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Prospects for the use of hydrogen technologies in commercial civil aviation

Abstract: The use of hydrogen technologies is the most effective way to decarbonise long-haul transport - including commercial aviation. Two leading technical solutions introducing hydrogen into the propulsion systems of civil airliners are the use of fuel cells generating electricity to power electric motors for propeller propulsion, and turboprop and turbojet/turbofan engines using hydrogen fuel. More than a dozen companies and research centers around the world are carrying out works aimed at introducing hydrogen-powered communication aircraft into operation by 2035.

Keywords: Aviation hydrogen technologies; Hydrogen aviation propulsion; Aviation electric propulsion; Fuel cells; Turboprop engines; Turbofan engines

Introduction

The journey to a zero-emission, decarbonized economy of the future is expected to rely heavily on a rapid departure from hydrocarbon fossil fuels and the electrification of most sectors of human activity. These measures, aimed at protecting the climate and natural environment, will encompass all modes of transportation—particularly long-distance transport—including road, rail, maritime, and aviation. Among the range of existing and emerging technologies, hydrogen-based solutions hold a prominent place. These leverage "green" hydrogen, produced in electrolysers powered by renewable energy sources, or "pink" hydrogen, generated through nuclear-powered electrolysers.

Currently, intensive research and development efforts are underway, and in an optimistic scenario, hydrogen-powered commercial aircraft may be introduced before the end of this decade. These aircraft would replace conventional aviation fuels, such as jet kerosene (used in turbofan and turboprop engines) and high-octane gasoline (used in piston engines). According to forecasts by McKinsey & Company, a global strategic management consultancy, hydrogen-powered aircraft are expected to enter the market by the late 2030s and could account for approximately one-third of global air traffic by 2050.

Hydrogen in Aviation: Nothing New Under the Sun

Hydrogen played a key role in the early days of aviation, enabling the development of aerostats—lighter-than-air craft that float due to buoyant force, as described by Archimedes' principle. Over two centuries ago, French inventor Jacques Charles constructed a hydrogen-filled balloon that undertook its maiden flight on August 27, 1783, in Paris. Hydrogen balloons, known as "charliers" after their creator, were quickly adopted by the military for reconnaissance and artillery targeting.

In the early 20th century, airships—balloons equipped with internal combustion engines—were developed. "Zeppelins," named after their German inventor, were used extensively in both military and civilian aviation for three decades. However, the era of hydrogen-powered airships came to an end following the catastrophic explosion of the famed German airship *Hindenburg* on May 6, 1937, during docking at Lakehurst, New Jersey, after a transatlantic flight.

Hydrogen made its return to aviation two decades later, this time as a fuel. In 1957, the United States conducted tests on a modified military aircraft, the Martin B-57B, in which one of its two Wright J65 turbojet engines could be switched mid-flight to hydrogen fuel instead of jet kerosene. During the first test, the hydrogen-powered engine operated for 20 minutes.

Hydrogen Technologies for Aviation Propulsion
There are two primary applications of hydrogen for aviation propulsion:

1. **Combustion Engines**:
Turbofan, turboprop, or (less commonly) piston engines burning compressed or liquefied hydrogen instead of jet kerosene or gasoline in atmospheric air.
2. **Electric Motors**:
Electric motors (driving propellers) powered by electricity generated in fuel cells using compressed or liquefied hydrogen and atmospheric air.

