Feasibility of Hydrogen Energy for High-Power Aerospace Applications: A Comprehensive Assessment

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Abstract. Hydrogen energy offers a clean, versatile, and renewable alternative to traditional fossil fuels, playing a crucial role in global decarbonization efforts. This paper assesses the feasibility of hydrogen energy for high-power applications in aerospace, highlighting its potential to reduce environmental pollution and enhance the energy supply. The study evaluates hydrogen turbofan engines, hydrogen fuel cell powertrains, and hydrogen fuel cell electric fan engines, demonstrating improvements in range and load capacity compared to conventional fuels. Additionally, the technical viability of hydrogen storage and distribution infrastructure, such as cryogenic storage, lightweight tank materials, and hydrogen fuel cell technology, is explored. The analysis focuses on fuel efficiency gains, emission reductions, and the integration of hydrogen-powered aircraft into current systems. Considerations include structural design, aerodynamic characteristics, weight distribution, refueling infrastructure, and regulatory compliance. This comprehensive evaluation underscores the significant potential of hydrogen energy in advancing the aerospace industry and contributing to global Sustainable Development Goals.

1 Introduction

Hydrogen energy holds considerable advantages in the aerospace sector in terms of performance and sustainability [1]. Hydrogen energy is proving to be a game-changer in the aerospace sector, offering substantial advantages in both performance and sustainability. Its high energy density enables longer ranges and greater thrust, while hydrogen fuel cells provide high efficiency with zero emissions, producing only water vapor. This makes hydrogen a clean alternative to traditional jet fuels, reducing greenhouse gases and pollutants [2]. Additionally, hydrogen is capable of being generated sustainably sourced from renewable materials, supporting the aerospace industry's efforts to reduce its carbon footprint [1]. As technology and facilities advance, A crucial role is expected to be played by hydrogen energy in enhancing performance and achieving environmental goals in aviation.

Globally, decarbonization has become a crucial objective in addressing climate change. Decarbonization has become a key strategy for addressing climate change on a global scale [3]. It is essential that greenhouse gas emissions, with a particular focus on carbon dioxide,

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be reduced to meet climate targets. The aerospace sector, known for its high energy consumption and emissions, faces significant pressure to reduce its carbon footprint. The application of hydrogen energy technology in this sector can significantly lower carbon dioxide (CO_2) emissions while enhancing the energy efficiency of aircraft, helping the aerospace industry achieve its decarbonization goals [2]. The advancement of hydrogen energy technology offers a practical solution for the aerospace sector. By adopting hydrogen energy, aircraft can achieve high power output while reducing environmental impacts. This not only meets the global demand for low-carbon development but also drives innovation and progress in aerospace technology [3].

To achieve this goal, various industries are actively exploring more environmentally friendly technologies and solutions. In this context, hydrogen energy, with its significant potential as a clean energy technology, is gradually becoming a focal point in the aerospace sector [4]. Particularly in high-power flight applications, the advantages of hydrogen energy not only offer new pathways for environmental protection but also bring new opportunities for the future development of aerospace technology.

2 Technical feasibility of hydrogen energy

2.1 Performance benefits

2.1.1 High energy density

Hydrogen offers the highest energy density per kilogram of any fuel, providing 120 MJ/kg based on its lower heating value [5]. This makes it an exceptionally potent fuel for aerospace applications. While hydrogen has a lower volumetric energy density of 8 MJ/L for its liquid form, gasoline boasts a higher volumetric energy density of 32 MJ/L [5]. It means hydrogen occupies more space for the same amount of energy. Technological advances in storage—such as metal hydrides, carbon-based materials, metal-organic frameworks (MOFs), and nanomaterials—allow efficient storage and use [6]. These innovations enable aircraft to store substantial amounts of energy in a manageable volume, supporting longer flight ranges and greater thrust [7]. The high energy density of hydrogen thus directly contributes to extended operational capabilities and enhanced performance for aerospace vehicles.

2.1.2 Efficient propulsion systems

Hydrogen's potential in propulsion systems is significant, whether used in combustion engines or fuel cells. In hydrogen combustion engines, hydrogen burns at a high flame temperature, which can be optimized to produce efficient thrust, though modifications to traditional engines are necessary to accommodate hydrogen's unique combustion characteristics [8]. Alternatively, Hydrogen fuel cells utilize an electrochemical reaction to convert chemical energy straight into electrical energy, often achieving efficiency rates above 50% [9]. This high efficiency in fuel cells minimizes energy losses and improves overall performance. Both types of propulsion systems, therefore, offer substantial performance enhancements compared to conventional internal combustion engines, delivering significant thrust and operational efficiency [8].

