ARUP

Hydrogen in aviation

© Chalabala

Executive summary

Decarbonising energy across many sectors is a global priority, none more so than in aviation. Hydrogen will play a key role in enabling UK aviation to achieve its net zero carbon commitment by 2050. This study assesses the growing role that hydrogen will play in the future of aviation across South Wales and South West England.

The flight path to net zero

While new generations of conventional aircraft and smarter operations will improve energy efficiency in the sector, it is expected that the use of new fuels and related technology, including sustainable aviation fuels, hydrogen, and electric, will account for between one half and three-quarters of the reduction of carbon emissions in aviation by 2050.

Hydrogen can be used directly as a fuel in modified jet turbines or in fuel cell power chains. It is also needed, indirectly, to produce sustainable aviation fuels. Hydrogen, therefore, will play a central role in decarbonising aviation.

Key phases in demand for hydrogen's use in aviation across both regions:

2025-2030
First generation hydrogen-fuelled aircraft in which conventional turbo-prop aircraft are converted to hydrogen fuel cell power trains are introduced to revenue service. SAF mandates of c. 10% for conventional aircraft.

Local production may be necessary for early adopter flights and for SAF. In South West England and South Wales, LanzaTech will provide most of the local production of SAF for aviation at scale. Direct hydrogen demand in the region is less than 1,000 tonnes per year.

2035-2045
Larger, second-generation aircraft, designed from the outset to be hydrogen fuelled, that use jet turbines (or hybrid configurations) are introduced to revenue service. SAF mandates of c. 30%, with additional requirements for advanced SAF types (e.g. PtL) for conventional aircraft.

In South West England and South Wales, Bristol Airport and its resident airlines will drive demand. Depending on the speed of transition and success of new technologies, the airport will need a direct hydrogen supply pipeline to meet demand for aircraft fuelling and ground operations.

Direct hydrogen demand in the region could be more than 60,000 tonnes per year, in the most ambitious scenario where easyJet prioritises its transition to hydrogen aircraft at Bristol Airport.

2050 and beyond
Increasing penetration of hydrogen-fuelled aircraft in airline fleets. SAF mandates of c. 65% or more, with at least half coming from advanced SAF types.

Direct hydrogen demand in the region could approach 120,000 tonnes per year, in the most ambitious scenarios.

Growing hydrogen infrastructure
The UK Government is committed to developing the UK's low carbon hydrogen capabilities, as a critical part of energy security and decarbonisation. However, aviation will need greater supplies of hydrogen than the Government have committed to. Liquefaction, storage and purification currently sit as a low priority on the Government agenda and the significant rise in electricity demand creates uncertainties. Gaining Government's support and commitment to resolving these areas will in turn enable investor confidence, ensuring the region's successful transition

Key drivers for the pace of hydrogen infrastructure development include a promised decision on the potential role of 100% hydrogen for heating by 2026 and individual airports' commitments to hydrogen.

To meet the dual demand of hydrogen for heating and hydrogen for aviation, gas distribution networks will need to repurpose and increase pipeline infrastructure, including to larger airports. Airports may also need to expand supply pipelines for fuelling aircraft and ground operation, including heating, and add new facilities to purify hydrogen post-transit.

Overcoming challenges to accelerate hydrogen use in aviation.
As infrastructure and safety standards are addressed, hydrogen is likely to become a more viable option for commercial air travel. Challenges to overcome include:

- Technology development to reduce the weight and size of the powertrain and hydrogen storage system.
- Hydrogen production and transport at the scale and form required by airports.
- Handling hydrogen in airports.
- Infrastructure for the delivery and distribution of liquid hydrogen at airports and onboard aircraft.

Fuelling sustainable growth for South West England and South Wales
South West England and South Wales is an ideal hub for advancing hydrogen in aviation, with its renewable energy resources, existing aerospace industry, robust infrastructure, supportive policies and international connectivity.

Bristol Airport will provide a springboard, with its size, growth, ambitious net zero targets, collaboration within Hydrogen South West and partnership with easyJet, which is pioneering hydrogen in aviation.

© vm

Introduction

Context and approach
Structure

© shapecharge

Introduction

Context and approach

Arup has been commissioned by Wales and West Utilities (WWU) to help them and the funder, OFGEM, to build a strategic and technical evidence base for the potential role of hydrogen in aviation in the South Wales and South West region. The region of c.7.5m people is outlined in Figure 1. It contains four medium-sized airports: Bristol International Airport, Cardiff Airport, Exeter International airport, and Newquay Airport. There are several smaller airports in the area, including Plymouth, Penzance, Land's End and St Mary's. According to the Fly Zero classification of airport size, all airports in the region are considered small-to medium-sized, with passenger numbers of ten million passengers per annum or fewer per annum. Bristol is the largest airport in the region, which served almost nine million passengers in 2019.

The approach and some methodology assumptions may be applicable to other regions across all gas distribution networks (GDN) interactions (and future development opportunities) with the aviation sector and wider aerospace supply chain. The study will help inform early thinking around the development of hydrogen in the South West and the South Wales Industrial Cluster and set the direction for further work in the region and beyond.

Arup engaged with stakeholders identified by the client and Hydrogen South West (HSW) and have subsequently delivered a literature review that collates relevant industry knowledge and developments in the UK aviation industry. The review covers current ambitions, barriers to deployment, and the geographical implications of using existing gas network infrastructure to supply hydrogen to points of demand, notably airports and locations for sustainable aviation fuel (SAF) production.

We have undertaken a demand assessment for aviation across the WWU footprint, focussing on Bristol Airport and other regional airports as case studies to gain a deeper understanding of their opportunities and barriers. This knowledge will help inform considerations of hydrogen in the aviation section in other regions in the UK.

The scope of work includes a discussion on hydrogen requirements in terms of demand, form, purity and other considerations, and how this may evolve in different phases between 2022 and 2050. Potential demands for hydrogen included in the study are ground operations, aircraft fuel, aerospace supply chain and SAF production.

Figure 1
Wales and West Utilities region and civil aviation airports.

Structure

The report structure is described and explained in these sections:

Section 3

An overview of the hydrogen sector in aviation globally.

Section 4

Key national and regional policies that have a bearing on hydrogen in aviation.

Section 5

Covers the aviation energy system, as this is crucial for an understanding of the future fuel pathways for production and transportation. Hydrogen and SAF can be produced via different pathways. These are explained in Section 5, together with the associated requirements for supporting utilities. Principally, green electrical energy and water for “green hydrogen” pathways, nuclear electrical energy for ‘pink hydrogen’ pathways, and natural gas and carbon capture for “blue hydrogen” pathways. The need to provide sufficient power, for example, has an important bearing on where facilities are located. Airports will need to revisit their masterplans to identify suitable locations and feasibility.

Section 6

Focuses on the South Wales and South West region, highlighting recent developments in the hydrogen sector. Hydrogen South West and the South Wales Industrial Cluster are organisations that enable investment and growth in the hydrogen activity in the region. The engagement of hydrogen stakeholders in the region was a key element of the study. In this section, we highlight the organisations which engaged in and contributed to the study.

Section 7

Discusses future aircraft technologies and timescales. It also highlights key developments and trials for the use of hydrogen and SAF to decarbonise the aviation sector.

Section 8

Describes other potential uses of hydrogen at airports, highlighting the economies of scale that could be achieved through committing to one fuel source.

Section 9

Details the methodology employed to estimate the potential hydrogen demand arising from aviation: as a direct fuel for aircraft; for SAF production; and for airport ground operations.

Section 10

Contains the case studies on the main airports in the region: Bristol, Cardiff, Newquay and Exeter. Here we provide possible demand scenarios and provide a commentary on implications for infrastructure. Reference is also made to the regional industrial hubs which may well be the primary hydrogen generation (and liquefaction) locations in the short- and medium-term at least.

Section 11

Covers hydrogen for SAF production in the region.

Section 12 and 13

The report finishes with Challenges and Key findings (Sections 12 and 13).

Overview

Aviation’s targets and strategies
Hydrogen’s role in new fuels
Aviation-driven demand for hydrogen
Liquefaction
Storage and buffering
Locations and connectivity

Overview

Aviation's targets and strategies

Global aviation accounts for c.2% of global human-caused carbon dioxide emissions as a result of using some 300 million tonnes of kerosene per year. Responding to this, the global aviation industry, through the International Civil Aviation Organization (ICAO), set targets in 2022 to achieve net zero carbon emissions by 2050 (ICAO, 2022). The UK set out its aviation targets in the Jet Zero Strategy, which similarly aims for net zero emissions by 2050 (Department for Transport, 2022). It also aims to deliver at least 10% sustainable aviation fuel in the UK fuel mix by 2030, and a target for domestic flights to reach net zero by 2040. In support of these aims, the UK government set up the Jet Zero Council to develop UK capabilities to deliver both net zero and zero emission technologies by:

- Developing and industrialising zero emission aviation and aerospace technologies.
- Accelerating the production of SAFs by investing in first-of-a-kind plants, supporting scientific research on a larger scale, and helping to drive down production costs.
- Working with the aviation industry to develop and deploy new technologies that can reduce emissions, such as electric aircraft and hydrogen-powered aircraft.
- Working with airports to develop the infrastructure needed to support zero emission flight for electric and hydrogen.
- Developing the regulations needed to safely operate zero emission aircraft and infrastructure.

The International Air Transport Association (IATA) passed a resolution in 2021 to achieve net zero carbon emissions from operations by 2050 (IATA, 2021). It published a strategy which outlined the different contributions (by 2050) required to achieve the target, globally:

- 65% sustainable aviation fuel
- 13% new technology, electric and hydrogen
- 3% infrastructure and operational efficiencies
- 19% offsets and carbon capture

Based on this view, over three-quarters of the 'solution' depends on new fuels and related technology.

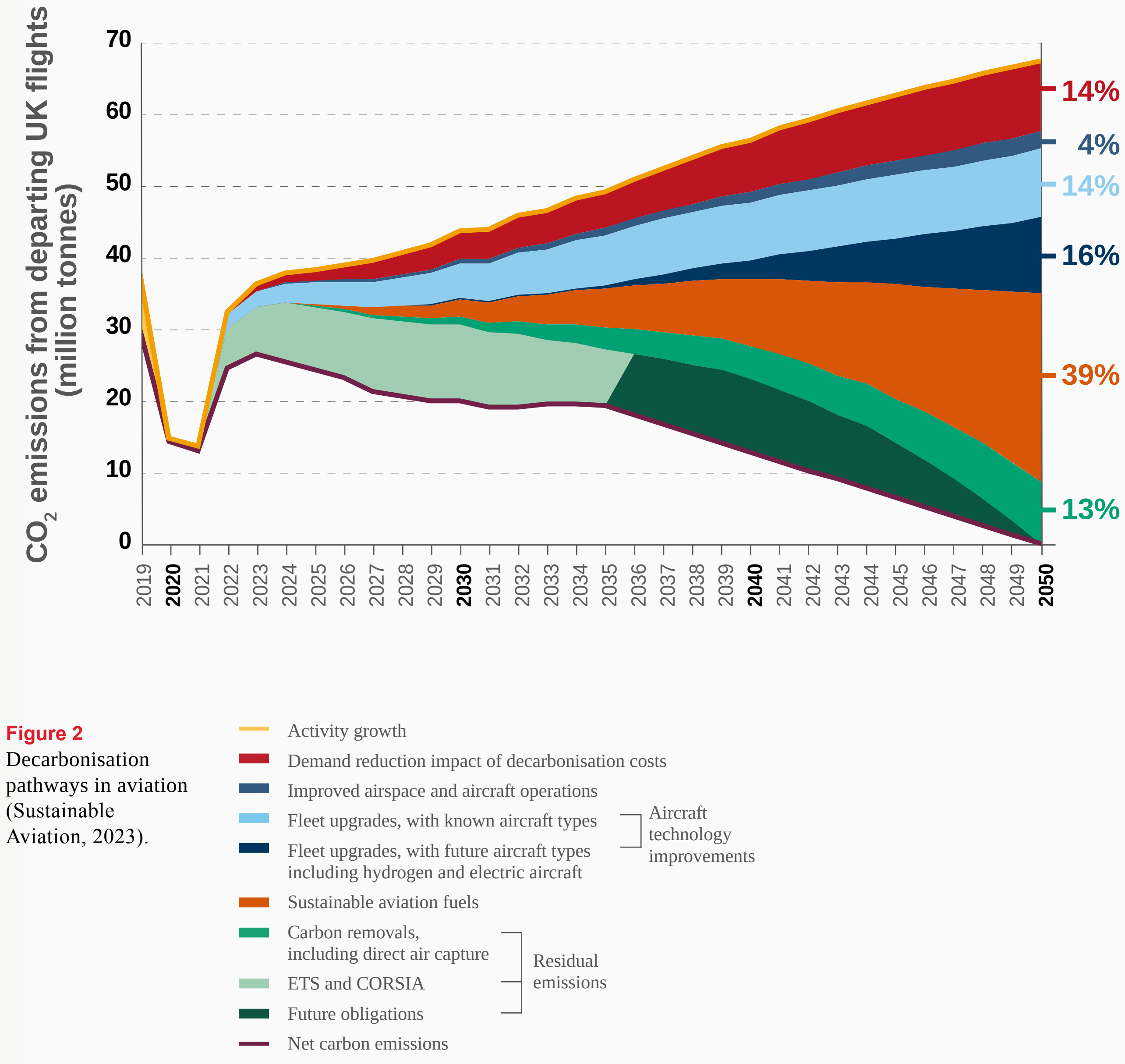


Figure 2
Decarbonisation pathways in aviation (Sustainable Aviation, 2023).

Sustainable Aviation provides a UK-based industry view of the decarbonisation of aviation over time. While different in detail from the IATA strategy, Sustainable Aviation also anticipates a future in which the majority of carbon reduction comes from new fuels.

While IATA represents airlines collectively, it is the commitment and decisions of individual airlines that will determine how and the extent to which net zero goals are achieved. easyJet, in addition to achieving net zero by 2050 has committed to reduce 57% of emissions through zero emission flights, and the remaining 43% through offsetting. easyJet will use SAFs initially to help reduce their footprint but see hydrogen as the main fuel used in later years (easyJet, 2022).

International Airlines Group (IAG) was the first globally to commit to net zero by 2050, and to powering 10% of its flights by SAF by 2030 (British Airways, 2023). By 2050, IAG expects 50% of its decarbonisation to come from SAF. Ryanair expects 34% decarbonisation through SAF. However, neither airline has publicly committed to using hydrogen. Regional airline, Loganair, has committed to make its aircraft fleet net zero by 2040 and are key candidates to make the most of the smaller hydrogen aircraft available that will come online in the near- and medium-term (UK Aviation, 2021).

Hydrogen's role in new fuels

The current consensus is that three fuel/propulsion technologies will play a role in decarbonising aviation:

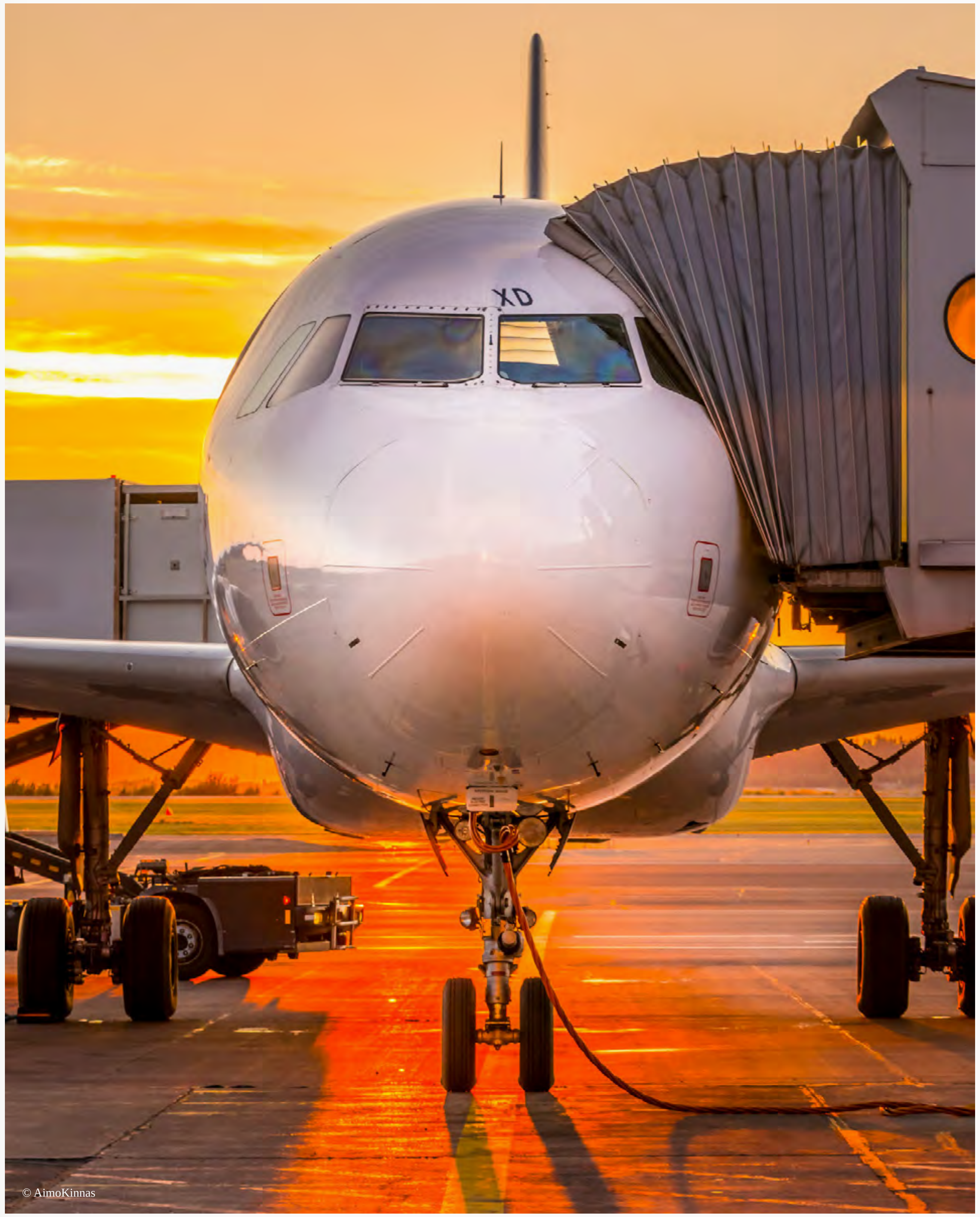
- Battery electric
- SAFs
- Hydrogen (burned in modified jet turbine aircraft, or used in fuel cells to generate electricity for electric aircraft)

Each of these approaches have distinct advantages and drawbacks which affect the applicability to a given type of flight (i.e. capacity and range). They also impact the timeframe over which the fuels, aircraft and propulsion systems are introduced to replace the conventional kerosene-fuelled aircraft.

Whether as a feedstock for SAF production or as a fuel in its own right, we can be reasonably confident that there will be a substantial, aviation-driven demand for hydrogen. The role for electric aircraft will be extremely limited due to limitations in energy density and the weight of the battery.

The total demand for hydrogen comprises three distinct components:

- Gaseous hydrogen used in the production of SAFs
- Gaseous hydrogen, of very high purity, used in fuel-cell powered aircraft
- Liquid hydrogen used in fuel-cell powered aircraft and in larger, turbine-powered aircraft



© AimoKinnas

Aviation-driven demand for hydrogen

The pace, extent and shape of the transition to pure hydrogen-fuelled aviation is subject to a range of uncertainties and dependencies. Above all, the safe use of the fuel must be proven: its production, transport, storage, handling and distribution within an airport environment and, of course, its use on passenger aircraft. Furthermore, airport/airline operational processes must not be made materially more onerous (e.g. turnaround times, exclusion zone limits as a result of using hydrogen. Key enabling technologies and processes for hydrogen (in particular, liquid hydrogen) are at different technology readiness levels (TRLs), which is not to say that they will not be matured, but the lower the TRL, the greater risk that unforeseen issues are encountered (Aerospace Technology Institute, 2022).

To cover the inherent uncertainties in this developing field, we have created three demand scenarios for hydrogen arising from aviation in the region. These are:

- A SAF-only scenario in which hydrogen-fuelled aviation does not achieve any material penetration in the period to 2050.
- An accelerated hydrogen scenario in which hydrogen-fuelled aircraft are introduced in line with current forecasts by manufacturers, and conventional aircraft are replaced over a 10-year◆ time frame.
- A more conservative scenario in which hydrogen-fuelled aircraft are introduced five years later than current forecasts by manufacturers, and conventional aircraft are replaced over a 10-year◆ timeframe.

In an accelerated hydrogen adoption scenario, the direct demand for hydrogen for aviation in the region might be as much as 120,000 tonnes[1] per year by 2050. A less optimistic view of the pace of adoption could lead to an annual demand closer to 65,000 tonnes. These figures include an allowance for tankering – amounting to approximately 30% of the total amount in each case.

Until 2035 to 2040, depending on the adoption scenario, we expect the direct demand for hydrogen to be much lower – driven by early adoption of the first generation of hydrogen fuel cell aircraft of modest size and range, using in the first year's gaseous hydrogen. At these annual demand levels (up to around 2,000 tonnes per year), local hydrogen production is plausible using, initially, locally generated, renewable electricity and then grid-supplied power.

After this first phase, demand for hydrogen for aviation could increase by several orders of magnitude when larger, longer range, liquid hydrogen-fuelled aircraft become available. Sometime after 2035, the first purpose-designed, liquid hydrogen-fuelled aircraft could be introduced to service, though the exact timing is uncertain at present.

At these much greater levels of demand, the bigger airports will have to move from either local hydrogen production or supply via road tankers to a larger scale of operation, requiring the supply of hydrogen by pipeline coupled with localised liquefaction facilities. It is noted that liquefaction of hydrogen (required for second generation aircraft) is an energy-intensive process and access to sufficient electrical energy is necessary.

