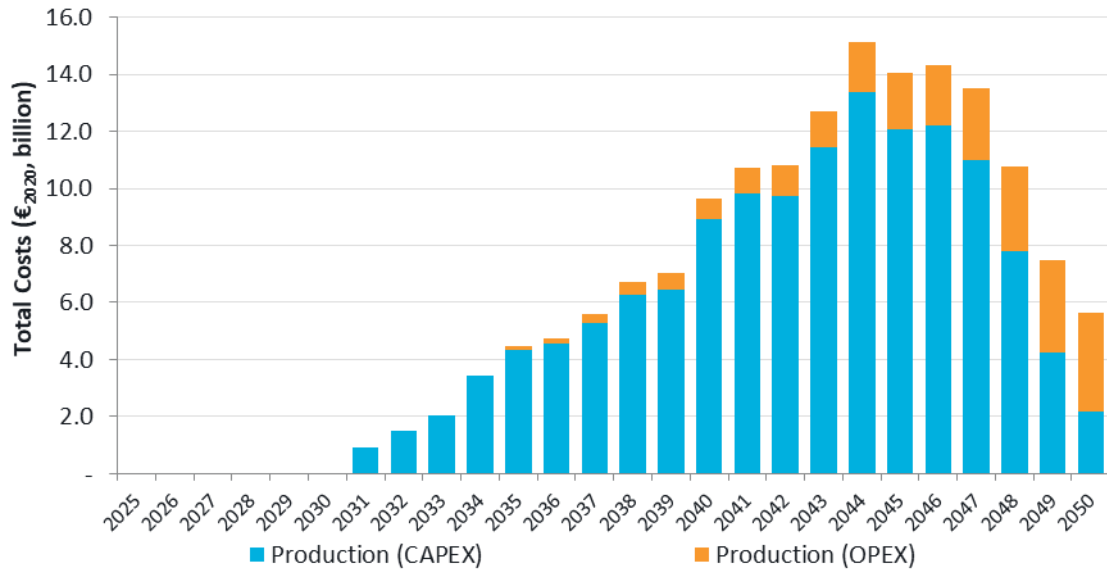
Figure 4.3: Production sites' share of production (All scenarios, 2035-2050)



Source: TUHH

4.12 Total production costs are shown in Figure 4.4. Costs increase, in spite of falling €/kg costs, in order to meet increasing levels of hydrogen demand, total projected production costs over the period are €161 billion.

Figure 4.4: Hydrogen production costs (2025-2050, EU Reference Scenario)



Source: TUHH, Steer analysis.

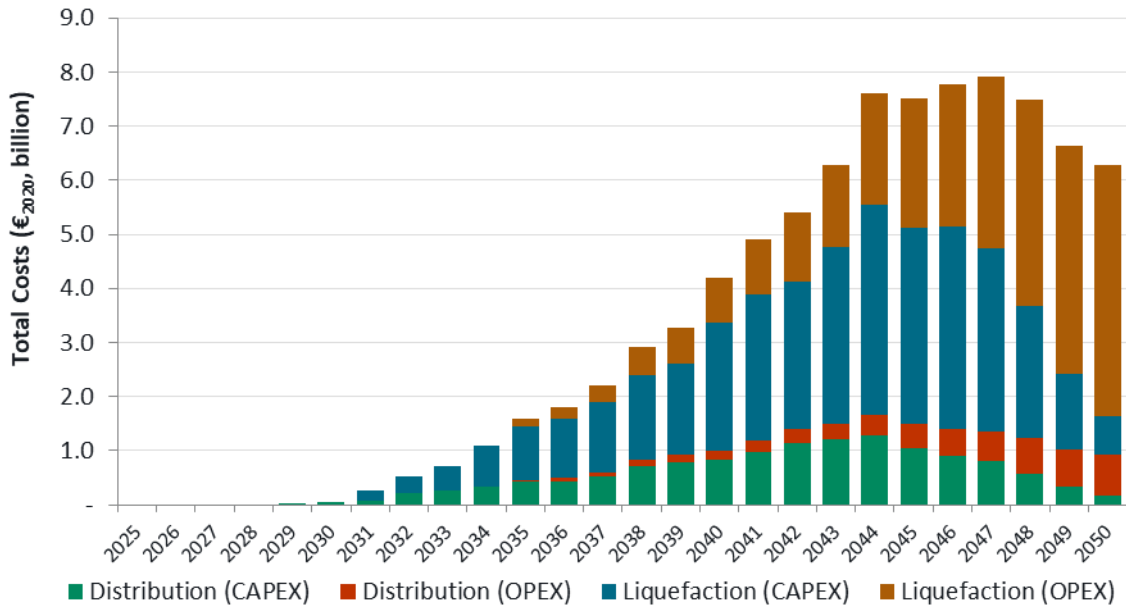
Fuel distribution

4.13 Fuel distribution costs include:

- transportation of hydrogen in either liquid form, using trucks and ships, or in gaseous form using on and offshore pipelines;
- filling costs associated with the transfer of liquid or gaseous hydrogen from production to distribution facilities, and between different stages within the distribution process;
- liquefaction, which takes place either close to or at the production site (for liquid transportation), or close to or at the airport (for gaseous transportation);
- renewable energy required to power the liquefaction process; and
- storage of hydrogen fuel within the supply chain.

4.14 Total distribution costs are shown in Figure 4.5. Costs increase in order to meet increasing levels of hydrogen demand with total projected distribution costs over the period of €86 billion.

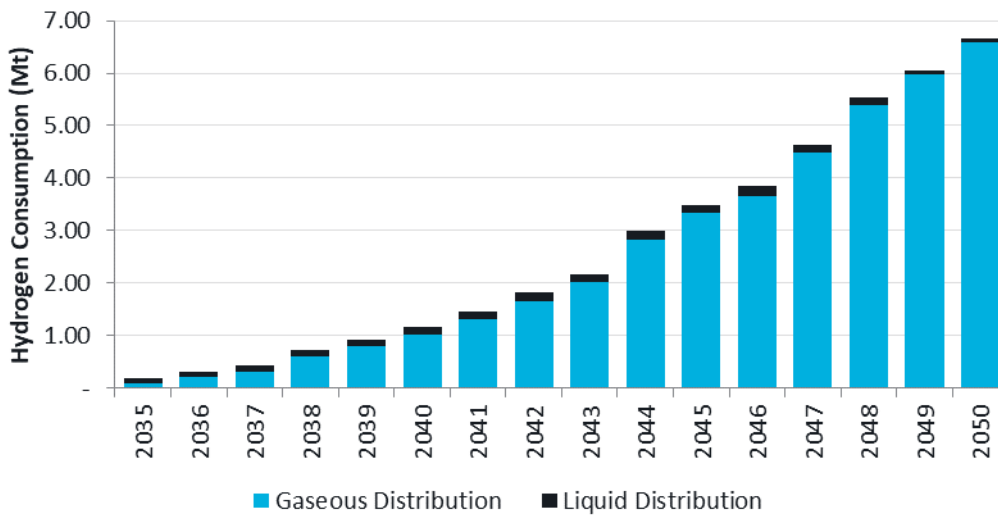
Figure 4.5: Hydrogen distribution costs (2025-2050, EU Reference Scenario)



Source: TUHH, Steer analysis.

4.15 While around half of fuel is distributed using liquefied distribution in 2035, (as shown in Figure 4.6) over the assessment period, gaseous distribution costs account for the large majority of the total distribution costs due to the use of this distribution method at higher volumes of fuel (by 2050, 99% of fuel is distributed in gaseous form).

