The Adoption of Hydrogen Fuel in Aviation: Incentives and Challenges for Decarbonization

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Abstract. The aviation industry is among the most challenging sectors to decarbonize, with traditional jet fuels contributing significantly to global CO_2 emissions. As the world seeks sustainable alternatives to mitigate climate change, hydrogen emerges as a promising renewable energy source for aviation. This paper explores the potential of hydrogen fuel to reduce greenhouse gas emissions in the aviation sector substantially. It examines the incentives driving the adoption of hydrogen fuel, including environmental benefits, regulatory support, and technological advancements. Additionally, the paper addresses the significant challenges associated with hydrogen fuel production, storage, and the development of necessary infrastructure. Key issues such as hydrogen's energy density, safety concerns, and the economic implications of transitioning to a hydrogen-based aviation system are analyzed. By evaluating both the opportunities and obstacles, the goal of this paper is to present a thorough understanding of hydrogen's function in the aviation sector's decarbonization initiatives. The goal is to underscore the importance of advancing hydrogen technology for sustainable aviation and to inspire further research and development in this critical field.

Keywords: Fuels, aviation, hydrogen, fuel cells.

1. Introduction

In 1903, the Wright brothers created the world's first powered airplane, the "Flyer I," in the United States, marking the birth of modern aviation [1]. During the First World War, with the increasing development of aviation, planes were widely used for reconnaissance and combat. After the war, aviation technology continued to develop, leading to the rise of commercial aviation. Then, in the Second World War, jet aircraft were used extensively, and post-war jet technology quickly entered commercial aviation. Today, aviation technology is highly advanced. Efficient jet engines, composite materials, and advanced electronic systems have made flying safer and more economical, which helps people a lot. However, a potential problem is that the environment is greatly polluted by the aircraft.

The element that is most prevalent in the universe is hydrogen, and has been recognized for its potential as a clean energy source for many decades. Hydrogen and oxygen mix in fuel cells to produce energy, with the only residue that remains is water vapor. This makes it a desirable choice for lowering the carbon footprint of various industries, including aviation. The adoption of hydrogen fuel in aviation promises to eliminate CO_2 emissions during flight, thus addressing one of the most challenging aspects of decarbonization.

2. Traditional Fossil Fuels for Aviation

Although the aviation sector contributes far less to global carbon emissions—2.1 percent compared to the 11 percent from road transportation—it garners more attention because of the jet engine contrails that have a greater worldwide impact. According to Graver et al., aviation contributes 2.5 percent more to emissions than other modes of transportation and releases 918 million metric tons of CO_2 into the atmosphere [1]. This increases with each new aircraft that is placed into service. Fig. 1 shows the information.

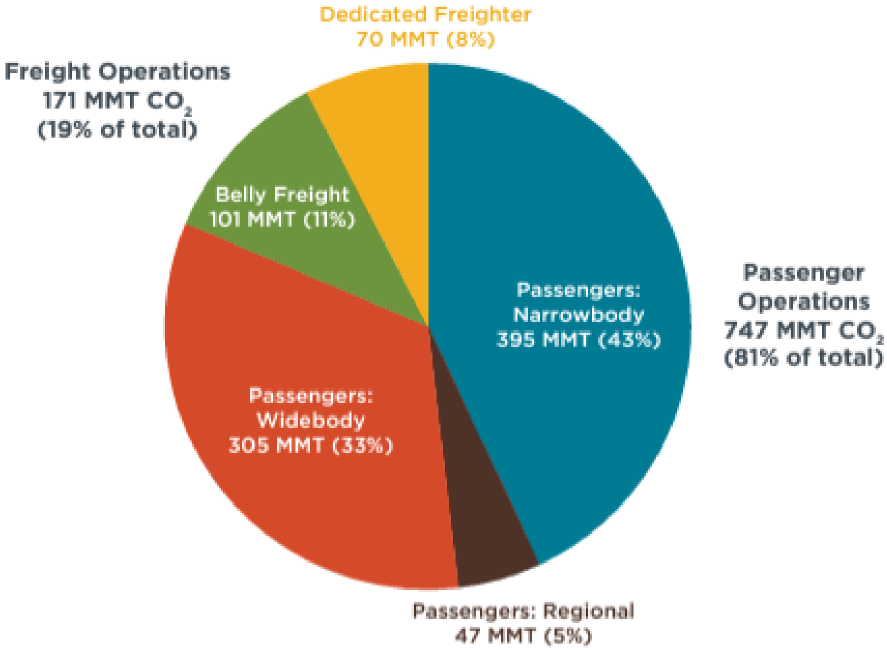

Fig. 1 CO_2 emissions in 2018 by operations and aircraft class [2].