[1] In this report, we primarily use the mass (kg, tonnes, etc.) of hydrogen to provide comparisons across the different forms in which it will be used in aviation (gaseous at various pressures, and liquefied). The energy content (MJ, GWh, etc.) will also be used where this is relevant.

◆ This 10-year timeframe is purely in the region and is driven by agreements made by easyJet and Bristol airport.

© baona

In the short-to medium-term, airlines will make increasing use of SAFs to meet net zero targets. If hydrogen were to be adopted at scale much later, such that SAF is the main fuel for the foreseeable future, we can see a regional requirement for 190,000 tonnes a year (in 2050) of SAF. There are multiple pathways with very different requirements for hydrogen in the production of SAFs, ranging from 2% by weight of finished SAF to over 50% for PtL SAFs. It appears that governments are considering mandating certain fractions of SAF types to encourage the development of the more environmentally acceptable solutions at scale (e.g. PtL SAFs). We look at some scenarios, but an upper demand of 190,000 tonnes a year of SAF in 2050 might bring an input requirement for between 25,000 and 60,000 tonnes of hydrogen per year.

Unlike the opportunity for local hydrogen production (up to certain limits) and the likely need to liquefy hydrogen at scale near to larger airports as demand rises, SAF production is not linked to an airport. LanzaTech has the only SAF production plant planned in the region with capacity to produce up to 79,000 tonnes a year (LanzaTech, 2023) of SAF by 2028 using the alcohol to jet pathway. It is possible that similar plants can be developed by LanzaTech and others up to 2050 to grow the region's production of SAF to over 400,000 tonnes a year. At this level of production, the facilities will be exporting at least half their production from the region, so demand for hydrogen for SAF production will not be directly linked to SAF usage arising from airports in the region.

Liquefaction

To minimise the amount of space taken up for fuel storage on board an aircraft, hydrogen must be liquefied. This will be necessary for longer-range flights and for flights with higher payloads. The requirement for hydrogen in the liquid state is a distinguishing feature of how hydrogen will be used in aviation in the longer term.

In principle, hydrogen can be liquefied at any point in the supply chain (including close to its production location, even if this involves transport from overseas). However, the handling and transport of liquid hydrogen is non-trivial, due to the low storage temperatures (-253^{0}C) that must be maintained and energy losses from boil-off. Once liquefied, the options for transport and distribution to an airport are more limited than if it were in its gaseous form, essentially relying on specialised tankers (road, rail or shipborne). Long distance pipelines of more than, say, 1km for liquid hydrogen are not considered to be a practical option.

The process of liquefaction itself is energy intensive. Liquefaction can account for around a third of the equivalent energy content of the hydrogen fuel (12 kWh/kg = 43.2MJ/kg for liquefaction, out of total energy of 33.3 kWh/kg for LH2) (Connelly, Penev, Elgowainy & Hunter, 2019). Consequently, liquefaction facilities require access to sufficient electrical power for the intended rate of production.

Storage and buffering

The demand for fuel at an airport varies across a range of different timescales: within a day, reflecting aircraft arrival and departure patterns, and across a year, reflecting the fact that days of the week, particular dates and holidays, and seasons during the year experience different levels of activity. Beyond this, there can be a requirement for strategic fuel storage to isolate an airport from external interruptions to the regular supply of fuel. All these factors apply to hydrogen, as they do to conventional aviation fuels (CAFs) and SAF blends. For such storage to be operationally useful, the means of supplying it (production, upstream storage, and transport) must be able to supply at well above average usage rates so that a depleted stock can be replenished in a reasonable time frame.

In addition, storing hydrogen at the airport will have safety and operational implications such as the maximum allowable storage at the airport and safety zones. While fuel farms are well understood in the context of kerosene, the storage of large quantities of liquid hydrogen is a different proposition. The largest liquid hydrogen storage in a double-walled spherical structure with 24-metre outer diameter has a capacity of 4,732 cubic metres of liquid hydrogen (c.336 tonnes of liquid hydrogen) (E. Fesmire & Swanger, 2021). It is located at NASA Kennedy Space Centre in Florida and was built to support future Artemis exploration missions to the moon and Mars. However, this is a specialist facility which, by its nature, is remote to minimise risks to the general public. It is not clear yet whether storage at anything approaching this scale will be feasible at an airport. If the region required 100,000 tonnes of liquid hydrogen per year, then a three-day strategic store would have to hold around 900 tonnes (allowing for some seasonality effects). This is roughly a minimum of two of the NASA storage facilities in terms of scale.

Locations and connectivity

Ultimately, SAF and hydrogen must be delivered to airports, thereby defining the end point of the supply chain. The destination for hydrogen for SAF production will be determined by the location of SAF production facilities (in this region, the first planned SAF production is LanzaTech's facility: Project Dragon at 79,000 tonnes per year of SAF by 2028). In contrast, hydrogen production can, in principle, occur anywhere: from local electrolysers at airports (or SAF production facilities), or regional/national production facilities, through to imports from overseas.

The connectivity between sources and destinations for hydrogen can be achieved in the following ways:

– Road or rail transport of compressed hydrogen

– Road or rail transport of liquefied hydrogen

– Hydrogen gas pipeline

The cost of transporting hydrogen, relative to the value of the hydrogen itself, and national and regional policies on local vs imported hydrogen, will influence the choice of location of facilities in the supply chain. For example, in one study, it was suggested that producing and liquefying hydrogen in Australia (with the potential for cheap, abundant solar resources to generate green electricity) and transporting it by ship to Europe might be cost-competitive with local production. Liquid hydrogen has already been exported from Australia to Japan, via ship, on a trial basis.

In the near term, there can be a case for very local hydrogen production (even at/near airports) where supply from other sources is unavailable or constrained. Such an approach would eliminate dependencies on a larger, and arguably less-mature, supply chain and so could accelerate early adoption of hydrogen as fuel. Indeed, ZeroAvia in the UK and Universal Hydrogen in the US both see the generation and supply of hydrogen (gaseous and then liquefied) as a core component of their business proposition.

We illustrate the rough order of magnitude of this local production with two example scenarios.

Local renewable energy and local production

The first assumes a typical scale solar PV generation at an airport of 20MW peak. Over a year, this might generate 20MW x 8760 x 20% av/pk = 35,040 MWh of electrical energy. With a PEM electrolyser, the conversion rate is around 60kWh/kg of hydrogen, i.e. 60MWh/tonne. In this case, annual gaseous hydrogen production would be c.580 tonnes. If liquid hydrogen is required, then an extra c.12MWh/tonne of energy is needed, so production would be closer to 490 kg of LH2 per year.

The main challenge associated with connecting an electrolyser directly to local renewable generation, is the low utilisation of the electrolyser due to daily and seasonal intermmittency of renewable energy generation. So for the solar generation case, hydrogen production will be mainly in the summer while hydrogen demand from the plant will be all year round.

Grid renewables and local production

If a grid connection were used, then production would be greater, given the ability to produce on a continuous basis for more hours per year. Assuming 80% operating utilisation with a 20 MW supply, the total energy supplied would be 20MW x 8,760 x 80% = 140,160 MWh, which would produce c.1,950 tonnes of LH2 per year.

However, as both demand and sources of supply grow, hydrogen can be expected to become a commodity item bought on national or international markets. Furthermore, it becomes impractical to scale very local hydrogen production to meet the demands of airlines at a medium or large airport once hydrogen has become a mainstream fuel for major categories of aircraft: an airport needing to produce, say, 100,000 tonnes of liquid hydrogen per year would require an electrical supply in the region of 1 GW.

The attraction of SAF as a fuel is that there is minimal impact on airport and airline operations or infrastructure. The transport of SAFs will follow that of conventional kerosene through the use of tankers or pipelines. In practice, SAFs will be blended at increasing ratios with CAF at designated facilities (outside airports) from where the certified blends will be delivered by tanker (road or rail) or pipeline. Indeed, for regulatory reasons, it is unlikely that unblended SAF will be delivered directly to an airport.

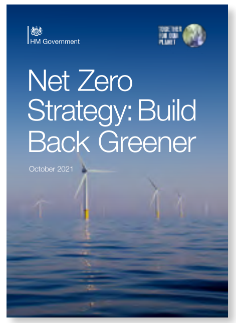
© Wales and West Utilities

UK and Welsh strategies, plans and policies

Net Zero Strategy
UK Hydrogen Strategy
Decarbonising Transport
Jet Zero Strategy
South Wales and South West Regional Strategy
Policies

UK and Welsh strategies, plans and policies

The UK Government has issued strategies and plans for how the UK will achieve net zero. Key for aviation are:



Click to download

Net Zero Strategy (2021)

The Net Zero Strategy builds on the UK Government's ten-point plan to reach net zero by 2050. This document put proposals forward to ensure the UK meets their carbon budget and ambitions to be a world leader in zero emission flight and lead UK SAF. It announced funds such as the Industrial Decarbonisation and Hydrogen Revenue Support scheme (providing £140m to fund new hydrogen and carbon capture business models), £240m for a low carbon hydrogen business model, and £1b for CCUS infrastructure. £180m of funding was pledged for the development of UK SAF plants. The document restated its ambition for green flight and the actions that had been taken to achieve this, such as £150m pa to ATI who are supporting green aircraft technology projects (HM Government, 2021). Key ambitions announced were: 10% SAF by 2030, 5GW low carbon hydrogen by 2030 and net zero aviation by 2050 was reiterated.

Click to download

UK Hydrogen Strategy (2021)

The UK Hydrogen Strategy outlines the role of hydrogen in achieving net-zero by 2050. It set a UK target of 10GW of low carbon hydrogen production capacity by 2030. The UK Government has published its low carbon hydrogen standards and is currently developing the business models that will set the strategic direction for the growth of hydrogen use in the UK. Clusters were identified, including the South Wales Industrial Cluster which is of particular importance in supplying hydrogen and SAF to South Wales and South West England.

Click to download

Decarbonising Transport (2021)

Within this document, the government outlines the path and plans to net zero transport. Commitments include consulting on the SAF mandate, Jet Zero strategy and the target for domestic aviation and airport operations decarbonisation by 2040. The paper also pledges support for R&D on zero emission flight infrastructure, UK airspace modernisation and zero carbon aircraft.

Jet Zero Strategy (2022)

The Jet Zero Strategy sets out the ambition to achieve net zero in aviation by 2050. Six measures were identified as key to achieving net zero by 2050: system efficiencies; SAF; zero emission flight; markets and removals; influencing consumers and addressing non-CO_2 impacts.

For removals, the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) will be introduced in 2024. For SAF, UK aviation fuel mix will consist of at least 10% SAF by 2030 (Department for Transport, 2023) and up to 75% by 2050. For zero emission flight, the first large zero emission flight will enter service by 2035.

There is a consultation currently under way on zero emission airport operations which will inform the policy in place to achieve net zero airport operations and domestic flights by 2040, which is also set out in the Jet Zero Strategy.

Airlines have still not ratified this pathway and there are no penalties proposed for emissions which exceed the Government's trajectory. British Airways and other airlines requested, in April 2023, additional support to prevent higher costs of SAF. From consulting with key stakeholders, the price of SAF is prohibitive – a key reason being the small supply made in the UK. In fact, currently, one site is producing SAF, but not in the quantities required for the UK aviation industry.

Click to download

South Wales and South West Regional Strategy

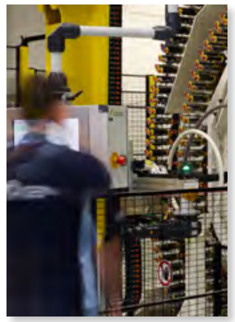
The South West of England has been declared a ‘High Potential Opportunity’ in 2022, putting the region on investors’ radar. The region is gearing up to become a zero emission aviation hub. Councils in the region have issued their climate action, industry and energy strategies to achieve net zero. Of particular note is the Western Gateway Prospectus (2022) and the Western Gateway Hydrogen Ecosystem (2022), which mark out the South Wales and South West region as hydrogen hubs and identify hydrogen as a key part to help the regions achieve net zero by 2050 (West of England, 2022).

The West of East Devon plan (2022) and CORSERV (a Cornwall Council-led business consortium) sustainability strategy (2022) both showcase Exeter and Newquay airports as real-world demonstrators for clean energy (CORSERV, 2023). The Newquay to Exeter route, in particular, offers an opportunity for one of the first hydrogen- or electric-aircraft routes, attracting companies to trial their technology there.

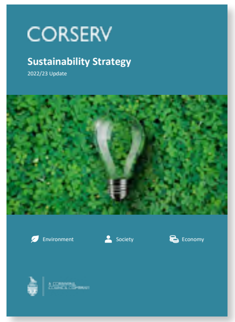
Following council strategies, the airports in the South West region are on a trajectory towards net zero. The Airport Carbon Accreditation Scheme is ‘the only institutionally endorsed, global carbon management certification programme for airports’. As an independent scheme, it certifies airport carbon emission reductions over six stages. Bristol Airport has achieved Stage 3+ – ‘neutrality’ – and both Exeter Airport and Newquay Airport have achieved Stage 1 – ‘mapping’. This focus from airports on decarbonising leads them down electric, hydrogen and SAF routes, as well as on-site generation. Cotswold Airport have ZeroAvia trialling 9–19-seater hydrogen fuel cell aircraft, ready for the market in 2025.

Aviation is treated in the UK as devolved authority; Welsh Government have issued their strategy (Welsh Government, 2021), stating aviation emissions needed to be lower by 2040 and Cardiff Airport needed to have carbon neutral buildings and on-site energy generation and export. They also issued ‘Hydrogen in Wales: A Pathway & Next Steps (2021)’ which focussed on ten initiatives to 2030 that lay the foundations for achieving net zero by 2050. Zero2050 (2021) details how Cardiff Airport is the only serious source of aviation emissions in Wales and discusses the routes to decarbonise through electrification, SAF, carbon pricing and fleet efficiencies.

The regions are reliant on support from Government to secure investment. Currently not enough low carbon hydrogen will be made in time to fuel the hydrogen aviation needs (as a direct fuel source and also for SAF). Additionally Government see liquefaction, storage and purification as a low priority; these elements for aviation are a high priority. The regions transition to zero emission flight must have this support from Government in time to ensure they gain investor confidence to enable their transition.



Click to download



Click to download

Policies

Policies are developing on the back of government strategies as the technology becomes more proven: there is currently no hydrogen (within aviation) policy or mandate due to the immature stage of the technology, but the UK has committed to a SAF mandate of 10% SAF blending from sustainable feedstocks commencing in 2025 and lasting until 2030. The UK Government is currently running a second consultation on the SAF (‘Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate’) to receive views on future mandates of SAF beyond 2030, including a PtL mandate, determining cost support schemes and the interaction with EU and international policy. From stakeholder interviews, there is speculation that these mandates will be similar to the EU SAF mandates.

In its ‘fit for 55’ programme, the EU mandated the blending of SAF into jet fuel with incremental percentage increase as outlined in the table below. The mandate also included the percentage of synthetic fuel in the jet fuel over time. The EU mandate includes provisions to ensure that SAF is produced sustainably from waste or renewable energy sources, and therefore set a cap on Hydrotreated Esters and Fatty Acids (HEFA) SAF.

Given the issues surrounding HEFA SAF, the EU has put a limit on how much SAF comes from HEFA, and, by 2034, this type of feedstock biofuel will not qualify as sustainable.

The recent independent report on ‘Developing a UK SAF Industry’ highlights the UK’s potential leadership in the development of non-HEFA SAF via carbon-containing sustainable waste streams, with much of the potential non-HEFA SAF capacity announced globally as UK-based. Major growth is expected to be in power-to-liquids (PtL) (synthetic fuels) followed by alcohol-to-jet (AtJ). The South Wales Industrial Cluster is one of the production sites for Alcohol to Jet (ATJ) SAF, ideally located for South Wales and South West aviation.

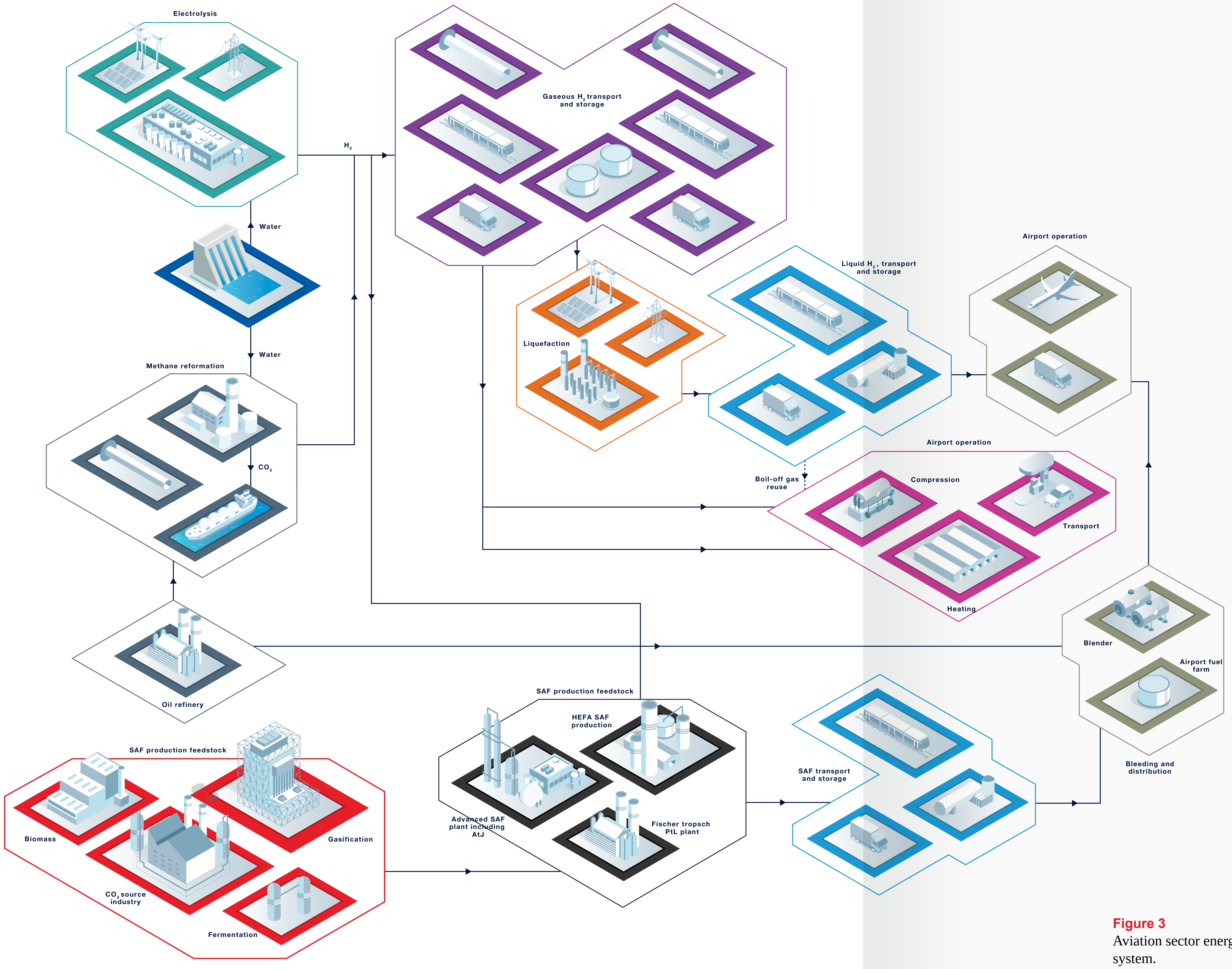
Airlines are key off-take partners, and future demand will likely be driven by SAF targets set by airline, due to customer demand for clean aviation. Certified SAFs are currently subject to a maximum blending ratio of up to 50% with kerosene, but industry and fuel standard committees are evaluating the future use of 100% SAF by 2030.

Table 1
EU mandated SAFs.

Fuel	2025	2030	2035	2040	2045	2050
SAFs	2%	5%	20%	32%	38%	63%
Synthetic aviation fuels	0%	0.7%	5%	8%	11%	28%

Future aviation sector energy system

Hydrogen and SAF production pathways
Hydrogen transport
Electrical grid supply
Connectivity options



Future aviation sector energy system

The hydrogen and SAF production and supply chain for aviation is shown conceptually in Figure 3.

Hydrogen and SAF production pathways

Alternative fuels in airports are expected to dovetail each other as the industry moves to net zero whilst considering energy security and diversity, affordability and available technology. Electric, hydrogen and SAF will be part of the fuel mix of the future aviation system. Multiple pathways exist and hydrogen will be required for many of the SAF fuels.

Figure 4 diagram depicts the production pathways of aviation fuels, with the green lines showing where hydrogen is an input requirement. Hence, the hydrogen demand within this sector will be growing from its need in SAF to eventually hydrogen on its own as an aircraft fuel.

Figure 3
Aviation sector energy system.

Hydrogen production

Hydrogen is a high-energy density gas with a net calorific value of ~120 MJ/kg compared with ~45 MJ/kg for natural gas and kerosene. Hydrogen produces only water when used in fuel cells or water and NOx when combusted in turbine engines, making it an excellent alternative fuel for use in transport applications, including aviation as well as airport operations consuming heat and power.

Hydrogen can be produced through several methods, each of which is assigned a colour definition depending on the carbon intensity of the production route. To qualify as low carbon hydrogen, emissions must be less than 20gCO_2e/MJ for all technologies (E4tech (UK) Ltd, Ludwig-Bölkow-Systemtechnik GmbH, 2021). The main low carbon hydrogen production methods are:

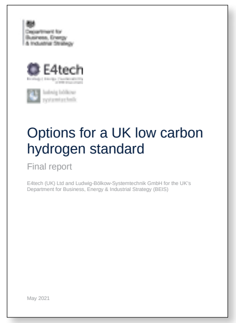
– Natural gas reforming and reverse water gas shift reaction to produce water hydrogen and carbon dioxide as a waste stream. If the carbon dioxide is released into the atmosphere, the hydrogen is classified as grey hydrogen. Carbon emissions from grey hydrogen ranges between 75-100 gCO_2e/MJ H2 LHV.