Figure 4.6: Share of hydrogen distribution streams (2035-2050, EU Reference Scenario)



Source: Steer analysis

Airport infrastructure

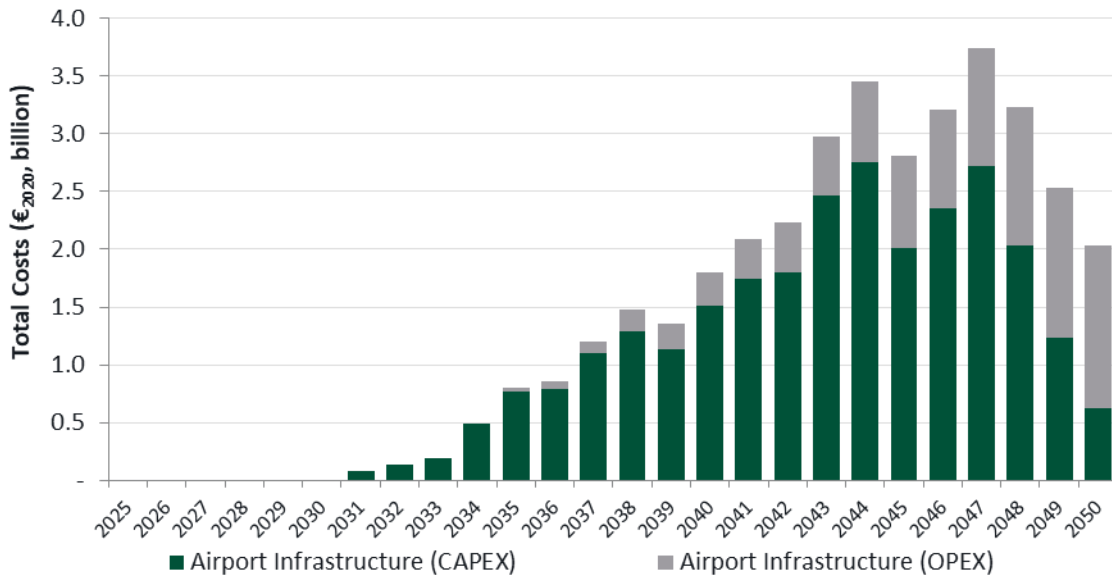
4.16 Airport infrastructure costs include:

- storage of liquid hydrogen fuel at the airport; and

- distribution of hydrogen within the airport to aircraft, using either bowisers or pipeline and hydrant supply.

4.17 Total airport infrastructure costs are shown in Figure 4.7. Costs increase in order to meet increasing levels of hydrogen flights, total projected airport infrastructure costs over the period are €37 billion. The uneven growth of total airport infrastructure costs is driven by the manner in which infrastructure is added across in-scope airports (described in paragraph 3.25); different-sized airports adding infrastructure in each year means the value of total investment varies from year to year.

Figure 4.7: Airport infrastructure costs (2025-2050, EU Reference Scenario)



Source: Doig + Smith, Steer analysis.

Aircraft

Development

- 4.18 While commercial confidentiality around aircraft development and production costs means there is limited information available on hydrogen aircraft development costs, desk research combined with consultation of aircraft manufacturers has enabled us to formulate an approximate projection. As part of our assessment, we have estimated the costs of developing one SMR aircraft type; based on the projected level of traffic, SMR aircraft account for over 80% of in-scope ATMs within the assessment period and over 94% of transport activity.
- 4.19 Current aircraft development costs vary significantly depending on whether the design is a completely new model, or a re-design or modification to an existing model. For example, the costs of developing the Airbus A350 have been estimated¹⁷ at €12.5 billion over seven years, versus a cost of €1.1 billion over two years to develop the A320 Neo (a derivative on the A320). €12.5 billion is likely to be a lower bound estimate for the cost of developing a first-generation hydrogen aircraft.

¹⁷ Nolte (DLR), Apffelstaedt (TUHH), Gollnick (DLR) and Rötger (IATA) (2012), Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency (prices converted to 2020€ from 2012\$)

- 4.20 When consulted on this topic, while unable to share specific cost figures, Airbus noted that the airframe for the first generation of hydrogen aircraft is likely to be similar to current SMR aircraft and that the development costs will be more aligned with developing a new aircraft model (as opposed to a re-design or modification), though are likely to be incurred over a slightly longer period of 10 years. This also implies that €12.5 billion is a reasonable lower bound estimate.
- 4.21 The EU Clean Aviation initiative estimates¹⁸ that product development costs for next generation aircraft will be €15 billion per aircraft type. While there is a large amount of uncertainty around development costs, we have assumed that aircraft development costs for a first-generation hydrogen aircraft are €15 billion over 10 years consistent with EU Clean Aviation initiative estimates, current aircraft development costs and information provided by Airbus.
- 4.22 While the cost of developing a hydrogen aircraft type is an incremental cost for an aircraft manufacturer, it is not clear that the production of the new aircraft type will incur incremental costs. While there are clearly costs involved in manufacturing aircraft and certain aircraft components may be cheaper or more expensive to produce, there is not any evidence to suggest that total aircraft production costs should be materially different to current aircraft production costs, once the design and technology of the new aircraft type have been developed (and associated costs incurred). We have therefore assumed that aircraft development costs are the only incremental costs associated with the development and production of first-generation hydrogen aircraft.

Operation

- 4.23 In addition to fuel and charges for airport infrastructure, aircraft operation costs that are often cited as having the potential to change with the introduction of hydrogen aircraft include maintenance and aircrew training and certification costs. However, it is not clear that either of these costs borne by airlines would materially change with the introduction of hydrogen aircraft.
- 4.24 With respect to maintenance, Table 4.1 shows the typical maintenance schedule for a commercial aircraft.

Table 4.1: Typical aircraft maintenance schedule

Check type	Activity	Frequency
Line maintenance	Inspection of wheels, brakes and fluid levels (oils and hydraulics)	Daily
A	General inspection of the interior and exterior for evidence of damage, corrosion, missing parts,	Every 400-1,000 flights or 200-1,000 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.	20-36 months

¹⁸ Strategic Research and Innovation Agenda report (2021), Clean Aviation

Check type	Activity	Frequency
D	Comprehensive inspection of the entire aircraft	6-10 years

Source: National Aviation Academy & Steer research

- 4.25 No information could be found within the literature on to what extent these procedures will change for hydrogen aircraft. While, for the proposed first generation SMR hydrogen aircraft, the majority of components on the aircraft remain the same as those on a conventional turbine aircraft, there will be differences with respect to the fuelling systems due to the fuel temperatures involved.
- 4.26 An EU Clean Aviation report¹⁹ noted that while maintenance costs may increase due to the need for additional checks in the initial years of hydrogen aircraft operation, in the long term, costs may decrease. Based on this we have assumed there are no material incremental costs associated with aircraft maintenance.
- 4.27 Similarly for aircrew training and certification, while crew would be required to be certified on hydrogen aircraft, there is not any evidence to suggest that costs associated with this would be materially different to those currently incurred to be trained and certified on a new conventional aircraft type. Based on this we have assumed there are no material incremental costs associated with crew training and certification.

Changes to aircraft operation costs arising from the need to purchase hydrogen fuel and aircraft, and the impact on airline operations, are discussed later in this chapter.

Overall Costs

Total costs

- 4.28 Total costs are shown in Table 4.2 and Figure 4.8 below.