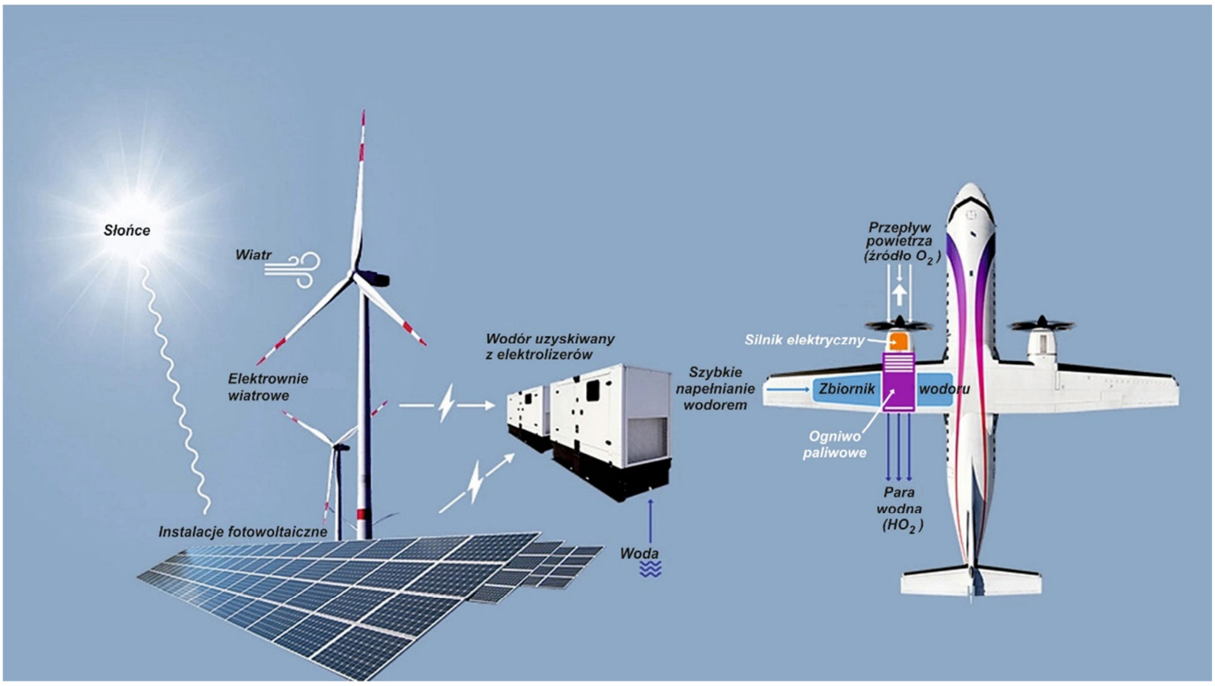
Hydrogen possesses exceptionally high calorific value—119.9 MJ/kg compared to approximately 43 MJ/kg for gasoline—and a heat of combustion of 141.9 MJ/kg, making it an almost ideal fuel [1]. However, its energy density presents a challenge:

Energy Density Comparison:
- Gaseous hydrogen at normal pressure and temperature: 10.05 kJ/liter
- Liquid hydrocarbons: 31,293 kJ/liter (3,114 times higher than hydrogen gas)
- Compressed hydrogen at 690 bar: 4,500 kJ/liter (7 times lower than liquid hydrocarbons)
- Liquid hydrogen at 20 K (-253°C): 8,491 kJ/liter (3.7 times lower than liquid hydrocarbons)

Challenges in Aircraft Design
One of the major challenges in designing hydrogen-powered aircraft is accommodating the significantly larger hydrogen storage tanks required due to its lower energy density compared to conventional fuels. In traditional aircraft, hydrocarbon fuel tanks are integrated into the wings. For hydrogen-powered aircraft, much larger tanks must be housed within the fuselage or integrated into a "blended wing body" design that combines the fuselage and wings. Additionally, cryogenic tanks for liquid hydrogen require robust thermal insulation, further increasing volume requirements.

Environmental Considerations
When hydrogen is combusted in atmospheric air in turbine engines, the byproduct is water. However, there is a risk of producing harmful nitrogen oxides (NOx) due to high-temperature reactions, similar to those in the combustion of coal and hydrocarbon fuels. By contrast, fuel cells powered by hydrogen and atmospheric air produce only clean water as a byproduct, with no harmful emissions, making them an environmentally superior alternative.

Hydrogen's high energy potential and versatility in aviation propulsion technologies offer a promising path toward sustainable and zero-emission air transport, despite the engineering challenges associated with storage and integration.



1. A schematic of zero-emission use of hydrogen fuel in commercial aviation within the propulsion system of a regional aircraft. The design features fuel cells powering electric motors that drive the propellers. The hydrogen fuel is produced by electrolyzers powered by "green" hydrogen derived from renewable sources such as photovoltaics and wind power plants (illustration: ZeroAvia).

In 1975, the American company Lockheed, commissioned by NASA's Langley Research Center, conducted pioneering work in designing large hydrogen-powered commercial aircraft. The conceptual study included designs for aircraft capable of carrying 130 passengers over distances of up to 2,780 km, 200 passengers up to 5,560 km, and 400 passengers up to 9,265 km [2].

A little over a decade later, the Soviet Union modified the Tupolev Tu-154, a three-engine commercial aircraft, adapting one of its engines to run on hydrogen. The prototype, named Tu-155, conducted its first test flight on April 15, 1988. However, the collapse of the Soviet economy in the late 1980s brought further testing to a halt.

Prototypes and Testing in the Early 21st Century

Renewed interest in hydrogen-powered aviation emerged in the late 2000s. This period saw the development of the first prototype hydrogen propulsion systems and aircraft.

1. **Boeing's Hydrogen-Powered Diamond DA20**

Boeing modified a small two-seat Diamond DA20 sports aircraft to run on an electric motor powered by fuel cells designed and manufactured by Intelligent Energy. The aircraft completed its first test flight on April 3, 2008.

