Hydrogen for aviation

A future decarbonization solution for air travel?

V2.0- February 2025

This document is an introductory-level explainer on the use of hydrogen to power civilian aircraft to reduce the environmental impact of aviation.
The topics covered are:
-The colors of hydrogen
-Hydrogen to power aircraft
-Current state of development
-Challenges and opportunities: costs, airport infrastructure or certification.

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1. Introduction

In 2021, IATA member airlines, airports, manufacturers, and air navigation service providers set a goal to reach net zero aviation carbon emissions by 2050 [1]. About 130 countries have set or are considering a similar target, some of which include domestic aviation [2].

Aircraft technology improvements and optimized flight and ground operations will reduce the rate at which carbon emissions grow but alone will not drive them to net zero. The most effective way to decarbonize the existing fleet of nearly 30,000 aircraft and the upcoming fleet in the next 15-20 years is sustainable aviation fuels (SAF). By 2050, this solution could account for up to 62% of the mitigated carbon emissions. But SAF is not being produced at scale today, representing only 0.3% of the 2024 fuel uptake [3]. Enabling government policies and innovative SAF pathways are urgently required to scale this up [4] [5]

At the same time, new energies and technologies must be accelerated so they too can have a substantial impact on the net zero CO_2 by 2050 goal.

Hydrogen has regained attention as a future solution to mitigate the environmental impact of aircraft and to help the sector reach net zero. The manufacture, transportation, and use of hydrogen is not new—the global economy has been using it for the last 100 years. In fact, the first hydrogen pipeline was built in the 1930s. Today, about 100 million tonnes of hydrogen are produced for the global economy (for comparison, aviation used about 280 million tonnes of jet fuel in 2023). It is mainly used in oil refining, fertilizers, and the chemical industry but is also seen on a small scale in cars, buses, and trains. Next in line is aviation.

This paper introduces hydrogen and its challenges and opportunities for aviation.

Key Takeaways

- When produced with renewable energy, hydrogen is a sustainable power source, widely available in nature, though not in its pure form
- It has three times the power density of kerosene so any given flight would need a third less fuel
- It is not “drop-in”. Its practical application requires new aircraft models and new ground infrastructure, processes, and skills
- The complexity of the factors involved make pricing difficult to predict
- Many aviation stakeholders and governments are investing in the potential of hydrogen
- Large passenger-carrying hydrogen flights could happen from 2035 onwards

2. What is hydrogen?

Hydrogen is the simplest, most common element we know. It has one electron, one proton, and one neutron and is the building block of the universe. It is, however, very reactive and so is rarely found in its pure form. It is most accessible in combination with other elements like carbon or oxygen, forming water (H_2O) and natural gas (CH_4) molecules.

Hydrogen is also present in common hydrocarbon fuels like jet fuel, gasoline, diesel, or SAF. A jet fuel / SAF molecule, for example, could have 12 carbon atoms and 23 hydrogen atoms. As such, hydrogen is required to make SAF through most pathways, and to refine conventional jet fuel. Under ideal conditions, for example,1 tonne of SAF made through the Power-to-Liquid (PtL) process would require nearly 450 kilograms of hydrogen for its manufacture.

3. What could make hydrogen a sustainable solution for aviation?

Pure hydrogen is a fuel that contains no carbon. When utilized, it therefore produces no CO_2 emissions, soot, or unburned carbon particles and can considerably reduce other non-CO_2 emissions like nitrogen oxides (NO_x).

The most sustainable and promising route for generating pure hydrogen is to split a water molecule into hydrogen and oxygen with electrical energy. This is achieved through a process called electrolysis and can be done with desalinized sea water at a marginal cost increase compared with using fresh water (about USD0.01/kg [6]). This hydrogen is called **green hydrogen**, if the electrical energy comes from renewable sources. **Yellow hydrogen** is used to classify hydrogen made from electrolysis but using energy from the grid, and **pink hydrogen** is used to describe hydrogen made using nuclear power. In theory, hydrogen can be produced anywhere in the world if those two ingredients, water and electricity, are available.