Table 4.2: Total costs (2025-2050, EU Reference Scenario)

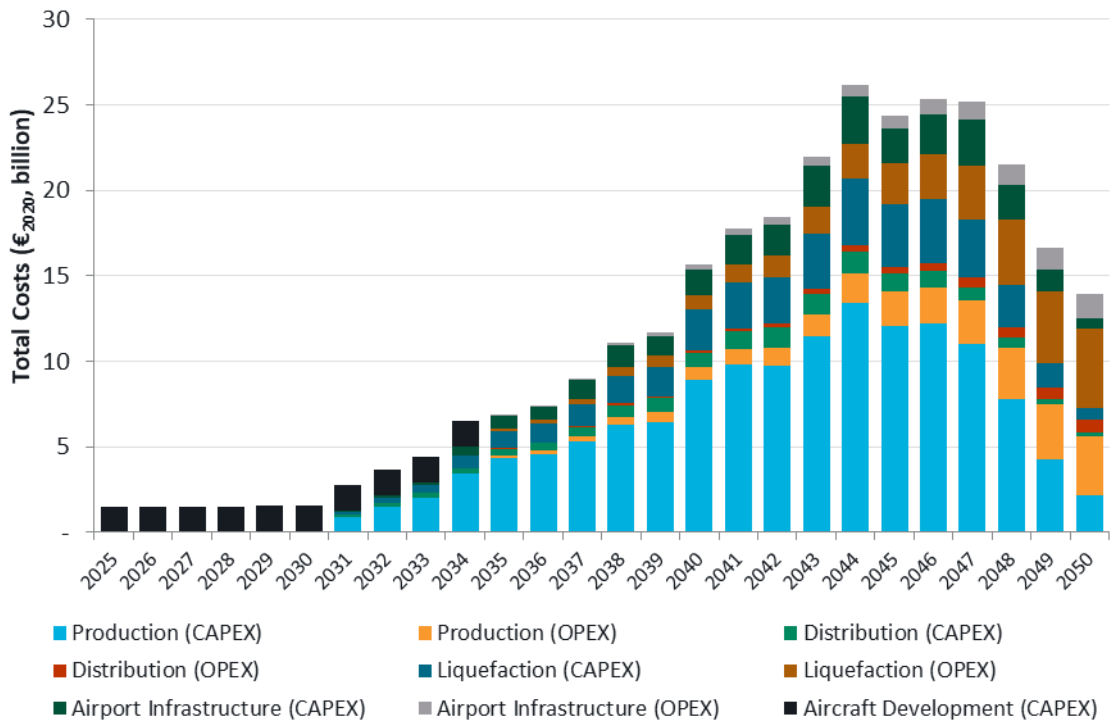
Cost element	Total Cost (€ ₂₀₂₀ , million)	2020 PV (€ ₂₀₂₀ , million)
Production	161,260	66,862
Distribution	18,461	7,653
Liquefaction	67,978	26,712
Airport Infrastructure	36,686	14,685
Aircraft Development	15,000	10,400
Total	299,385	126,310

Source: TUHH, Doig + Smith, Steer analysis.

- 4.29 Costs increase throughout the assessment period in order to meet increasing levels of hydrogen demand, total projected costs over the period are €299 billion, equivalent to €126 billion in 2020 present value terms. As described above, the uneven nature of the growth in total costs is driven by the manner in which hydrogen infrastructure is rolled across airports, with different-sized airports (requiring different quantities of fuel and supporting infrastructure) adding hydrogen facilities in each year.

¹⁹ McKinsey & Clean Sky 2 (2020)

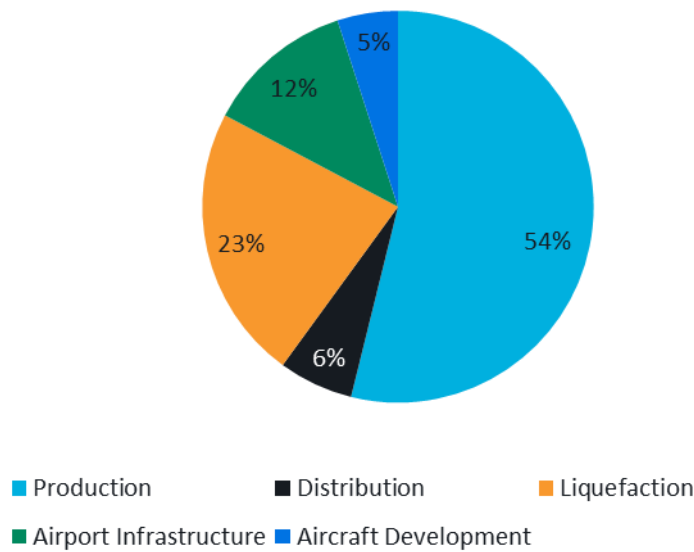
Figure 4.8: Total costs (2025-2050, EU Reference Scenario)



Source: TUHH, Doig + Smith, Steer analysis.

4.30 The share of the main cost categories across the assessment period is shown in Figure 4.9. The costs associated with aircraft development and the construction of airport infrastructure together account for 17% of total costs across the period and hence are relatively small in comparison to the fuel supply chain costs.

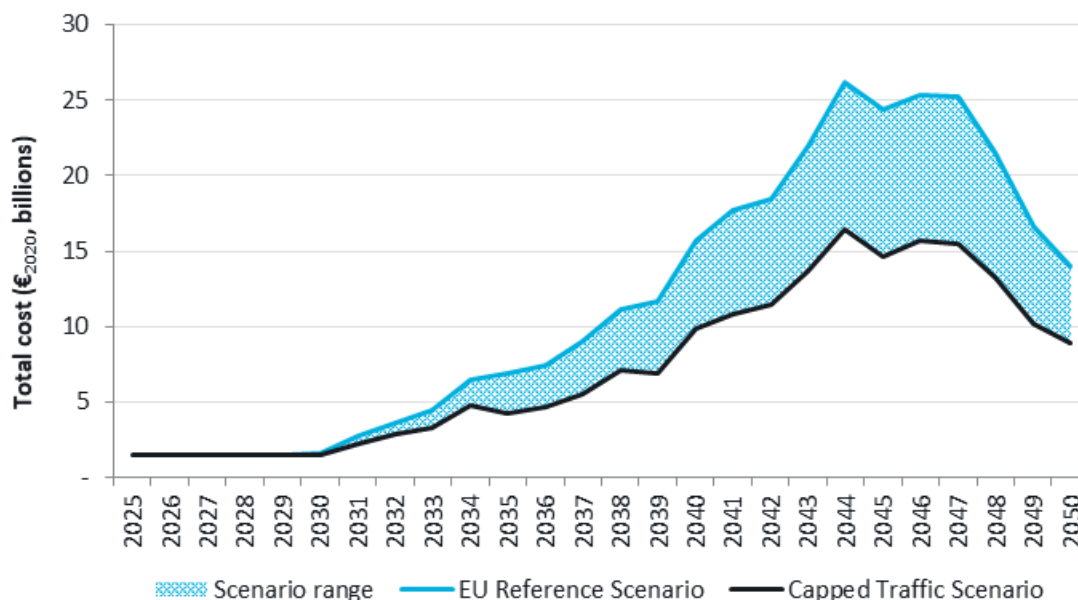
Figure 4.9: Total cost distribution (2025-2050, EU Reference Scenario)



Source: TUHH, Doig + Smith, Steer analysis

4.31 The range of total costs across the assessment period and the two traffic scenarios is shown in Figure 4.10. Compared with the EU Reference Scenario with total costs of €299 billion (€126 billion present value), total costs under the Capped Traffic Scenario are €190 billion (€82 billion present value), equivalent to a 36% reduction, due to the lower demand for hydrogen fuel (and therefore associated infrastructure).