– Natural gas reforming and reverse water gas shift reaction that produces carbon dioxide as a waste stream. This carbon dioxide is then captured and sequestered for permanent storage. Hydrogen produced in this method is called blue hydrogen. Blue hydrogen has emissions of around 10-45 gCO_2e/MJ H2 LHV.

– Water electrolysis with electricity from renewable sources to produce green hydrogen. Green hydrogen therefore has very low emissions, around 0-5 gCO_2e/MJ H2 LHV attributed to the emissions of water and any chemicals.

– Water electrolysis with electricity from nuclear power plant to produce pink hydrogen. Pink hydrogen also has very low emissions, between 0-5 gCO_2e/MJ H2 LHV.

– Biomass sources gasification produces hydrogen and carbon dioxide. The carbon dioxide can then be captured and stored, resulting in negative carbon emissions.



Click to download

Currently, most hydrogen produced in the UK is grey, with an increasing number of producers now using carbon capture to produce blue hydrogen. Although green hydrogen remains only a small portion of the overall market (around 1% of the hydrogen produced globally), it is expected that, as the UK grid moves towards renewable electricity, low carbon electricity will become cheaper, more reliable and more readily available, leading to a growing share of green hydrogen production.

To fully decarbonise airport operations, hydrogen will be needed to power systems in which electrification is limited. This may include, as well as the use of hydrogen as an aviation fuel, the use as a fuel for ground airside and landside vehicles, ground support equipment and possibly to displace natural gas for heating.

The quality of hydrogen produced is dependent on its production method. Hydrogen produced through electrolysis has a higher quality than that produced through methane reforming or gasification. Produced hydrogen goes through a purification step to meet the quality required at the end use, as pipeline transport introduces impurities that will need removing. This could be as simple as installing a filter to the pipeline.

The quality and form of hydrogen required at the airport depends on its final use. High-purity hydrogen is required for applications using fuel cells, such as ground vehicles and electric fuel cell aircraft. Lower-purity hydrogen can be used in combustion systems in aircraft propulsion or in heating systems for airport buildings. Furthermore, compressed gaseous hydrogen is used on ground vehicles and small hydrogen aircraft, while liquid hydrogen will be used for larger commercial aircraft.

SAF production

SAF can be produced from a multitude of feedstocks and is viewed as a priority near-term solution towards the decarbonisation of the aviation industry. Challenges of SAF include obtaining similar volumetric energy densities to kerosene, as SAF is usually less energy dense, although higher energy density on a weight basis, while also producing SAF on a large commercial scale

There are several synthesis routes available to produce SAF, as shown in Figure 4. All synthesis routes require hydrogen to hydrogenate olefins. The Fischer-Tropsch process require hydrogen as a feedstock. Alcohol to jet only requires hydrogen as a feedstock when produced from CO_2.

In the Alcohol to Jet route, convert methanol or ethanol is converted to jet fuel. Carbon dioxide sourced from carbon capture facilities and hydrogen can react to produce carbon monoxide syngas which is then reacted further with hydrogen to produce methanol. Methanol can then be converted to dimethyl ether to then produce light olefins which synthesises gasoline and jet fuel. Alternatively, methanol can be converted to ethanol (via Wurtz reaction), subsequently used to produce SAF.

Ethanol to SAF is a simpler process with fewer steps; and has the highest carbon yield of SAF. Bioethanol and recycled carbon ethanol from CO (derived from gas fermentation processes) can also be used to produce SAF and would not require any hydrogen feedstock.

Another synthesis route is the Fischer Tropsch process that reacts carbon dioxide with hydrogen to produce linear alkanes of desired length. The alkane can then be reformed or isomerised to produce the correct ratio of fuels that make up SAF (diesel is oxidised chemical, kerosene is isomerised, and naphtha is an aromatic hydrocarbon).

Table 2
Advantages and disadvantages of Fischer Tropsch and Alcohol to Jet methodologies.

Factor	Fischer Tropsch power to liquid	Alcohol to Jet (methanol)
Advantages	Unselective cobalt and iron catalysts	Can produce paraffins, naphthene, iso-paraffins, etc., higher octane rated fuels
Disadvantages	Linear paraffins only Significant refining to produce fuel products High cost and scaling issues Lower overall yield	Expensive zeolite catalyst Unreacted methanol difficult to recover Catalyst lifespan
Hydrogen needed	513.5 kg H2 per ton SAF	172.8 kg H2 per ton SAF

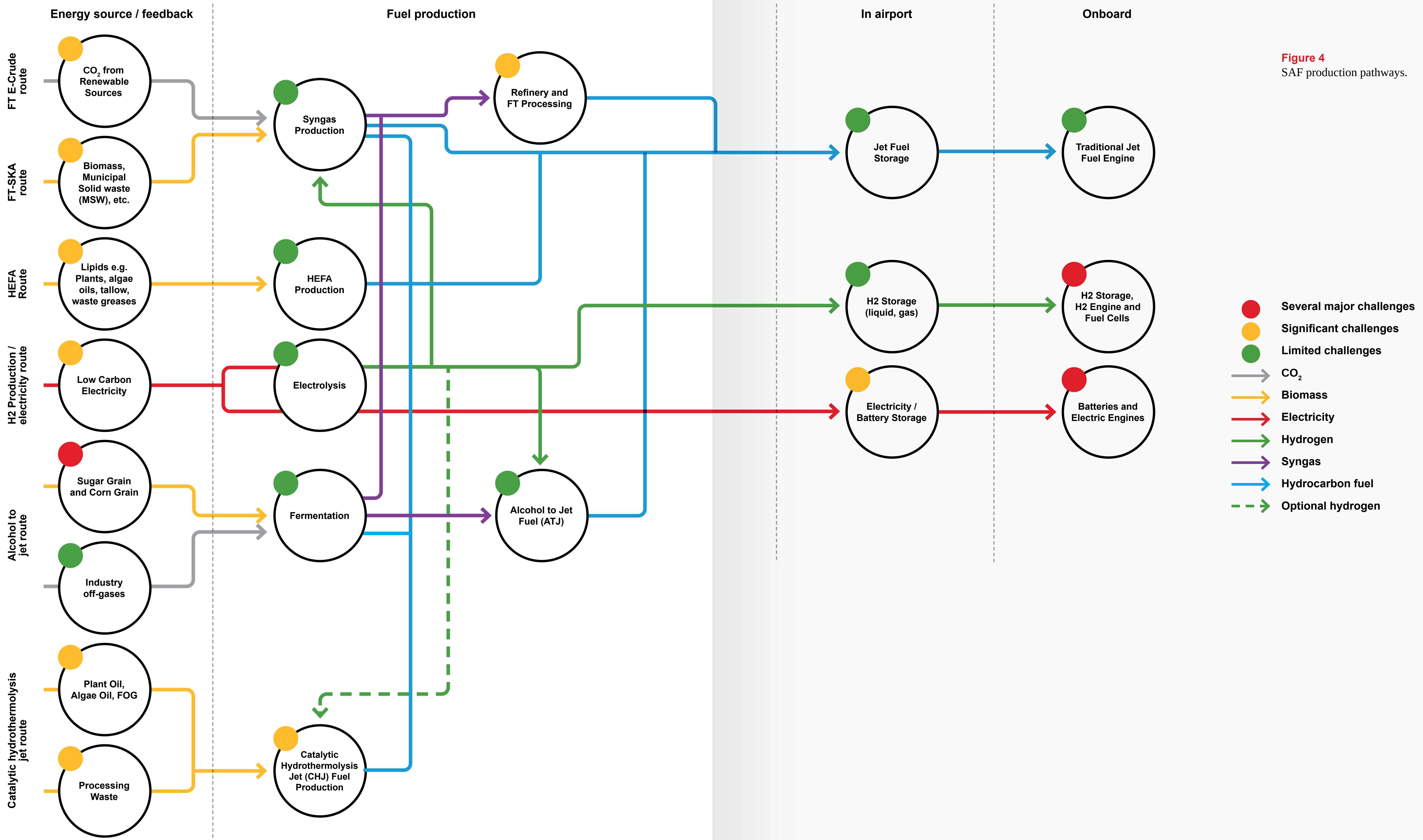


Figure 4
SAF production pathways.

Hydrogen transport

UK gas network

The UK has an established natural gas transmission and distribution network. In the future, this network is envisaged to transport hydrogen, either in a blend with natural gas or as a 100% hydrogen form to where the demand is. Aviation is expected to need a large volume of hydrogen and the gas networks are expected to play a key role in enabling hydrogen flight at scale to reach net zero.

Pipelines offer the most efficient and economic transport mode for large volumes and can be used to transport gaseous hydrogen with relatively low compression effort over long distances. However, if the pipeline infrastructure doesn't exist, extensive and expensive new infrastructure will be required to connect production and demand sites, compression facilities and other above-ground installations, and are likely to only be economically feasible for high-demand sites. The UK gas networks are currently developing the technical and safety evidence required for repurposing large parts of the natural gas network for transporting hydrogen. Issues to be addressed include materials compatibility and hydrogen embrittlement, safety mitigation measures and the development of reliable compressors for high volumes of gas. Repurposing of existing natural gas pipeline infrastructure can reduce or alleviate the capital cost issue; however, the safety and technical questions on the compatibility of the infrastructure need to be answered to enable that. Additionally, hydrogen may require odourising for safety purposes; however, the inclusion of sulphur-containing odorants could be an issue for fuel cells which require pure hydrogen. It is also likely that contaminants picked up from the inside of even brand-new pipelines will need to be removed prior to use in high-purity hydrogen applications.

As we increase the UK's capacity for hydrogen production, producers will look into injecting hydrogen into the gas grid to transport to areas of high demand. Depending on the blend percentage, hydrogen might need to be pre-blended with natural gas before injection into the grid to ensure homogeneity of the gas in the network to maintain the required energy flow and avoid exceeding acceptable limits. For injection into a distribution network at lower pressures (typically < 7 bar), compression might not be needed (BEIS, 2021). On the other hand, gaseous hydrogen can be compressed and transported through pipelines at high pressure (typically > 85 bar). However, to do this, the pipeline system needs to be assessed to ensure it is hydrogen-ready. The assessment includes looking at the compatibility of the pipeline material and other components of the system (valves, fittings, compressors, etc.) to accept hydrogen in blends up to 100%. Therefore, repurposing of a system may require the replacement of components not compatible for hydrogen service.

In compression, the hydrogen gas is purified, pressurised to the storage pressure in vessels with thick walls to prevent impingement, fugitive losses and maintain pressure. For the storage of large volumes of hydrogen, a large number of compression vessels will be required and will have an implication on the space requirements and the safety measures required. Compression is done using positive-displacement compressors. Compression can be done on both small and large scales and is therefore suitable for storage on the airport site and offsite, with hydrogen being transported on tube trailers to the airport. Compression is less energy intensive than liquefaction (between 0.6-3.6 kWh/kg depending on adiabatic efficiency, inlet and outlet pressures) (DOE, 2009).

As well as needing to receive hydrogen supplies, it is important for airports to have on-site storage, acting as a buffer to improve resilience and to ensure they always have fuel ready in case of network outages or in case of daily/seasonal variations in demand.

Hydrogen has a very low volumetric energy density, therefore it is stored under pressure to reduce the cost and footprint of the storage system. Although there are several methods of hydrogen storage which usually rely on chemical adsorption of complex hydrides, these technologies are expensive, not well established and often small scale. The two developed technologies considered in this report (TRL of 7 or more) are liquefied and compressed hydrogen in vessels.


© Leonid Eremeychuk

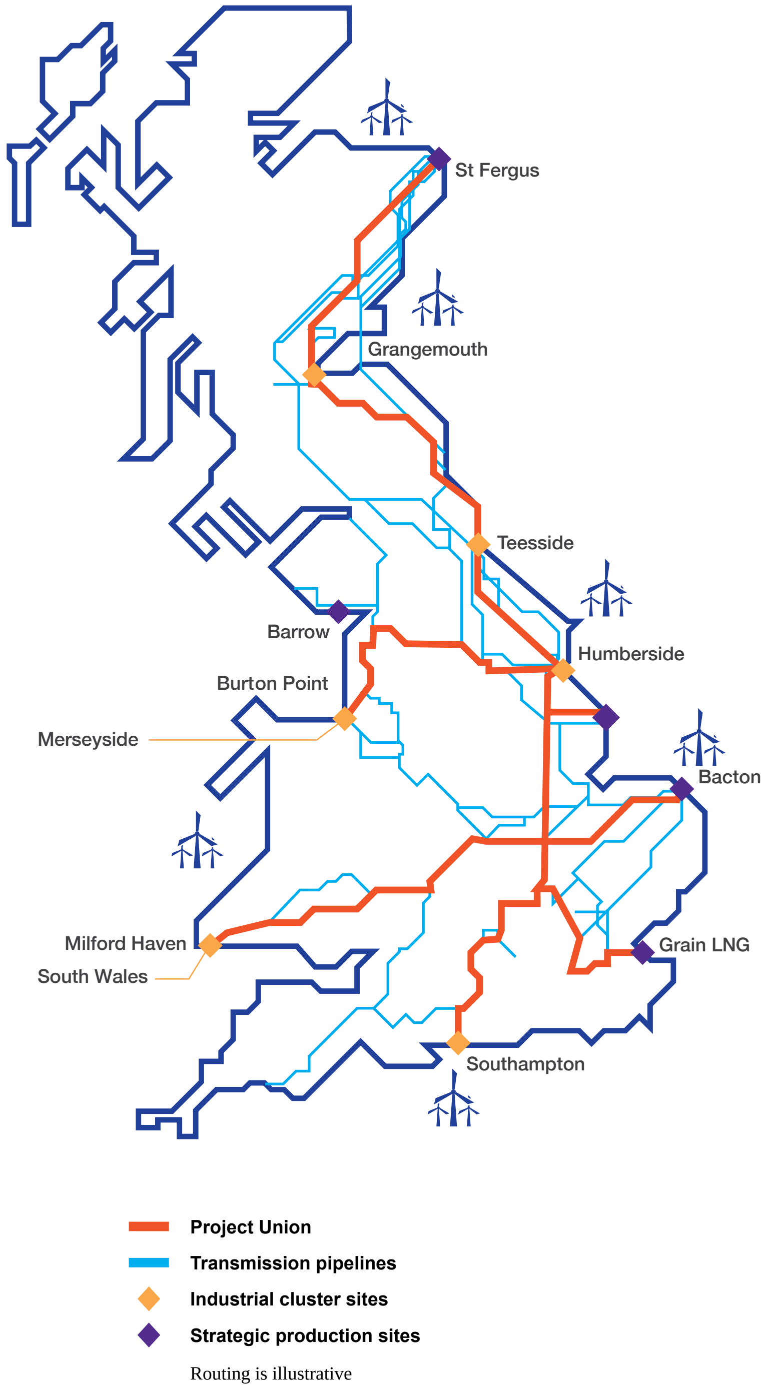
Project Union

One of the key projects in the UK that will transport hydrogen between major industrial clusters using the gas networks is Project Union. It aims to establish a 'backbone' connecting the Grangemouth, Teesside and Humberside clusters, as well as linking up with Southampton and Grain, the North West and South Wales clusters, and will repurpose around 25% of the current gas transmission pipelines (see pipeline map, right). National Gas anticipates that this backbone could carry at least a quarter of the gas demand in the UK today.

The project proposes to convert pipelines in a phased approach by the end of the mid-2030s. By 2045, the pipeline will transport 100% hydrogen across the UK, including a direct line to the South Wales Industrial Cluster. This will potentially minimise the storage requirements for airports, should they be connected to the pipeline, as they would only use what is required at any one time.

Other developments in the continent include the European Hydrogen Backbone (EHB), an initiative that includes the development of hydrogen infrastructure using existing and new pipelines (European Hydrogen Backbone, 2023). This network objective is to deliver a competitive, pan-European, renewable and low-carbon hydrogen market. The network includes three subsea independent connections from the UK (originating from Bacton and Humberside) to the EHB.

Figure 5
Proposed hydrogen pipeline network in the UK (National Gas, 2022).




© National Grid

© Petmal

South West and South Wales hydrogen transportation

Airports in the South West and South Wales are in rural destinations and are not located near to traditional anchor demands for power and industry, with the exception of Cardiff Airport which is near Barry and Cabot, a future hydrogen supplier. With the demands for hydrogen in the long term set to rise, this leads to the gas networks having a larger role to play, as airports will not necessarily have the electrical capacity to generate hydrogen on site at scale. The only airport using hydrogen is Cotswold Airport, which is receiving green hydrogen from Octopus Energy to fuel ZeroAvia flights. ZeroAvia is developing a 100m landside to airside cryogenic hydrogen pipeline, which it will use to fuel its future aircraft and airside vehicles. This will help demonstrate the use case and safety requirements of liquid hydrogen use case at airports.

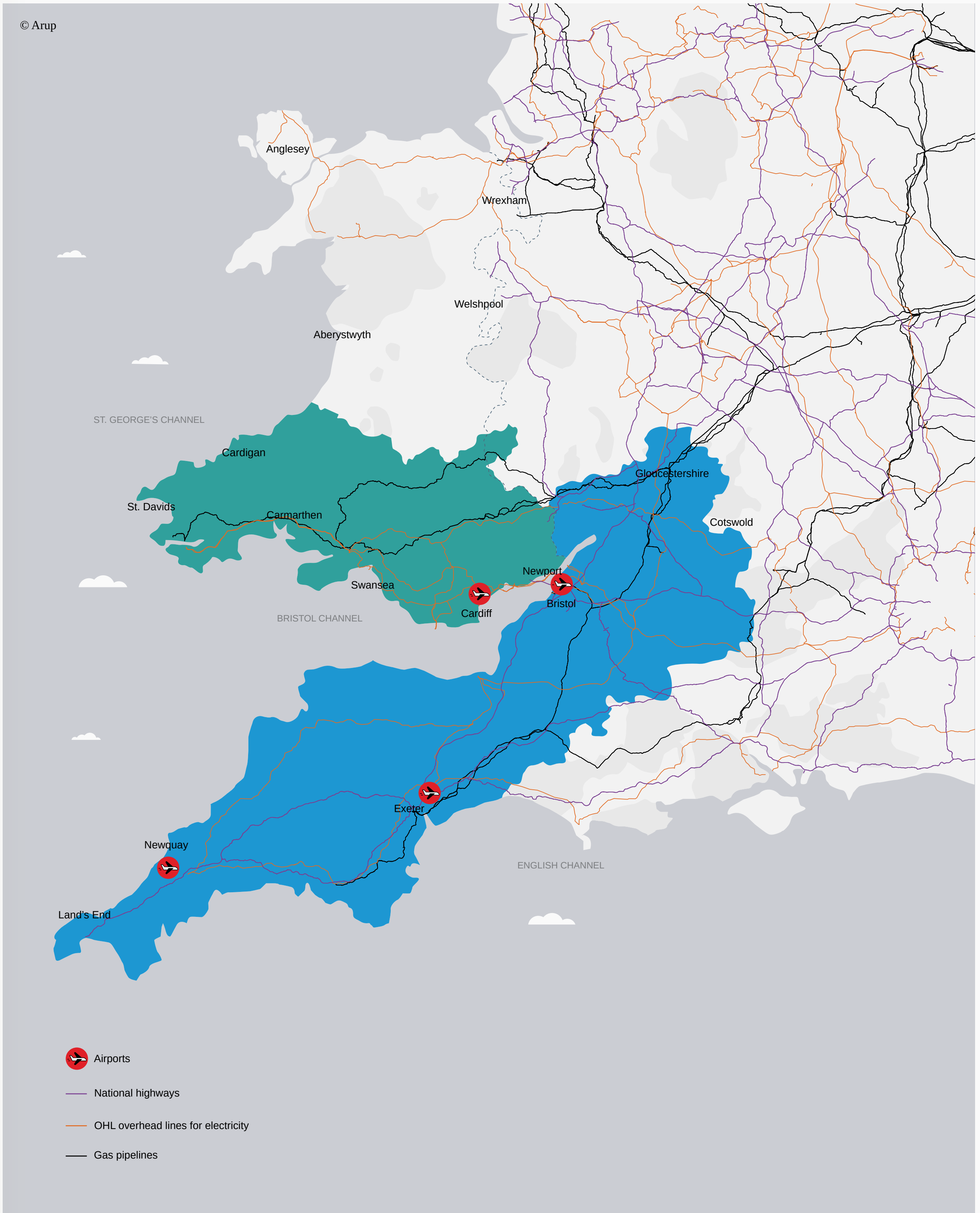
It is expected that, whilst airport demand grows, hydrogen will be tankered in gaseous form. However, there will likely come a point where the airports will need to transition to piped hydrogen, as generation on site will be limited by cost, space, green electricity availability and electrical capacity.

The airports in the region that have a natural gas connection shown below (Table 4).

The current pipeline to the airports will likely be carrying gas for heating airports, not fuelling aircraft. Therefore, when an airport transitions to hydrogen fuelling, it will need to understand when its existing pipelines will be 100% hydrogen, the transport capacity of the pipeline and possible future upgrades and new pipelines. The airport and GDN will need to assess the best solution; tankering or installing a direct 100% hydrogen supply from dedicated hydrogen generation plants or ports for imported hydrogen.

Airport	Existing main serving site	Pressure tier of existing main	Existing pk6 demand (scm/h)	Existing peak 6 demand (kwh)
Bristol	125mm PE	Medium (2bar)	533	5774
Cardiff	6" steel	Intermediate (7bar)	273	2958
Exeter	N/A	N/A	N/A	N/A
Newquay	4" steel	Intermediate (7bar)	689	7464

Table 4
Airport gas pipelines.



