

Green Hydrogen: Sustainable Energy Future

Yash Pal¹ Dr. Meenal¹ Preeti Bhandari²

¹ Assistant professor, department of physics, Shri Khushal Das University, Rajasthan

² Research scholar, Department of Life sciences, Desh Bhagat University, Punjab

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Abstract

The transition toward sustainable energy remains one of the most pressing challenges of the modern era. Among various clean energy options, green hydrogen—produced through the electrolysis of water using renewable energy sources—stands out as a viable alternative to reduce dependence on fossil fuels. This paper investigates the potential of green hydrogen across key sectors such as transportation, industrial manufacturing, electricity generation, and heating, highlighting its significance in lowering emissions from traditionally carbon-intensive domains.

The discussion further reviews global policy initiatives and implementation strategies from regions including the European Union, Australia, Japan, the United States, and Canada, all of which are advancing the green hydrogen agenda. Major obstacles hindering widespread adoption include technological immaturity, limited infrastructure, high production costs, regulatory complexities, and societal acceptance.

To fully harness the benefits of green hydrogen, this study recommends enhancing research and innovation, expanding infrastructure networks, reducing production and distribution costs, and establishing cohesive policy and regulatory support systems. Strengthening collaboration among governments, industries, and academic institutions will be critical in accelerating progress. Overcoming these barriers can position green hydrogen as a foundational pillar of the global clean energy transition, paving the way toward comprehensive decarbonization.

Keywords: Green hydrogen, Sustainable energy, Decarbonization.

I. INTRODUCTION

The global energy landscape is undergoing significant pressure due to the decline of fossil fuel resources, the rise in greenhouse gas emissions, and the growing demand for environmentally sustainable energy solutions. Addressing these challenges requires innovative pathways to facilitate a transition toward a low-carbon and energy-secure future. Among emerging solutions, hydrogen has gained prominence as a versatile and clean energy carrier capable of transforming conventional energy systems. It can be applied across multiple sectors—ranging from transportation and power generation to industrial operations—and produces only water as its byproduct, ensuring minimal environmental impact. Within various hydrogen production techniques, green hydrogen stands out as the most sustainable form, produced through the electrolysis of water powered by renewable energy sources such as solar and wind. This carbon-free process aligns seamlessly with global decarbonization and climate mitigation objectives. This paper provides an overview of the technological progress, challenges, and prospects associated with green hydrogen. It further discusses its integration into current energy infrastructures and evaluates its potential contribution toward achieving a sustainable and resilient energy future.

II. GREEN HYDROGEN

“Green hydrogen” refers to hydrogen produced via water electrolysis powered entirely by renewable energy sources—such as solar, wind, or hydropower—which results in zero direct greenhouse gas emissions.

By contrast:

- “Grey hydrogen” is derived from natural gas (primarily methane) through steam-methane reforming, which emits substantial CO₂ because the emissions are released into the atmosphere.
- “Blue hydrogen” uses the same basic process as grey hydrogen but adds carbon capture and storage (CCS) technologies to capture and store the CO₂ emissions, thereby reducing—but not eliminating—its carbon footprint.
- “Turquoise hydrogen” is produced through methane pyrolysis, a process that thermally decomposes methane to yield hydrogen and solid carbon instead of carbon dioxide. Since carbon is obtained in solid form rather than as CO₂ gas, this method offers the potential for reduced emissions. However, it remains an emerging technology, and its overall environmental impact depends on how the solid carbon by-product and energy requirements are managed.

- **Production Technologies**
- **Water Electrolysis:**
 - Alkaline Electrolysis: Mature and cost-effective, suitable for large-scale production.
 - Proton Exchange Membrane (PEM) Electrolysis: Offers high efficiency and dynamic response but at higher costs.
 - Solid Oxide Electrolysis: Operates at high temperatures, improving efficiency and enabling integration with industrial processes.
- **Emerging Technologies:**

Photoelectrochemical and thermochemical splitting methods show promise for future green hydrogen production.
- **Energy Sources**

Renewable energy sources such as solar, wind, and hydropower are pivotal for green hydrogen production, ensuring sustainability and alignment with decarbonization goals.