Figure 4.10: Projected total cost scenario range (2025-2050)

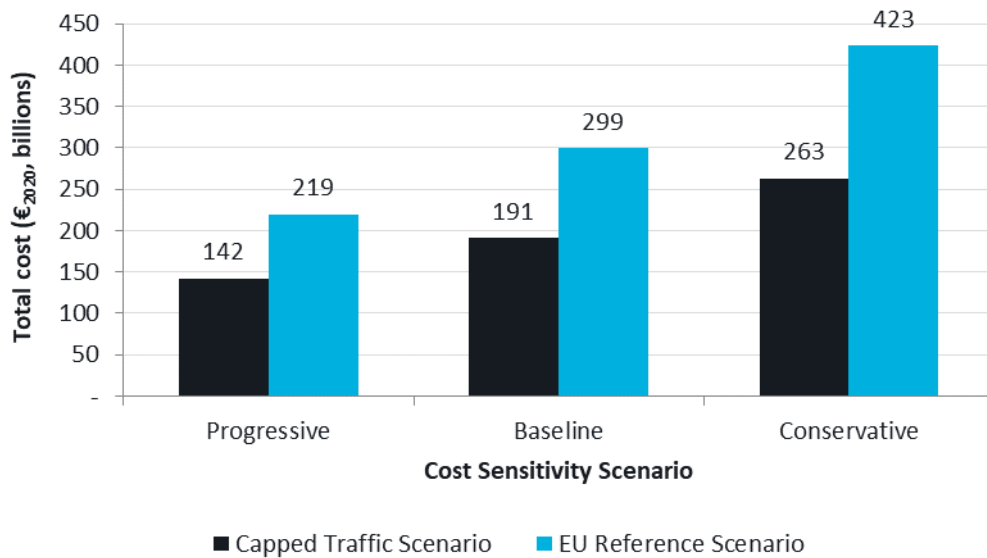


Source: TUHH, Doig + Smith, Steer analysis

Cost scenarios

- 4.32 The production and distribution cost projections, derived from TUHH’s optimisation model, are based on extensive literature review and analysis of the hydrogen supply chain, which generates a range of potential values for economic, financial and technical inputs to the model. The costs used to project the fuel supply chain costs shown above are based on the baseline cost scenario within TUHH’s optimisation model, which represents the median input values.
- 4.33 The projections also include a progressive cost scenario (using the first quartile of input values) and a conservative cost scenario (using the third quartile of input values). Figure 4.11 shows the total costs over the assessment period, under the conservative, baseline and progressive cost scenarios (airport infrastructure and aircraft development costs are unchanged).
- 4.34 The cost scenario range represents a 27% decrease or 41% increase versus the baseline cost scenario under the EU Reference Scenario, with a 25% decrease and 38% increase under the Capped Traffic Scenario. The range illustrates some of the uncertainties around the size of the investment required for the aviation fuel supply chain, discussed further in the following chapter.

Figure 4.11: Cost and traffic scenario range (2025-2050)

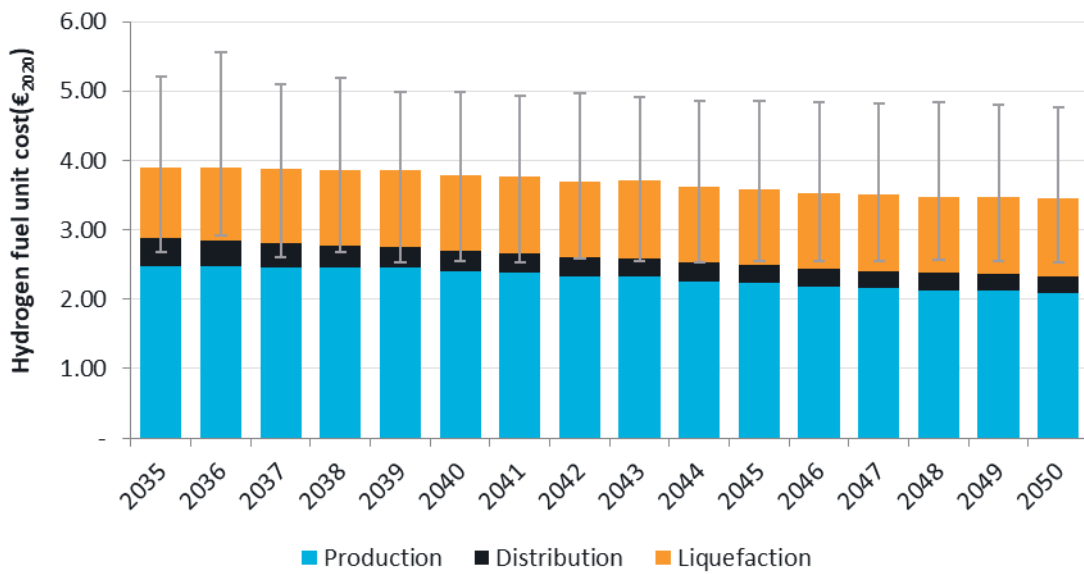


Source: TUHH, Steer analysis

Unit costs

- 4.35 Unit hydrogen costs (€/kg) have been calculated using total hydrogen demand, opex and an equivalent annual cost (EAC) value for capex. The EAC cost is equivalent to the annual capital cost of an asset, which represents the annual cost of owning, operating, and maintaining an asset over its useful life. EAC is calculated using each capital asset’s useful life and the weighted average cost of capital (WACC) – further information on these assumptions is set out in Appendix A.
- 4.36 Unit hydrogen fuel costs, comprising production, distribution and liquefaction costs (i.e., the costs that would be charged to airlines as fuel costs) are shown in Figure 4.12; costs fall by 10% from €3.90 per kg in 2035 to €3.45 per kg in 2050. This is driven by a combination of decreasing unit production costs (due to productivity improvements) and an increasing share of gaseous distribution throughout the period, which means greater use of (cheaper) pipeline distribution and (more expensive) decentralised liquefaction infrastructure. The unit costs are based on TUHH’s baseline cost scenario, with the progressive and conservative scenarios shown as a range above and below the baseline costs.

Figure 4.12: Unit costs (2035-2050, EU Reference Scenario)



Source: TUHH, Doig + Smith, Steer analysis.

4.37 The projected unit hydrogen fuel price, compared with the projected price of other aviation fuels between 2035 and 2050, is shown in Figure 4.13, which includes:

- kerosene, based on the current market price²⁰, which does not include any projected price changes given the relatively high current price and historical price volatility.
- kerosene with carbon pricing and fuel tax applied; assuming an increase in the carbon price from around 50 €/t CO₂ in 2020 to 200 €/t CO₂ in the year 2050²¹ and a fuel tax applied at the rate proposed in the EU Fit-for-55 package (10.75 €/GJ from 2033 onwards).
- The average of three biofuel-based sustainable aviation fuels (SAFs)²², HEFA, Alcohol-to-Jet and gasification fuels, which use different types of feedstocks and production processes; and
- eFuel SAF²³ (synthetic kerosene produced with electricity from renewable sources).

4.38 Based on the fuel cost projections used, liquid hydrogen fuel costs are projected to be higher than untaxed kerosene throughout the assessment period, though are lower than the other fuel types, including kerosene with taxes and carbon pricing applied.

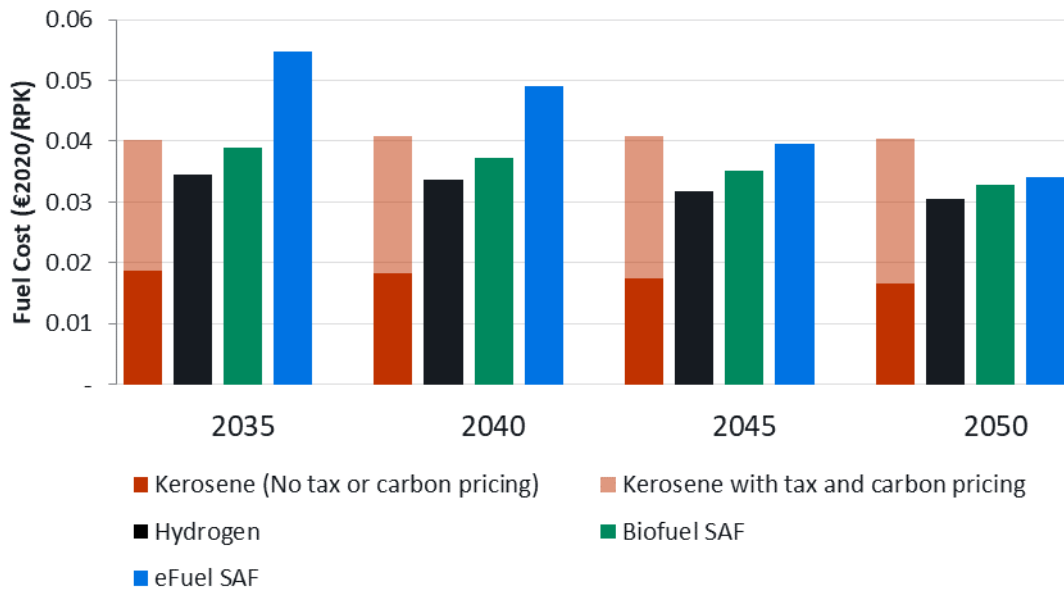
²⁰ US Energy Information Administration (EIA) Kerosene-Type Jet Fuel 11 July 2022 (converted to euros)