2.1.3 Reduced weight

The use of hydrogen energy can lead to a reduction in the weight of fuel systems and associated components, thanks to hydrogen's light molecular weight [10]. This weight reduction is crucial in aerospace applications, where minimizing mass is essential for optimizing fuel efficiency and overall performance. Hydrogen fuel cells, which are relatively compact and lightweight compared to traditional internal combustion engines, further contribute to this benefit. By integrating lighter fuel systems and components, aircraft can achieve better fuel efficiency, which improves overall performance and allows for more innovative and aerodynamic aircraft designs [11]. Reduced weight translates into less energy required for lift and propulsion, enhancing overall operational efficiency.

2.1.4 Rapid refueling

Hydrogen refueling systems are being developed to match the speed and convenience of conventional jet fuel refueling, aiming to minimize downtime for aircraft. Faster refueling enables more frequent flights and supports quicker service in both commercial and military contexts. The ability to rapidly replenish hydrogen fuel can provide significant operational advantages and streamline aircraft operations [12].

2.2 Cryogenic storage

The procedure entails cooling hydrogen to temperatures below -253°C to transform it into a liquid form. It significantly enhances the density of hydrogen, allowing for storage with higher efficiency plus transport in comparison with its gaseous form. Despite its advantages, cryogenic storage is energy-intensive, requiring substantial energy input for liquefaction and maintaining cryogenic conditions [13]. Additionally, advanced insulation technologies are necessary to manage the boil-off, or evaporation, of liquid hydrogen, which contributes to high infrastructure costs [14].

2.3 Lightweight tank materials

The development of lightweight tank materials is crucial for the efficient storage of hydrogen, especially in applications such as automotive hydrogen tanks. Advanced materials, including carbon fiber composites, offer significant weight reduction and enhanced structural integrity compared to traditional metals. This reduction in weight is particularly beneficial for vehicle performance and efficiency [15].

2.4 Hydrogen fuel-based engines

In the aerospace sector, hydrogen energy can be applied through various technologies, including hydrogen turbofan engines and hydrogen fuel cell power systems. Each of these technologies offers distinct advantages and disadvantages [9].

2.4.1 Hydrogen turbofan engines

They combine the high energy density of hydrogen in relation to the efficiency of turbofan engines, making high power easily occur on this type of engine. They are suitable for long-range and high-thrust applications. When using hydrogen as fuel, the efficiency can be further enhanced due to hydrogen's high energy density, allowing the engine to provide significant thrust with lower fuel consumption. Hydrogen turbofan engines can also leverage existing turbofan engine technologies with established design principles and manufacturing processes. Nevertheless, since the energy utilization efficiency is slightly lower, engineers should Improve the structural design of existing aircraft to accommodate liquid hydrogen fuel storage and try to eliminate the emissions of water vapor and nitrogen oxides [9].

2.4.2 Hydrogen fuel cell power systems

They offer high energy conversion efficiency, typically around 45-50%, which is significantly higher than traditional internal combustion engines. This high efficiency results from the fuel cells' capability to shift chemical energy into electrical energy with minimal energy loss. Furthermore, hydrogen fuel cells emit only water, with no carbon dioxide or other pollutants, minimizing environmental impact. The modular design of fuel cell systems provides flexibility, making them adaptable for various power needs and configurations. However, people should redesign the aircraft structure to accommodate liquid hydrogen fuel storage and a new hydrogen fuel cell power system. They also hold a low power density, which means they currently cannot achieve high power [9]. (See Table 1)

Table 1. Comparison of hydrogen turbofan engine and hydrogen fuel cell power system [9]

	Hydrogen turbofan engine	Hydrogen fuel cell power system
Efficiency	40%	40%-50%
Environmental Influence	No carbon monoxide, carbon dioxide, sulfide and hydrocarbon emissions; There are water vapor and nitrogen oxide emissions	No carbon monoxide, carbon dioxide, sulfide, hydrocarbons and nitrogen oxide emissions; Steam discharge
Technological Difficulty	Existing aviation turbines need to be modified or redesigned to accommodate hydrogen fuel; Raised hitch requirement; Improving aircraft structure and safety requirements; Meet liquid hydrogen storage requirements	Development of efficient, high power density, fast start fuel cells; Develop motor, electronic power equipment cables, and other electrical components that meet airworthiness standards; Improve aircraft structure and safety requirements to meet liquid hydrogen storage needs
The Ways of Working	Turbofan engines that use hydrogen fuel provide thrust through a fan	Hydrogen fuel cells are employed to generate electricity, while thrust is delivered by electric or ducted fans.
Advantages	Zero carbon emissions, a small amount of pollutant	Zero carbon emissions, zero pollutant emissions;