Electrical grid supply

On the assumption that airports will require hydrogen at a minimum for fuelling aircraft, it will need to have liquefaction capability on site (unless it is purely using small, short distance aircraft which remain in gaseous form). Liquefying hydrogen requires a huge amount of energy and airports will need to consider how they gear up electricity capacity for this procedure, in addition to other electrical demands (expected to be 5-10 times today's usage). The electrical grid may need to upgrade its supply of electrical power for this, unless the airport can create a local renewable supply to take the pressure off the electrical grid.

Connectivity options

Airports will have greater electricity demands by 2050. Hydrogen can help reduce this demand, but of course may involve new/replaced pipelines.

Large diameter pipelines can transport more energy than electrical power lines. For example, a typical 400 kV line can carry up to 2.8 GW. Overhead power lines are highly visible, and using multiple lines to carry the levels of power that can be carried by a gas pipeline is likely to face societal opposition. Underground cables can be used, but the cost to install these is around five times more expensive, although with a lower opex compared to overhead. A full life cycle assessment would need to be conducted.

The capital costs for different sizes of pipeline and for different electric transmission systems (normalised for power and distance) are shown in Table 5.

The conclusion is that, for very large power requirements needing a new 48-inch pipeline, the capex is similar to a new 380kV AC supply but offers higher level of flexibility for energy storage and transport. Also, there is a negative visual impact using electrical cables vs no impact for underground piping. Both piping and cabling will have consent challenges, so the anticipated timescales for both installations will vary and will need to be started sooner rather than later.

Should the hydrogen demand be low enough to transport via train or truck, and under 200 miles from the production facility, this will be an alternative, but will increase the local road traffic. Moreover, according to current policy, diesel trucks are the only vehicles that can transport hydrogen, so the carbon impact will not necessarily be zero.

Int. Dia/in	Units	100%	75%	25%
48	£1,000/GW/km	136.1	181.1	534.9
36	£1,000/GW/km	393.6	513.9	1,541.7
20	£1,000/GW/km	1,041.7	1,388.9	4,166.7
Voltage				
380 kV AC	£1,000/GW/km	160.0		

Note: % = utilisation

Table 5
Capital costs of new gas and electricity transmission.

Road transport of liquid hydrogen

Road transport of hydrogen is a known technology option. There are two main types of road tanker: pressurised tube trailer or cryogenic liquid tanker. Pressurised tube trailers transport compressed hydrogen gas by road at pressures between 200 and 500 bar. This option primarily moves small quantities over relatively short distances to discrete demand centres. These are relatively large heavy goods vehicles which require access space at the discharge location.

For medium quantities and medium to longer distances between discrete demand centres, where there is no pipeline option, cryogenic liquefied hydrogen tankers (hydrogen cooled to -253°C) are an economical option. Though used in the US, they are not certified in the UK as yet.

Example: a 40ft liquid hydrogen trailer has about 3,000kg capacity. It takes 3hours to fill up and ½ hrs. to unload, and some liquid is lost as it remains in the distribution infrastructure to retain the cryogenic temperatures. If an airport required 50,000T of hydrogen per year, that would be around 46 tanker trips to and from the airport per day, as well as the associated operational impacts both at the production facility and airport during fuelling. To achieve the minimum space requirement for tanker unloading, if you had tankers coming to the airport every hour (two per hour) and utilised all 24 hours, you would need to have space for eight tankers for unloading and turning around.

There are also associated costs with tankering, which have roughly been detailed below. For one-way distances of between 50km and 300km, a cost model indicates a range from around £0.05/kg to £0.25/kg. Of course, these costs are dependent on the supplier agreement.

Given this information, each airport may have their own maximum operational tolerance limit for trucking before requiring piped hydrogen or seeking further electrification. With electrification grid capacity expecting to be constrained, there might be a requirement for gas to cover the shortfall if installation can be completed in better timeframes.

For airports not on motorway roads, such as Newquay, Cardiff and Bristol, this increased traffic of HGVs could be negative for the local community. Given that Exeter Airport does not have a gas supply, has relatively low demand and has close proximity to the main road, trucking to the airport could make sense if it doesn't choose to use on-site generation or local sourcing.

© Petmal

Rail and shipped transport of liquid hydrogen

Cryogenic rail tankers are suitable for medium quantity delivery to discrete centres over long distances on the rail network from one industrial centre to another. These can contain 7-8 tonnes of liquid hydrogen, so three times more than road transport. However, at the time of writing, in the UK, policy/incentives and the supply chain are not developed enough to utilise this method of transporting hydrogen.

The safety case for liquid hydrogen being transported on rail cars in an urban setting (and issues such as the use of tunnels) will have to be resolved. Additionally, airports without a rail link directly to site will be unable to use this method of transport. Cardiff Airport is the only airport in the South Wales and South West region with a rail link, so could be well placed for this method, provided safety issues are resolved.

Notwithstanding the specific challenges of liquid hydrogen, using the rail network as a means of moving significant quantities of fuel is a tried and tested approach and reduces the number of vehicles on the road.

The transport of liquid hydrogen by ship and further concepts are being investigated; however, as no airport in the region is situated at a shipping port, the liquid hydrogen would still need transporting via other means to the airport.

Summary of hydrogen transportation costs

The cost of transporting gaseous hydrogen, at scale, via a pipeline, varies according to assumptions made, but as an order of magnitude is around £0.10 per kg per 1,000 km. Road tanker transport costs for liquid hydrogen are of the order of £1.00 per kg per 1,000km – though in practice, one-way journey lengths will be much less than 1,000 km. For journeys of, say, 100km, the road transport cost will add around £0.09 per kg of liquid hydrogen, which is still a small fraction of the cost of production.

Long distance transport of liquid hydrogen by ship is relatively inexpensive, with Gulf or northern African routes possibly adding around £0.06 per kg – again, a small fraction of the cost of liquid hydrogen production.

Therefore, the cost of transport is not a dominant factor in siting facilities. Far more significant is securing a location which minimises the costs of hydrogen production and, to a lesser extent, its liquefaction. Assuming journeys of <100km, road transport and gas pipelines appear to cost roughly the same, although the disruption to local activities, guarantee of supply and operational impacts look favourable on gas supply.

UK hydrogen and SAF projects

Hydrogen projects in the region

Stakeholder engagement

© Scharfsinn86

UK hydrogen and SAF projects

Improved hydrogen infrastructure will boost producers' ability to export to customers and industrial users across the country. This section of the report covers some of the expected projects.

Hydrogen projects in the region

The South West and South Wales region is home to important and ambitious partnerships working towards achieving net zero, including Hydrogen South West (HSW), Western Gateway (WG) and South Wales Industrial Cluster (SWIC). Hydrogen is highlighted as a key enabler for net zero with potential use in the various sectors, with Western Gateway aiming to make a material contribution to delivering the UK's ambition of half of its 10GW low carbon hydrogen production from electrolytic sources by 2030. HSW aims to drive hydrogen development in the region by raising the profile of the hydrogen activity in the South West, promoting the region to Government, building cross-sector partnerships, supporting projects and their delivery positions and ultimately making the South West a centre for excellence for hydrogen. SWIC aims to achieve a net zero industrial cluster in South Wales by 2040 with a key role of hydrogen and carbon capture technologies.

The region is also the home of global aerospace companies with hydrogen technology development programmes, including Airbus, GKN Aerospace, Rolls-Royce and others. ZeroAvia's development within the HyFlyer II project is based on Cotswold Airport, from which the first test flight of their 19-seater, hydrogen-electric -powered aircraft was demonstrated in early 2023.

The region benefits from large renewable energy generation developments, including the Celtic Sea floating offshore wind development, onshore wind projects in mid-Wales and relatively high generation capacity of solar energy. Moreover, the region houses Hinkley Point nuclear power station and will be receiving green electricity from Morocco via the Xlinks connection into North Devon.

There are over 20 ports and harbours in the region, giving it access to the Irish and Celtic Seas, and English and Bristol Channels. The port of Milford Haven in South Wales is one of the UK's major ports, specifically for the South Hook LNG terminal which is one of the largest liquefied natural gas terminals in Europe and serves around 20% of UK natural gas daily need.

The region's access to energy, both green and fossil, has attracted investment into low carbon hydrogen production development activity including:

- Blue hydrogen production at Milford Haven which could facilitate the decarbonisation of Pembroke Power Station. Carbon capture and storage technologies will be utilised and carbon capture and storage with the prospect of shipping the captured CO_2 to the North West to be stored using the HyNet assets.
- Green hydrogen production facilities ranging in size between 10-100 MW capacity, utilising renewable energy generated in the region. The total generation capacity of green hydrogen production projects in the region is in the region of 400MW. Projects include RWE's 110 MW hydrogen production plant at Pembroke Net Zero Centre, developments at Bristol Port and the recently NZHF -supported projects including Trecwn, HyBont and Langage Green hydrogen projects, and possible developments at Aberthaw Power Station and Appledore.
- Pink hydrogen production from nuclear energy generation at Hinkley Point with planned Hynamics development near Bristol Port with 100 MW hydrogen production capacity.

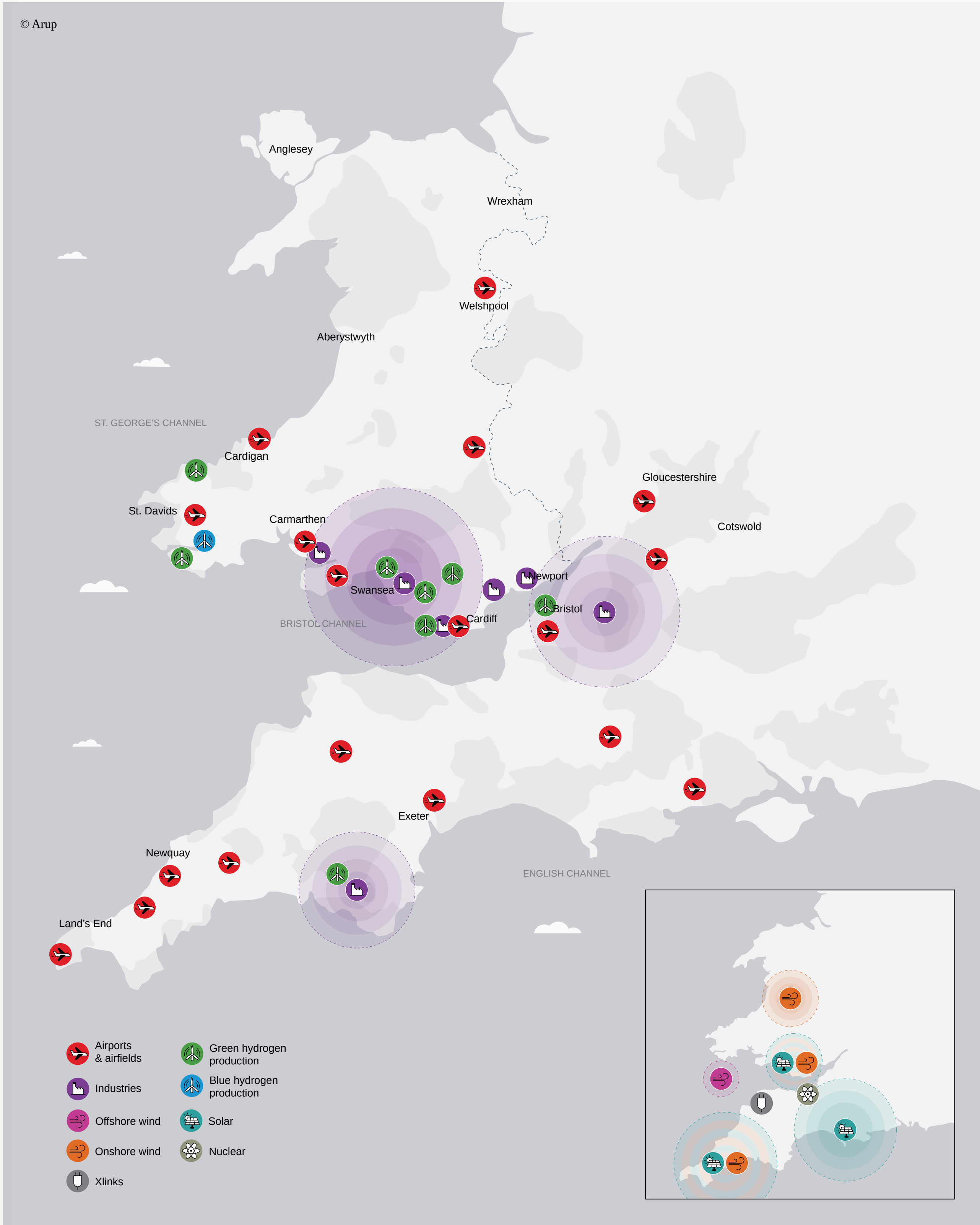
One of the five main UK SAF production projects announced to start production in 2028 is based in Port Talbot. The Dragon project is being developed by LanzaTech to convert industrial off gases to ethanol using the LanzaTech Gas Fermentation technology, then to convert the ethanol to SAF using the LanzaJet Alcohol-to-Jet technology. The plant will have a production capacity of 100 million litres of SAF per year.

The activity in the region is supported by universities and centres of excellence at universities and industrial innovation centres. These include:

- The Institute for Advanced Automotive Propulsion Systems (IAAPS) at University of Bath which will house the first green hydrogen production plant in the South West. The facility will be used by developers to test their hydrogen technologies and products.
- The hydrogen research and decarbonisation centre in University of South Wales at which the viability of hydrogen production from indigenous renewable energy sources will be investigated and the benefits of using hydrogen as an energy storage medium for these intermittent renewables will be evaluated.
- The Renewable Hydrogen Research and Demonstration Centre (Cardiff University),
- GKN Aerospace Global Technology Centre which focuses on moving emerging aerospace technologies into products, developing high-rate aerospace manufacturing, enabling agile innovation and supporting the training of future engineers in the aerospace industry.
- Airbus Zero Emission Development Centre (ZEDC) to develop hydrogen propulsion technologies as part of the ZEROe programme.
- Rolls-Royce, actively engaged in the development of hydrogen technology: AE2100 aero engine demonstrator, fuel cell partnership with Hyundai, new facility for cleaner, quieter jet engines.

Figure 6 illustrates where the hydrogen ecosystem are occurring across WWU's region.

Figure 6
The region's hydrogen ecosystems (big map) and low carbon electricity (small map).



Stakeholder engagement

At the outset of this project, in a workshop with the client, a wide group of stakeholders was identified to engage and interview. This group comprised councils, producers, aviation technology providers, off-takers, airports, airlines, consultants, water companies, R&D, industry bodies and so on. They gave this report industry information and opinions/viewpoints on the regions hydrogen demand. We do not expect that their engagement is an endorsement of this report; however, their inputs were valuable in our response to the scope set by Wales & West Utilities. We also appreciate those stakeholders who input into the project but chose not to provide their logo. This group naturally evolved over time, but we are grateful for the inputs from the stakeholders shown on the right.

© David Schaffer

Partner support from

Future aircraft

Hydrogen aircraft
Conventional aircraft

© steved_np3

Future aircraft

It is envisaged that the future fleet of aircraft in the UK will consist of a mix of battery electric, hydrogen fuel cell electric, hydrogen combustion and SAF aircraft.

Hydrogen propulsion systems using fuel cells (electric), hydrogen turbines (combustion) and hybrid solutions are still under development to meet the requirements of the various aircraft sizes and flight ranges, with the first small aircraft from ZeroAvia publicising to come into operation around 2025 and Cranfield Aerospace around 2026. A significant risk to these dates includes gaining regulator approval, which might be a cause for delay. Following this will be" the larger regional and narrow body aircraft being developed by Airbus, GKN aerospace and others to address the largest proportion and highest emission of the global fleet expected to enter into service after 2035.

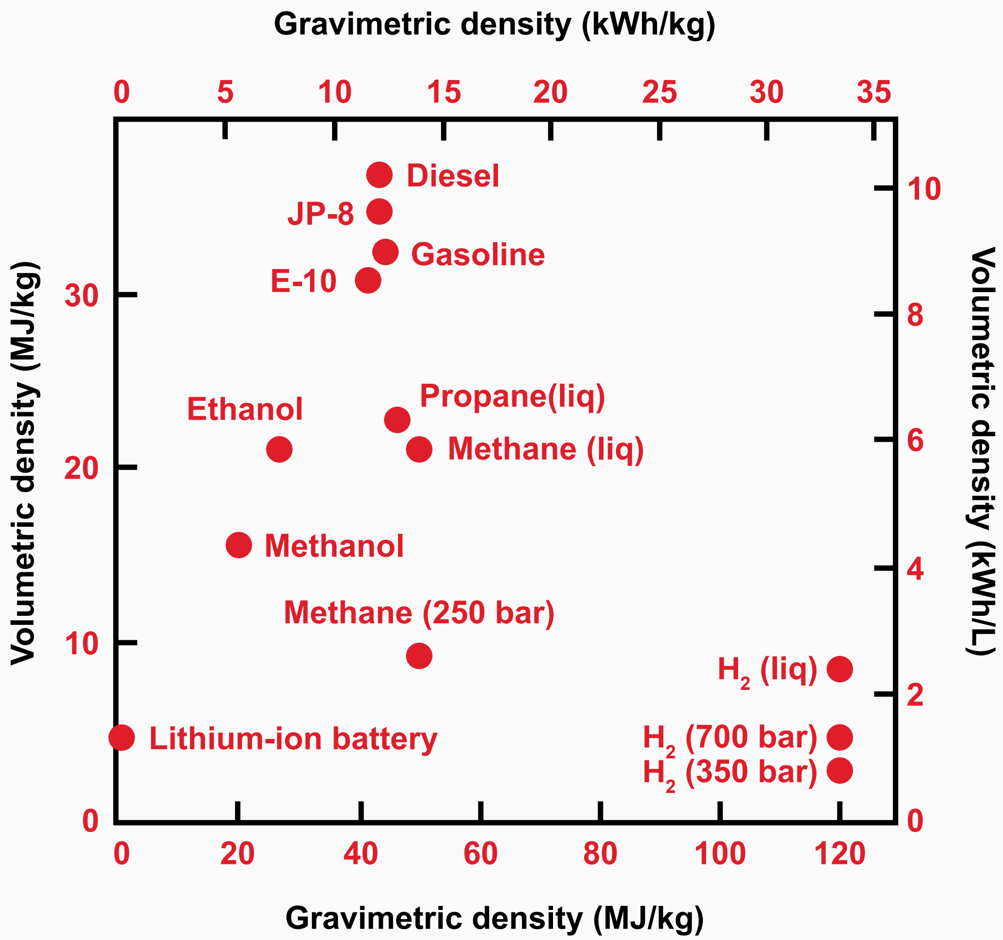
Energy density, supply and the safety of future fuel alternatives are a big challenge and make the sector difficult to decarbonise. The time and cost it takes to develop these fuels is also important to consider, as many fuels and their technologies are still in development. The graph to the right shows the relationship between the energy densities; volumetric (MJ/L) and gravimetric (MJ/kg) and type of fuel. SAFs have, or thereabouts, the same energy density as kerosene, but hydrogen (at 120 MJ/kg) has approximately three times the gravimetric energy density of kerosene (at c. 43 MJ/kg), meaning the weight of hydrogen fuel for a given amount of energy is only a third of that of kerosene – an important advantage in the context of aviation. Therefore, the weight penalty for carrying extra fuel as liquid hydrogen is lower than for kerosene which opens the possibility of 'tankering'[2] of hydrogen.

However, the volumetric energy density of liquid hydrogen is less than a third of that for kerosene, resulting in a significant challenge for storing enough hydrogen on board without impacting the passenger capacity of the aircraft.


© Chalabala

[2] Tankering in this context is the practice of uploading fuel to an aircraft in excess of that which is needed for the immediate next leg of a flight. This can be attractive, despite the weight penalty, if the cost of fuel is materially lower at a given airport.

Figure 7
Energy density of possible aviation fuels (Office of Energy Efficiency and Renewable Energy, 2023), Physicsworld, (2023).



Hydrogen aircraft

The timeline below indicates the future hydrogen aircraft published market entry dates, based on public domain information. Delays to these dates can be expected due to the many uncertainties and complexities of the development.

Smaller airports are likely to be among the first adopters of hydrogen-powered flights. This is because the first hydrogen fuel cell aircraft are likely to be small aircraft used for short haul operations. Moreover, the smaller fleet hydrogen requirements and demand size make them more adequate for the current scale of the hydrogen production.

The anticipated flights in 2025 are generally going to be <150nm, 9-19 passenger aircraft, and are ideal for short hops and serving islands such as the Scilly Isles. In fact, Skybus, Cranfield Aerospace Solutions and Britten-Norman are working together to deploy the hydrogen fuel cell Islander aircraft to Scilly Isles from Land's End as early as 2026. They are also exploring the potential of introducing a hopper service between the South West and South Wales airports by utilising Skybus's existing presence at Exeter and Newquay Airports. The fuel required would be sufficient from a tanker delivery, rather than gas pipeline distribution; and, according to our interviews, one flight of up to 150nm would require about 100–150kg gaseous hydrogen. Flights <300nm are anticipated to use gaseous hydrogen; however, beyond this, liquid hydrogen is required.

Hydrogen consumption will grow as uptake grows; however, it is too early to tell how fast this might happen. The smaller developers such as CAeS and ZeroAvia are helpful to understanding how to operate hydrogen aircraft both from airlines, airports and supplier perspectives. It is through these that we will gain better understanding on the safety, regulation, handling and operation of the aircraft, which will help inform the ZEROe aircraft in 2035.

It is anticipated that, as commercial hydrogen aircraft (c.200 passengers) are not expected until 2035, the consumption by 2050 after fleet renewals is going to be in its infancy. Typically, airlines will look 6-10 years in advance of an aircraft replacement to what the new aircraft will be. They consider operational use (challenging, given Airbus ZEROe will likely still be in design and unproven for a 2035 start, and airports will need to demonstrate the infrastructure is there and safe to operate), safety, passenger capacity, price, distance, whole life cost, amongst other things. Hence, unless Airbus can demonstrate operational use in 2028, the proliferation of aircraft carrying >100 passengers in the South Wales and South West region, rolling out the ZEROe in 2035, is going to be low. However, come 2040, it may be more reasonable to expect more ZEROe or hydrogen aircraft in an airline's fleet. If an aircraft has a c.20yr lifespan, it will take many years to change the fleet to all hydrogen, which will take us well beyond 2050. Hence, providing the projects are successful and hydrogen aircraft are rolled as anticipated, the hydrogen supply by 2050 is expected to need gas infrastructure in place.