²¹ Based on the [ICCT](#) (2022) lower bound estimate (converted to Euros at parity to the Dollar)

²² GARS Workshop Aviation and the Environment presentation (2022), aireg via DLR

²³ Renewable electricity requirements to decarbonise transport in Europe with electric vehicles, hydrogen and electrofuels (2020), Ricardo

Figure 4.13: Hydrogen cost vs. kerosene and SAFs (EU Reference Scenario & Baseline Cost Scenario, 2035-2050)

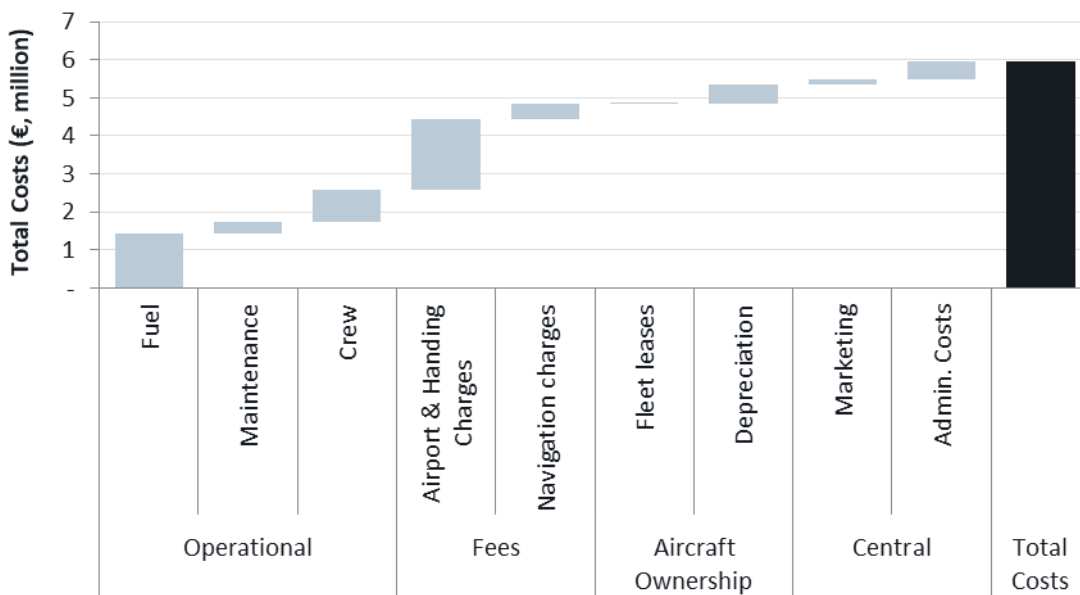


Source: IATA, Ricardo, TUHH, Doig + Smith, Steer analysis

Impact on fares

4.39 The incremental costs described above will ultimately be passed onto airlines (as the customers of fuel producers, aircraft manufacturers and airports), who in turn will pass some or all of these costs onto passengers. The extent to which passenger fares will increase due to the introduction of hydrogen aircraft will therefore largely be driven by the extent to which airlines’ costs increase. As an example of the elements making up airline costs, Figure 4.14 shows a breakdown of operating costs for a European low-cost carrier (easyJet).

Figure 4.14: Breakdown of typical airline operating costs



Source: easyJet 2019 Annual Report

4.40 Airport and handling charges (31%) and fuel (24%) together account for over half of total airline operating costs; anticipated changes to each cost category of airlines’ costs arising from the use of hydrogen aircraft are shown Table 4.3.

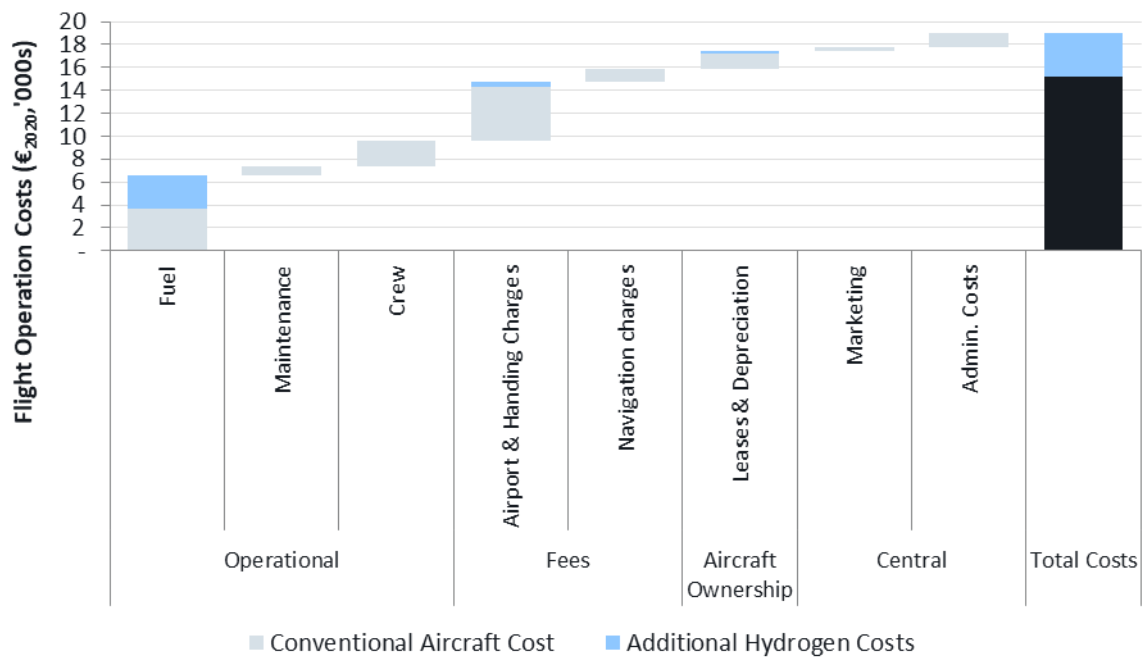
Table 4.3: Changes to airline operating costs

Cost category	Share of costs	Operations Impact	Cost Impact
Fuel	24%	Requirement to use new fuel type	Significant increase
Maintenance	5%	Requirement to maintain new aircraft type	No material impact
Crew	14%	Requirement for pilots to train on new aircraft type None for cabin crew	No material impact
Airport & Handling Charges	31%	Requirement for new airport and groundhandling infrastructure (which airports will increase charges to fund)	Increase
Navigation Charges	7%	None	None
Fleet Leases	<1%	Requirement to lease new type of aircraft	Increase
Depreciation	8%	Requirement to purchase new type of aircraft	Increase
Marketing	3%	None	None
Admin. Costs	8%	None	None

Source: easyJet 2019 Annual Report, Steer analysis

4.41 Figure 4.15 shows the impact on airline costs for a representative flight between Dublin and Vienna in 2050 – both airports are supplied through gaseous distribution of hydrogen.