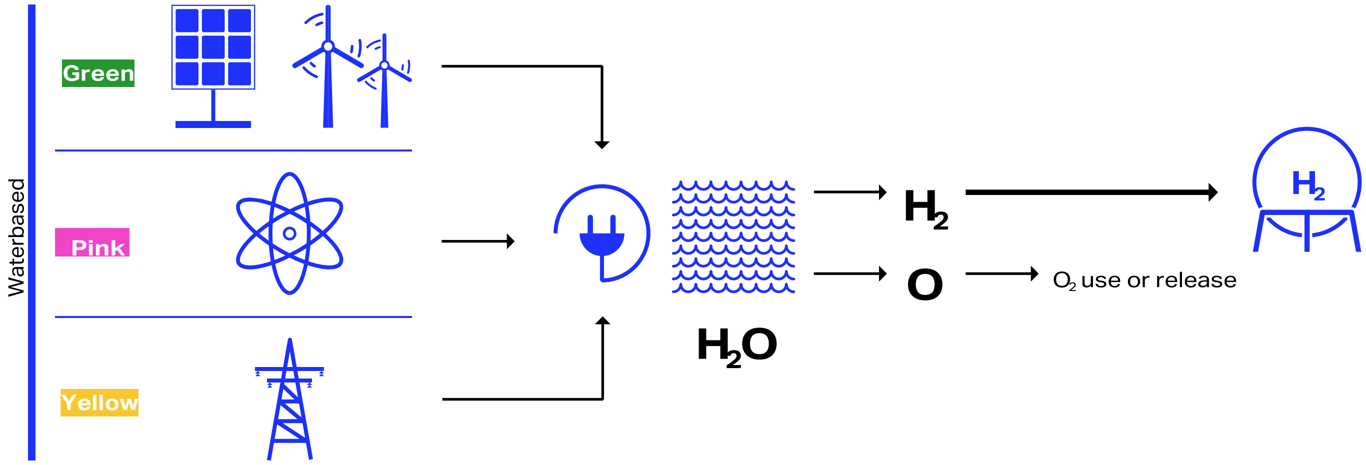

Chart 1 Schematic of green, pink, and yellow hydrogen generation

Most hydrogen produced today, however, comes from natural gas (CH_4), through a process called steam methane reforming. This separates the CH_4 molecule into C and H_4. The hydrogen is captured, and the C (carbon) is released into the atmosphere in the form of CO_2. This is informally known as **grey hydrogen**. Clearly, producing hydrogen in this way would not solve the climate change crisis.

An extra step can be added to this process in which the CO_2 is captured and stored. This can reduce the hydrogen's carbon footprint by up to 90%. This pathway is called **blue hydrogen** production. The carbon capture facilities can increase the cost significantly and currently are unable to capture all the CO_2 emitted so a completely carbon-free fuel isn't assured at this stage.

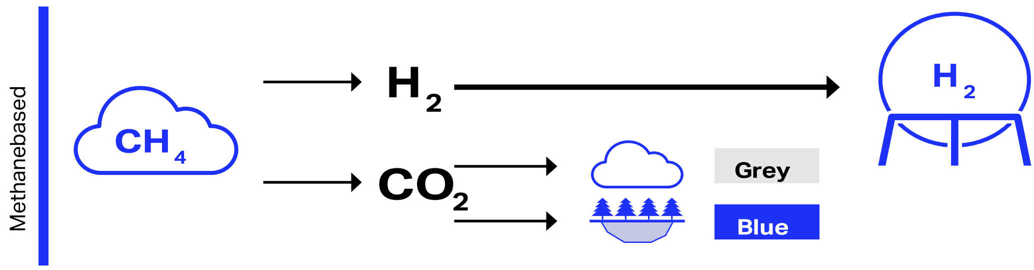

Chart 2 Schematic of blue and grey hydrogen generation

4. What are the opportunities and challenges for aviation?

Assuming that it is produced sustainably, using hydrogen to power aircraft will eliminate aviation carbon emissions (CO_2) from aircraft operations.

In addition, hydrogen has three times more energy per kilogram than kerosene-based jet fuel, while electric batteries have ~60 times less energy per kilogram. Moreover, hydrogen is not limited by feedstock availability if manufactured entirely from seawater and renewable energy.

The properties of hydrogen could also present operational advantages. Because it is three times more energetic than fossil fuel, a hydrogen-powered aircraft would need only a third of the fuel mass to complete a given flight. This represents an immediate operating advantage and enables an aircraft's design to use a lighter structure, smaller and lighter wings, and smaller engines.