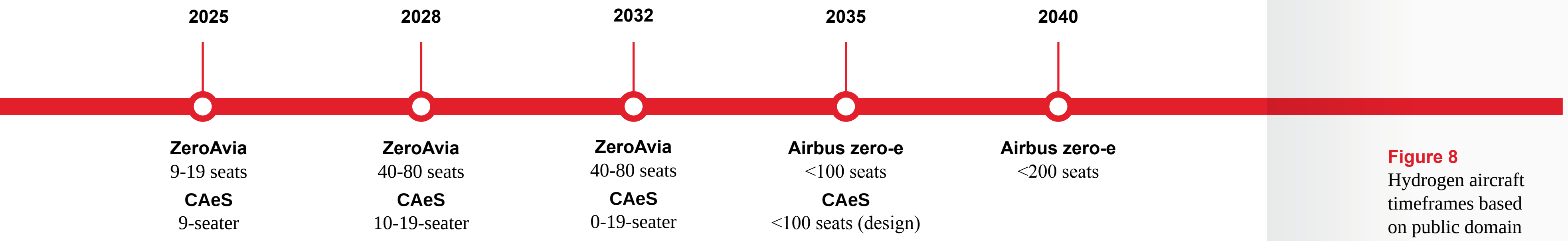


Figure 8
Hydrogen aircraft timeframes based on public domain information.

There is an opportunity, however – if large regional airports enable airlines to operate a hydrogen fleet, the roll-out of hydrogen aircraft for an airline could be airport by airport; those airports which invest early in hydrogen infrastructure will have greater uptake and recovery of their costs (before the market dilutes their share). Tankering of hydrogen in an aircraft is not seen as a weight penalty, due to the light nature of the fuel. Aircraft would refuel only at their home airport and take their fuel to their destination and back again. Given hydrogen infrastructure is expensive and takes time to roll out, it is likely that the only way to continue to service all routes by a hydrogen aircraft is to tanker. However, this sort of roll-out will see uneven decarbonisation across the region, creating potentially political tensions.

The airlines operating in the South Wales and South West region that have so far committed to hydrogen aircraft in their fleets are Loganair and easyJet. Other airlines have invested in hydrogen aviation, such as British Airways investing in ZeroAvia. The biggest flight operator in the region in 2019 was easyJet with 34% of the flights. Ryanair had 12% of the flights but have only committed to SAF aircraft, likewise TUI. Loganair's operating model lends itself well to using smaller aircraft developed by Cranfield Aerospace, ZeroAvia and others, so these aircraft are likely to be the most hydrogen-demanding in operation from 2026.

Hydrogen has been explored as a possible aviation fuel since 2008, with the Boeing single-seater aircraft demonstrating that hydrogen and fuel cell technologies can be used for aircraft propulsion. This was followed by research and development projects that used technologies developed within the automotive sector to demonstrate the feasibility of hydrogen in small aircraft. The largest hydrogen aircraft to be demonstrated in short flight are:

– Universal Hydrogen 40-seater Dash-8 commuter on 6 March 2023.

– ZeroAvia 19-seater Dornier 228 in the HyFlyer II project on 19 January 2023.

Other flight demonstrations are H2Fly (in preparation), hydrogen-powered drones by Boeing in 2013, Tupolev Tu-155 in the 1980s, and the COMAC's hydrogen fuel test aircraft in 2020.

The UK Aerospace Technology Institute (ATI) is currently funding a number of key projects for the development of hydrogen aircraft, and these include the H2GEAR project led by GKN Aerospace, three liquid hydrogen jet engine projects by Rolls-Royce, HyFlyer II led by ZeroAvia and project Fresson led by Cranfield Aerospace Solutions. In addition, Airbus announced its ZEROe programme which focusses on the development of large hydrogen aircraft powered by hydrogen.

Conventional aircraft

SAF can already be blended with jet fuel up to a limit to comply with fuel standard ASTM D1655, and ASTM D7566 for blending synthetic fuels with jet fuel. A 50% limit is currently acceptable for most SAF types. This limit is set to ensure that jet fuels contain the required level of aromatics specified by ASTM D1655. Typical conventional aviation fuel (CAF) contains 8-25% aromatics; however, SAF has no aromatic hydrocarbons. This has an impact on both aircraft fuel systems and fuel infrastructure on the ground, since SAF has different density, lubricity and chemical composition.

New aircraft can be made compatible with 100% SAF through different materials for the seals or calibrated gauging. Older aircraft which are not certified for 100% SAF would either need to be retrofitted and made SAF -compatible or airports would need to ensure availability of both SAF and CAF. This would require separate storage and handling of both fuel types and careful management of aircraft refuelling to prevent uploading the wrong fuel. It could be more convenient for airports to only stock blended fuel compatible with all aircraft.

Fully formulated SAF can be produced to contain both paraffins and aromatics and so all can be used as a drop-in fuel direct replacement to CAF. The disadvantage of fully formulated SAF is that, with an increased aromatic content, an increased level of carbon particulates would be emitted relative to non-formulated SAF, impacting local air quality and propensity for contrail formation, thereby reducing the non-CO_2 benefits of SAF.

Boeing and Airbus are the largest commercial aircraft manufacturers; whilst both are relatively aligned on the transition to net zero for aviation and the timescales and technological advancements associated, only Airbus is pursuing a hydrogen-fuelled aircraft. Both manufacturers have committed to their aircraft being ready to run on 100% SAF by 2030. Otherwise, aviation needs to decarbonise by airlines renewing their fleet at an accelerated pace for the most efficient technology to be utilised. Airspace routes need to be modernised to allow for more efficient routing across the world, giving aircraft shorter routes, or routes with more preferential weather. Finally, aviation fuel needs to be decarbonised, first by SAF, but ultimately the most promising zero emission fuel for this job (according to Airbus) is liquid hydrogen (Airbus, 2020).

The first flight with 100% SAF in both engines on a commercial aircraft was carried out by ATR (Franco-Italian aircraft manufacturer) in June 2022. The test flight is part of the 100% SAF certification process of ATR aircraft that started in September 2021 and should be completed by 2025. The SAF used in this test flight (Neste MY Sustainable Aviation Fuel™) reduces greenhouse gas emissions over its life cycle by up to 80%, compared to fossil jet fuel use.

The first A380 powered by 100% sustainable aviation fuel took to the skies in March 2022. The flight lasted about three hours, operating on Rolls-Royce Trent 900 engine on 100% SAF. The fuel, 27 tonnes of unblended SAF, was provided by Total Energies for this flight. This was the third Airbus aircraft type to fly on 100% SAF over the course of 12 months: the first was an Airbus A350 in March 2021 followed by an A319 neo single-aisle aircraft in October 2021.

© Airbus

Other hydrogen uses at airports

© Scharfsinn86

8 Airports uses | 9 Methodology | 10 Case studies | 11 SAF production | 12 Challenges | 13 Key findings | 14 References

Other hydrogen uses at airports

Hydrogen is well documented for its use across multiple energy vectors, whether for heating, fuelling ground transport, storage and grid balancing, as a feedstock for high-heat processes in industry (not in airports) and more. Ultimately, the more uses of hydrogen for a business, the better.

In the case of airports, the vast majority of hydrogen demand will come from aircraft use; then, potentially, ground operations and heating, and grid balancing. The airport could also become a hydrogen hub if it generates its own hydrogen or has a developed infrastructure to supply it to the local community for refuelling or other purpose.

Liquefaction is likely to be required at airports; however, it is energy intensive and expensive and will require significant additional real estate to house the liquefaction plant and allow for safety distances. It potentially provides an opportunity for the excess heat lost during the process of liquefaction to heat buildings.

Of note is the decision on using hydrogen blending in heating in 2023, with 100% hydrogen for heating being decided in 2026. It is currently not commercially viable to obtain pure hydrogen from a low percentage hydrogen blended gas supply, so should the 100% hydrogen infrastructure for heating not go ahead, the airport will need to consider its other options to obtain hydrogen. Furthermore, the purity requirements of the hydrogen extracted from the gas network will be dependent on the end use. While 98% hydrogen purity is acceptable for heating and combustion, 99.999% is required in applications powered by fuel cells.

Airports will be debating how to decarbonise their buildings in line with the 2040 policy for zero emissions, but how they do this could be via a number of ways: air source, ground source, deep geothermal, or through hydrogen heating, to name a few. Should hydrogen heating be the way forward, this will be a decision by the UK Government as hydrogen blending and 100% is still being reviewed for safety, compatibility and feasibility. The existing gas supplies to the networks will need surveying and refurbishing or replacing to ensure they are sufficient to carry increased or even 100% hydrogen mixes. Should airports be supplied 100% hydrogen heating, this would be of suitable purity to combust in aircraft and heat the buildings. However, it would not be pure enough for fuel cells.

It is important for the GDN to understand the airport hydrogen demand in total so that the pipeline diameter and suitability can be assessed in advance of the demand (for hydrogen for aviation fuel and for hydrogen heating) so that a pinch point does not occur. Once the 2026 100% hydrogen heating decision is made, this will be the clearest direction for GDNs on whether to replace/widen/refurbish existing supplies. It is likely that, if 100% hydrogen heating is the pathway for the UK, existing airport supplies will need to be replaced with wider pipelines so that they can carry hydrogen for aviation fuels and heating.

Ground Support Equipment (GSE) at airports is undergoing transition to zero emissions, with the majority currently going electric in the short term over hydrogen or biofuels. Various trials are initiated to help the development into this area, such as Project Acorn at Bristol Airport led by easyJet, which is trialling zero emission turnarounds. Heathrow Airport has invested in electric vehicles airside, and British Airways has conducted automated and fully electric pushback devices using Mototok's 'Spacer' trials at Heathrow. Compared to electric vehicles, hydrogen offers a longer use time and shorter refuelling times, and no charging space requirements, which at a time-constrained airport would make sense in the operation. In 2015, FedEx, the US Department of Energy, Plug Power and Charlatte America developed the world's first hydrogen fuel cell GSE (Fuel cell trucks, 2023). Some of the first adopters of fuel cell forklift trucks are Amazon, Walmart and Plug Power, demonstrating the use case for airports to follow. That said, Menzies Aviation are investing in electric GSE and have introduced electric hi-loaders at Manchester Airport. Overall, airports will be decarbonising their GSE in the region to comply with the 2040 zero emission airport operations policy, but it is uncertain on the hydrogen demand required, given the mix of solutions available (Airports International, 2022). For hydrogen to become part of the fuel mix for GSE, it needs to be available at the airport with the appropriate infrastructure and to be cost competitive.

FedEx to double EV range with hydrogen fuel cell range extender

© Argonne National Laboratory

Methodology for the aviation demand

Flight schedules
Passenger demand forecast
Future scenario development
Hydrogen and SAF model assumptions

Methodology for the aviation demand

The demand scenarios for hydrogen and SAF in the region and the case study airports were based on information gathered through literature review and stakeholder engagement on hydrogen aircraft developments, entry into service and market penetration. The Fly Zero 'Market Forecasts and Strategy' and 'Hydrogen infrastructure and operations' were used as the base for hydrogen demand scenarios. They were then further refined using recent developments, announcements and stakeholders' input and taking into considerations the specifics of the airports and the South Wales and South West region. The SAF demand at the airports was based on the mandates for the UK and the EU. Subsequently, hydrogen demand for SAF production was calculated using assumptions on the contribution of the various pathways for the production of SAF and its evolvement out to 2050.

The demand for hydrogen and SAF was calculated for the main airports in the region with consideration of the different developments and decarbonisation plans at each airport. A summary of the steps followed to develop the model is shown in the flow chart and text in Figure 9. It is important to note that the demand scenarios presented in this report are not forecasts.

In preparing this report, we have relied on information provided by others, and we do not accept responsibility for the content, including the accuracy and completeness of such information. In no circumstances do we accept liability in relation to information provided by others.

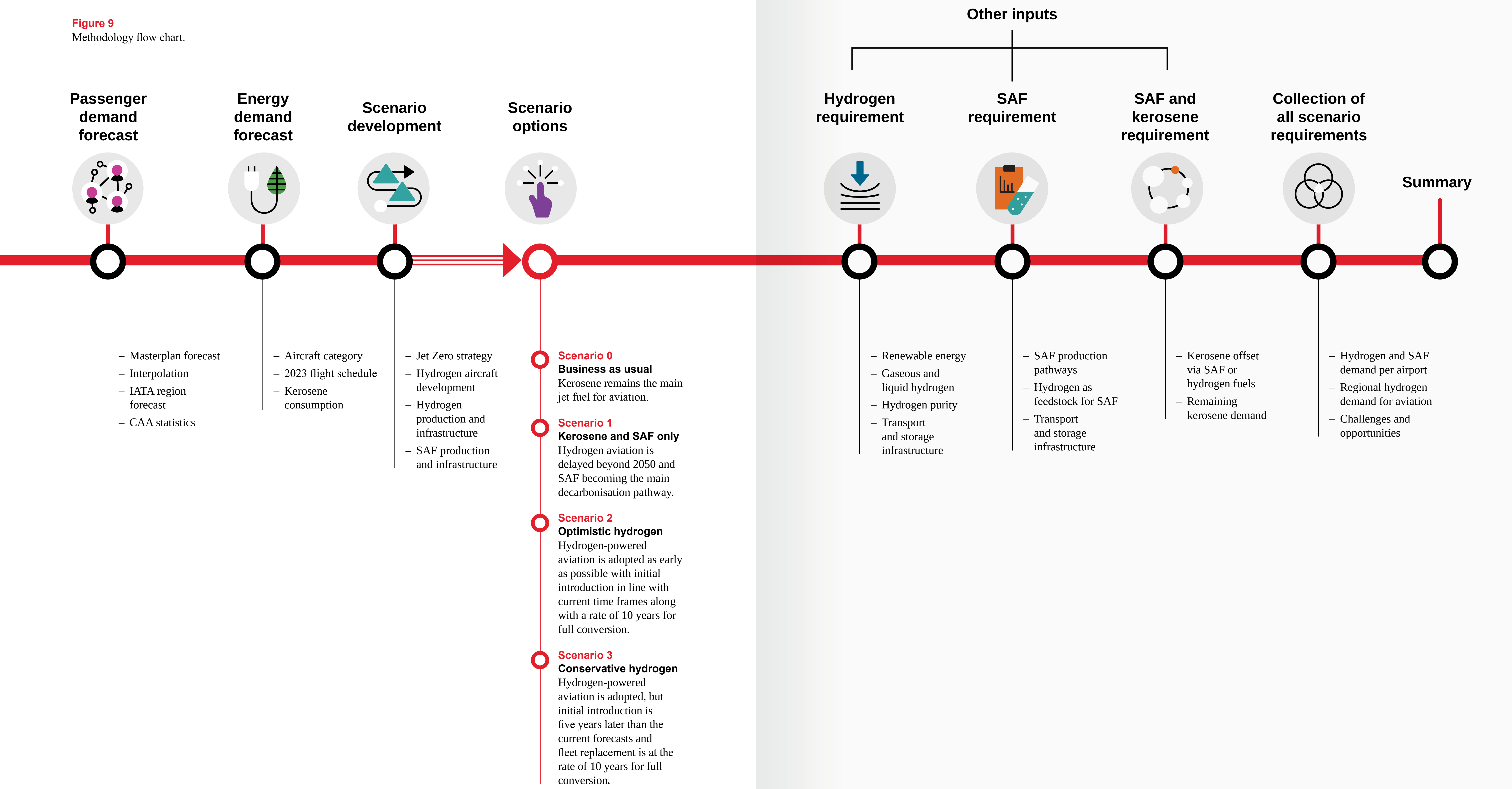
We emphasise that any forward-looking projections, forecasts or estimates are based upon interpretations or assessments of available information at the time of writing. In this report, we have created scenarios with assumptions based on the information gathered from literature and stakeholder engagement. The realisation of the prospective energy demand information is dependent upon the continued validity of the assumptions on which it is based. Actual events frequently do not occur as expected, and the differences may be material. For this reason, we accept no responsibility for the realisation of any projection, forecast, opinion or estimate.

Findings are time-sensitive and relevant only to current conditions at the time of writing. We will not be under any obligation to update the report to address changes in facts or circumstances that occur after the date of our report that might materially affect the contents of the report or any of the conclusions set forth therein.

We do not in any circumstances accept any duty, responsibility or liability to any third party whatsoever (including retail investors whether by bond issue or otherwise) that has relied on this report.

© stellalevi

Figure 9
Methodology flow chart.



Flight schedules

OAG flight schedules were used to build up the fuel demand and carbon emissions using a 2023 baseline. Based on this reference year, emissions and demand have been grown using interannual growth rate ratios. In addition, the flight schedule from each airport was further reviewed to map out airport flight destinations and distances, and also the type and size of aircraft operating from the airport.

Passenger demand forecast

The energy required for aviation was modelled for the period from 2023 to 2050 in Bristol, Cardiff, Exeter and Newquay Airports. To prepare the energy demand for aviation, a number of sources were used, including:

– OAG flight schedule information for 2023. This was used to calculate the fuel consumption per route in 2023.

– Industry load factors (LF) per airline, which allowed to convert the 2023 schedule seats to estimated passengers. The LF were curated from the 2019 airline financial results.

– Latest masterplan forecast information for passenger growth to 2050.

– IATA Europe region annual growth rate.

– CAA aircraft statistics for general aviation.

The aviation demand of energy for 2023 was modelled using the aircraft performance information (fuel consumption and cruise speed) and the flight schedule for 2023. To calculate the demand out to 2050, the assumption that energy requirement will grow with the same trend as passenger traffic has been adopted. This assumption was selected due to the limited level of publicly available information for each airport. Technology and fleet improvements in the past have shown a continuous reduction of energy required per passenger in air transport and we have extrapolated this trend in this study.

The previous assumption for aviation demand growth was not applied to general aviation (GA), as this depends on other external factors, such as the saturation of the runway capacity and the business development of aero clubs and private jets. Indeed, as scheduled aviation grows, the ad hoc usage of airport and runway capacity for GA purposes might be expected to be curtailed.

Masterplans for the airports in the study were published before COVID-19. Aviation demand was, in the case of Bristol and Newquay, extracted from the masterplan as the 2023 traffic has recovered to pre-pandemic levels. Due to the demand changes after the pandemic in Exeter and Cardiff Airports, pre-pandemic masterplans would require a growth in traffic – fivefold in Cardiff and tenfold in Exeter, based on 2023 traffic levels – to reach the 2050 masterplan demand. For these airports, a recovery of the pre-pandemic traffic was utilised as the demand input.

We have provided demand estimates at five-year intervals. Any intermediate values are linear interpolations of these five-yearly milestones. For smaller airports without long-term predictions, as in the case of Newquay, an interannual growth equivalent to the IATA Europe region forecast has been adopted.

The table below presents the passenger traffic growth per airport with specific sources of the passenger traffic. Future capacity or expansion constraints may result in the demand at any of these airports to spill into other airports in the region. Spillage has happened historically in Bristol Airport, which was allowed to expand after overcoming appeals in 2023. Therefore, the results should preferably be considered in a regional basis, as the demand per airport may fluctuate in the future.

In the region in 2019, Bristol Airport served around three-quarters of air passenger and hence the transition to hydrogen aviation by the airport and its airlines will be the dominant factor in the region's overall move to hydrogen-fuelled aviation. We recognise that hydrogen uptake will vary between airports and could potentially be more challenging for smaller airports to transition, due to the high cost of infrastructure development; however, potential development of a hydrogen aviation hub at Bristol could enable and accelerate the transition in other neighbouring airports.

We note that airports, airlines and their owners will have internal growth plans which they may not choose to make public. The passenger numbers we present here may not necessarily align with such internal assumptions. However, we have matched Bristol Airport's draft masterplan figure of 19 million passengers in 2045, which, as the largest airport in the region, means the overall passenger figures for the region will be broadly aligned.

Future demand for aviation will be subject to a number of risks, as we have seen in recent years with, for example, the pandemic and increases in energy costs. Public attitudes to flying may also alter in response to the effects of climate change. Unlike some other countries which have a large domestic market, the UK's aviation industry is particularly sensitive to policy changes in other countries as national lockdowns have demonstrated. These are mostly downside risks, which can either lead to a short term dip in passenger numbers, or a lasting delay to expected growth.

Table 6
Passenger demand assumptions.

MPPA	2019	2025	2030	2035	2040	2045	2050
Bristol	9.0	12.0	13.4	15.0	16.9	19.0	21.4
Cardiff	1.7	0.9	1.1	1.2	1.3	1.5	1.7
Exeter	1.0	0.5	0.6	0.7	0.8	0.9	1.0
Newquay	0.5	0.5	0.6	0.7	0.7	0.8	0.9
Total	**12.2**	**13.9**	**15.7**	**17.6**	**19.7**	**22.2**	**25.0**

IATA Europe region forecast – reference for the passenger growth (2.14%)
Draft masterplan information
Masterplan extrapolation (this may not align with the BRS internal view)
Actual information
Modelling of pre-pandemic demand recovery only

Future scenario development

Three scenarios were developed to estimate the aviation hydrogen demand in the region. These were developed against a benchmark business as usual scenario (Scenario 0) in which kerosene remains the main fuel for aviation. The three scenarios are:

Scenario 1
SAF-only scenario in which hydrogen-fuelled aviation does not achieve any material penetration in the period to 2050.

Scenario 2
An accelerated hydrogen scenario in which hydrogen-fuelled aircraft are introduced in line with current forecasts by manufacturers, and conventional aircraft are replaced over a 10-year◆ time frame.