Figure 4.15: Breakdown of flight operation cost increases (2050)



Source: Airbus, easyJet, IATA, EIA, TUHH, Doig + Smith, Airport financial statements, Steer analysis

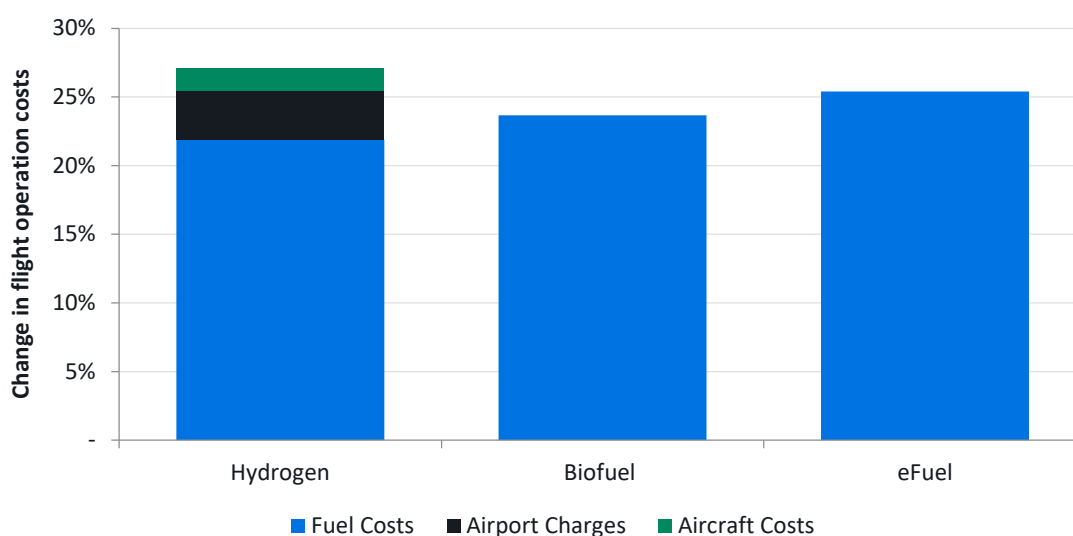
4.42 The changes to the cost of operating the flight are as follows:

- 82% increase in fuel costs based on the difference between kerosene (with no carbon pricing and fuel tax applied) and hydrogen prices described above, taking into account the volume of each fuel type required for an approximately 1,700km flight.
- 11% increase in airport and handling charges, arising from airports charging the cost of their increased investment costs to airlines.
- 19% increase in aircraft ownership costs, arising from aircraft manufactures charging the first-generation hydrogen aircraft type development costs to customers.

4.43 Overall, the increased cost of operating the flight is 27% (with a range of 12% to 40% under the progressive and conservative cost scenarios respectively), some or all of which is likely to be passed onto passengers through higher fares. Airlines “yield-manage” their fares and operate in a competitive market, which means fares are not always fully reflective of changes to costs, particularly in the short term. However, in the longer term, a sustained increase to airlines’ costs would need to be passed on to passengers through higher fares in order to maintain profit margins.

4.44 As shown in Figure 4.16, for the other alternative fuels shown in Figure 4.13, the 92% increase in fuel costs for hydrogen compares to an increase in fuel costs of approximately 99% and 107% for eFuel and biofuel SAFs, equivalent to a 24% to 25% increase in total flight operation costs. However, it should be noted that as SAFs are drop in fuels that can be used by conventional aircraft, unlike hydrogen, no other flight operating costs are affected by the use of SAFs.

Figure 4.16: Total change in flight operation costs with alternative fuels (2050)



Source: Airbus, easyJet, IATA, EIA, TUHH, Doig + Smith, Airport financial statements, Steer analysis

4.45 In addition to the impact on airline costs, the operational impact of using hydrogen aircraft may also indirectly impact passenger fares. If refuelling aircraft with hydrogen increases aircraft turnaround times (which, given the additional complications of refuelling with hydrogen, is possible), airlines will need to operate fewer flights, which means they will need to increase fares to maintain the same level of revenue.

5 Policy Support

5.1 This chapter sets out:

- some of the challenges and potential policy support options with respect to hydrogen fuel production and distribution; and
- some of the challenges and potential policy support options with respect to the use of hydrogen infrastructure within the aviation sector.

Hydrogen fuel supply

Challenges

Renewable energy supply

5.2 In order for sufficient quantities of green hydrogen to be available to meet the projected demand for hydrogen aviation fuel, there will need to be sufficient quantities of renewable energy available to power the production, storage, distribution and liquefaction processes. This will be a challenge with respect to the overall supply of renewable energy and competition for this supply, as there will be significant green hydrogen demand for other economic sectors, as well as for general electricity production, as other sectors look to decarbonise.

5.3 Based on the projected level of hydrogen demand in 2050 within our assessment, under the EU Reference Scenario, over 67 gigawatts (GW) of wind and solar PV power (40 GW under the Capped Traffic Scenario) will be required for the hydrogen production process for the supply of the 100 in-scope airports alone. In 2020, the EU's total wind and solar PV power generation capacity was 344GW and total power generation capacity was 990GW²⁴. This implies a significant ramp up of renewable electricity capacity is needed if it is to meet the demand from both green hydrogen and other economic sectors. While electricity prices have been coming down in recent years, and are projected to continue to do so, prices may increase if supply is unable to meet demand.

Electrolysis capacity

5.4 While electrolyzers are a mature technology having been used in industrial processes such as the chlor-alkali process for a long time, dedicated hydrogen production via electrolysis is a tiny fraction of the total hydrogen produced globally every year (0.03% of total hydrogen produced). Europe currently has approximately 40% of global electrolyser capacity²⁵. There is therefore a major challenge in scaling up production of green hydrogen to deliver the required quantities by 2050 and in parallel significantly bring down investment and operating costs.

²⁴ Installed capacity in the European Union, [IEA](#)

²⁵ Hydrogen, [IEA](#)

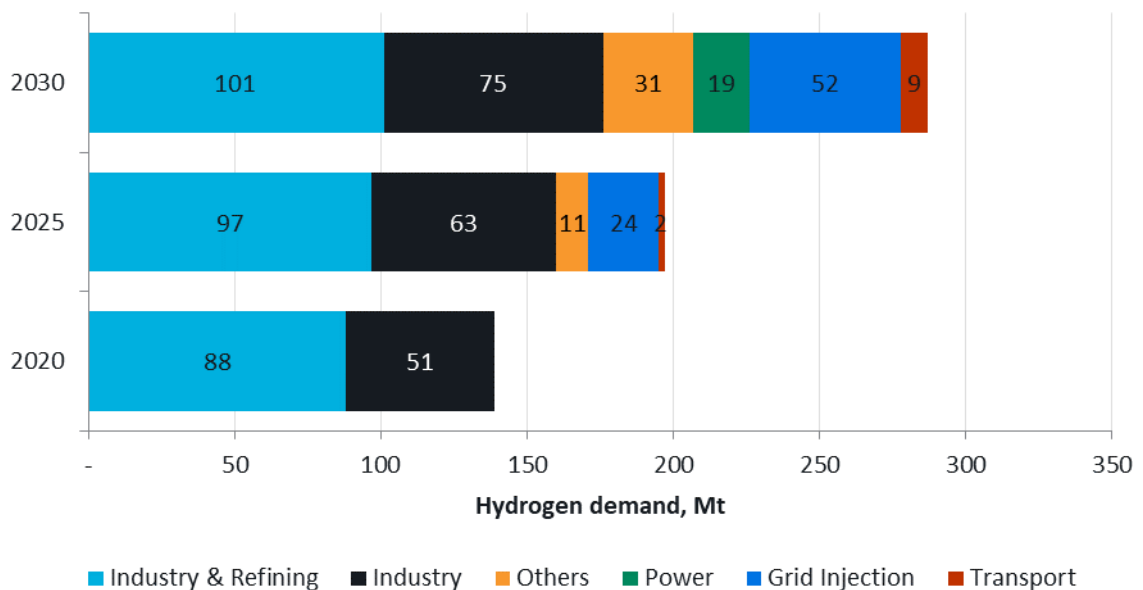
5.5 Electrolysis capacity is already growing rapidly, with the both the IEA²⁶ and IRENA noting that a large number of projects are planned or have recently become operational. Capacity has the potential to reach a level capable of producing between 4.9Mt and 8.3Mt of green hydrogen by 2030; however, this is still well short of the 2030 80Mt target required to reach net zero emissions by 2050. Therefore, significant further effort is required to encourage further capacity generation.