Traditional fossil fuels generate power for aircraft through combustion in jet engines. Jet engines intake large amounts of air, which mixes with jet fuel to form a combustible mixture. This mixture is ignited, then creating high-temperature, high-pressure combustion gases. The gases are expelled through nozzles, driving turbines that power the aircraft's propulsion system. This thrust propels the aircraft forward, enabling it to perform its airborne missions effectively. It is a brief description of how Traditional fossil fuels work in aircraft. However, in the combustion process, pollution emissions are increased by the heavy reliance on fossil fuels in the power and transportation sectors, which has detrimental externalities and degrades the environment [3]. Some of the chemical equations can show the generation of chemical substances.

$$C_8H_{18}+12O_2 \rightarrow 8CO_2+9H_2O \quad (1)$$

$$C_6H_{12}+9O_2 \rightarrow 6CO_2+6H_2O \quad (2)$$

3. Three Types of Hydrogen

In that case, hydrogen fuel is becoming a requirement in the sustainable and low-emission energy problems. Grey, blue, and green hydrogen are the three different forms of hydrogen. Table 1 shows the process/technology, source and carbon output of hydrogen types.

Table 1. Spectrum color of hydrogen types based on carbon output [4].

	Grey Hydrogen	**Blue Hydrogen**	**Green Hydrogen**
Process/ Technology	Steam methane reforming (SMR) Auto-thermal reforming (ATR)	Carbon capture and storage (CCS)	Electrolysis
Source	Natural gas, gasifier coal, or heavy oil	CO_2-rich stream	Water
Carbon output	8.5–10 kg	0.8–4.4 kg	No carbon emissions

Grey hydrogen, blue hydrogen, and green hydrogen are three types of hydrogen that are different from the sources used in their production and what they would generate. As the table shows, the sources of grey hydrogen are natural gas, gasifier coal, or heavy oil, and the process is steam methane reforming (SMR), where CH_4 reacts with steam to produce hydrogen and carbon dioxide. So, the production of grey hydrogen would create large amounts of carbon dioxide, which pollutes the environment greatly. The next one is blue hydrogen. It is the enhanced form of gray hydrogen. Blue hydrogen is produced similarly to grey hydrogen. However, blue hydrogen production employs carbon capture and storage (CCS) technology to absorb and store the carbon dioxide, preventing it from being discharged into the atmosphere. This is how the two types of hydrogen are different from one another. Through seizing and preserving carbon dioxide, blue hydrogen causes less pollution. The last one is green hydrogen. Green hydrogen's source is water. In the process of green hydrogen electrolysis, water splits into hydrogen and oxygen. So green hydrogen production uses entirely renewable energy without causing carbon dioxide, it is the most environmentally friendly type of hydrogen.

4. The Storage of Hydrogen in Aircraft

An aircraft can store hydrogen in three locations: the space behind the passenger cabin, a tank in front of the cabin, and a tank behind. Another alternative is to install two hydrogen tanks in the fuselage tail and one at the top of the cabin [5]. In the first place, hydrogen will change the aircraft's balancing point. Conversely, if medium-range aircraft were to utilize the top tank, the energy potential might rise by 6 to 19 percent. Fig. 2 shows the storage part.

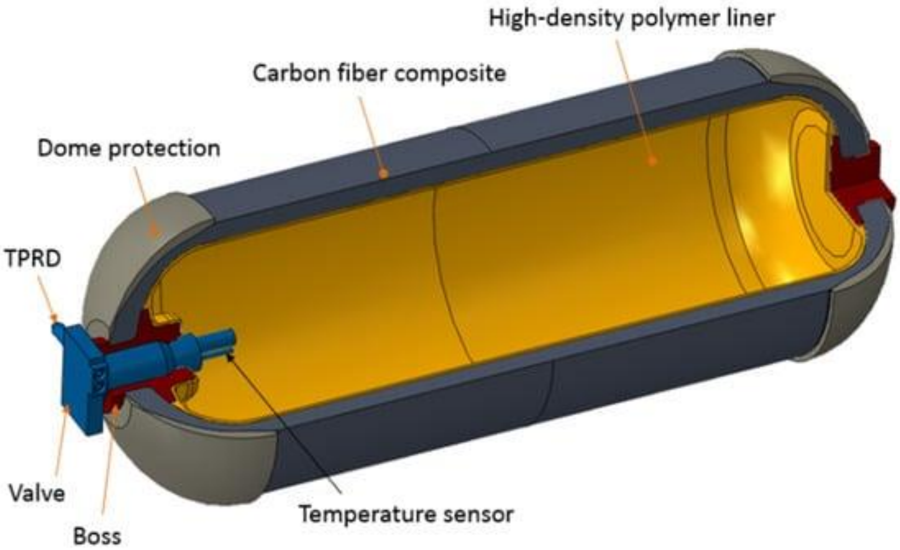

Fig. 2 Tank components for storing hydrogen [6].