However, these physical properties also present challenges. For hydrogen to be practically applicable in aviation, it must be liquefied, and this requires the fuel to be chilled to a temperature lower than -253° C. As a result, it will be necessary to develop specially insulated tanks and next-generation fuel distribution systems. In addition, the larger volume of hydrogen will require additional storage capacity in the aircraft. Thus, this power source is not a "drop-in" fuel. Retrofitting existing aircraft models or developing new ones is a must.

Though the volume occupied by the fuel would be four times larger—because liquid hydrogen is less dense than kerosene—fuel tanks could be accommodated by a longer fuselage. Most concepts for narrowbody aircraft predict a 5–10 meter longer fuselage for this reason [7]. Passenger capacity may therefore not be an issue new designs. A recent study released by the World Economic Forum (WEF) [9] shows that reduced passenger capacity is only an issue for those aircraft that are retrofitted with hydrogen, especially regional turboprop aircraft. In these cases, some seats must be removed to accommodate the hydrogen tanks. The study also shows that a "clean sheet" design aircraft could potentially carry more passengers than an equivalent kerosene-powered aircraft [8].

On the ground, most of the infrastructure would need to be adapted, including trucks, trains, pipelines, and storage tanks. While most studies conclude that hydrogen could be as safe or even safer than kerosene, handling liquid hydrogen will present unique challenges and hazards. Specialized equipment and procedures will be required to address risks of frostbite, leakages, spills, and fires [9]. These challenges, and the changes in airport operations are tackled in depth in the IATA/ACI/Airbus [Concept of Operations of Battery and Hydrogen-Powered Aircraft at Aerodromes](#).

5. How can hydrogen be used to power aircraft?

There are presently two main pathways to extract the energy from hydrogen and use it to power an aircraft. One is reversing the electrolysis process explained above and recombining hydrogen with oxygen to create water and generate electricity. This is done in a fuel cell, which works in a similar way to a battery, by converting chemical energy to electrical energy. The electrical energy generated through this process can then be used to power an electric motor for a fully electric or a hybrid-electric aircraft.

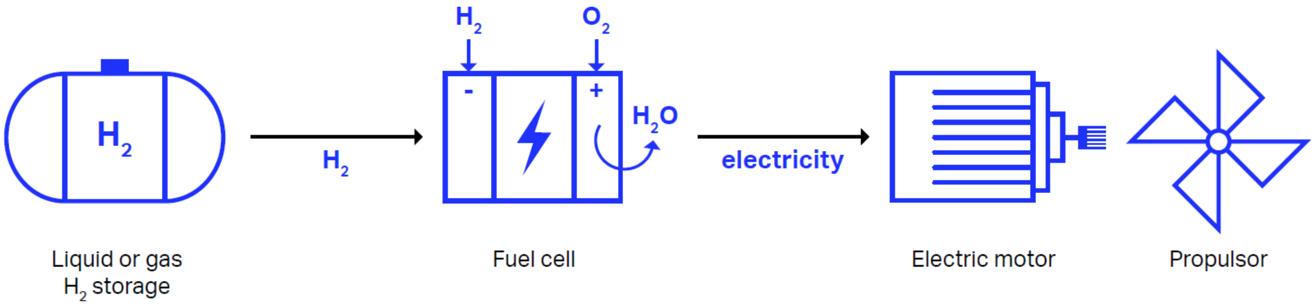

Chart 3 Hydrogen fuel cells to power electric aircraft

Various hydrogen fuel cell-powered aircraft are under development today (see figure 5). The limitation of fuel cells and electric propulsion is the amount of power that can be extracted and used. This limitation has to do with fuel cell efficiency (and therefore weight), propeller performance, heat management, motors and electric power distribution systems, and the added weight due to the electrical equipment.