Scenario 3
A middle scenario in which hydrogen-fuelled aircraft are introduced five years later than current forecasts by manufacturers, and conventional aircraft are replaced over a 10-year◆ time frame.

◆ The 10-year replacement time frame is based on an accelerated time frame that easyJet hope to adopt, should Bristol Airport enable hydrogen aircraft. Aircraft operating at this airport would be replaced at a quicker rate than the rest of their fleet (typically 20-30 years). This assumption has been retained for all four airports in this analysis which we note might be optimistic; but, given that the hydrogen volumes for these airports are significantly lower than expected at Bristol, the impact on the overall picture of hydrogen demand in the region is expected to be minimal.

Hydrogen and SAF model assumptions

The following assumptions were used to calculate the hydrogen and SAF demand for the airports.

Hydrogen model assumptions

– Aircraft market introduction scenarios used to model the aviation energy, as presented in Table 1. These were adapted using the Fly Zero reports, recent announcements and information from stakeholder engagement.

– Hydrogen aircraft fuel efficiency is equal to that of a kerosene aircraft.

– No change to flight cruise speed with the change of aircraft.

– Hydrogen aircraft development per category and entry into service is as shown in the table.

– The aircraft types for future hydrogen replacement were defined by seats. There were no network routes at the airports of the study exceeding the range that could be provided by future hydrogen aircraft.

– General aviation kerosene fuel burn per trip based on a GA aircraft consumption (100 kg/h) and a 60-minute cruise.

– Flight networks and seats per route are not modified in this model. A 10% downgrade on the seats per flight has been applied when converting to hydrogen aircraft, due to the spatial requirements to accommodate tanks. This ratio has been estimated using industry information from aircraft producers, such as Airbus – the company plans for the narrow body design with an A321 aircraft size and an A320 passenger capacity. On average, we estimate the seat reduction across all aircraft types for hydrogen to be approximately 10%.

– The cruise speed and great circle distance (GCD) distance is used as an input in the model to obtain the time for a route. The cruise speed and great circle distance (GCD) is used as an input in the model to obtain the travel time for a route. The cruise duration and speed were assumed equivalent for the cruise and climb. An additional 20 minutes (0.33h) was added to include an element of landing and take-off (LTO) in the energy estimation.

– The total consumption per flight was calculated in kg of kerosene and converted to hydrogen, assuming a conversion with an energy density of kerosene as 43MJ/kg and of hydrogen as 120 MJ/kg.

– No cargo-only flights are accounted for in the model. According to CAA statistics in 2022, there is less than 100 annual tonnes transported in CWL and 1 annual tonne in BRS. OAG schedules did not contain any demand for freighters.

Market	Flight distance	Passengers	Example Aircraft	Entry into service year
General aviation*	NA**	2-19 ***	Range from Cessna 150 training/hobby aircraft to Cessna Citation and other business jets	2026***
Commuter	300 nm	5-20	ZeroAvia Dornier	2026
Regional	1,000 nm	21-120	Airbus ZEROe ATR-72 Turboprop, fuel cell and/or hydrogen combustion	2035-2040
Narrow body	2,400 nm	121-220	Airbus ZEROe, turbofan, hydrogen combustion	2040-2045
Kerosene/SAF only aircraft	Above 2,400 nm	221 and above	A321/737 10 MAX / and widebody aircraft	Existing fleets

Table 7
Aircraft market introduction.

* For Bristol Airport, the monitoring report data for GA has been used.
** General aviation that covers hobby flying but also long distance, non-scheduled business flying.
*** GA aircraft should have less than 19 seats to be considered non-commercial aviation (EASA, 2018).
**** Considered similar to the commuter aircraft date, due to seating capacity on GA aircraft.

Tankering

Until hydrogen infrastructure is developed at most airports, hydrogen fuel tankering will be required to make hydrogen aviation feasible through reducing the impact of increased refuelling time on the average turnaround time, enabling back-to-base flights, therefore not limiting possible destinations and maximising aircraft schedule utilisation. Hydrogen is advantageous over other aviation fuels as it has a small fuel penalty and no carbon penalty, due to tankering. Should any protectionist measures be taken that prevent tankering, this will significantly change the hydrogen business model, making it much less viable. The following assumptions were used for tankering:

– Depending on future hydrogen aircraft replacement, turnarounds have been considered possible for tankering. Tankering was applied to routes shorter than the following range per aircraft category:

Category	Maximum route length for tankering (NM)
General aviation	NA (assumption applied to flight plan)
Commuter	150 NM
Regional	500 NM
Narrow body	1,000 NM
Kerosene-only aircraft	Not applied (Kerosene only)

Table 8
Range limitation for tankering.

– The limit on the maximum route length for tankering does not consider additional fuel requirements such as alternate fuel or contingency fuel.

– Tankering has been studied on the airline operating the flight: easyJet could adopt tankering to allow early operation to non-hydrogen-equipped outstations.

– For all easyJet departures, if the route was below the maximum route length for tankering, they have been considered for tankering.

– For other turns, only 50% of the departures have been selected for tankering as the airlines may have their based outside Bristol, where they commit to tankering.

– The resulting energy for flight required for tankering was identified as requirement of 40% additional supply of hydrogen for the airports in the region.

– No specific fuel penalty has been applied to tankering departures in the model.

Energy efficiency

– Energy efficiencies have been applied to the overall energy requirements for aviation, independently, if kerosene or hydrogen propulsion. This has been set as a 1% annual reduction in energy requirement due to improvements in aircraft efficiency and optimised flight operation (Xinyi Sola Zheng, 2020).

– The reduction has been applied at the end of the model, to obtain the results with the expected efficiencies and without them.

Fleet assumptions

Airbus plans to release, in 2035, a hydrogen aircraft with approximately 100 seats. Industry models consider an entrance of the aircraft in market for 2037 or 2040. The picture beyond the release of this aircraft will be defined after this milestone, according to the aircraft producer.

There is no official timeline for when the first hydrogen-powered commercial aircraft with over 150 seats will fly. While several aerospace companies and startups are actively developing hydrogen technology for aviation, scaling up the technology for larger aircraft presents significant engineering and logistical challenges.

Fleet replacement cycles are now in the range of 20-30 years, which will make for only gradual growth of hydrogen aircraft in the airline fleets. However, even if this typical replacement cycle applies to the industry as a whole, it has been suggested by easyJet that, at specific hubs where hydrogen is introduced, airlines may prioritise the introduction of new, hydrogen-fuelled aircraft, rebasing conventional aircraft to other hub locations. Thus, at a particular hub, the introduction of hydrogen aircraft might be more rapid, and we have used a ten year replacement cycle to reflect this possibility.

SAF model assumptions

In the UK, 26 million litres of SAF were supplied in 2022 (Department for transport, 2023). This is equivalent to 0.138% of the aviation fuel demand in 2019 (Office for National Statistics, 2023). Due to the very small provision of SAF in 2022, SAF has been assumed as marginal supply in 2023 and has been modelled as available from 2024. The demand scenarios for SAF are based on the current government mandates for the blend of SAF into Jet fuel. The UK government has set a target of including 10% SAF in all jet fuel by 2030.

The demand model prepared considered the following assumptions:

– Kerosene fleet becomes 10% SAF aircraft from 2030.

– Kerosene and SAF have the same energy density.

– SAF aircraft efficiency is equal to kerosene aircraft.

– No change to flight cruise speed with the change of aircraft.

– SAF production and blending occurs centrally and distributed to airports blended. Therefore, airports' uptake of SAF is uniform across all UK airports.

– SAF is produced via various pathways with different technology maturity. The pathways contribution to the SAF demand is assumed based on the recent UK Government consultation on SAF, including the cap on HEFA SAF and the mandate for PtL SAF.

– UK mandate to include 10% SAF by 2030 and mandate in discussion for 75% SAF by 2050. PtL is assumed to follow the sub category targets set by the EU which aligns with the very high scenario in the UK mandate consultation.

– Hydrogen is used as a feedstock for the production of SAF via the alcohol to jet and power to liquid pathways.

– LanzaTech is the main SAF developer in the region, so hydrogen demand for SAF is dominated by their activity.

– The uptake of SAF was assumed essentially zero in 2023. This is due to the marginal penetration in the market now according to RTFO data for 2022 (Department for Transport, 2023).

Case studies

Bristol Airport
Cardiff Airport
Exeter Airport
Newquay Airport

In the following pages, we will discuss Bristol Airport in more detail, providing an overview of the airport's operation, flight destinations and operators and its projected growth up to 2050.

We will then discuss the potential hydrogen demand for each airport and the required infrastructure to support its operation. A lighter summary of the hydrogen requirements has been provided for Cardiff, Exeter and Newquay Airports.

© Scharfsinn86

Bristol Airport

Context

Bristol Airport is a medium-sized airport located to the south of the city of Bristol in a rural setting in the Mendip Hills, an Area of Outstanding Natural Beauty, in North Somerset. The airport has good road access via the A38 with bus services connecting the airport to Bristol and Weston-super-Mare. The road connectivity in the region expands its catchment area, reaching Gloucester, Exeter and Cardiff (overlapping with the catchment areas of Cardiff and Exeter Airports). There is, however, no direct rail service to the airport.

In 2022, Bristol Airport's passenger numbers recovered to 89% of the pre-COVID passenger peak, reaching almost eight million, and is expected to achieve record passenger numbers in 2023. It recently won approval to increase its passenger capacity cap from 10 to 12 million passengers per year. The airport's draft masterplan, published in 2017, forecasts the number of passengers at the airport to grow to 19 million per year by 2045.

12m
Passengers per year

2030
Net zero operation target

3.6m
Population coverage within a 1.5 hr driving distance

The airport supports flights to around 130 destinations in 35 countries, dominated by flights to Europe with distances below 3,000 nm. In 2019 (the peak year for passengers), the airport handled almost nine million passengers. Around 414,000 tonnes of CO_2 was emitted from over 31,000 departing aircraft in that year. The airport has a target to achieve net zero for its own operations by 2030 and is a signatory to sustainable aviation and also the net zero 2050 target which includes Scope 3 emissions.

Over three-quarters of Bristol's ATMs are accounted for by just three airlines: easyJet is the largest airline at Bristol with over 50% of the ATMs, followed by Ryanair with 18%, and Jet2 with 10%. easyJet has published ambitious aims for rolling out hydrogen-powered aircraft in their fleet to achieve net zero by 2050.

Bristol Airport and easyJet are working together on Project Acorn to trial hydrogen-powered ground support equipment to develop the experience of storing and handling hydrogen at the airport and alongside other fuels. Through the project, they expect to learn about airside safety considerations and to develop an understanding of hydrogen refuelling processes.

Bristol Airport has an aspiration to become an airport hydrogen hub in collaboration with the Hydrogen South West partners.

Figure 10
Bristol Airport catchment zone and routes.

Passenger growth
A key input assumption for this study is the expected number of passengers at milestones during the time frame of interest (to 2050). Note that this is not a forecast but a scenario upon which the possible demands for hydrogen can be based.

Historical and projected annual passenger numbers are shown in Figure 11. The forward projection has been aligned with the public draft masterplan of 19 million passengers per year in 2045.

Energy estimates as a guide to hydrogen demand limits
We estimate that airlines at Bristol used around 155,000 tonnes of kerosene in 2019 for flights departing the airport. Were this rate of usage per passenger to continue, the demand for kerosene would approach 370,000 tonnes in 2050. Of course, improvements in aircraft efficiency would mean that this an upper limit. A 1% a year compound efficiency improvement in aircraft/propulsion systems would reduce this upper limit to around 290,000 tonnes per year by 2050. If this were totally replaced by hydrogen on a like-for-like energy basis, the annual requirement for hydrogen in 2050 would be around 105,000 tonnes. (Note that this excludes the impact of airlines 'tankering' hydrogen – that is, uploading extra hydrogen at Bristol so that a return flight is possible without the need to upload fuel at an outstation.) Nevertheless, it provides an order of magnitude estimate as a reference point for the ultimate possible demand for hydrogen.

Direct demand for hydrogen
Table 9 indicates the possible demands for gaseous and liquid hydrogen at Bristol Airport, from hydrogen-fuelled aircraft, based on the method of analysis set out in Section 9. Note that this includes tankering, which, in 2050, accounts for around 28.6% of the total hydrogen demand in our figures.

Scenario 1 (SAF-only demand) obviously does not generate any demand for hydrogen for aircraft directly fuelled by hydrogen. (See later for the hydrogen demand in for the production of SAFs.)

The demand for hydrogen directly used by aircraft falls into two very clear phases: up to 2035 and possibly 2040 when demand is for around 100 tonnes a year and driven by first generation gaseous hydrogen-fuelled aircraft, and a second phase when demands could rise by two to three orders of magnitude to as much as 50,000-100,000 tonnes a year (by 2050) after the introduction of liquid hydrogen-fuelled aircraft.

For the first phase, the relatively modest demands for gaseous hydrogen could be met by local electrolysis, or delivery by pressurised tube trailers carrying c.1.3 tonnes of hydrogen each. Fewer than one pressurised hydrogen tanker delivery a day would be necessary. At this scale, there is little need for a hydrogen pipeline.

For the initial part in the second phase when demand rises to, say, 2,000 tonnes a year of liquid hydrogen, local electrolysis and liquefaction is potentially plausible with a grid connection supplying around 20MW of electrical power. Alternatively, at this level, around two liquid hydrogen tanker deliveries (each with c.3.5 tonnes) a day would be necessary. But within five years of this, demand could rise 30-fold and, at this level and beyond, local hydrogen production is implausible. At 50,000 tonnes per year, this would require over 40 liquid hydrogen tanker deliveries per day, which is also

Bristol Airport

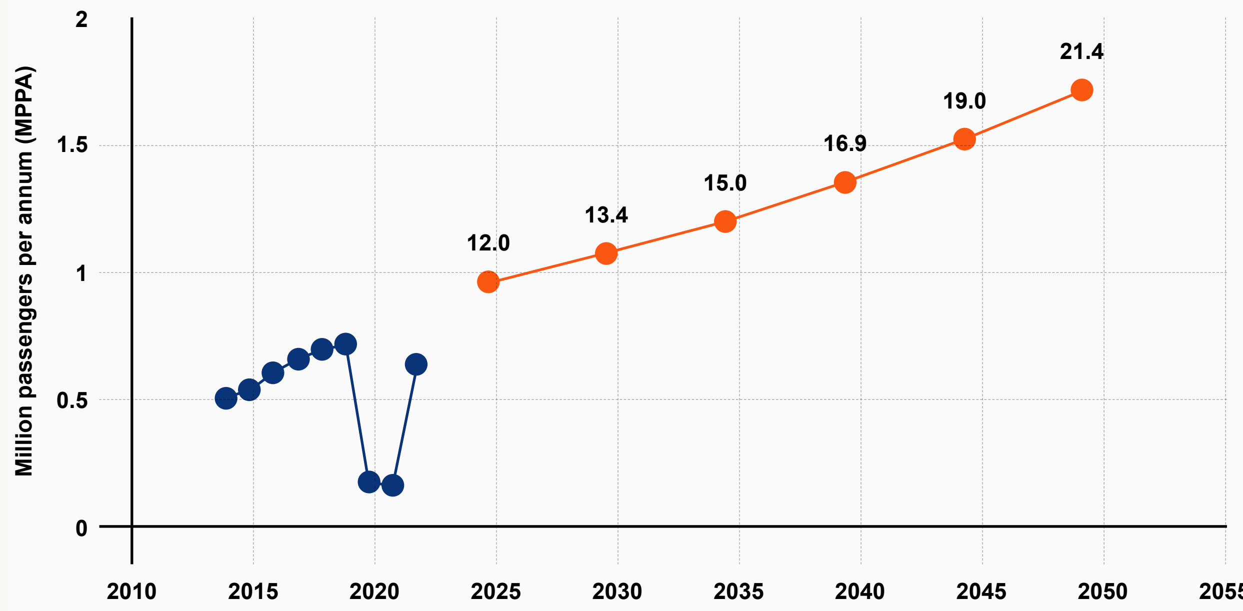


Figure 11
Bristol Airport passenger growth scenario.

Historic projection
Forward demand

Tonnes/year	BRS	2025	2030	2035	2040	2045	2050
Scenario 2	Gaseous hydrogen	-	100	100	100	100	100
	Liquid hydrogen	-	-	-	1,500	50,300	100,400
	Total		**100**	**100**	**1,600**	**50,400**	**100,500**
Scenario 3	Gaseous hydrogen	-	-	50	100	100	100
	Liquid hydrogen	-	-	-	-	1,600	52,000
	Total	**-**	**-**	**50**	**100**	**1,700**	**52,100**

Table 9
Hydrogen demand arising from hydrogen-fuelled aircraft at Bristol Airport.

implausible. Instead, a pipeline supply of hydrogen to (or near) the airport, with local liquefaction, would be required. At 50,000 tonnes a year, electrical power approaching 100MW would be required for liquefaction, rising towards 200MW for 100,000 tonnes per year.

Hydrogen supply
Bristol Airport is about 15 miles away from Bristol port, which anticipates being a production site for green hydrogen, as well as an importer of ammonia for use at the port and distribution to the region. The port will require infrastructure to do this, and demand profiles show that a meaningful hydrogen demand (and hence requirements for piped infrastructure into Bristol Airport) will occur, at the earliest, around 2040.

Currently there is a 5″pipeline supplying the airport with natural gas operating at 2 bar. By 2045, if the pipeline is converted to 100% hydrogen, the supply will meet demand and a larger supply will be required. A 15″pipeline operating at 7 bar would be required by 2050.

The airport will need to have a purchasing strategy which is likely to be dynamic up to 2050, as the supply volumes or prices will vary considerably. Whether BRS can purchase hydrogen locally from electrolysis providers or whether it leans on SWIC for blue hydrogen, or even relies on other regions of the UK or abroad, these will be variable. Importing all 80,000 tonnes of liquefied hydrogen (worst case) via shipping to Bristol port could cost c.£95m in operational costs per year, plus then cost to transport it to the airport.

Liquid hydrogen via tankers
This calculation assumes 3.5 tonnes per tanker and 365 days of delivery. Considering the number of tankers per scenario, from 2045 (S3) 2050 (S2) it would be recommended to start using a pipeline. The limit for the operation of tankers has been considered to be one tanker an hour.

LH2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	-	-	1	39	79
Scenario 3	-	-	0	1	41

Gaseous hydrogen via tube trailers
Gaseous hydrogen includes liquid hydrogen demand as it is transported as gaseous hydrogen generally. Assumes 1.3 tonnes per tanker with hydrogen pressure of 500 bar and 365 days of delivery. Gaseous hydrogen will be unfeasible from 2045. The limit for the operation of tankers has been considered to be one tanker an hour.

Gaseous H2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	-	-	4	107	212
Scenario 3	-	-	0	4	109

Local hydrogen production through electrolysis
Local hydrogen production (electrolysis) would be feasible until 2040 (S2). The limit for electrolytic hydrogen production on site is considered as 10 MW.

Local H2 production (MW)	2030	2035	2040	2045	2050
Scenario 2	0.8	0.76	12.7	399.8	797.8
Scenario 3	-	0.4	0.7	13.2	412.1

Hydrogen liquefaction
The following table includes the energy for compression. The liquefaction should be feasible until 2050, assuming an update of the grid.

Local liquefaction (MW)	2030	2035	2040	2045	2050
Scenario 2	-	-	2.9	96	191
Scenario 3	-	-	-	3	98.8

Hydrogen pipeline size
To illustrate the change in the required hydrogen pipeline to meet the growth in demand at the airport, the pipeline size is calculated at 20 m/s average hydrogen speed for 2 bar and 7 bar pressures. Recognising that small diameter pipelines (0.01 inch) are not commercially available or viable, and understanding the need for Gas Networks to invest in the most cost effective infrastructure solutions for the future, it is plausible that a larger diameter PE pipeline designed to meet the 2050 demand is installed and operated at low pressure at the early years and increase in operating pressure with time to meet the increase in demand. Such investment will also provide assurance on fuel security to airports and flight operators allowing them to further invest in their fleet conversion.

Pipeline diameter (inch)	2030	2035	2040	2045	2050
Scenario 2 (7 bar)	0.01	0.01	0.20	6.5	12.5
Scenario 2 (2 bar)	0.04	0.04	0.7	22	44
Scenario 3 (7 bar)	-	0.01	0.01	0.20	6.5
Scenario 3 (2 bar)	-	0.02	0.04	0.7	22

With it being unlikely that Bristol Airport will generate their own hydrogen supplies, and to avoid infrastructure being the pinch point of airport hydrogen conversion (and any related industries that would benefit from early hydrogen supplies, such as ground transport), hydrogen pipelines should be installed in advance of 2040.

Hydrogen requirements for ground operations and airport heating

In addition to the hydrogen demand for aviation fuel, hydrogen can be used at the airport to refuel ground vehicles and for terminal building heating. The demand for hydrogen based on the three scenarios is shown as follows:

Scenario 1

Hydrogen is not used at the airport for ground vehicles or terminal building heating.

Scenario 2

Hydrogen becomes the main fuel for ground vehicles and for heating.

Scenario 3

Hydrogen is also used to support the decarbonisation of ground vehicles and heating with an assumed contribution of 50% of the total energy consumption.

The future demand for hydrogen for GSE will depend on the hydrogen fleet economics and performance, and the availability of hydrogen at airports, especially airside. The demand for hydrogen for building heating will depend on the Government policy decision on hydrogen for heating in 2026 and solutions to NOx emissions from hydrogen boilers.

The demand for hydrogen for ground vehicles took as reference the consumption of diesel at the airport, estimated at 386,622 litres in 2019. The diesel demand was converted to kWh using an energy density of 10.7 kWh/litre to give 4,136,855 kWh of energy. Similarly, gas consumption for heating was estimated to be 4,117,33 kWh in 2019. To consider the growth of energy for ground operations and heating, the same passenger demand as previously input for the energy model is used. This assumption originated from the limited information about ground service equipment operating at the apron of Bristol Airport and the known terminal surface to be developed up to 2050 in Bristol Airport, which has only revealed indicative expansion plans for the terminal in diagrams.