Demand for hydrogen

5.6 In 2018, total hydrogen demand in Europe was estimated at 8.3Mt²⁷ and the largest share of this demand came from industrial uses (46%, principally ammonia, methanol and other chemicals) and refineries (45%), while transport accounted for under 0.1% of demand. 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 hydrogen-consuming industries by 2030²⁸; given this, and other global initiatives, the Commission expects global demand for green hydrogen to increase to 211Mt by 2030.

5.7 The projected global industry demand to 2030 is shown in Figure 5.1; while transport (including aviation usage) is projected to increase, it still accounts for only 3% of projected demand in 2030.

Figure 5.1: Projected hydrogen demand (2020-2030)



Source: Steer analysis of IEA data for their Net Zero Scenario²⁹.

5.8 Therefore, even if sufficient quantities of renewable energy and electrolyser capacity were available to produce large quantities of green hydrogen that could be used as aviation fuel, the

²⁶ Hydrogen, [IEA](#)

²⁷ Hydrogen Europe, Clean Hydrogen Monitor 2020

²⁸ Fit for 55 package, COM/2021/550 final

²⁹ IEA, [Global hydrogen demand by sector in the Net Zero Scenario, 2020-2030](#),

aviation industry faces significant competition for this given the need for other industries that use far large quantities of hydrogen to decarbonise (and to increase their use green hydrogen).

Policy support options

- 5.9 Many of the challenges associated with the hydrogen fuel supply chain stem from the fact that, based on current trajectories, projected renewable energy and hydrogen production capacity will not be sufficient to produce the quantity of hydrogen required to meet net zero targets by 2050.
- 5.10 It is also difficult to envisage that the aviation sector alone will be able to fund or finance the cost of the fuel supply infrastructure required to accommodate hydrogen aircraft. Instead, it seems likely that the wider hydrogen ecosystem will need to develop for the aviation industry to be able to utilise the necessary infrastructure, for example by being supplied with green hydrogen from general (as opposed dedicated) production facilities or by utilising already established distribution networks used by other transport modes and industries. An exception to this is hydrogen liquefaction facilities at airports, which are specific to the aviation industry.
- 5.11 Therefore, in order to increase green hydrogen production and distribution capacity, potential policies that could be enacted at a national or EU level to increase supply capacity include:
- direct financial support, in form of grants or cheap loans to finance technology research and the construction of fuel production infrastructure;
 - indirect financial support, such as tax breaks or subsidies, which would incentivise investment in infrastructure; and/or
 - supply-side measures, such as usage mandates or floor prices, which would provide more certainty to suppliers to invest in capacity.
- 5.12 While there is some uncertainty around the level of investment required, the magnitude of the costs mean that (even within the progressive cost scenario in Figure 4.11), within Europe, significant support may be required from the EU, which has the means and resources to lend to fund large-scale infrastructure projects through the European Investment Bank (EIB) and to issue collective debt. The EU can also enact Europe-wide legislation to incentivise investment in infrastructure, which would be less effective at a national level. The EU facilitates the development of international agreements and standards, for example in relation to international trading, and safety and production standards.
- 5.13 Following Brexit, the UK would need to undertake similar policy initiatives separately, although UK policy is currently broadly aligned with the approaches being considered by the EU.
- 5.14 A high degree of cooperation and coordination is likely to be required at a European level to implement large-scale hydrogen fuel infrastructure in the most effective and efficient manner that utilises economies of scale and countries' comparative advantage in the fuel supply chain. For example, Figure 3.2 demonstrates that certain regions of Europe are significantly better suited for hydrogen production than others, which means production facilities should be concentrated in these regions.

Hydrogen aircraft and infrastructure

Challenges

Airports

- 5.15 As has been discussed above, depending on how hydrogen fuel is delivered to the airport, in order to accommodate hydrogen flights, airports will require:
- for liquid hydrogen fuel, specialised cryogenic storage, distribution and filling infrastructure; and
 - for gaseous hydrogen fuel, in addition to the above, liquefaction facilities at or close to the airport.
- 5.16 The costs associated with implementing this infrastructure will be significant. In addition to the projected €18 billion required for on-site cryogenic distribution and storage facilities, airport operators, or fuel companies operating at airports, will also be required to fund some or all of the cost of constructing and operating liquefaction facilities required for the on-site supply of liquid fuel for aircraft. These facilities will not only require additional space (which will incur additional costs if off site) but also access to large quantities of renewable energy.
- 5.17 As an example, based on our assessment, in 2050, Amsterdam's Schiphol Airport would require 242,000 tonnes of liquid hydrogen fuel to meet aircraft demand. The fuel would be delivered in gaseous form via pipeline and would need to be liquefied at or close to the airport. Based on the energy requirements³⁰ of the liquefaction process for the year, this would require around 0.3 GW of power, equivalent to 0.7%% of the Netherlands' electricity production capacity in 2020³¹. The total power requirement to liquefy the hydrogen required across the 100 airports is 8.2 GW, which is equivalent to 0.8% of the EU's total power generation capacity of 990GW in 2020.
- 5.18 The major challenges for airport operators and their partners, including groundhandling providers and fuel suppliers, are therefore funding and financing the investments required for hydrogen infrastructure, and having access to sufficient quantities of renewable energy for its operation. As has been discussed above, there will be considerable competition for renewable energy capacity not only from other steps within the hydrogen fuel supply chain but also from other economic sectors.

Airlines

- 5.19 Before ordering hydrogen aircraft, airlines will require sufficient assurance that hydrogen fuel supply and airport infrastructure is available, and established enough that prices are competitive, in order to make their investment in hydrogen aircraft worthwhile. Airlines will not order hydrogen aircraft if they do not believe the hydrogen fuel ecosystem will be in place, which, as has been discussed, will be a significant challenge to overcome.
- 5.20 As discussed in Chapter 3, once hydrogen airport infrastructure is established, it will require additional safety and operational procedures, given the need to keep liquid hydrogen at extremely low temperatures. While these additional procedures are expected to be feasible, there is a risk that they will lead to increased aircraft turnaround times, decreasing the

³⁰ Assuming 7 kwh per 1kg of hydrogen and annual up time 6,000 hours

³¹ Netherlands Energy Profile, [IRENA](#)

number of flights that can be operated and therefore having an impact on airline (and airport) revenues. This would need to be passed on to passengers through higher fares.

- 5.21 In addition to the potential impact of aircraft operations on passenger fares, as shown in Figure 4.15, the impact of using hydrogen aircraft for a typical European flight is projected to increase fares (if no carbon pricing or taxes are applied to kerosene), which means passengers will not be incentivised to purchase tickets for flights operated by hydrogen aircraft over those operated by conventional aircraft.
- 5.22 Therefore, in addition to assurances around the availability of fuel supply infrastructure, the main challenge for airlines is that flights operated by hydrogen aircraft will be potentially too expensive to operate, and therefore not competitive with those operated by conventional aircraft.

Policy support options

- 5.23 As with fuel supply infrastructure, many of the challenges associated with airport infrastructure are driven by the magnitude of the costs and uncertainty for airports and airlines whether the other party will also invest in hydrogen equipment or infrastructure. Therefore, in order to address this, potential policies that could be enacted at a national or EU level to increase supply capacity include:
- direct financial support, in form of grants or cheap loans to finance technology research (e.g., decentralised liquefaction facilities) and the construction of airport infrastructure;
 - indirect financial support, such as tax breaks or subsidies, which would incentivise investment in infrastructure; and/or
 - supply-side measures, such as airline fuel usage or airport fuel supply mandates (as has been proposed by the ReFuelEU initiative for SAFs), which would provide more certainty for other investors.
- 5.24 The EU could also play a central role within the aviation sector, through the European Aviation Safety Agency (EASA), with a safety certification regime, encompassing aircraft, airports, maintenance and staff training.
- 5.25 The other major area where policy support could be provided is on the demand side with respect to the price competitiveness of hydrogen aircraft versus those powered by other fuels. As shown in Figure 4.13, carbon pricing and taxes on kerosene can make hydrogen more price competitive than kerosene, which in turn is likely to incentivise the use of hydrogen aircraft by passengers and their uptake by airlines.