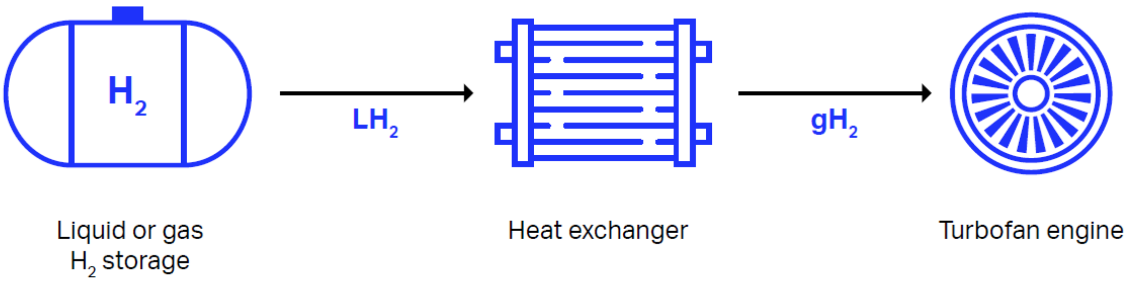

Chart 4 Hydrogen gas turbine to power civil aircraft

Engines on!

The two largest aircraft engine manufacturers in the world announced plans to start a series of rig, engine, and flight tests to prove the efficient and safe use of hydrogen on aircraft gas turbines in preparation for entry-into-service of a zero-emission aircraft [19] [20].

To power larger and faster aircraft like single-aisles turbofan aircraft (similar to A320/ B737), hydrogen needs to be used in a different way.

Hydrogen gas is flammable, just like kerosene, so it is possible to use it in a jet engine much like we use conventional fuels today. One of the first jet engines in the world, the Von Ohain, was, in fact, tested with hydrogen in the 1930s. In the 1950s, NACA (now NASA) flew a B-57 with hydrogen in one of its engines, and in the 1980s, Tupolev converted a Tu-154 to fly on hydrogen [10]. Since then, the US National Aeronautics and Space Administration (NASA), Boeing, Lockheed Martin, Airbus, Cranfield University, the German Aerospace Centre (DLR), and the Aerospace Technology Institute (ATI), among others have created conceptual models of aircraft powered by hydrogen.

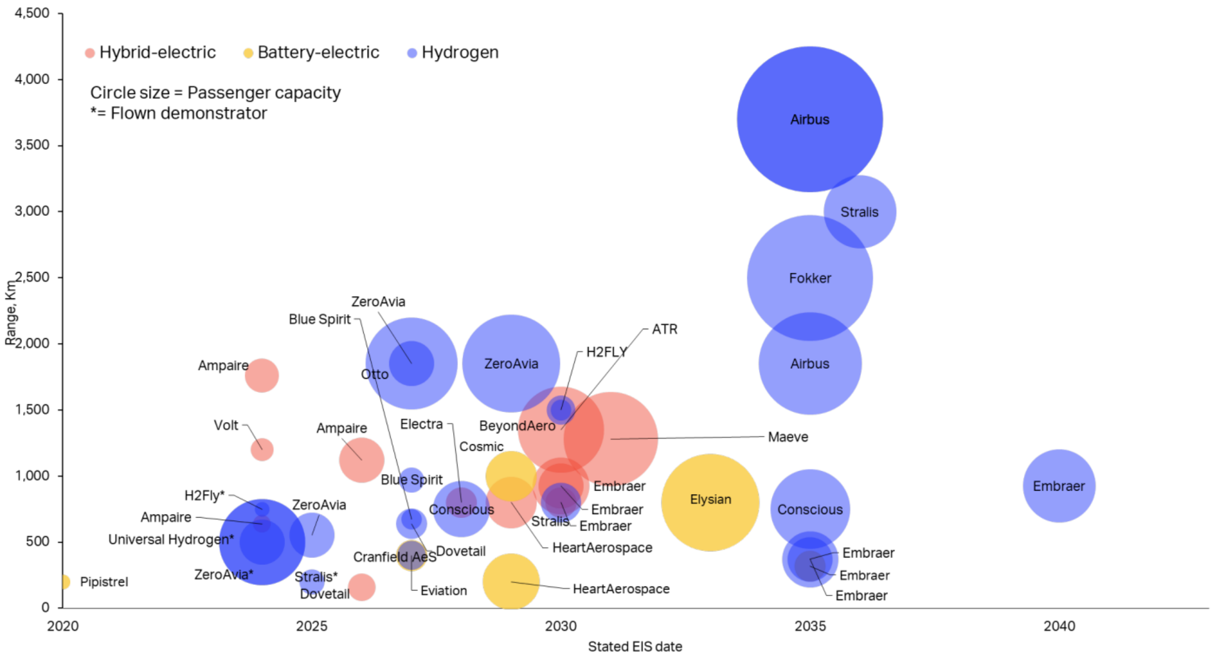

Chart 5 Hydrogen, battery, and hybrid-electric aircraft projects: Source IATA Sustainability and Economics

6. What is the current state of development?

Aircraft technology

To date, IATA has tracked over USD4 billion of announced investment into adopting hydrogen for aviation. This aggregated number includes engine demonstrator programs, aircraft fuel system test rigs, retrofits of existing aircraft, climate science experiments, and airport infrastructure studies.