2. **Antares DLR-H2 (Germany)**

In parallel, Germany began testing the Antares DLR-H2, an aircraft equipped with a propeller-driven electric motor powered by fuel cells. The first flight took place on July 7, 2009, at Hamburg Airport. In November of the same year, the aircraft successfully flew at altitudes above 2,500 meters, demonstrating the efficiency of its onboard fuel cells under low-pressure conditions. The propulsion system was developed by the German Aerospace Center (DLR) Institute of Technical Thermodynamics in Stuttgart in collaboration with Lange Aviation.

3. **Boeing Phantom Eye**
In 2010, Boeing introduced the Phantom Eye, an unmanned hydrogen-powered high-altitude reconnaissance aircraft. Designed for observation, reconnaissance, and communication support, the aircraft could remain airborne for up to four days carrying a payload of approximately 200 kg. The propulsion system consisted of two 2.3-liter piston engines adapted from Ford Fusion car engines and modified to burn hydrogen. High-altitude operation (up to 20,000 meters) was enabled by multi-stage turbochargers supplying oxygen from atmospheric air.
4. **Rapid 200FC (Italy)**
In the same year, flight tests began for the Rapid 200FC hydrogen-powered aircraft developed by the Polytechnic University of Turin as part of an EU-funded project. Compressed hydrogen (stored at 350 bar) was supplied to a fuel cell that powered a 40 kW electric motor. An auxiliary lithium-polymer battery served as an additional power source.
5. **AeroVironment Global Observer**
The United States continued developing hydrogen-powered high-altitude reconnaissance aircraft designed for long-duration flights in the stratosphere. On January 11, 2011, the unmanned AeroVironment Global Observer completed its first hydrogen-powered test flight. Its propulsion system, powered by fuel cells, drove four high-efficiency electric motors. Earlier test flights relied on battery power.
6. **HY4 (Germany)**
In 2016, the German Aerospace Center (DLR) began testing the HY4, an experimental aircraft powered by electric motors supplied by fuel cells. The aircraft was equipped with a tank containing 9 kg of compressed hydrogen, four 11 kW fuel cells, and two 10 kWh lithium batteries.

Hydrogen Propulsion for Commercial Aviation
At the start of the 21st century (2000–2002), Airbus, a leader in European commercial aviation, conducted a study under the EU-funded "Cryoplane" project. The study explored the future of hydrogen-powered passenger aircraft using turbofan engines. It addressed aerodynamic configurations, onboard systems, propulsion units, airport infrastructure, safety considerations, environmental compatibility, and market introduction scenarios. The project analyzed potential designs, including:

- A **12-seat business jet** with a range of 6,500 km,
- A **regional aircraft** for 44 passengers with a range of up to 2,800 km,
- A **regional aircraft** for 70 passengers with a range of up to 3,700 km,
- A **medium-range aircraft** for 185 passengers with a range of up to 7,400 km, and
- A **long-range aircraft** for 380–550 passengers with a range of up to 15,700 km.

These developments underscore the growing potential of hydrogen as a fuel for both experimental and commercial aviation, offering a path toward sustainable and zero-emission air travel.

2. Three conceptual designs for hydrogen-powered commercial aircraft developed by Airbus as part of the ZEROe program, which could be introduced into service by 2035: a short-range turboprop aircraft for 100 passengers, a medium-range turbofan-powered aircraft for 200 passengers, and an aircraft with an unconventional, futuristic aerodynamic configuration based on a blended wing body combining the features of a traditional fuselage, wings, and tail (illustration: Airbus)

In September 2020, Airbus unveiled three conceptual designs for hydrogen-powered commercial aircraft as part of its **ZEROe** program. According to the company, these aircraft could enter service by 2035. The proposed designs include:

1. **Short-Range Turboprop Aircraft**:

A regional turboprop aircraft designed to carry 100 passengers, targeting short-haul routes.