	emissions; The applicability of hydrogen fuel can be improved on the basis of traditional aviation turbofan engines to form hydrogen fuel turbofan engines. Easy to achieve high power	The power system is easier to combine with distributed electric propulsion technology and the energy utilization efficiency is high
Disadvantages	Improving the structural design of existing aircraft to accommodate liquid hydrogen fuel storage; Emissions of water vapor and nitrogen oxides; The energy utilization efficiency is slightly lower	Redesign the aircraft structure to accommodate liquid hydrogen fuel storage and a new hydrogen fuel cell power system; Discharge steam; Low power density, currently cannot achieve high power

3 Performance capabilities

3.1 Enhancing fuel efficiency

Hydrogen energy technology has the potential to revolutionize fuel efficiency in aviation, offering significant improvements over traditional aviation fuels. One of the standout advantages is the high energy density of hydrogen by weight, which is considerably greater than that of conventional jet fuels. Hydrogen’s energy density—around 120-142 MJ/kg—far exceeds that of aviation gasoline (46-47 MJ/kg) or kerosene-based fuels [16]. This means that hydrogen can deliver more energy per unit of weight, which can translate into increased range and operational efficiency for aircraft.

Hydrogen fuel cells, which convert hydrogen into electricity, provide a particularly efficient energy conversion method. They typically achieve efficiency rates of around 55%, which is significantly higher than the 30-40% efficiency of traditional jet engines [17]. This higher efficiency is because fuel cells do not rely on combustion, which is inherently less efficient due to heat losses. Instead, electricity is generated by fuel cells through an electrochemical reaction, resulting in less energy wasted as heat and more energy available for propulsion. Moreover, hydrogen can be used in advanced gas turbines specifically designed for its use. These turbines can be optimized to burn hydrogen more efficiently than conventional turbines. The development of these engines aims to harness hydrogen’s high energy density while minimizing energy losses. As the technology evolves, the design of hydrogen-powered turbines will improve, leading to even better fuel efficiency and extended flight ranges [9].

Efficiency gains from hydrogen technology not only lower fuel costs but also contribute to the overall reduction in the environmental influence of aviation. Through the use of hydrogen more effectively, aircraft can achieve longer ranges and reduced operational costs, making hydrogen a viable alternative for future air travel.

3.2 Reducing emissions levels

Hydrogen energy technology offers significant advantages in reducing emissions, aligning closely with global sustainability goals. Unlike conventional aviation fuels that release considerable amounts of CO_2, nitrogen oxides (NOx), and other pollutants, hydrogen combustion produces only water vapor as a byproduct. This clean combustion profile positions hydrogen as a key player in efforts to lower the environmental footprint of aviation [1,4].

One of the most compelling aspects of hydrogen energy is its zero CO_2 emissions during use. When hydrogen is burned in engines or used in fuel cells, the primary byproduct is water vapor, effectively eliminating CO_2 emissions from the combustion process. This is a stark contrast to traditional jet fuels, which release substantial quantities of CO_2 and contribute significantly to global warming. The aviation industry, accountable for about 2.5% of global CO_2 emissions, stands to make a significant impact on emission reductions by adopting hydrogen technology [18].

Additionally, hydrogen combustion generates no NOx, which is another significant pollutant from traditional aviation fuels. NOx contributes to smog formation and acid rain, impacting air quality and environmental health. By using hydrogen, aviation can mitigate these pollutants, leading to cleaner air around airports and improving public health outcomes. This is especially relevant in densely populated areas where airport emissions can have a more pronounced impact on local air quality [4].

4 Aircraft design and operational integration

4.1 Aircraft design

4.1.1 Structural design

The structural design of hydrogen-powered aircraft is fundamentally different from that of traditional jet-powered aircraft due to the unique properties of hydrogen. Hydrogen is reserved either as a gas with high pressure or as a cryogenic liquid, each requiring specific structural considerations. For high-pressure hydrogen storage, the aircraft must incorporate tanks capable of withstanding pressures up to 700 bar (10,000 psi) [19]. These tanks are often made from advanced composite materials, which are both lightweight and extremely strong. The materials must resist the high pressures without deformation or failure, which is crucial for maintaining aircraft safety and performance.