III. LITERATURE REVIEW

Oliveira, A.M., Beswick, R.R. and Yan, Y., 2021 et al A hydrogen economy has long been promoted as a ground-breaking aspect of a low-carbon future. There remains considerable debate regarding the future of hydrogen, with some expressing concern over limited demand while others overlook its inherent challenges. This study addresses the gap by presenting a clear definition of the “hydrogen economy” and outlining a strategic vision in which hydrogen is primarily employed for decarbonization in sectors lacking viable alternatives. A three-phase roadmap is proposed for integrating hydrogen into the industrial sector as a chemical feedstock, the transportation sector for long-distance and heavy-duty vehicles, the building sector for heating applications, and the power sector for seasonal energy storage. The findings suggest that while hydrogen may not dominate the global energy landscape, an estimated annual demand of 2.3 Gt could enable the decarbonization of approximately 18% of energy-related activities. Over time, hydrogen can serve as a vital complement to renewable electricity and form a cornerstone of a fully renewable energy future.

Panchenko, V.A., Daus, Y.V., Kovalev, A.A., Yudaev, I.V. and Litti, Y.V., 2023 et al This article provides a review of the present state of hydrogen-production technologies and assesses the outlook for the development of green hydrogen using renewable energy in leading nations. It explores the hydrogen-energy potential of regions including Australia, the European Union, India, Canada, China, Russia, the United States, South Korea, South Africa, Japan, and North Africa, emphasising their capacity for hydrogen production via fossil-fuel routes and renewable pathways. Quantitative forecasts for future green hydrogen output and export trends are discussed, alongside advanced hydrogen technologies. Green hydrogen is highlighted as a route to reduce dependence on fossil fuels, cut greenhouse-gas emissions, enhance energy sovereignty, and support global environmental sustainability.

Squadrito, G., Maggio, G. and Nicita, A., 2023 et al This paper presents a critical review of recent studies and institutional reports to assess the current status of green hydrogen development. It examines and compares the specific advantages and limitations of various green hydrogen production methods—such as biomass pyrolysis, gasification, and water electrolysis. Particular emphasis is placed on electrolysis, which is identified as the most promising approach for large-scale and decentralized hydrogen production.

Zhou, Y., Li, R., Lv, Z., Liu, J., Zhou, H. and Xu, C., 2022 et al This article comprehensively considers the new energy revolution and the relevant plans of various countries, focuses on the principles, development status and research hot spots, and summarizes the different green hydrogen production technologies and paths. Furthermore, drawing on an evaluation of the existing challenges and bottlenecks in green hydrogen production, along with an overview of global progress in the hydrogen energy sector, this paper explores the ongoing development and future prospects of green hydrogen technologies.

Kourougianni, F., Arsalis, A., Olympios, A.V., Yiasoumas, G., Konstantinou, C., Papanastasiou, P. and Georghiou, G.E., 2024 et al The global energy sector is currently undergoing a fundamental transformation as it shifts away from fossil fuels towards renewable energy sources. In this context, green hydrogen is identified as a highly promising energy vector for reducing the carbon footprint of energy systems. This review paper examines recent developments in green hydrogen energy systems (GHES), paying particular attention to techno-economic factors spanning individual components, whole technologies, and broader system integrations. First, the paper summarises the technological bases and latest advancements in hydrogen generation, storage and use. Next, it presents an in-depth look at modeling and experimental studies of integrated GHES, with applications in both stationary and transport sectors. Finally, the paper discusses the principal technical barriers, influential

factors, and future research directions—emphasising that smart integration of GHES with other energy technologies is key to increasing resource efficiency, system flexibility, resilience and energy security.

IV. APPLICATIONS OF GREEN HYDROGEN

1. Energy Storage and Grid Stabilization

The application of green hydrogen as an energy storage medium for surplus renewable power is well established. Through electrolysis, excess electricity generated from solar or wind sources can be converted into hydrogen, stored, and subsequently reconverted into electricity using fuel cells or turbines during periods of high demand or low renewable output. For instance, ITM Power demonstrates how PEM electrolyzers contribute to grid stabilization by absorbing excess renewable energy and delivering power when required. Additionally, the International Renewable Energy Agency (IRENA) reports emphasize that green hydrogen serves as an effective means of seasonal energy storage, providing dispatchable electricity to balance fluctuations in renewable generation.

