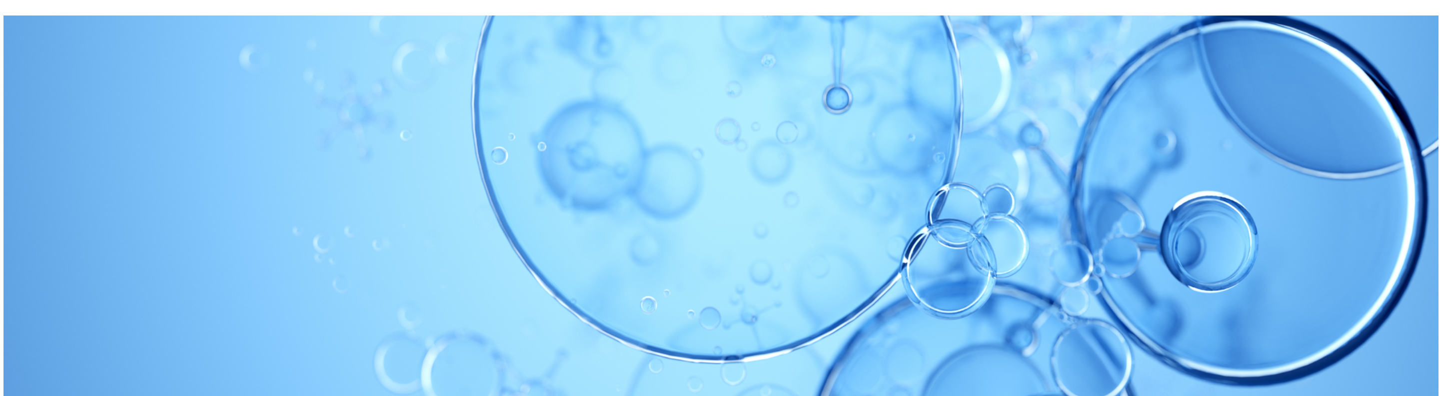
Hydrogen's essential role in the decarbonization of aviation

By Angus Reid-Kay and Alastair Blanshard, ICF

Introduction

In 1957, the engineers at Lockheed Martin's Skunk Works turned to hydrogen to give them an edge in the design of the next generation spy plane. The U2 had already proved invaluable during the Cold War and buoyed by success, the US Air Force initiated Project Suntan to use hydrogen fuel to make a faster, better successor. While the project was eventually shelved in favor of the SR-71, the team made extraordinary progress, including converting and testing a conventional turbojet to run on hydrogen, and building much of the ground infrastructure that would eventually be critical to the hydrogen used for the Apollo space missions.



Hydrogen is again a key topic, this time for its potential to decarbonize aviation. Here we provide an overview of the current state of hydrogen fuels, the key challenges and outlook, and the pioneering efforts from entrepreneurs such as ZeroAvia and Universal Hydrogen to make this a reality.

There are many visions of the future for aviation and unique challenges for each of them. Hydrogen will likely play a central role, but the scope and nature of this role will be driven by complex factors across multiple industries. A virtuous cycle exists with increasing scale, driving reductions in the cost of production, increasing availability and convenience of supply, and unlocking the technological advantages of hydrogen as a solution. However, this cycle is currently non-existent, and will only accelerate if we progress past some early tipping points. In the past few months, the EU, U.S., Japan, and numerous organizations have announced bold plans to stimulate the hydrogen industry and nurture the development past these tipping points. The resulting progress in the next few years will determine much of the outcome over the following decades.

How can aviation use hydrogen?

Hydrogen can be created and consumed via a number of approaches, each with different sustainability, economic, and practical attributes (mapped below).

