

Hydrogen as a Sustainable Energy Carrier for Mechanical Engineering Applications: A Critical Mini Review

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Abstract: Hydrogen has emerged as one of the most promising energy carriers for achieving sustainable and low-carbon energy systems. Its high gravimetric energy density, zero direct carbon emissions at the point of use, and compatibility with renewable energy technologies make hydrogen an attractive solution for future mechanical engineering applications. Recent developments in water electrolysis, hydrogen storage, fuel cells, and transportation infrastructure have accelerated industrial adoption worldwide. This mini-review discusses hydrogen production technologies, storage methods, engineering applications, current technical challenges, and future research directions from a mechanical engineering perspective.

Keywords: Hydrogen Energy, Green Hydrogen, Fuel Cells, Renewable Energy, Mechanical Engineering, Energy Storage.

1. INTRODUCTION

Global efforts to reduce greenhouse gas emissions have accelerated the transition toward sustainable energy systems. Among the available clean-energy technologies, hydrogen has attracted considerable attention because it can store renewable energy, support industrial decarbonization, and replace fossil fuels in sectors that are difficult to electrify.

Unlike conventional fuels, hydrogen is an energy carrier that must be produced from primary energy sources. The most common production methods include water electrolysis, steam methane reforming, biomass conversion, and thermochemical cycles. Green hydrogen, generated through renewable-powered electrolysis, is increasingly regarded as the most sustainable option.

Mechanical engineers contribute significantly to hydrogen technology through the design of electrolyzers, compressors, pressure vessels, pipelines, heat exchangers, fuel-cell systems, and hydrogen refueling infrastructure.

2. HYDROGEN PRODUCTION TECHNOLOGIES

Hydrogen is commonly classified according to its production pathway.

2.1 Green Hydrogen

Green hydrogen is produced by water electrolysis using electricity generated from renewable resources such as solar and wind energy.

Advantages

- Zero direct carbon emissions.
- Supports renewable-energy integration.
- Long-term sustainability.

Limitations

- High production cost.
- Dependence on renewable electricity availability.

2.2 Blue Hydrogen

Blue hydrogen is produced from natural gas through steam methane reforming combined with carbon capture and storage (CCS).

Advantages

- Lower carbon emissions than conventional production.
- Mature industrial technology.

Limitations

- Carbon capture efficiency.
- Continued dependence on fossil fuels.

2.3 Grey Hydrogen

Grey hydrogen is produced using conventional steam methane reforming without carbon capture.

Although economically attractive, it generates significant carbon dioxide emissions and is therefore inconsistent with long-term decarbonization objectives.

Table 1. Comparison of Hydrogen Production Technologies

Production Method	Carbon Emissions	Relative Cost	Industrial Maturity
Green Hydrogen	Very Low	High	Developing
Blue Hydrogen	Moderate	Moderate	Commercial
Grey Hydrogen	High	Low	Highly Commercial

3. ENGINEERING APPLICATIONS

Hydrogen technologies are increasingly adopted across several mechanical engineering sectors, including:

- Fuel-cell electric vehicles.
- Gas turbines.
- Industrial process heating.
- Renewable energy storage.
- Aerospace propulsion.
- Marine transportation.
- Backup power systems.
- Chemical processing industries.

Fuel cells convert hydrogen directly into electricity with high efficiency while producing water as the only direct by-product. Hydrogen also enables long-duration storage of renewable energy, helping stabilize electrical grids with high solar and wind penetration. Research_Paper_3_FINAL (Part 2)

4. CRITICAL DISCUSSION

Despite significant progress in hydrogen technologies, several engineering challenges continue to limit large-scale commercial deployment.

The primary challenge is hydrogen storage. Because hydrogen has a very low volumetric energy density, it must either be compressed to high pressures (typically 350–700 bar), liquefied at cryogenic temperatures, or stored in advanced solid-state materials. Each approach presents technical and economic limitations.

Another important issue is hydrogen embrittlement, where prolonged exposure to hydrogen reduces the ductility and fatigue resistance of metallic components such as pipelines, pressure vessels, and valves. Careful material selection and protective engineering designs are therefore essential.

Hydrogen transportation infrastructure also remains underdeveloped in many countries. Significant investment is required to construct pipelines, refueling stations, compression systems, and storage facilities capable of supporting future hydrogen economies.

Finally, the current cost of green hydrogen remains higher than conventional fossil fuels due to electrolyzer costs and renewable electricity prices. Continued technological improvements and economies of scale are expected to reduce production costs over the coming decade.

Table 2. Engineering Challenges and Recommended Solutions

Low Volumetric Energy Density	High-pressure tanks and cryogenic storage
Hydrogen Embrittlement	Advanced alloys and composite materials
Infrastructure Development	Modular hydrogen distribution networks
High Production Cost	Improved electrolyzer efficiency and renewable integration
Safety and Leakage	Smart sensors and continuous monitoring systems

5. CONCLUSION

Hydrogen has become one of the most promising energy carriers supporting the global transition toward sustainable energy systems. Its ability to integrate renewable electricity, supply industrial processes, and provide clean transportation makes hydrogen a strategic technology for future mechanical engineering applications.

Although challenges related to storage, transportation, infrastructure, material durability, and production costs remain significant, continuous technological advances are steadily improving commercial feasibility. Future research should prioritize high-efficiency electrolyzers, advanced hydrogen storage materials, AI-assisted system monitoring, and durable engineering materials capable of operating safely under hydrogen exposure.

Mechanical engineers will continue to play a fundamental role in designing safe, efficient, and economically viable hydrogen systems that support global decarbonization and sustainable industrial development.

REFERENCES

- [1] Staffell, I., et al. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science*, 12, 463–491.
- [2] Dawood, F., Anda, M., & Shafiullah, G. M. (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy*, 45, 3847–3869.
- [3] International Energy Agency. *The Future of Hydrogen*.
- [4] International Renewable Energy Agency. *Green Hydrogen Cost Reduction*.
- [5] Hydrogen Council. *Hydrogen Insights Report*.
- [6] *Fuel Cell Fundamentals*.
- [7] *Hydrogen and Fuel Cells*.
- [8] Momirlan, M., & Veziroglu, T. N. (2005). The properties of hydrogen as fuel tomorrow. *International Journal of Hydrogen Energy*, 30(7), 795–802.