Studies dating back to the 1970s, and confirmed by recent research, suggest that hydrogen could be used not only to power small regional aircraft but also transatlantic aircraft, covering all but the extra long-haul flights and thereby addressing some 90% of global aviation emissions [11] [12] [7] [13] [8]. Initial developments, however, focus on short and medium-haul operations.

Airport infrastructure

Hydrogen would affect airports through new refueling and storage infrastructure for aircraft and through the possibility of using it as a power source for ground support vehicles and passenger and cargo ground transportation. There are an ever-rising number of reports investigating hydrogen's integration into airports, including the recent IATA/ACI/Airbus report Concept of Operations of Battery and Hydrogen-Powered Aircraft at Aerodromes. Airports have also partnered with aircraft manufacturers and hydrogen providers to understand the requirements of hydrogen.

Hydrogen development

Today, renewable energy is already the cheapest form of energy in some regions, and this trend is certain to grow. According to the International Renewable Energy Agency, this could make green hydrogen competitive with fossil fuels in the mid-2030s—before the entry into service of hydrogen aircraft [6]. The drop in price would reflect cheaper renewable energy prices, the maturing of electrolyzing technologies, and the increase in hydrogen demand, making supply more plentiful.

There are over 70 countries with a hydrogen strategy to decarbonize different sectors of their economies. This does not mean that aviation would necessarily be the prime customer for hydrogen, and, in fact, forecasts show that aviation could account for 8%–12% of the global hydrogen energy supply in 2050. It is vital, however, that the potential use of hydrogen for aviation is integrated into national strategies [13].

A peek into future aircraft concepts

ZeroAvia retrofitted a 19-seater Dornier 228 aircraft to test and mature hydrogen systems and technologies. The Dornier 228 with the ZA600 powertrain became the largest-ever fuel cell-powered aircraft to fly when it made its maiden flight. The company has completed over 12 test flights to date.
© ZeroAvia

Airbus announced plans to realize Zero-carbon emissions aircraft by 2035. One of its concepts is a turbofan-aircraft with a capacity of 200 passengers and a range of 2,000 nautical miles. Airbus has partnered with over 200 airports to advance the hydrogen ecosystem.
© Airbus

GKN Aerospace is leading the ATI-funded Project H2GEAR, which aims to develop a liquid hydrogen propulsion system for sub-regional aircraft by 2026.
© GKN Aerospace

H2Fly Flew in 2023 the first-ever liquid hydrogen-powered aircraft in collaboration with AirLiquide. The flight lasted for more than 3 hours and the company continues to advance liquid hydrogen technologies for longer range aircraft applications.
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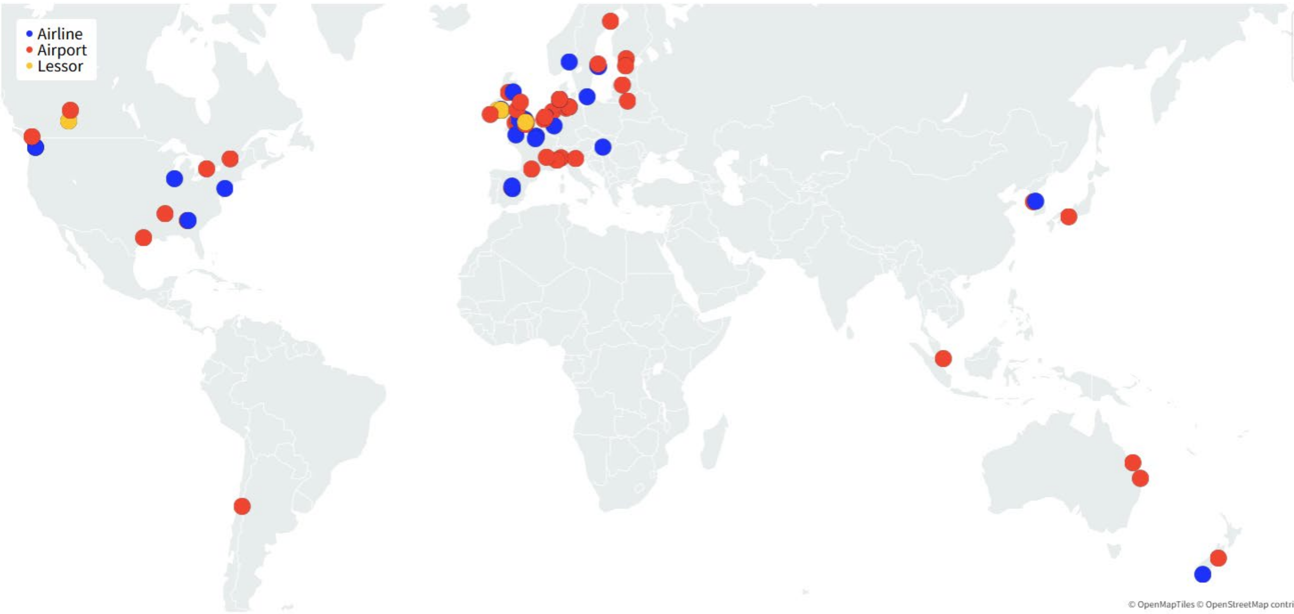
7. Which airlines are involved in developing hydrogen solutions?