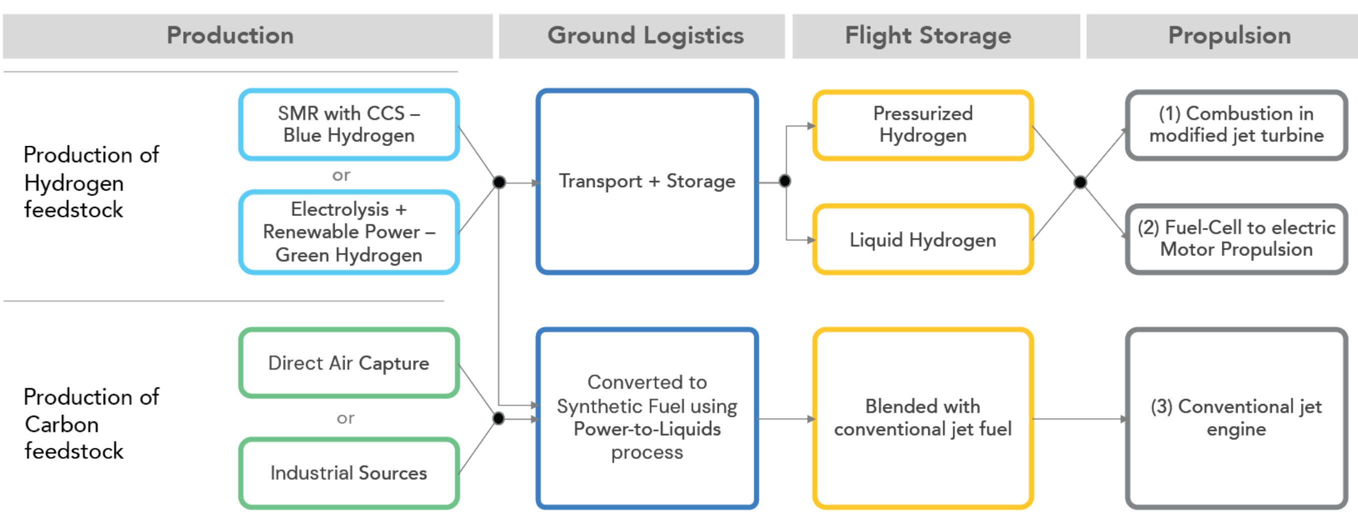
When used for aviation propulsion, hydrogen can replace kerosene through three mechanisms:

- Combustion, where hydrogen is burned in a turbine similar to current jet engines.
- To generate electricity using fuel-cells, which can then power electric motors.
- As a feedstock to create synthetic kerosene, also known as e-fuel and power-to-liquid (PtL). This will be increasingly important if we reach the limitations on the volume of biological feedstocks that can be sustainably collected.

Each of these mechanisms is currently being explored, with the Airbus ZEROe proposals using a combination of the first two, Universal Hydrogen and ZeroAvia using fuel cells, and a recent demonstration by KLM and Shell using e-fuels.

Each approach has pros and cons. Synthetic fuel produced from hydrogen using the PtL pathway is a "drop-in" fuel, meaning it is comparable to conventional jet fuel and can use the same infrastructure, both on the ground and in the air. However, synthetic fuels also require a source of carbon, which must be directly extracted from the atmosphere to be sustainable, and there are considerable energy losses incurred during the conversion from hydrogen to a liquid fuel.

HYDROGEN PATHWAYS FOR AVIATION PROPULSION



Using the hydrogen directly, either as a fuel to create electricity in a fuel-cell, or to combust directly, is an appealing solution to simplify and significantly reduce the fuel cost. Direct combustion minimizes the changes required for aircraft designs, but also reduces the efficiency advantages. By comparison, using the hydrogen to produce electricity in fuel cells is significantly more efficient at converting a given unit of fuel into useful propulsion. However, this would require a wholesale change to the powertrain on the aircraft we use, and while the hydrogen fuel is lighter than kerosene for a given volume of energy, it is much less dense and requires significantly more volume for storage, even when pressurized or liquified.

At the core it's a simple choice: Do we change our aircraft designs to suit the fuel, or change the fuel to suit the aircraft?

Our belief is that the outcome will depend on the class of aircraft. The comparative advantage of hydrogen diminishes at longer ranges, both because the volume needed to store the hydrogen becomes prohibitive, and because the efficiency advantage is smaller when compared to the higher bypass and pressure ratio of the larger engines on wide-body aircraft. At the smaller end, electric aircraft using batteries will likely prove the best solution for ultra-short haul regional traffic, as the cost and complexity to use electricity directly is far less than the cost to convert the electricity to hydrogen on the ground and then back to electricity on the aircraft. This leaves the middle of the market as the most appealing market for hydrogen. As the largest and most profitable market segment, it is also a favorable hunting ground.