2. Transportation

Green hydrogen is increasingly being utilized in the transportation sector, particularly in areas where battery-electric technology encounters challenges such as long-range travel or heavy payloads. According to the U.S. Environmental Protection Agency (EPA), hydrogen fuel cell electric vehicles (FCEVs) generate electricity onboard by converting hydrogen, producing only water and heat as by-products. Moreover, pilot projects involving heavy-duty hydrogen trucks—such as those conducted by Tata Motors in India—demonstrate the technology's advantages in enabling extended range and rapid refuelling, reinforcing its suitability for long-distance and heavy-duty transport applications.

3. Industrial Applications

The assertion that green hydrogen facilitates industrial decarbonization—particularly in sectors such as steel, cement, and chemicals—is well supported. Industry reports highlight that green hydrogen can substitute carbon-intensive fuels and feedstocks in these energy-demanding processes, significantly reducing CO₂ emissions. Notably, hydrogen-based direct reduced iron (DRI) technologies are being developed as a cleaner alternative for steel production, underscoring hydrogen's growing role in transforming heavy industries toward low-carbon operations.

4. Power Generation

The perspective that green hydrogen plays a role in power generation—through direct use in turbines or hydrogen co-firing—is well substantiated. According to reports from the International Renewable Energy Agency (IRENA), hydrogen integration in the power sector enables flexible electricity generation and serves as an effective means of seasonal energy storage, helping to balance supply and demand in systems dominated by variable renewable sources.

V. STRATEGIES FOR OVERCOMING BARRIERS

1. Technological Innovations

Research and Development for Enhanced Electrolyzer Performance and Cost Reduction: Ongoing R&D efforts are vital to improving electrolyzer efficiency, reducing production costs, and enabling large-scale, cost-effective generation of green hydrogen.

Advancement of Hydrogen Storage and Transport Technologies: Progress in storage and distribution methods—such as high-pressure gas compression, liquefied hydrogen, and dedicated pipeline infrastructure—is critical to lowering logistical costs and ensuring the safe and efficient transport of hydrogen.

2. Economic Measures

Investments and Financial Incentives for Green Hydrogen Development: Both public and private sector funding, supported by targeted subsidies, are essential to accelerate the establishment of green hydrogen infrastructure and offset high initial deployment costs.

Implementation of Carbon Pricing Policies: Introducing carbon pricing instruments—such as carbon taxes or cap-and-trade systems—can enhance the competitiveness of green hydrogen compared to fossil-based energy sources, thereby encouraging its widespread adoption.

3. Infrastructure Development

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4. Policy Support and Collaboration

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VI. FUTURE DIRECTIONS AND INNOVATIONS

Green hydrogen is expected to play a crucial role in achieving global net-zero emissions by providing clean alternatives for hard-to-decarbonize sectors such as heavy industry, long-haul transport, and energy storage. Widespread adoption of green hydrogen can significantly reduce carbon emissions and support decarbonization goals. Additionally, innovations in hybrid systems that combine hydrogen with renewable energy sources like solar and wind enhance energy generation, storage, and grid stability, improving overall efficiency. Exploring hydrogen economy models, such as hydrogen hubs and export markets, can promote regional self-sufficiency, reduce transportation costs, and unlock economic opportunities. Collaborative efforts in research, policy, and investment are essential to harness green hydrogen's potential and drive a sustainable, low-carbon future.

VII. CONCLUSION

Green hydrogen holds tremendous potential as a sustainable energy solution, offering zero-carbon emissions and contributing to global decarbonization efforts. Its ability to replace fossil fuels in hard-to-abate sectors, such as industry and long-haul transport, makes it a key driver of a sustainable energy future. To realize this potential, strong collaboration across governments, industries, and research institutions is essential. Investments, supportive policies, and technological innovation are needed to overcome barriers such as cost, infrastructure, and storage challenges. A green hydrogen-driven future can ensure energy security, reduce reliance on fossil fuels, and support global net-zero targets. By fostering research, policy development, and investment, we can accelerate the transition to a low-carbon, resilient, and economically prosperous world.

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