Appendices

A Modelling Assumptions

Hydrogen fuel demand projections

- A.1 The baseline traffic scenario is derived from EU reference scenario projections³² of intra-European aviation activity between of 2019 and 2050 and the lower traffic scenario assumes, through the use of market-based demand management measures, that traffic does not recover to above pre-COVID (2019) levels throughout the assessment period (business travel recovers up to 50% of 2019 levels and leisure travel recovers up to 2019 levels). The geographical definition of Europe used within the traffic projection is the EU27, EEA, Switzerland and the UK. EU reference scenario projections are given in passenger kilometres (pkm), equivalent to revenue passenger kilometres (RPKs).
- A.2 To develop a 2019 baseline for both scenarios, we conducted an analysis of the in-scope traffic between European airports in 2019 (taken from OAG schedules analyser), where in-scope traffic is defined as flights on routes within the maximum range of first-generation hydrogen aircraft (3700km). The 100 airports used within the assessment are those with the highest number available seat kilometres (ASKs) on in-scope routes in 2019. The 2019 aircraft traffic movements (ATMs) and ASKs at each airport grow throughout the assessment period in line with intra-European transport activity growth rates in each traffic scenario, with the number of ASKs and RPKs per ATM remaining constant throughout the period.
- A.3 To quantify the amount of hydrogen required for the hydrogen ATMs and RPKs in each traffic scenario we assumed the energy required for a hydrogen flight was equal to that used in an equivalent kerosene flight. To reflect fleet turnover, an average reduction of 1.1% in fuel burn for kerosene aircraft was assumed across the assessment period (in line with the EU Reference Scenario projections) and no fuel burn efficiency improvements were assumed for hydrogen aircraft (given one aircraft type is used throughout the assessment period). This is shown in the table below.

Table A.1: Projected hydrogen fuel demand (Mt, 2035-2050)

Scenario	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047	2048	2049	2050
EU Reference Scenario	0.2	0.3	0.4	0.7	0.9	1.2	1.5	1.8	2.2	3.0	3.5	3.9	4.6	5.5	6.1	6.7
Capped Traffic Scenario	0.1	0.2	0.3	0.5	0.6	0.8	1.0	1.2	1.4	1.9	2.2	2.4	2.8	3.4	3.6	4.0

Source: Steer

³² [EU Reference Scenario 2020](#)

Cost projections

Fuel supply chain

- A.4 All fuel supply costs, including renewable energy requirements, production, distribution, liquefaction, storage and filling, have been quantified using a cost-minimising optimisation model developed by TUHH with more details provided within a recent TUHH papers³³³⁴. The model draws upon extensive research and quantifies the required upfront investment costs required for each asset type used in each stage of the fuel supply process, as well as the ongoing opex costs once the assets are operational, based on the level of hydrogen demand through the assessment period. The cost projections assume capex costs are incurred in advance of when each asset is commissioned, during construction (which does not affect the total costs over the period but does affect the timing of the costs and the present value of the costs).
- A.5 Distribution costs to the 100 airports from the four European hydrogen production sites are estimated based on the minimum cost journey of the hydrogen via either gaseous or liquid distribution methods using costs per kilogram of hydrogen per kilometre transported from TUHH's optimisation model. Gaseous methods make use of a 'backbone' pipeline network between the production site and the airport vicinity and then smaller diameter pipelines that connect the airports to the hydrogen distribution network. In cases where water crossings exist between optimum production sites and airports undersea pipelines are used at an additional cost. Liquid distribution methods include trucking overground or a combined journey of trucking and shipping in the cases where water crossings exist.

Airport Infrastructure

- A.6 Airport infrastructure capex costs (quantified by Doig +Smith) include on-site airport storage and distribution costs. Costs have been estimated at each airport throughout the assessment period based on the level of projected fuel demand and the associated distribution and storage capacity requirements. Airport infrastructure opex costs are based on TUHH's optimisation model, where opex associated with operating relevant hydrogen infrastructure has been applied to airport infrastructure.

Unit costs

- A.7 Unit hydrogen costs (€/kg) have been calculated using total hydrogen demand, opex and an equivalent annual cost (EAC) value for capex. EAC is calculated in each year, for each asset, the cumulative capex to date (asset value), the asset's useful life (n) and the real weighted average cost of capital (WACC) as a discount rate, using the following formula:

$$EAC = \frac{\text{Asset Value} \times WACC}{1 - (1 + WACC)^{-n}}$$

³³ Sens, Piguel, Neuling, Timmerberg, Wilbrand and Kaltschmitt (2022), [Cost minimized hydrogen from solar and wind – Production and supply in the European catchment area](#)

³⁴ Sens, Neuling, Wilbrand, Kaltschmitt (2022), [Conditioned hydrogen for a green hydrogen supply for heavy duty-vehicles in 2030 and 2050 – A techno-economic well-to-tank assessment of various supply chains](#)

- A.8 The WACC has been estimated within TUHH's optimisation model using appropriate values for the required level of investment. These are a 14.2% cost of equity, 2% cost of debt, a 50% gearing and a long-term inflation rate of 2% to generate a nominal WACC of 8.1% and a real WACC 6.0%.
- A.9 The capital assets lives used within the EAC calculation are shown in the table below.

Table A.2: Asset lives

Infrastructure type	Asset useful live (years)
Solar PV power	30
Wind power	25
Electrolyser	27
Liquefaction	30
Storage	30
Pipeline	40
Ship	25
Truck	8
Filling	15
Airport	30

Source: TUHH

Impact on fares

- A.10 To estimate the impact on airline costs and passenger fares (assuming all cost increases are passed onto passengers) on a SMR aircraft (with 173 seats) between Dublin and Vienna (1,708km) in 2050 we have:
- Increased fuel costs per available seat kilometre (ASK) by the difference between hydrogen and kerosene fuel costs (per MJ) in 2050 based on the fuel price assumptions set out in paragraph 4.37;
 - Increased airport and handling charges per ASK, by increasing the value of the two airports' fixed asset bases³⁵ (which grow by 1% a year from 2020) by the asset value of the required on-site storage and distribution facilities (and assume all of this increase is passed onto airlines through charges).
 - Increased aircraft ownership costs per ASK based on the increased development costs for Airbus (and assume all of this increase is passed onto airlines). The increased costs are based on:
 - The average net price of A320neo; \$130 million list price (converted to 2020€) with an average discount of 30%.
 - The A320neo development cost as a proportion of the price, assuming a €1.1 billion³⁶ development cost, a margin of 2.5%³⁷ and 1,000 aircraft as the breakeven point.

³⁵ Taken from Flughafen Wien AG Annual Report 2020 and daa Annual Report 2020

³⁶ Nolte (DLR), Apffelstaedt (TUHH), Gollnick (DLR) and Rötger (IATA) (2012), Quantitative Assessment of Technology Impact on Aviation Fuel Efficiency (prices converted to 2020€ from 2012\$)

³⁷ Airbus Annual Reports (Average Airbus net profit margin 2019-2019)

- Based on the A320neo price and development cost share, an increase to the development costs, and therefore price, for SMR hydrogen aircraft with a development cost of €15 billion.

Control Information

Prepared by

Steer
14-21 Rushworth Street
London SE1 0RB
+44 20 7910 5000
www.steergroup.com

Prepared for

Transport & Environment
Square de Meeus 18,
1050 Brussels
Belgium

Supported by:

European Climate Foundation
Riviermarkt 5
2513 AM The Hague
The Netherlands

Steer project/proposal number

24135101

Client contract/project number

Author/originator

Mark Scott

Reviewer/approver

Peter Wiener

Other contributors

Harry Clarke

Distribution

Client: Project Team Steer: Project Team

Version control/issue number

V1.4

Date

13 April 2023