Building a virtuous supply and demand cycle

Access to a clean supply of hydrogen is crucial and is likely to be driven by developments outside the aviation industry. Over 100 million tonnes of hydrogen are already consumed every year, up from 40 million tonnes in 1980 and equivalent to about 4% of global final energy and non-energy use. Just over a third is used in oil refining, and just under a third for ammonia production. Methanol and steel production drive much of the rest, but beyond these applications the demand is currently very limited.

Almost all the hydrogen used today is not sustainable. As shown in the following table, the most common production process is steam methane reforming (SMR) of natural gas, which produces more than 830 MT of CO2 per year, equivalent to the CO2 emissions of the U.K. and Indonesia combined. The second most common process uses coal as a feedstock and is even worse from an environmental perspective.
The remaining production methods, either capture and sequestrate the carbon or create the hydrogen using clean renewable power. While this improves their environmental credentials, it also adds considerable cost.

Hydrogen production pathway	Production method	Emissions tCO2 / tH2	Current Production (Mt H2 / year)1
Grey	Steam Methane Reforming (SMR) without carbon capture and sequestration (CCS)	10	~ 53
Blue	SMR with CCS	1	< 1
Brown	Coal gasification	19	~ 16
Pink	Electrolysis from nuclear energy	0	< 1
Green	Electrolysis from renewable energy	0	< 1

Source: IEA Report, The Future of Hydrogen
Note: (1) Current production of pure hydrogen, additional hydrogen is produced as part of other products

The EU Hydrogen roadmap is focused on creating a sustainable supply of green hydrogen to decarbonize the existing application—essentially accelerating production of green hydrogen to replace grey hydrogen—and potentially using others as steppingstones on the way. This will be a monumental challenge and will take place over decades. To put this into context, the historical consumption of hydrogen has grown at just under 3% per year, so a straight extrapolation would suggest an additional demand of nearly 30 million tonnes by 2030.

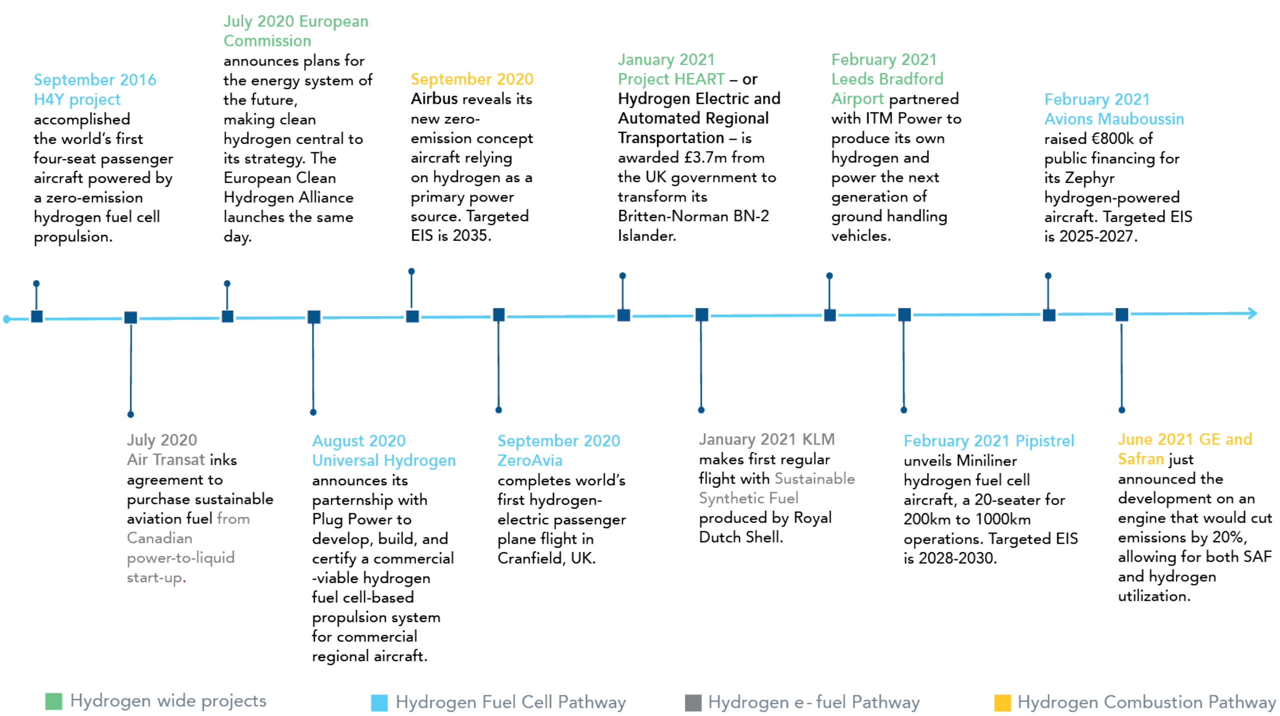
The target set by the EU aims for annual production of 10 million tonnes of green hydrogen in 2030, which would not even meet this growth in demand from existing applications, let alone decarbonize the current level of use or meet the demand from potential growth cases such as aviation. However, this will accelerate the virtuous cycle of green hydrogen production, with wider effects than just driving production. Other nations have announced similar programs, including the U.S. Energy Earthshot project that aims to bring the cost of hydrogen to $1 per kg by 2030. Japan has a similar goal with a more moderate ambition of $3/kg by 2030. This will start a snowball effect, rapidly bringing hydrogen into the mainstream.