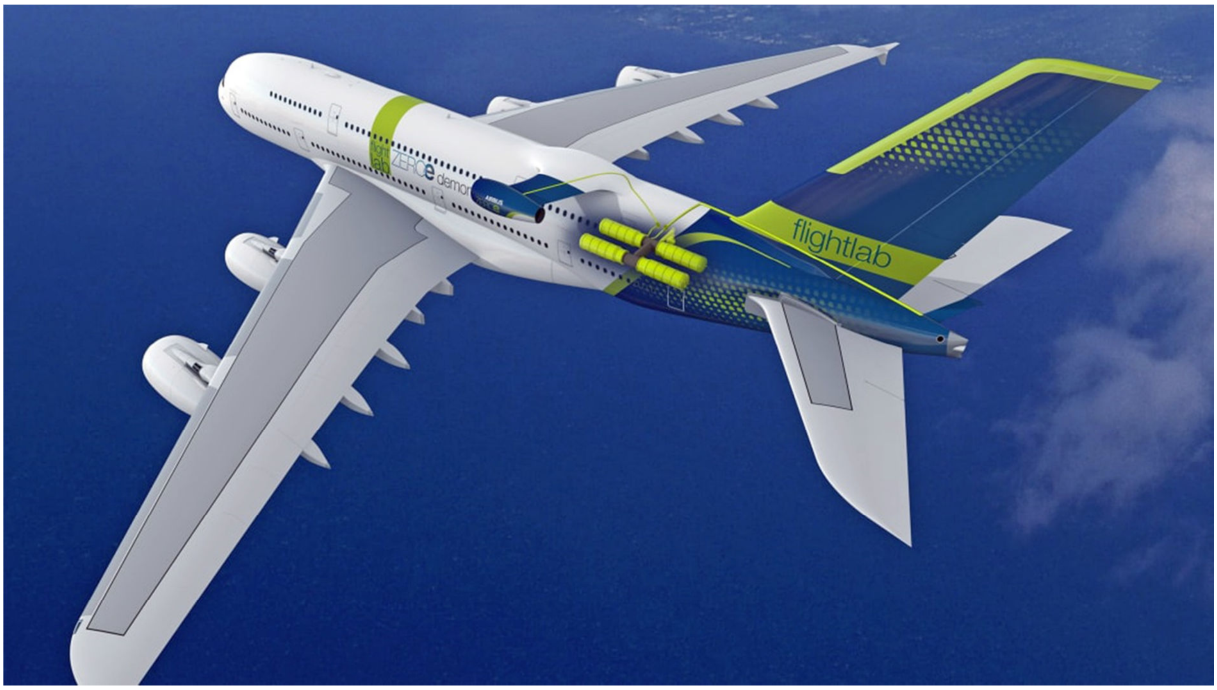
2. **Medium-Range Turbofan Aircraft**:

A conventional turbofan-powered aircraft with a capacity for 200 passengers, suitable for medium-haul operations.

3. **Futuristic Blended-Wing Body Aircraft**:

An unconventional, futuristic design featuring a blended-wing body configuration. This design integrates elements of the fuselage, wings, and tail, creating an aerodynamic structure that combines functionality and efficiency.

All three designs rely on turbine engines powered by hydrogen fuel, showcasing Airbus' commitment to leveraging hydrogen as a clean, sustainable energy source for commercial aviation. These concepts highlight the potential for hydrogen to revolutionize air travel, aligning with global goals for decarbonization and sustainable transportation.



3. A laboratory aircraft based on a modified Airbus A380 will be used for testing future hydrogen propulsion systems for commercial aviation (illustration: Airbus).

In November 2022, Airbus announced plans to develop hydrogen-electric propulsion systems powered by fuel cells for use in commercial aircraft. As part of the **ZEROe** program, Airbus aims to test this propulsion system on a flying laboratory built from an Airbus A380, the largest commercial aircraft ever built. Test flights for the new engine are scheduled for 2026, with the goal of deploying a hydrogen-powered aircraft by 2035.

Mathias Andriamisaina, head of the ZEROe test program, noted that the A380's aerodynamic stability and the placement of the test engine's nacelle at the rear of the fuselage would allow for comprehensive testing of the new propulsion unit without complications. Glenn Llewellyn, Airbus Vice President for Zero-Emission Aircraft, stated that successful trials would pave the way for the development of a 100-seat hydrogen-powered aircraft with a range of 1,600 km.

FlyZero: The UK Aerospace Technology Institute's Ambitions

Other organizations are also pursuing hydrogen-powered aviation. In December 2021, the UK's **Aerospace Technology Institute (ATI)** presented its "FlyZero" study, which envisions a large, long-range hydrogen-powered commercial aircraft with a capacity of 279 passengers and a range of 5,250 km. Supported by leading aerospace companies such as Airbus, Rolls-Royce, and General Electric, the FlyZero initiative has outlined three concept aircraft:

1. **FZR-1E: Regional Hydrogen-Electric Aircraft**
    - **Capacity**: 75 passengers
    - **Propulsion**: Six electric engines powered by hydrogen fuel cells
    - **Design**: Comparable in size to the ATR 72 regional aircraft, but with a wider fuselage diameter of 3.5 meters (compared to 2.8 meters) to accommodate hydrogen tanks.
    - **Performance**: Cruising speed of approximately 601 km/h with a range of 1,480 km.
2. **FZN-1E: Medium-Range Hydrogen-Turbofan Aircraft**
    - **Capacity**: Medium-haul passenger aircraft with two hydrogen-fueled turbofan engines mounted at the rear of the fuselage.
    - **Design Features**:
    - T-tail configuration with an additional forward-mounted horizontal stabilizer.
    - Fuselage 10 meters longer than the Airbus A320neo, with a 1-meter wider rear fuselage section to accommodate hydrogen systems.
    - Foldable wingtips for compatibility with standard airport gate widths.
    - **Performance**: Cruising speed of 830 km/h with a range of 4,400 km.
3. **FZM-1G: Long-Range Hydrogen-Turbofan Widebody Aircraft**
    - **Capacity**: 279 passengers
    - **Performance**: A range of 10,650 km, comparable to the Boeing 767-200ER.
    - **Design**:
    - Fuselage width of 6 meters, similar to the Airbus A350 or Boeing 777.
    - Wingspan of 52 meters (171 feet).
    - Two hydrogen-fueled turbofan engines mounted under the wings.
    - Hydrogen tanks positioned within the fuselage, ahead of the wings, with design considerations for compatibility with standard airport gate dimensions.

The Race for Hydrogen-Powered Aviation

Airbus and ATI's initiatives illustrate the global shift towards hydrogen-powered aviation, leveraging cutting-edge technology to address sustainability challenges. Airbus' ZEROe program focuses on modular, scalable hydrogen propulsion systems, while FlyZero explores a wide range of aircraft configurations. Together, these programs underscore the industry's commitment to decarbonizing air travel and redefining the future of aviation.

4. One of the hydrogen aircraft concepts developed by the UK's Aerospace Technology Institute (illustration: ATI).

In 2021, the Swedish company **GKN Aerospace** launched a collaborative program aimed at developing technical solutions for three critical subsystems of hydrogen-powered engines for medium-range commercial aircraft. The **H2Jet** project, valued at $2.8 million, involves a consortium of aerospace manufacturers working with the Swedish Energy Agency, Chalmers University of Technology, Lund University, KTH Royal Institute of Technology, University West, Research Institutes of Sweden (RISE), and Oxeon. The project focuses on hydrogen-fueled turbofan and turboprop engines. In parallel, GKN Aerospace is also developing the **H2Gear** program, which explores liquid hydrogen propulsion systems for regional aircraft using fuel cells.

The American engine manufacturer **Pratt & Whitney** is integrating its PW1100G turbofan engine with technologies developed under the **HySIITE** project (Hydrogen Steam Injected, Inter-Cooled Turbine Engine). This solution aims to achieve zero CO2 emissions, reduce NOx emissions by 80%, and cut fuel consumption by 35% compared to the baseline PW1100G engine, which powers aircraft such as the Airbus A220. The engine is expected to enter service as early as 2035. On February 21, 2022, the U.S. Department of Energy awarded Pratt & Whitney a $3.8 million grant under the ARPA-E **OPEN21** program for a two-year research initiative. This funding supports the development of a combustion chamber and heat exchanger to recover water vapor from exhaust gases, which is then injected into the combustion chamber to enhance power, supplied to the compressor for intercooling, and used as a coolant for the turbine.

The **ZeroAvia** company, founded in 2017 to advance hydrogen aviation propulsion, has also made significant strides. In 2021, ZeroAvia began work on a 2 MW hydrogen propulsion system for regional commercial aircraft. Initially, the company conducted tests using a Piper PA-46-350P as a flying laboratory, but the aircraft was severely damaged during an emergency landing in April 2021. Development has since continued using a modified **Dornier 228**. In this experimental aircraft, one turboprop engine has been replaced with a prototype hydrogen propulsion system, consisting of an electric motor powered by two fuel cells and a lithium-ion battery.

The Future of Hydrogen-Powered Aviation

The examples provided clearly illustrate the growing momentum toward decarbonizing civil aviation. Leading aerospace companies, research institutions, and governments in highly developed countries are increasingly supporting research and development efforts in this area. Over the next two decades, hydrogen-powered aircraft are expected to enter service:

- **Turboprop Aircraft**: For short- and medium-haul routes.
- **Turbofan Aircraft**: For medium- and long-haul routes.
- **Fuel Cell Electric Propulsion**: For regional aircraft, complemented by battery-electric propulsion for ultra-short routes.

This trajectory suggests that the widespread adoption of zero-emission or low-emission propulsion systems in aviation will soon become a reality, marking a significant step toward sustainable air transportation.

Source materials

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