To store hydrogen, the technology remains a significant part. These processes are chemical (e.g., employing ammonia and metal hydrides at ambient settings), liquefaction (with the hydrogen in liquid form at −235 °C, 1 bar), and compression (with a gas state at 50–150 pressure, 25 °C) [1].

5. Employ Hydrogen Fuel Cells as a Source of Energy

5.1. APU

Considering the aviation industry's extensive experience with gas turbines, direct hydrogen combustion seems like the most sensible option, especially for larger aircraft, in the near future. However, given their greater efficiency than gas turbines, fuel cells will most likely be used as auxiliary power units (APUs) in hybrid systems. An aircraft's APU is a component that supplies power for uses other than propulsion. APU is typically used for ground power supply and backup power source. It provides electrical power to start the main engines, supply electricity for the aircraft's systems, and provide air for air conditioning and heating when the aircraft is on the ground. During the flight, when the main engine is shut down, the APU becomes a backup power source to provide energy to the aircraft to help operate the aircraft and ensure its safety. APU plays a crucial role in aviation.

Additionally, APUs have lower power requirements, ranging from approximately 90 kW (Airbus A320) to 450 kW (Boeing 787), making the use of fuel cells more practical. Fuel-cell-based APUs have the potential to generate a larger portion of the total energy required by aircraft than conventional APUs, a concept often referred to as "more-electric aircraft." This would enable the primary or exclusive usage of conventional or hydrogen-fueled gas turbines for propulsion energy. Consequently, turbines could be designed to be more efficient due to the elimination of secondary power losses and the ability to operate under more precise conditions [7].

5.2. Varieties of Fuel Cell Types

5.2.1. PEMFC

Proton exchange membrane fuel cells (PEMFC) are viewed as efficient fuel cells and generate minimal pollution. It works at a low temperature and can start rapidly. PEMFC can work efficiently and meet various power demands, which is suitable for many kinds of applications. Hydrogen ions get through the PEM easily because it is a thin plastic sheet. Active catalysts in the form of widely distributed metal alloy particles (mostly platinum) are present on both sides of the membrane. Hydrogen is supplied to the fuel cell's anode side, where it combines with metal alloy particles to form hydrogen ions (protons), which are released from hydrogen atoms. Before returning to the fuel cell's cathode side, where oxygen is supplied, the electrons travel as a usable electric current. When protons diffuse through the membrane to the cathode, where the hydrogen atom recombines and interacts with oxygen to produce water, the process is finished [8]. Fig. 3 shows the process.

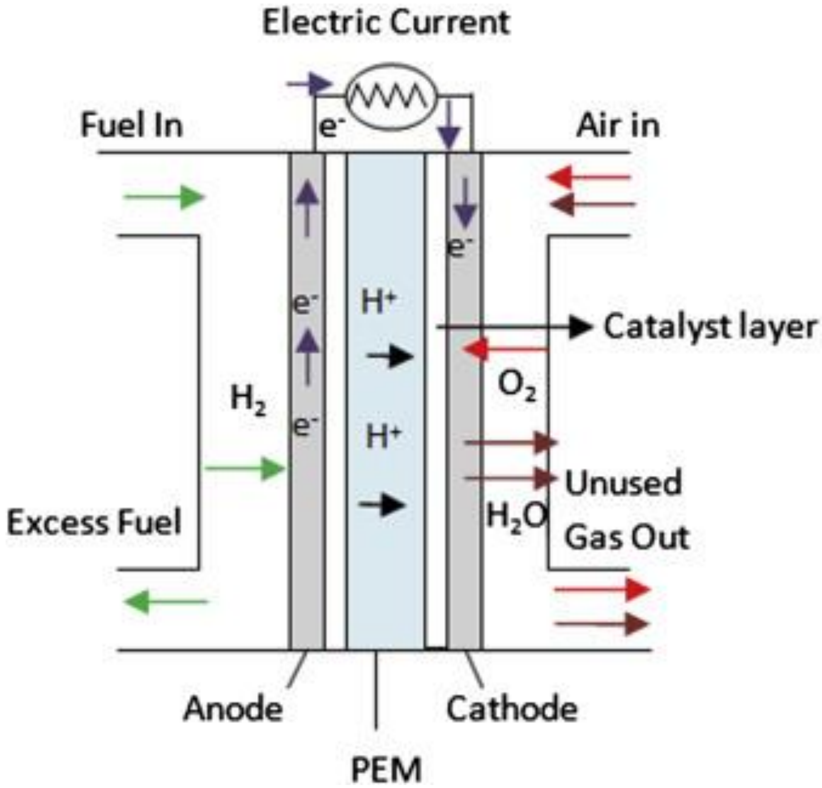

Fig. 3 Diagrammatic representation of proton exchange membrane fuel cell. PEM, proton exchange membrane [9].