The following are the results for the use of hydrogen in ground operations and airport heating:

Hydrogen demand for vehicles (tonnes/year)	2019	2025	2030	2035	2040	2045	2050
Scenario 1	0	0	0	0	0	0	0
Scenario 2	120	140	160	180	200	220	250
Scenario 3	60	70	80	90	100	110	125

Hydrogen demand for heating (tonnes/year)	2019	2025	2030	2035	2040	2045	2050
Scenario 1	0	0	0	0	0	0	0
Scenario 2	120	150	190	190	250	250	250
Scenario 3	60	75	95	95	125	125	125

© Wales and West Utilities

Cardiff Airport

Context

Cardiff Airport is located by the Bristol Channel, South West of the city of Cardiff. It serves flights to around 52 destinations in 22 countries, dominated by regional flights to Europe with flight distances below 3000 nm. In 2019, aviation activity from 8,271 departing flights generated 60,500 tonnes of CO_2. About 89% of Cardiff Airport's emissions are generated from regional flights and 13% from domestic flights. The airport aims to be carbon neutral by 2040, according to its Environmental Flight Path Framework.

The airport has good road access via the trunk roads exiting the M4 motorway. Its catchment area within a 1.5 hour driving distance reaches across the South Wales region, crossing over to the Bristol area to the east, and therefore overlapping with the catchment area of Bristol Airport. There is no direct rail service to the airport but it benefits from nearby Rhoose Cardiff International Airport railway station which is 10 minutes away by shuttle bus.

At peak (2007), Cardiff Airport served 2.1 million passengers. It recovered to 52% of the pre-COVID (2019) passenger numbers in 2022 and is expected to remain at similar levels to 2022 according to 2023 OAG schedule information, indicating a slow recovery. The Cardiff Airport masterplan, published in 2018, considered a growth rate of 5.8% per year from 2017 to 2026, followed by 2% growth per year from 2026 to 2040. The masterplan forecast the growth at the airport to reach 3.2 million passengers by 2040; however, the current figures indicate a slower growth rate and potential slower recovery to pre-COVID levels. Consequently, we have conservatively assumed recovery to pre-COVID levels by 2050 in our demand model.

TUI was the largest operator in Cardiff, operating 45% of the seats offered, followed by Air France-KLM (18%) and Ryanair (17%). Cardiff Airport is a hub for BA aircraft maintenance, servicing aircraft operation from/to Heathrow and Gatwick airports.

800k
Passengers per year

2040
Net zero operation target

2.77m
Population coverage within a 1.5 hour driving distance

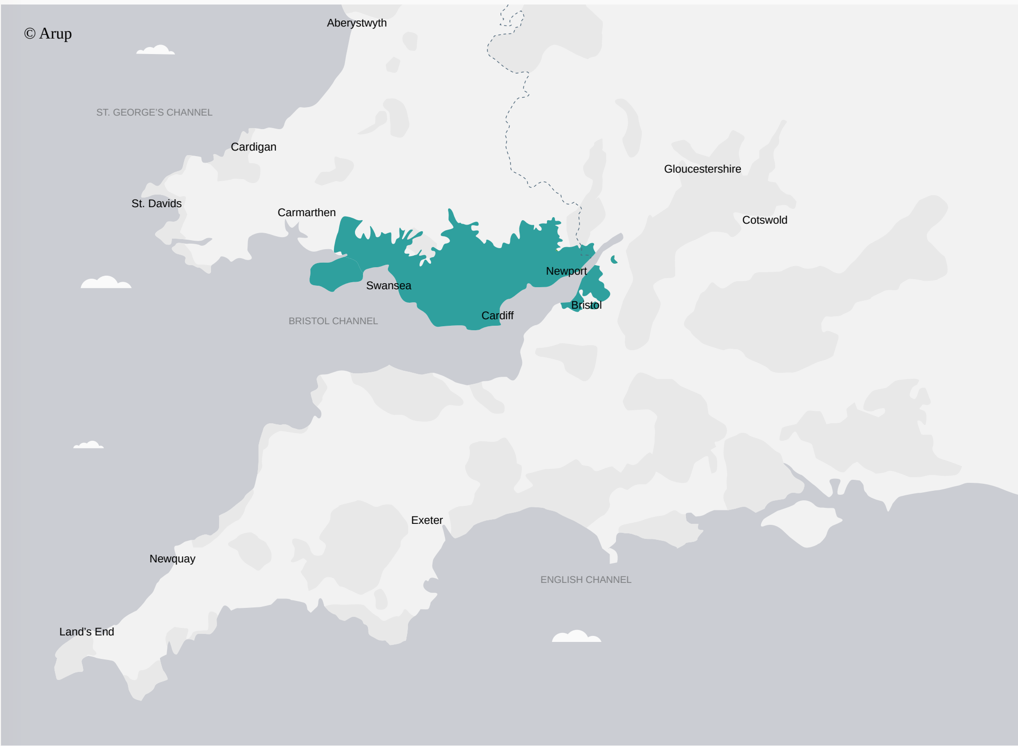


Figure 12
Cardiff Airport catchment zone and routes.

Passenger growth
Stakeholder consultations provided a view of Cardiff Airport growing to the pre-pandemic size of Liverpool Airport, of 5 MPPA, by 2050. The development of this traffic would have required a fivefold increase of traffic and an approximate interannual growth of 6.6%. Due to the divergence from the IATA and ICAO forecast for the region, generally providing a maximum of 3% growth in the Europe region, an alternative growth to recover the pre-COVID levels of traffic at Cardiff Airport was adopted. This represented a 2.3% interannual growth in passengers.

Commercial air transport movements accounted for 52% of the total activity at Cardiff Airport in 2019. The other two most important segments of ATM demand were aeroclub (27.5%) and private flights (15%). These three ATM types account for 95% of the demand at the airport.

Energy estimates as a guide to hydrogen demand limits
We estimate that airlines at Cardiff will use around 15,000 tonnes of kerosene in 2023 for flights departing the airport. Were this rate of usage per passenger to continue, the demand for kerosene would approach 28,000 tonnes in 2050. Of course, improvements in aircraft efficiency would mean that this an upper limit. A 1% a year compound efficiency improvement in aircraft/propulsion systems would reduce this upper limit to around 20,000 tonnes per year by 2050. If this were totally replaced by hydrogen on a like-for-like energy basis, the annual requirement for hydrogen in 2050 would be around 7,000 tonnes. (Note that this excludes the impact of airlines 'tankering' hydrogen – that is, uploading extra hydrogen at Cardiff so that a return flight is possible without the need to upload fuel at an outstation.) Nevertheless, it provides an order of magnitude estimate as a reference point for the ultimate possible demand for hydrogen.

Direct demand for hydrogen
The table to the right indicates the possible demands for gaseous and liquid hydrogen at Cardiff Airport, from hydrogen-fuelled aircraft, based on the method of analysis set out in Section 9. Note that this includes tankering, which, in 2050, accounts for around 28.6% of the total hydrogen demand in our figures.

The demand for hydrogen directly used by aircraft falls into two very clear phases: up to 2035 and possibly 2040 when demand is for around 300 tonnes a year and is driven by first generation gaseous hydrogen-fuelled aircraft, and a second phase when demands could rise by one to two orders of magnitude to as much as 6,000 to 10,000 tonnes a year (by 2050) after the introduction of liquid hydrogen-fuelled aircraft.

For Cardiff Airport, the relatively modest demands for gaseous hydrogen could be met by local electrolysis, or delivery by pressurised tube trailers carrying c.1.3 tonnes of hydrogen each. Fewer than one pressurised hydrogen tanker delivery a day would be necessary. At this scale, there is little need for a hydrogen pipeline.

For the initial part in the second phase when demand rises to, say, 1,000 tonnes a year of liquid hydrogen, local electrolysis and liquefaction is potentially plausible with a grid connection supplying around 10MW of electrical power. Alternatively, at this level, around one to two liquid hydrogen tanker deliveries (each with

Cardiff Airport

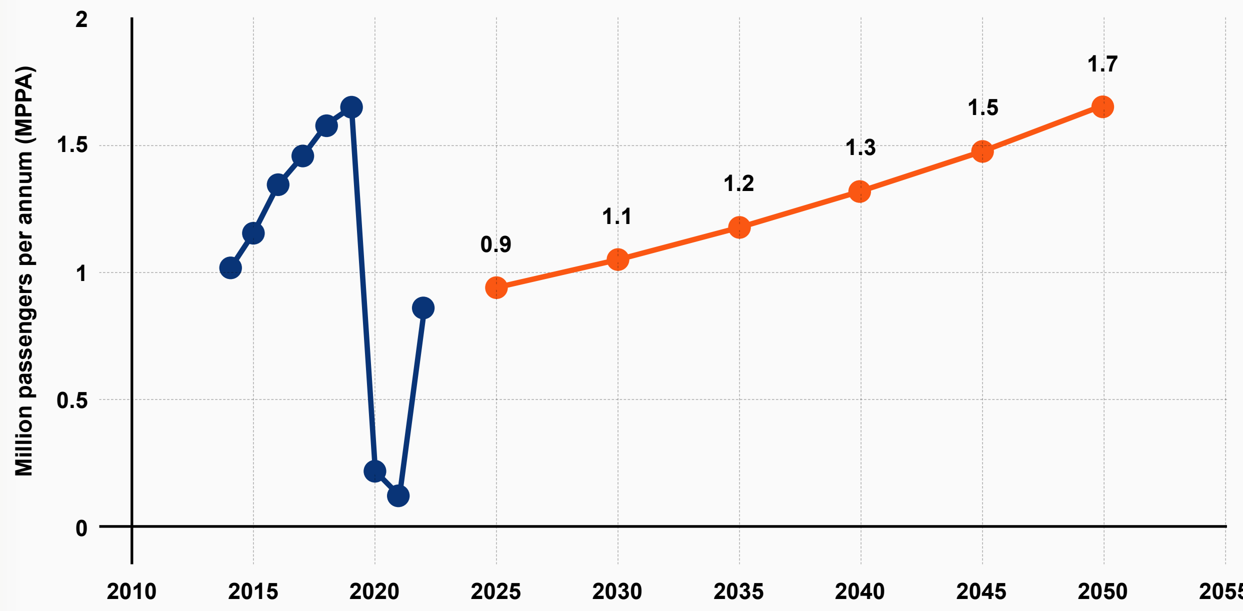


Figure 13
Cardiff Airport passenger growth scenario.

Historic projection
Forward demand

Tonnes/year	CWL	2025	2030	2035	2040	2045	2050
Scenario 2	Gaseous hydrogen	-	300	300	300	200	200
	Liquid hydrogen	-	-	-	800	5,400	9,300
	Total	**-**	**300**	**300**	**1,100**	**5,600**	**9,500**
Scenario 3	Gaseous hydrogen	-	-	100	300	200	200
	Liquid hydrogen	-	-	-	-	800	5,500
	Total	**-**	**-**	**100**	**300**	**1,000**	**5,700**

Table 10
Hydrogen demand arising from hydrogen-fuelled aircraft at Cardiff Airport.

c.3.5 tonnes) a day would be necessary. By 2050, demand could require around nine tanker movements a day, which would be a major operation. So, at this demand level, a pipeline supply of hydrogen to (or near) the airport, with local liquefaction, would begin to be a plausible option to replace tanker deliveries.

Hydrogen supply

Cardiff Airport is about five miles away from Aberthaw Power Station, which is anticipated to be a production site for green hydrogen, and 35 miles from Port Talbot, which will home the LanzaTech SAF production plant and will be the final destination of the planned HyLine new hydrogen pipeline. These developments around the airport give it the opportunity to utilise locally produced fuel (H2 and SAF) to decarbonise its operation, including aviation fuel.

Considering Cardiff Airport's relatively small demand for hydrogen, due to its size, its supply can be delivered via trucks from hydrogen production sites or can consider a dedicated pipeline to the Aberthaw hydrogen production plant. The pipeline can be further utilised by connecting it to strategic points on the LTS and NTS network to support the gas network transition to hydrogen.

Liquid hydrogen via tankers

This calculation assumes 3.5 tonnes of liquid hydrogen per tanker and 365 days of delivery. Considering the relatively infrequent tanker trips required, this could be a feasible option at least until 2050 and hence no pipeline is required.

LH2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	-	-	1	4	7
Scenario 3	-	-	-	-	3

Gaseous hydrogen via tube trailers

Assuming 1.3 tonnes at 500 bar of gaseous hydrogen is provided, gaseous hydrogen will become unviable after 2050, as up to 21 tankers would be required every day. The limit for the operation is about one tanker per hour.

Gaseous H2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	1	1	3	12	21
Scenario 3	-	1	1	3	12

Local hydrogen production through electrolysis

Local hydrogen production (electrolysis) would be feasible until 2040 (S2). The limit for electrolytic hydrogen production on site is considered as 10 MW.

Local H2 production (MW)	2030	2035	2040	2045	2050
Scenario 2	2.4	2.3	8.6	44.7	75.9
Scenario 3	0	1.1	2.1	8.6	45.7

Hydrogen liquefaction

The following table includes the energy for liquefaction and the related, less energy-demanding process of compression. The liquefaction should be feasible until 2050, assuming an update of the grid.

Local liquefaction (MW)	2030	2035	2040	2045	2050
Scenario 2	-	-	1.5	10.3	17.8
Scenario 3	-	-	-	1.6	10.5

Hydrogen pipeline size

To illustrate the change in the required hydrogen pipeline to meet the growth in demand at the airport, the pipeline size is calculated at 20 m/s average hydrogen speed for 2 bar and 7 bar pressures. Recognising that small diameter pipelines (0.02 inch) are not commercially available or viable, and understanding the need for Gas Networks to invest in the most cost effective infrastructure solutions for the future, it is plausible that a larger diameter PE pipeline designed to meet the 2050 demand is installed and operated at low pressure at the early years and increase in operating pressure with time to meet the increase in demand. Such investment will also provide assurance on fuel security to airports and flight operators allowing them to further invest in their fleet conversion.

Pipeline diameter (inch)	2030	2035	2040	2045	2050
Scenario 2 (7 bar)	0.04	0.04	0.14	0.70	1.2
Scenario 2 (2 bar)	0.13	0.13	0.47	2.4	4.2
Scenario 3 (7 bar)	-	0.02	0.04	0.14	0.70
Scenario 3 (2 bar)	-	0.06	0.12	0.47	2.5

Exeter Airport

Exeter Airport is a small international Airport located in the rural setting of East Devon. The airport has a population coverage of 1.63 million within an hour and a half driving distance and can be accessed via the M5. The airport serves flights to around 37 destinations in 14 countries. Currently, there is no existing gas pipeline supply to the airport.

Exeter Airport masterplan provided a view of the airport growing to 3.2 MPPA by 2030 (Exeter International, 2008), and 5 MPPA by 2050 when considering the same annual growth. The development of this traffic would have required an approximate interannual growth of 9.3%. Due to the divergence from IATA and ICAO forecast for the region, generally providing a maximum of 3% growth in the Europe region, an alternative growth to recover the pre-COVID levels of traffic in Exeter Airport was adopted. This represented a 3.04% interannual growth in passengers.

A summary of the hydrogen requirements up to 2050 is provided below. Note that this includes tankering, which, in 2050, accounts for around 28.6% of the total hydrogen demand in our figures.

We estimate that airlines at Exeter will use around 9,000 tonnes of kerosene in 2023 for flights departing the airport. Where this rate of usage per passenger to continue, the demand for kerosene would approach 17,000 tonnes in 2050. Of course, improvements in aircraft efficiency would mean that this an upper limit. A 1% a year compound efficiency improvement in aircraft/propulsion systems would reduce this upper limit to around 12,000 tonnes per year by 2050. If this were totally replaced by hydrogen on a like for like energy basis, the annual requirement for hydrogen in 2050 would be around 4,000 tonnes. (Note that this excludes the impact of airlines "tankering" hydrogen – that is uploading extra hydrogen at Exeter so that a return flight is possible without the need to upload fuel at an outstation). Nevertheless, it provides an order of magnitude estimate as a reference point for the ultimate possible demand for hydrogen.

Considering Exeter Airport's relatively small demand for hydrogen due to its size, its supply can be delivered via trucks from hydrogen production sites.

Table 11
Hydrogen demand arising from hydrogen-fuelled aircraft at Exeter Airport.

Tonnes/year	EXT	2025	2030	2035	2040	2045	2050
Scenario 2	Gaseous hydrogen	-	600	600	600	600	500
	Liquid hydrogen	-	-	-	600	3,100	5,300
	Total	**-**	**600**	**600**	**1,200**	**3,700**	**5,800**
Scenario 3	Gaseous hydrogen	-	-	300	600	600	500
	Liquid hydrogen	-	-	-	-	600	3,300
	Total	**-**	**-**	**300**	**600**	**1,200**	**3,800**

Liquid hydrogen via tankers
This calculation assumes 3.5 tonnes of liquid hydrogen per tanker and 365 days of delivery. Considering the relatively infrequent tanker trips required, this could be a feasible option at least until 2050 and hence no pipeline is required.

LH2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	-	-	1	3	5
Scenario 3	-	-	-	-	2

Gaseous hydrogen via tube trailers
Assuming 1.3 tonnes at 500 bar of gaseous hydrogen is provided, gaseous hydrogen will need in 2050 up to 13 tankers every day. This is equivalent to about 1 tanker per 2 hours which is still feasible until 2050.

Gaseous H2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	1	2	3	8	13
Scenario 3	-	1	2	3	9

Newquay Airport

Exeter Airport is a small airport located in Cornwall. The airport has a population coverage of 0.80 million within an hour and a half driving distance. The airport serves flights to around 22 destinations in 6 countries.

Newquay Airport masterplan (provided a view of the airport growing to 0.92 MPPA (Cornwall Airport Newquay, 2015). The development of this traffic is equivalent to an approximate interannual growth of 2.6%.

A summary of the hydrogen requirements up to 2050 is provided below. Note that this includes tankering, which, in 2050, accounts for around 28.6% of the total hydrogen demand in our figures.

We estimate that airlines at Newquay will use around 5,000 tonnes of kerosene in 2023 for flights departing the airport. Were this rate of usage per passenger to continue, the demand for kerosene would approach 9,000 tonnes in 2050. Of course, improvements in aircraft efficiency would mean that this an upper limit. A 1% a year compound efficiency improvement in aircraft/propulsion systems would reduce this upper limit to around 6,500 tonnes per year by 2050. If this were totally replaced by hydrogen on a like for like energy basis, the annual requirement for hydrogen in 2050 would be around 2,500 tonnes. Nevertheless, it provides an order of magnitude estimate as a reference point for the ultimate possible demand for hydrogen.

Considering Newquay Airport's relatively small demand for hydrogen due to its size, its supply can be delivered via trucks from hydrogen production sites or consider local hydrogen production.

Liquid hydrogen via tankers

This calculation assumes 3.5 tonnes of liquid hydrogen per tanker and 365 days of delivery. Considering the relatively infrequent tanker trips required, this could be a feasible beyond 2050 and hence no pipeline is required.

LH2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	-	-	1	2	2
Scenario 3	-	-	-	1	2

Table 12
Hydrogen demand arising from hydrogen-fuelled aircraft at Newquay Airport.

Tonnes/year	NQY	2025	2030	2035	2040	2045	2050
Scenario 2	Gaseous hydrogen	-	200	200	200	200	200
	Liquid hydrogen	-	-	-	600	2,100	2,900
	Total	**-**	**200**	**200**	**800**	**2,300**	**3,100**
Scenario 3	Gaseous hydrogen	-	200	200	200	200	200
	Liquid hydrogen	-	-	-	-	600	2,100
	Total	**-**	**200**	**200**	**200**	**800**	**2,300**

Gaseous hydrogen via tube trailers

Assuming 1.3 tonnes at 500 bar of gaseous hydrogen is provided, gaseous hydrogen will need in 2050 up to 7 tankers every day. This is equivalent to about 1 tanker per 3 hours which is still feasible until 2050.

Gaseous H2 via tanker (# per day)	2030	2035	2040	2045	2050
Scenario 2	1	1	2	5	7
Scenario 3	-	1	1	2	5


© izusek

Hydrogen for sustainable aviation fuel production

Regional SAF production
Regional SAF demand

© aapsky

Hydrogen for sustainable aviation fuel production

While hydrogen production and liquefaction local to an airport is a plausible option, at least for initial demands, SAF usage will ramp up more quickly and there is no reason why SAF production should be linked to any airport location, any more that CAF production is.

SAF production does require hydrogen, so the scale of potential hydrogen demand arising from this, in the region, is relevant to the study.

We consider two points of view. The first reflects what is known of the production plans of SAF producers which are based in the region – in this case LanzaTech. The second aggregates potential SAF demand from the airports in the region. There is no reason why these two figures should be the same: SAF can be readily 'imported' or 'exported" from the region. And indeed, with schemes such as Book and Claim, there are scenarios where the SAF itself is not physically transported to the client that bought it – another airline uses the SAF, but the purchasing airline counts the carbon credit.

Regional SAF production

Based on information from LanzaTech, their ambition is to produce 79,000 tonnes of SAF, with the plant entering operation in 2027 and reaching full capacity by 2028, and with potential growth to 400,000 tonnes by 2050.

Our estimate of hydrogen demand for SAF production in the region using ATJ technology will range from 2,000 tonnes per year initially up to 8,000 tonnes per year.

We note that at 400,000 tonnes per year, the facilities would be producing around twice the regional demand in 2050, even in a SAF-only scenario. Thus, the facilities would be exporting SAF from the region.

Regional SAF demand

Clearly, a world in which hydrogen aircraft have not made an impact (Scenario 1) will have the greatest demand for SAF in the region, reaching around 190,000 tonnes per year in 2050. In contrast, Scenario 2, with a rapid and regionally prioritised transition of aircraft to hydrogen, will require the least SAF. The interesting feature of this scenario is that, in the later years, SAF demand at the airports declines because of the rapid penetration and replacement of conventional aircraft by hydrogen-fuelled aircraft. In Scenario 3, with a delayed adoption of hydrogen aircraft, SAF demand at the airports continues to grow out to 2050, albeit starting to plateau in the later years. The total demand for SAF in this scenario lies between 125,000 and 135,000 tonnes per year in 2050.