By January 2025, at least 35 airlines have publicly announced involvement in different hydrogen-powered aircraft projects (this number has more than doubled since the end of 2023). Some airlines are investing directly in research and development projects. ZeroAvia, for example, has received funding from IAG, Alaska Airlines and United Airlines. In the United Kingdom, EasyJet has announced investment into Rolls Royce to accelerate the introduction of a hydrogen-powered engine. There are also pre-order agreements in place for hydrogen aircraft and several contribution agreements between airlines and manufacturers to promote hydrogen solutions.



Source: IATA Sustainability and Economics
Note: This map simplifies borderlines for better data visibility, which does not imply IATA's endorsement of any territorial claims or borderlines.

Chart 6 Hydrogen projects as of January 2025

8. What is the economic potential of hydrogen-powered aircraft?

Though there is uncertainty over the operating cost of hydrogen aircraft, there are indicators that suggest it could be roughly equivalent to a kerosene-powered future aircraft and cheaper than a 100% SAF-powered flight. Two factors dominate the predictions. First, the cost of green hydrogen is expected to drop nearly 80% in the next 10 years. Second, though hydrogen could continue to be more expensive than kerosene on a per-kilogram basis, its superior energy content means only a third of the fuel mass is required to complete a flight. Therefore, airlines would buy three times less hydrogen compared with fossil fuel, effectively making the new power source cheaper.

A recent publication predicted that a hydrogen narrowbody aircraft could have a 5% lower operating cost than an equivalent technology kerosene-burning aircraft, considering ownership, maintenance, and fuel costs [14].

The ICAO Long Term Aspirational Goal study also indicates that hydrogen is the only alternative fuel that could reach price parity with untaxed kerosene before 2040 [15]. A similar analysis by the Air Transport Action Group suggests that the costs of net zero transition could be mitigated by the early adoption of hydrogen aircraft [16].

9. What policy measures can help boost hydrogen development for aviation?

Governments can help the early adoption of hydrogen-powered aircraft through

- incentives and investment to accelerate the technology. This could be in the shape of research grants to help manufacturers de-risk the technology.
- continued investment into understanding the climate impact of aviation and the impact of alternative fuels.
- including hydrogen in low-carbon fuel standards and defining a standard on the lifecycle emission of hydrogen.
- scaling-up renewable energies.
- incentives for the development of hydrogen manufacturing and liquefying infrastructure and airport infrastructure.

10. Conclusion

Hydrogen-powered flight would eliminate tailpipe carbon emissions[1]. Though many challenges exist, several manufacturers, research centers, and universities are actively working on resolving them to enable this technology.

Normal aircraft development times can easily last for 10 years or more once the program has been announced. Realistically, this means hydrogen-powered aircraft are still a few years away. But the work must begin today to make this a reality. Airlines, airports, and manufacturers need to continue collaborating to understand the upcoming challenges, find the best solutions, and maximize the potential that zero-carbon flights can provide.

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