In the calculation of the size of full hydrogen, PEMFC (solid red line) also reduces the electrical propulsion's weight, as Fig. 4 shows.

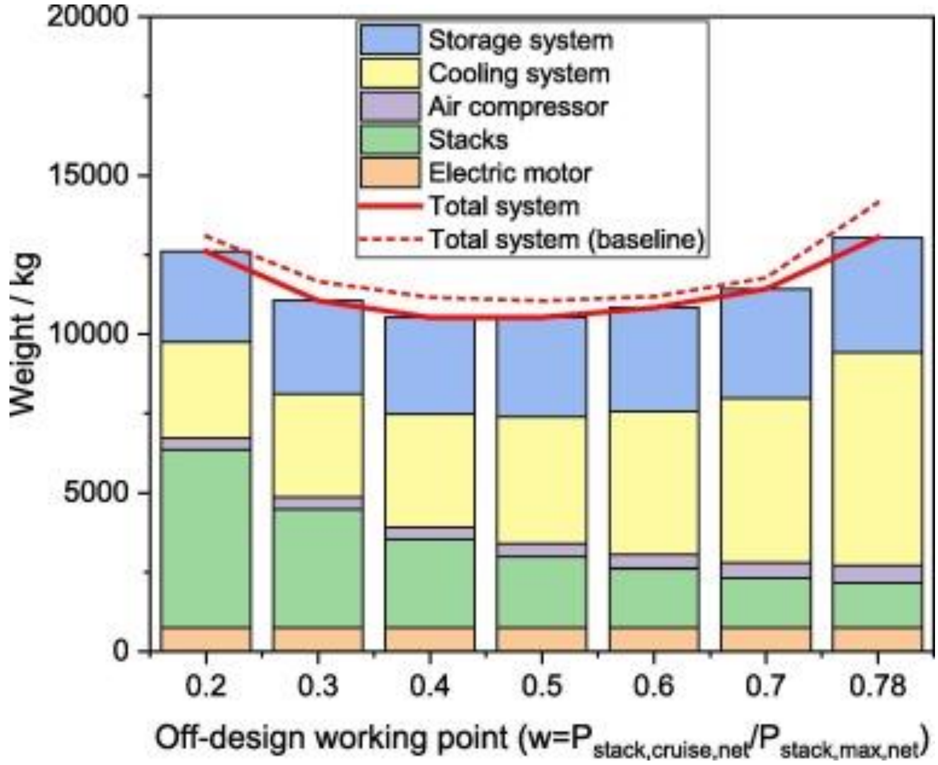

Fig. 4 Weight distribution of the components of the electrified propulsion for different off-design working points in the case of high-performance PEMFC [10].

5.2.2. AFC

An apparatus that can transform chemical energy into electrical energy is the alkaline fuel cell (AFC). An Alkaline Fuel Cell (AFC) uses the OH− ion as the charge carrier rather than a proton since it uses KOH aqueous solution as the electrolyte. H+ ions are created at the anode during the electro-oxidation of the fuel, and these ions combine with OH- ions to make water. In the meantime, electrons are transmitted via an external circuit. At the cathode, these electrons eventually combine with water and oxygen to produce OH- ions. The following can be used to summarize the overall response [11]:

$$2H_2 + O_2 \rightarrow 2H_2O + \text{electrical energy} + \text{heat} \tag{3}$$

AFC is the newest type of fuel cell technology. AFC has lower temperature demand compared to PEMFC. It also provides fuel flexibility, improves reaction kinetics, and significantly reduces fuel crossover.