When using cryogenic hydrogen, which is stored at extremely low temperatures (around -233 °C), the aircraft's structure must include highly effective thermal insulation to prevent heat transfer that could cause the hydrogen to boil off. This involves using materials that can handle such extreme cold without becoming brittle or failing [20,21]. The placement of these storage tanks within the aircraft is critical; they must be integrated in a way that maintains the aircraft's center of gravity and balance. Additionally, because hydrogen is highly flammable, safety features such as leak detection systems and reinforced tank casings are essential to prevent accidents. This intricate design process ensures that the aircraft is safe, reliable, and capable of efficient operation with hydrogen as a fuel.

4.1.2 Aerodynamic Characteristics

The aerodynamic design of hydrogen-powered aircraft must address the challenges posed by hydrogen's low density and the associated storage systems. Hydrogen's low volumetric energy density necessitates that storage tanks be either significantly larger or uniquely shaped compared to conventional jet fuel tanks. This can affect the aircraft's aerodynamic profile, potentially increasing drag and altering airflow around the aircraft [22].

To counteract these effects, engineers use advanced aerodynamic design techniques. For example, the aircraft might need to have larger wings or different fuselage shapes to accommodate the hydrogen tanks while maintaining aerodynamic efficiency. Computational Fluid Dynamics (CFD) simulations and wind tunnel testing are employed to refine these designs. CFD simulations help predict how air flows over the aircraft, allowing engineers to reduce drag and improve fuel efficiency [23]. Wind tunnel tests provide empirical data on how the design performs in real-world conditions. (See Fig. 1).

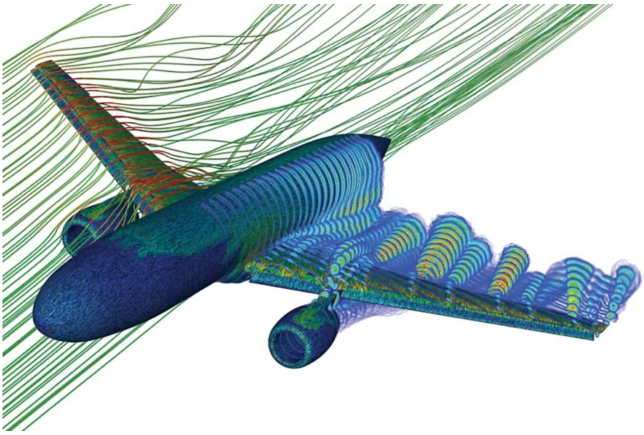

Fig. 1. Ansys Fluent simulation of an external aerodynamics study of a commercial aircraft [23]

4.2 Weight distribution

Effective weight distribution is crucial for significantly impacting the performance and safety of hydrogen-powered aircraft. Hydrogen storage systems, whether high-pressure tanks or cryogenic tanks, add significant weight to the aircraft. Proper weight distribution ensures that the acceptable limits for the aircraft's center of gravity are maintained, which is vital for stability and handling during flight. The placement of hydrogen tanks must be carefully considered to maintain balance. For instance, if the tanks are too heavy or improperly positioned, they could shift the aircraft's center of gravity, affecting its stability and control. Designers must also balance the added weight of the hydrogen storage systems with the need to maximize payload capacity, which includes passengers and cargo. Advanced materials and structural design innovations can help manage the additional weight, such as using lightweight composites to reduce the overall mass of the aircraft. Effective weight management also involves optimizing the aircraft’s design to compensate for the weight of hydrogen storage. This might include adjusting wing configurations or employing innovative structural designs to ensure that the aircraft remains efficient and performs well despite the added weight. Overall, proper weight distribution is key to achieving the desired performance and safety of hydrogen-powered aircraft.

4.3 Fueling infrastructure

The development of fueling infrastructure for hydrogen-powered aircraft is a complex and essential task. Hydrogen refueling stations must be designed to handle the specific requirements of hydrogen fuel, which not only can be stored as a high-pressure gas but also as a cryogenic liquid. High-pressure refueling stations require systems to compress, store, and dispense hydrogen safely. Cryogenic refueling stations must have advanced insulation and cooling systems to keep the hydrogen in its liquid state and to prevent heat-induced vaporization. Refueling infrastructure must be integrated into existing airport facilities to ensure that hydrogen-powered aircraft can be refueled efficiently and safely [13,14]. This includes designing refueling stations that can handle the high pressures or low temperatures required for hydrogen. Efficient hydrogen distribution networks are also crucial, involving pipelines, specialized transport vehicles, and storage facilities to transport hydrogen from production sites to refueling stations.