SAF tonnes/year	Airport	2025	2030	2035	2040	2045	2050
Scenario 1	Bristol	3,500	18,400	34,900	65,300	106,300	164,400
	Cardiff	300	1,600	3,000	5,700	9,200	14,100
	Exeter	100	800	1,600	3,000	5,100	8,200
	Newquay	100	500	1,000	1,800	2,900	4,400
	Total	4,000	21,300	40,500	75,800	123,500	191,100
Scenario 2	Bristol	3,500	18,400	34,900	65,300	106,300	18,900
	Cardiff	300	1,600	3,000	5,700	7,600	200
	Exeter	100	800	1,600	3,000	3,700	-
	Newquay	100	500	1,000	1,800	1,600	-
	Total	4,000	21,300	40,500	75,800	119,200	19,100
Scenario 3	Bristol	3,500	18,400	34,900	65,300	106,300	115,800
	Cardiff	300	1,600	3,000	5,700	9,200	7,800
	Exeter	100	800	1,600	3,000	5,100	4,000
	Newquay	100	500	1,000	1,800	2,900	1,600
	Total	4,000	21,300	40,500	75,800	123,500	129,200

Table 13
SAF demand across each airport and scenario to 2050.

We estimate the amount of hydrogen needed in the production of SAFs. There are multiple pathways with different feedstocks and relative amounts of hydrogen required for production.

We have used three representative pathways:

– 2% of hydrogen per kg of SAF required, assuming a low advanced SAF pathway including Alcohol to Jet.

– 30% of hydrogen per kg of SAF required, assuming a high advanced SAF pathway including Alcohol to Jet.

– 50% of hydrogen per kg of SAF required, assuming a PtL pathway.

The initial demand for SAF is expected to be met from SAF produced via the HEFA pathway. However, as the demand increases, ATJ and PtL SAF production facilities will come online to meet the growing demand and take the largest share of the market. Furthermore, EU mandates are expected to cap the amount of HEFA SAF and set targets for advanced SAFs and for PtL.

As an example, we have a scenario in 2050 in which there is 37% PtL, 4% HEFA and 59% advanced SAF. We provide upper and lower estimates of the hydrogen demand by considering the advance SAF to be produce via the 2% hydrogen pathway or via the 30% hydrogen pathway.

High scenario

– The High scenario assumes advanced SAF made via a 30% of hydrogen per kg pathway, as per a high advanced SAF pathways.

– Note that PtL and HEFA fractions are also included.

H2 for SAF tonnes/year	Airport	2025	2030	2035	2040	2045	2050
Scenario 1	Bristol	400	4,900	10,400	21,500	36,400	59,600
	Cardiff	-	400	900	1,900	3,100	5,100
	Exeter	-	200	500	1,000	1,800	3,000
	Newquay	-	100	300	600	1,000	1,600
	Total	**400**	**5,600**	**12,100**	**25,000**	**42,300**	**69,300**
Scenario 2	Bristol	1,100	6,500	13,300	27,700	47,300	9,200
	Cardiff	100	600	1,200	2,400	3,400	100
	Exeter	-	300	600	1,300	1,700	-
	Newquay	-	200	400	800	700	-
	Total	**1,200**	**7,600**	**15,500**	**32,200**	**53,100**	**9,300**
Scenario 3	Bristol	1,100	6,500	13,300	27,700	47,300	56,200
	Cardiff	100	600	1,200	2,400	4,100	3,800
	Exeter	-	300	600	1,300	2,300	1,900
	Newquay	-	200	400	800	1,300	800
	Total	**1,200**	**7,600**	**15,500**	**32,200**	**55,000**	**62,700**

Low scenario

– The Low scenario assumes advanced SAF made via a 2% of hydrogen per kg pathway, as per a low advanced SAF pathways.

– Note that PtL and HEFA fractions are also included.

H2 for SAF tonnes/year	Airport	2025	2030	2035	2040	2045	2050
Scenario 1	Bristol	100	1,200	3,300	9,000	16,800	32,400
	Cardiff	-	100	300	800	1,500	2,800
	Exeter	-	100	100	400	800	1,600
	Newquay	-	-	100	200	500	900
	Total	**100**	**1,400**	**3,800**	**10,400**	**19,600**	**37,700**
Scenario 2	Bristol	-	900	2,900	8,400	16,100	3,700
	Cardiff	-	100	300	700	1,200	-
	Exeter	-	-	100	400	600	-
	Newquay	-	-	100	200	200	-
	Total	**-**	**1,000**	**3,400**	**9,700**	**18,100**	**3,700**
Scenario 3	Bristol	-	900	2,900	8,400	16,100	22,500
	Cardiff	-	100	300	700	1,400	1,500
	Exeter	-	-	100	400	800	800
	Newquay	-	-	100	200	400	300
	Total	**-**	**1,000**	**3,400**	**9,700**	**18,700**	**25,100**

Challenges

© courtneyk

Challenges

Uncertainty in the time scale of development

One of the key challenges in applying hydrogen for aircraft propulsion is the uncertainty surrounding the time scale of development. While hydrogen-powered aircraft show promise as a potential solution for reducing aviation emissions, the development and implementation of this technology on a large scale is still in its early stages, which makes planning and investment decisions challenging for both aircraft manufacturers and airlines.

Aircraft and infrastructure

The transition to hydrogen propulsion for aircraft requires significant modifications to both the aircraft and the existing infrastructure. Hydrogen fuel cells and engines have different requirements compared to traditional jet engines, necessitating redesigns of aircraft systems, including fuel storage, delivery and distribution. Additionally, existing airports would need to upgrade their infrastructure to accommodate the storage and handling of hydrogen fuel, which adds complexity and cost to the implementation process.

Cost of hydrogen and SAF

The cost of hydrogen production and availability of SAF is a major concern. Currently, the cost of producing hydrogen at scale is high, making it less economically viable compared to conventional jet fuels. Additionally, the availability of alternative aviation fuels, which also require hydrogen for their production, poses a challenge. The development and production of these fuels in large quantities is still limited, and the cost-effectiveness of scaling up production remains uncertain.

Hydrogen production and transport to the airport at scale

Producing and transporting hydrogen at scale presents significant challenges. Hydrogen production methods, such as electrolysis or steam methane reforming, require large amounts of energy and infrastructure to produce and store hydrogen in sufficient quantities for aviation. Moreover, the transportation of hydrogen to airports raises concerns about the efficiency, safety and environmental impact of the logistics involved.

Gaseous and liquid hydrogen handling in the airport environment

Handling hydrogen in the airport environment presents safety challenges, due to its unique properties. Both gaseous and liquid hydrogen require specific storage, handling and safety measures to prevent leaks or accidents. These measures include specialised infrastructure, training for personnel, and robust safety protocols. Ensuring the safe handling of hydrogen throughout the supply chain is crucial to gaining public and industry confidence.

Water supply

Hydrogen production, particularly through electrolysis, requires significant amounts of water. Scaling up hydrogen production for aviation could strain local water resources, especially in areas where water scarcity is a concern. Finding sustainable water sources or developing alternative production methods that minimise water usage will be essential for the widespread adoption of hydrogen as an aviation fuel.

Hydrogen purity

Maintaining the purity of hydrogen throughout the production, storage and transportation process is crucial for the use in aircraft propulsion. This is particularly important if the hydrogen is to be used in fuel cell electric aircraft propulsion. Impurities in hydrogen can affect the performance of propulsion systems and increase the risk of corrosion or damage to aircraft systems. Ensuring consistent hydrogen purity standards across the supply chain will be necessary for reliable aircraft operation.

Regulations and policy, particularly around safety

The regulatory framework for hydrogen-powered aircraft is still in its early stages. Developing comprehensive safety regulations and policies is crucial to address the unique challenges associated with hydrogen as an aviation fuel. Government agencies, industry stakeholders and international organisations need to collaborate to establish safety standards, certification processes and operational guidelines that provide confidence and assurance to the aviation industry.

Liability, particularly around the difficulty in testing gaseous hydrogen

Liability is a significant concern when introducing a new and relatively untested technology like hydrogen propulsion. It is more difficult to keep samples of hydrogen through the distribution system to test quality than with kerosene. Establishing liability frameworks and conducting thorough testing and validation procedures will be necessary to mitigate risks and ensure safety.

Key findings

Key findings

There is potential high demand for hydrogen in South Wales and South West England by 2050.

The South West of England and South Wales have a highly favourable environment for the development of hydrogen aviation. Its renewable energy resources, existing aerospace industry, robust infrastructure, supportive policies, and international connectivity position the region as an ideal hub for advancing hydrogen propulsion technologies in the aviation sector.

By capitalising on these advantages, the region can contribute to the global effort of decarbonising aviation and shaping a sustainable future for the industry.

In the region, hydrogen demand for aviation will be primarily driven by Bristol Airport, considering its size, growth rate, ambitious net zero targets and collaboration within Hydrogen South West. The Airport's work and collaboration with easyJet, an airline with a focus on hydrogen, provides another springboard for the acceleration of hydrogen use in aviation.

Hydrogen infrastructure is set to expand

The UK government intends to support the development of hydrogen infrastructure, making it more convenient and cost-effective to transport and store. This, along with the development and implementation of safety standards for hydrogen production and use, will increase hydrogen's popularity, while decreasing the risk of accidents. Hydrogen fuel cells and tanks are becoming lighter and more efficient via new materials and manufacturing techniques. In a number of countries, hydrogen refuelling infrastructure has been already developed.

Key drivers for the pace of hydrogen infrastructure development will be the target to achieve 100% hydrogen for heating by 2026, and the individual airports' commitments to hydrogen. In order to meet dual demand for hydrogen for heating and hydrogen for combusting in aircraft, airport gas supply pipelines may need to be replaced. The hydrogen will need purification at the destination to ensure impurities during transit are removed. Depending on the speed of the transition and success of the hydrogen aircraft technology, by 2050 Bristol Airport will need a direct hydrogen pipeline as the existing pipeline will have insufficient capacity to meet the demand for aviation hydrogen fuel and any other demand such as for heating.

As infrastructure and safety standards are addressed, hydrogen aviation is likely to become a more viable option for commercial air travel. Hydrogen-powered aircraft have a number of advantages over traditional jet aircraft, including producing lower emissions and lower operating costs than SAF. This could make hydrogen aviation an attractive option for airlines looking to reduce their environmental impact and operating costs.


© Wales and West Utilities

Demand for hydrogen will evolve

The key observation from this study is that the demand for hydrogen for aviation divides into two phases. Initially, the demand for hydrogen in the aviation sector will be for the production of SAF with relatively low levels of demand for ground operations and small hopper aircraft. With LanzaTech in South Wales as the dominant SAF producer in the region, it could be well positioned as a key supplier of the region's SAF by 2030. It will also become a hydrogen user for SAF production.

The demand will shift towards hydrogen as a direct fuel for aviation as larger regional hydrogen aircraft enter service and as challenges to its use at airports are overcome. These include:

- Technology development to reduce the weight and size of the powertrain and hydrogen storage system.
- Hydrogen production and transport at the scale and form required by airports.
- Handling hydrogen in the airport environment.
- Infrastructure for the delivery, storage and distribution of liquid hydrogen at the airport and onboard aircraft.
- Sufficient electricity supply for liquefaction.

The evolution of demand for hydrogen will therefore divide into two phases. The first is up to 2035 or 2040, during which predominantly smaller aircraft are converted to a hydrogen power train. At these levels of demand (up to c. 1,000 tonnes per year) local production of hydrogen might be feasible, and indeed necessary, if a wider hydrogen supply chain is not available with sufficient capacity.

The tipping point for the second phase of much larger demand for hydrogen (10s to 100s of thousands of tonnes per year) will come with widespread introduction of purpose-designed, liquid-hydrogen fuelled aircraft (as distinct from conversions), such as Airbus's ZEROe concept and Rolls-Royce's future liquid hydrogen jet engines. We estimate this phase to be from approximately 2037 onwards. Even when factoring in differences in airlines' and aircraft manufacturers' strategies – with some believing that a SAF-based solution is the approach to adopt for the foreseeable future – this second phase of demand will still be triggered by the shift from aircraft conversions to aircraft purpose-built to be fuelled by SAF or hydrogen.

To achieve net zero targets in aviation, there is a high likelihood that hydrogen will be necessary, whether as a direct fuel for aircraft or indirectly via SAFs. This has two potential implications for gas distribution networks: Firstly, hydrogen may need to be supplied through pipelines to SAF production sites. Secondly, there may be a need for direct or near supply of hydrogen to larger airports. Either one or both of these options would be crucial in realizing a future for aviation that heavily relies on hydrogen as a fuel source.

References

- Aerospace Technology Institute. (2022). UK Capability in Zero-Carbon Aircraft Technologies.
- Airbus. (2020, October). Retrieved from Hydrogen in aviation: how close is it?: https://www.airbus.com/en/newsroom/stories/2020-10-hydrogen-in-aviation-how-close-is-it
- Airports International. (2022). Retrieved from Looking back at 2022: Green GSE: https://www.airportsinternational.com/article/looking-back-2022-green-gse
- Aviation environment federation. (2023). Should we fly less? The inequality of air travel.
- BEIS. (2021). Hydrogen Production Cost 2021. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011506/Hydrogen_Production_Costs_2021.pdf
- Brian Pettinato, T. K. (2022). Chapter 3 - Machinery basics. In Machinery and Energy Systems for the Hydrogen Economy. Elsevier.
- British Airways. (2023). BA Mediacentre. Retrieved from Sustainability at British Airways 2023: https://mediacentre.britishairways.com/factsheets/details/86/Factsheets-3/217?category=1&pgck=L2ZhY3RzaGVldHM
- Connelly, E., Penev, M., Elgowainy, A., & Hunter, C. (2019). Current Status of Hydrogen Liquefaction Costs. DOE Hydrogen and Fuel Cells Program Record.
- CORSERV. (2023). Sustainability Strategy. Retrieved from https://www.westofengland-ca.gov.uk/news/government-backs-south-west-as-world-leader-in-smart-and-sustainable-aviation/
- Department for Transport. (2022). Jet Zero strategy: delivering net zero aviation by 2050.
- Department for transport. (2023). Pathway to net zero aviation: Developing the UK sustainable aviation fuel mandate.
- DOE. (2009). Energy requirements for hydrogen gas compression and liquefaction as related to vehicle storage needs.
- DOE. (2019). Current Status of Hydrogen Liquefaction Costs.
- E. Fesmire, J., & Swanger, A. (2021, August). Overview of the New LH2 Sphere at NASA Kennedy. Retrieved from DOE/NASA Advances in Liquid Hydrogen: https://www.energy.gov/sites/default/files/2021-10/new-lh2-sphere.pdf
- E4tech (UK) Ltd, Ludwig-Bölkow-Systemtechnik GmbH. (2021, May). Options for a UK low carbon . Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1024173/Options_for_a_UK_low_carbon_hydrogen_standard_report.pdf
- EASA. (2018). Operations in General Aviation. Retrieved from EASA Pro: https://www.easa.europa.eu/en/domains/general-aviation/operations-general-aviation
- easyJet. (2022). Summary of net zero roadmap. Retrieved from Net zero pathway: https://corporate.easyjet.com/~/media/Files/E/Easyjet/documents/easyjet-nz-roadmap.pdf
- emep. (2019). EMEP/EEA air pollutant emission inventory guidebook 2019.
- European Hydrogen Backbone . (2023). Introduction. Retrieved from https://www.ehb.eu/page/european-hydrogen-backbone-maps
- F Yin, A. G. (2012). Performance of Multi-fuel Hybrid Engine for Blended wing Body Aircraft. Flight Performance and Propulsion.
- FlyZero. (2022). FlyZero – Key Findings. Retrieved from https://www.ati.org.uk/wp-content/uploads/2022/03/FlyZero-Roadshow-Presentation-030322.pdf
- Fuel cell trucks. (2023). PLUGPOWER: hydrogen fuel cell powered airport ground support equipment. Retrieved from https://fuelcelltrucks.eu/project/plugpower-hydrogen-fuell-cell-powered-airport-ground-support-equipment/
- HM Goverment. (2021, October). Net Zero Strategy: Build Back Greener. Retrieved from Assets Publishing Service: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1033990/net-zero-strategy-beis.pdf
- IATA. (2021). 77th IATA Annual General Meeting resolution.
- IATA. (2022). Global Outlook for Air Transport. Retrieved from https://www.iata.org/en/iata-repository/publications/economic-reports/global-outlook-for-air-transport---december-2022/
- IATA. (2022, June). Net zero 2050: operational and infrastructure improvements. Retrieved from https://www.iata.org/en/iata-repository/pressroom/fact-sheets/fact-sheet-netzero-operations-infrastructure/
- ICAO. (2021). ICAO welcomes new net-zero 2050 air industry commitment. Retrieved from https://www.icao.int/Newsroom/Pages/ICAO-welcomes-new-netzero-2050-air-industry-commitment.aspx

References

- ICAO. (2022). 41st ICAO Assembly adopted a collective long-term global aspirational goal (LTAG) of net-zero carbon emissions by 2050. Montreal: ICAO.
- ICAO. (2023). ICAO forecasts complete and sustainable recovery and growth of air passenger demand in 2023 . Retrieved from https://www.icao.int/Newsroom/Pages/ICAO-forecasts-complete-and-sustainable-recovery-and-growth-of-air-passenger-demand-in-2023.aspx#:~:text=Air%20passenger%20demand%20in%202024,over%20the%202019%2D2024%20period
- LanzaTech . (2023). Project Dragon: LanzaTech plans to produce sustainable aviation fuel in Port Talbot. Retrieved from https://www.lanzadragon.wales/
- National Gas. (2022, May). Project Union. Retrieved from Launch report: https://www.nationalgas.com/document/139641/download
- Office for National Statistics. (2023). Carbon based fuel use by type, 1990 to 2020.
- Office of Energy Efficiency and Renewable Energy. (2023, June 12). Hydrogen Storage. Retrieved from Office of Energy Efficiency and Renewable Energy: https://www.energy.gov/eere/fuelcells/hydrogen-storage
- Sustainable Aviation. (2023). Net Zero Cargon Road-map. Retrieved from https://www.sustainableaviation.co.uk/wp-content/uploads/2023/04/SA9572_2023CO_2RoadMap_Brochure_v4.pdf
- UK Aviation. (2021). Loganair commits to being Carbon Neutral by 2040. Retrieved from https://ukaviation.news/loganair-commits-to-being-carbon-neutral-by-2040/
- Welsh Goverment. (2021). The Wales Transport Strategy. Retrieved from https://www.gov.wales/sites/default/files/publications/2021-03/llwybr-newydd-wales-transport-strategy-2021-full-strategy_0.pdf
- West of England. (2022, July). Government backs South West as world leader in Smart and Sustainable Aviation. Retrieved from https://www.westofengland-ca.gov.uk/news/government-backs-south-west-as-world-leader-in-smart-and-sustainable-aviation/
- Xinyi Sola Zheng, D. R. (2020). Fuel burn of new commercial jet aircraft: 1960 to 2019. icct.
- Physicsworld. (2023). A 700 Whkg−1 Rechargeable Pouch Type Lithium Battery
- Quan Li (李泉) 1,2, Yang Yang (杨旸)1,2,3, Xiqian Yu (禹习谦)1,2,3 and Hong Li (李泓)1,2,3
- © 2023 Chinese Physical Society and IOP Publishing Ltd
- Chinese Physics Letters, Volume 40, Number 4. Quan Li et al 2023 Chinese Phys. Lett. 40 048201 DOI 10.1088/0256-307X/40/4/048201

Acronyms

ATI	Aerospace Technology Institute
ATJ	Alcohol to Jet
ATM	Air Traffic Movement
BAU	Business as Usual
BRS	Bristol Airport
CAeS	Cranfield Aerospace Solutions
CAF	Conventional Aviation Fuel
CWL	Cardiff Airport
CCUS	Carbon Capture Utilisation and Storage
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DfT	Department for Transport
EXT	Exeter Airport
GDN	Gas Distribution Network
GSE	Ground Support Equipment
GW	Gigawatt
H2	Hydrogen
HEFA	Hydrotreated Esters and Fatty Acids
HSW	Hydrogen South West
ICAO	International Civil Aviation Organization
IAG	International Airlines Group
IATA	International Air Transport Association
kWh	Kilowatt-hour
Kg	Kilogram
LH2	Liquid Hydrogen
LHV	Lower Heating Value
MJ	Megajoule
MPPA	Million Passengers Per Annum
MW	Megawatt
MWh	Megawatt-Hour
NAPKIN	New Aviation Propulsion Knowledge and Innovation Network
NQY	Newquay Airport
PAX	Passengers
PEM	Polymer Electrolyte Membrane
PtL	Power to Liquid
R&D	Research & Development
RTFO	Renewable Transport Fuel Obligation
SAF	Sustainable Aviation Fuel
SCM/h	Standard Cubic Metre per Hour
SWIC	South Wales Industrial Cluster
TRL	Technology Readiness Levels
WWU	West and Wales Utilities

ARUP

Contact

John Beasley
Director

t: +44 20 7755 4669
e: john.beasley@arup.com

8 Fitzroy St,
London W1T 4BJ

Ahmad El-Kharouf
Senior Engineer

t: +44 114 283 3774
e: ahmad.el-kharouf@arup.com

3 St Paul’s Place,
Norfolk St, Sheffield S1 2JE

Emily Wiltshire
Senior Consultant

t: +44 20 7755 0219
e: emily.wiltshire@arup.com

8 Fitzroy St,
London W1T 4BJ

Alberto Rivas Cid
Consultant

t: +44 20 7755 5535
e: alberto.rivas-cid@arup.com

8 Fitzroy St,
London W1T 4BJ