The existing applications for hydrogen provide a ready source of demand, particularly with demand-side policies such as blend quotas discussed in policies such as the EU Hydrogen roadmap. In the longer term, the aspiration for hydrogen to play a much larger role in other industries—such as energy storage and heating, as well as transportation—is often discussed.

Hydrogen has an uphill battle to claim a significant market share of ground transportation and ultra-short haul aviation. In 2018, just 4,000 fuel cell electric vehicles were sold, compared to 2.5 million electric vehicles. Electric vehicles are consequently seeing a far greater build-out of supporting infrastructure and the scale of production is rapidly decreasing costs, meaning they are likely to dominate the mass market for the foreseeable future.

TIMELINE OF KEY AVIATION HYDROGEN EVENTS

A timeline of aviation's green hydrogen developments



Source: ICF analysis

In the longer-term, we do believe hydrogen will have a role to play in niches of the automotive market, as supply becomes increasingly accessible and the market looks for faster refueling and longer range. But this is likely to be a slow shift, beginning in markets where limited refueling infrastructure is required, for example in captured markets such as taxi, local city buses, or specific parts of the rail network.

Hydrogen is likely to play a more significant and immediate role in decarbonizing long-range modes of transport like aviation, where the required batteries would be excessively voluminous or heavy, and where there are limited alternatives.

Building up from the ground up

Aggregating demand from both airside and landside consumers, supported by local partnerships, will represent the key early opportunity for airports to aggregate enough demand to justify the infrastructure, and several airports are already leading this space. Gatwick and Leeds Bradford have both partnered with ITM Power for hydrogen refueling stations. Toulouse-Blagnac Airport will install an on-site electrolyzer built by McPhy to meet the needs of two hydrogen recharging stations. Arlanda airport has operated a hydrogen refueling station for taxis since 2015, and many other airports have similar initiatives.

Airport infrastructure will need to adapt to handle hydrogen, and airports should consider a range of factors. These include (i) infrastructure requirements for the storage and transfer of hydrogen, (ii) management of hydrogen volumes on-site, controlled by managing offtake demand volumes and storage capacity, and (iii) availability of sufficient volumes of green hydrogen. The complexity and cost of these challenges will likely be influenced on the ability to adapt existing infrastructure or introduce new infrastructure to accommodate hydrogen.

Aviation stakeholders will likely need to work together to tackle some major challenges, such as the transportation of green hydrogen from production to consumption locations. One solution to this challenge is on-site hydrogen production at airports. This would require significant renewable energy available within a reasonable distance from the airport, which necessitates large amounts of land and natural resources such as sun and wind—not always available around airports. Another solution would be for new infrastructure to be built to transport hydrogen from production locations to airports. Hydrogen can be transported in different ways; for example, Universal Hydrogen transports hydrogen in modular hydrogen capsules on the existing intermodal container freight network. Transporting and safe handling of hydrogen is a priority as hydrogen is colorless, odorless, and highly flammable. This would require a selection of proper containers and materials for transport, additional leakage detection measures, and avoidance of any ignition sources during transport and storage.