5.2.3. PAFC

The phosphoric acid fuel cell (PAFC) is among the limited number of commercially available fuel cells. Numerous installations of these cells exist globally. PAFCs achieve a power generation efficiency of 40% and function at temperatures between 150 and 300°C. At lower temperatures, they have poor ion conductivity, and carbon monoxide (CO) significantly poisons the platinum catalyst [12]. The chemical equations can show the reactions:

$$\text{anode: } H_2g \rightarrow 2H+aq+2e^- \tag{4}$$

$$\text{cathode: } 12O_2g+2H+aq+2e^- \rightarrow H_2Oliq \tag{5}$$

$$\text{overall reaction: } 12O_2g+H_2g+CO_2 \rightarrow H_2Oliq+CO_2 \tag{6}$$

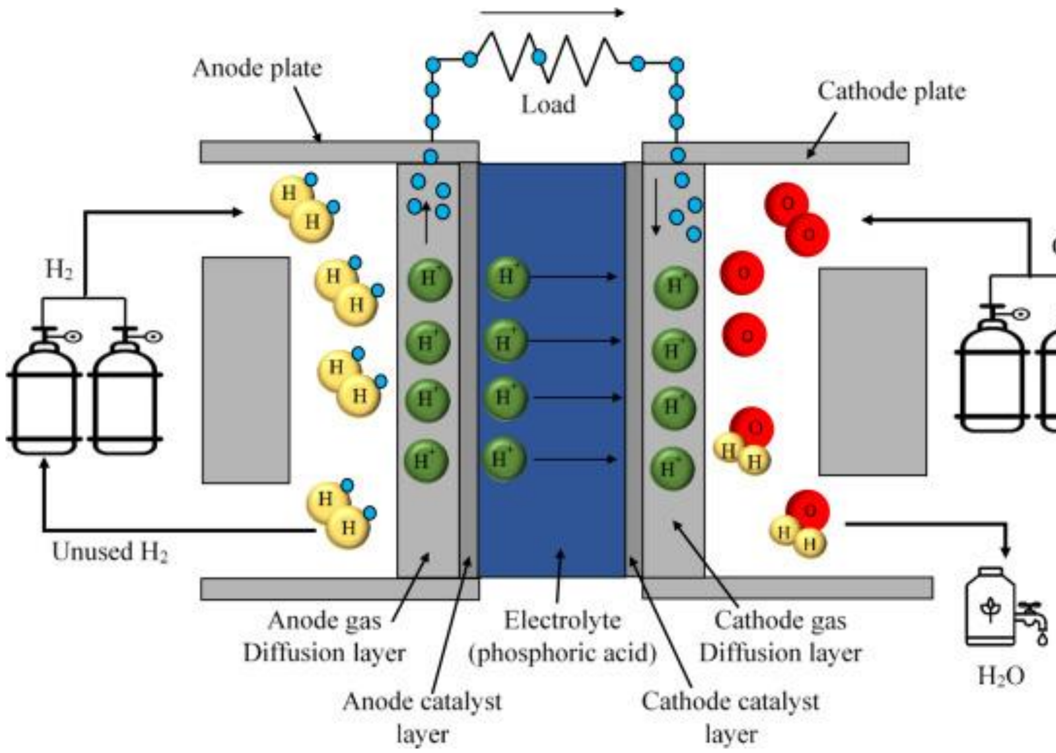

Fig. 5 Schematic diagram of a phosphoric acid fuel cell [13].

Fig. 5 shows the principle of a PAFC. This technology is the most developed and commercially mature among fuel cells, with stationary installations reaching up to 50 MW. Around 200 test facilities are in use globally, mainly for cogeneration purposes. The power range for PAFC batteries spans from 200 kW to 50 MW [12].

6. Conclusion

In contrast to conventional fossil fuels, which produce significant volumes of carbon dioxide, hydrogen fuel plays a crucial part in decarbonization. Hydrogen fuel holds significant promise for decarbonizing sectors like aviation that are challenging to electrify.

More people are realizing how revolutionary hydrogen fuel has the potential to be in the energy sector. Unlike fossil fuels, hydrogen, when used in fuel cells, emits only water vapor, transforming it into a sustainable and clean energy source. This characteristic makes it particularly attractive for industries with high carbon footprints, such as aviation. The aviation sector faces significant challenges in reducing its carbon emissions due to the high energy requirements of long-distance flights and the limitations of current battery technology. Hydrogen fuel offers a viable alternative that can meet these energy demands while minimizing environmental impact.

With the increasingly serious environmental problems, the government may introduce new policies to support hydrogen energy. Hydrogen energy or other renewable energy would be greatly developed in different sectors, not only in aviation but also in maybe vehicles. As the incentives of the government and policy, hydrogen can become a cornerstone of sustainable aviation and contribute to a cleaner and more resilient energy future.

In conclusion, hydrogen fuel holds the promise of a sustainable future for aviation, offering a viable path to decarbonization. With sustained investment, innovation, and collaborative efforts, the aviation industry can overcome the challenges and embrace hydrogen as a cornerstone of its sustainability strategy. This transition will not only benefit the environment but also position the aviation industry as a leader in the global effort to combat climate change.

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