4.4 Regulatory compliance

Stringent standards set by aviation authorities such as the International Civil Aviation Organization (ICAO) and the Federal Aviation Administration (FAA) must be met by hydrogen-powered aircraft. These standards cover safety, performance, and operational requirements to ensure that hydrogen aircraft are safe for use [3].

The certification process for hydrogen-powered aircraft involves extensive testing, including ground tests and flight trials, to verify that all systems function correctly under various conditions. This process ensures that the aircraft meets all safety and performance criteria before it is approved for operation. Additionally, hydrogen-powered aircraft must comply with environmental regulations related to emissions and fuel efficiency.

5 Environmental and economic impacts

5.1 Environmental benefits of reduced carbon emissions

The environmental benefits of hydrogen energy as an aviation fuel are significant, primarily due to its ability to dramatically reduce carbon emissions and other pollutants. The use of hydrogen fuel cells and hydrogen turbines can substantially decrease greenhouse gas emissions from aircraft during flight, thereby positively impacting the environment.

The combustion process of hydrogen fuel is extremely clean, with water vapor being the only byproduct. This means that burning hydrogen does not produce carbon dioxide (CO_2) or other harmful gases such as nitrogen oxides (NOx). This is in stark contrast to conventional aviation fuels, which release substantial amounts of CO_2 and NOx, both of which are major contributors to global warming and air pollution [6]. For instance, the International Energy Agency (IEA) reports that the aviation sector accounts for roughly 2.5% of global CO_2 emissions. [21]. Using hydrogen as a fuel can significantly reduce this percentage, helping to slow the process of global warming.

5.2 Long-term cost savings

While the initial investment for hydrogen aviation is relatively high, the potential for significant long-term operational cost savings can substantially reduce airline operating expenses.

Future fuel costs of hydrogen could become more competitive compared to traditional aviation fuels. As hydrogen production technologies advance, especially with the maturation of water electrolysis and economies of scale, the cost of hydrogen production is projected to decline significantly. The cost of producing hydrogen from renewable energy is gradually falling, thanks to technological progress and increased production scales. According to predictions from the International Hydrogen Energy Association, the production cost of hydrogen may eventually be on par with or even lower than traditional aviation fuels, thereby reducing long-term operational costs.

Maintenance costs for hydrogen fuel cell systems are generally lower than for traditional jet engines. Hydrogen fuel cell systems have a simpler structure with fewer mechanical parts, resulting in less maintenance work [23]. Moreover, the use of hydrogen reduces internal corrosion and wear in engines, further lowering long-term maintenance costs. This is particularly important in long-term operations, as maintenance costs are a significant component of airline operating expenses. Reduced maintenance needs and extended component lifespans can lead to substantial cost savings.

Although the initial investment in hydrogen aviation technology is high, significant long-term cost savings can be achieved through technological advancements and decreased production costs [24]. These savings not only help airlines reduce operational expenses but also drive the aviation industry toward a more sustainable and environmentally friendly future. Such long-term cost savings will further enhance hydrogen's economic attractiveness and practical application potential as an aviation fuel.

6 Conclusions

Hydrogen energy shows significant potential in high-power flight, especially in aerospace. As an eco-friendly and renewable energy source, hydrogen can both significantly reduce greenhouse gas emissions and aid in achieving global decarbonization goals. In terms of cost, performance and sustainability, hydrogen energy shows clear advantages over conventional aviation fuels. The application of hydrogen turbofan engines, hydrogen fuel cell power systems and hydrogen fuel cell electric fan engines can significantly improve the range and load capacity, which provides broad prospects for the future development of the aerospace field.

However, there are still some challenges to the full roll-out and application of hydrogen energy, especially in terms of hydrogen storage and distribution infrastructure. Although advances in cryogenic storage technology and lightweight tank materials have laid the foundation for hydrogen energy applications, further optimization is needed to reduce costs and improve safety. In addition, the continued advancement of hydrogen fuel cell technology will be a vital component in improving the performance of hydrogen energy applications in aviation.

Considering the advantages of hydrogen energy and its technical feasibility in the aerospace field, we believe that hydrogen energy is expected to become the main energy solution in the aerospace field in the future. Future research and development should focus on solving current technical bottlenecks and promoting the commercialization process of hydrogen energy technology to achieve its full deployment in high-power flight applications.

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