A further challenge revolves around the actual timing of consumption, and the storage implications such timing has. Storing hydrogen is costly since it needs to be maintained in a highly compressed state or liquefied. Therefore, storage costs reduce when hydrogen is consumed at airports in real-time. This may require offtake agreements between hydrogen suppliers and consumers (i.e. airlines), which could be a constraint as suppliers will need significant commitments from airlines. A potential solution to this issue is joint agreements between the airport and the local community, county, or surrounding region to share the hydrogen offtake commitments and create an ecosystem linked to the airport.

Taking flight

There are considerable initiatives to enable hydrogen to take to the air. ZeroAvia has raised nearly $74 million to date to develop a hydrogen powertrain for aircraft and has considerable backing from seasoned investors and operators such as British Airways. This supports a clear vision to deliver a first commercial offering for small, short range aircraft in 2024, and rapidly building power and range to enter the 100-200 seat narrow-body market around 2030.

By contrast, Universal Hydrogen are looking for a direct entry to the regional aircraft market, with conversion kits for existing turboprop airframes. Recognizing the lack of infrastructure, their scope spans hydrogen logistics with a modular transportation technology that can rapidly scale across geographies.

While the nimble, focused start-ups are leading the market, they will face mounting pressure from incumbents. Airbus revealed its ZEROe concept aircraft in 2020, with three potential configurations to use liquid hydrogen as a fuel for modified gas turbines. This marketing appears to be backed up with action, with a job search in June showing open positions for over 30 roles focused on the development of hydrogen technologies. While publicly ambitious, Airbus is privately more pragmatic on the long-term prospects. A February briefing to EU officials obtained through a freedom-of-information request states that hydrogen will be limited to regional and short-range aircraft from 2035, with long-range aviation continuing to rely on conventional gas turbines.

None of these initiatives will come to fruition without support. Developing the use of hydrogen in aviation faces high upfront costs, significant development risks, and the future opportunities are significant but many years away. Government support will be critical, either to de-risk early investments (such as the U.K. governments £12.3m grant to ZeroAvia's HyFlyer II Project) and to increase the benefits from the use of low carbon fuels, such as California's Low Carbon Fuel Standard and the U.K.'s Renewable Transport Fuel Obligation.

Certification will be a potential bottleneck. The challenge to bring a prototype into commercial operation is significant, and there is an inundation of conventional, electric, and hydrogen aircraft programs lining up for the process. This will strain the resources of the institutions and clear processes supported by adequate resources will be necessary to ensure new technologies can enter the market quickly and safely.

What's next?

Hydrogen will become increasingly important to the decarbonization of aviation, either as a stand-alone fuel or as a feedstock for the PtL production pathway of e-fuels. It's unlikely that we will be able to meet the decarbonization ambitions of the aviation industry, and therefore the Paris agreement, without significant use of hydrogen. Airports can play a key role today by establishing supplies of hydrogen for ground vehicles, and the operational experience of airlines will be invaluable to the emerging OEMs. However, the ability of aviation to drive the transition alone is limited. It will be reliant on governments and other larger industries to stimulate the cycle of increasing scale and cost reductions past the early tipping points.

About the authors

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Angus Reid-Kay is a senior associate within ICF's Aviation group. Most recently, Angus has played a central role in guiding the delivery of a major project on a technical and strategic level that has resulted in significant client account growth. Angus leads the analysis and project delivery of a range of projects within ICF's Aviation team. He specializes in traffic forecasting, operational modelling, airport transaction advisory and aviation market reviews, and also has experience in measuring carbon emissions and noise at airports. He builds and manages forecasting models that enable him to run various analyses and multiple scenarios that are driven by different sets of assumptions, and applies advanced MS skills to analyze data and present key insights in a clear and digestible manner to clients.

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Alastair is a Chartered Engineer (CEng) and holds a MEng in Aeronautical engineering. Passed level 2 of the Chartered Financial Analyst (CFA) exams. He specialises in operations, strategy development and advanced analytics. As a consultant, he has developed pragmatic, innovative strategies, including expansion, acquisition, cost reduction and partnership projects.

As lead for the ICF Sustainable Aviation team, he works with airlines, airports, start-ups and investors to reduce the environmental impact of the aviation sector. Alastair has vast experience supporting SAF offtake agreements and investments, developing and implementing decarbonisation strategies, assessing carbon emissions and schemes, and supporting clean-technology start-ups.

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