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Green Hydrogen: Production from Renewable Energy Sources, Challenges and Future Prospects

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Abstract

A promising sustainable energy source for attaining global decarbonisation and lowering reliance on fossil fuels is green hydrogen. With almost no greenhouse gas emissions, it is created by electrolysing water using renewable energy sources like solar and wind. Green hydrogen has major environmental benefits over traditional coal and natural gas-based hydrogen production techniques. Alkaline electrolysis, proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis are the three main technologies that are critically assessed in this chapter along with the basic concepts of water electrolysis. A thorough analysis is conducted of the main obstacles, which include high production costs, energy losses, storage challenges, transportation problems, and inadequate infrastructure. Additionally highlighted are recent technological developments in large-scale deployment strategies, system efficiency, and catalyst design. Lastly, prospects and policy for the future

Finally, future prospects and policy frameworks supporting the global hydrogen economy are presented. Green hydrogen is expected to play a crucial role in achieving carbon neutrality and sustainable energy security in the coming decades.

Keywords: Green hydrogen, Electrolysis, Renewable energy, Energy storage, Hydrogen economy, Decarbonization

1. Introduction

Everyday life, industry, and national development all depend on energy. Currently, natural gas, coal, and petroleum provide the majority of energy. These fuels are scarce and emit toxic gases that contribute to pollution and global warming. Clean and renewable energy sources are therefore desperately needed.

Since hydrogen only produces water when used, it is regarded as a promising clean fuel. The environmental benefit of hydrogen is diminished, though, because the majority of it is still made using fossil fuels. A better option is provided by green hydrogen. It doesn't produce carbon emissions and is made from water with renewable electricity. As a result, green hydrogen is becoming more and more popular as a fuel for industry, transportation, and energy storage in the future.

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Importance of Hydrogen as an Energy Carrier

Property	Significance
Clean combustion	Produces only water as by-product
High energy density	More energy per unit mass than petrol or diesel
Energy storage	Stores excess solar and wind energy
Wide applications	Transport, electricity and industries

2. Principles of Green Hydrogen Production/ Water Electrolysis

Green hydrogen is primarily produced through the electrolysis of water. In this process, electrical energy drives the decomposition of water into hydrogen and oxygen gases.

Overall electrochemical reaction:

$2H_2O\ (l) \rightarrow 2H_2\ (g) + O_2\ (g)$

Half-cell reactions:

Cathode (reduction):
$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$

Anode (oxidation):
$4OH^- \rightarrow O_2 + 2H_2O + 4e^-$

The efficiency of the process depends on electrode materials, electrolytes, temperature, and system design. Three main electrolysis technologies are widely used.

3. Methods of Green Hydrogen Production

3.1 Alkaline Electrolysis

The oldest and most widely used technique is alkaline electrolysis. It uses an aqueous alkaline solution as the electrolyte, usually sodium hydroxide (NaOH) or potassium hydroxide (KOH).

Because of their affordability and stability, nickel-based electrodes are frequently used. The process runs at pressures of up to 30 bar and temperatures between 60 and 90°C.

Low capital costs, extended operational lifespans, and technological maturity are among the benefits. Nonetheless, the system exhibits moderate efficiency and a comparatively slower response to varying renewable power.

Typical efficiency: 60–80%.

3.2 Proton Exchange Membrane (PEM) Electrolysis

A solid polymer membrane that conducts protons and separates hydrogen and oxygen gases is used in PEM electrolysis. To improve reaction kinetics, precious metal catalysts like iridium or platinum are needed.

High current density, small size, quick startup, and high-purity hydrogen production are all provided by this technology. Integration with wind and solar energy systems is especially appropriate.
The primary drawback of noble metal catalysts and membrane materials is their high cost. Efficiency range: 65–85% on average.

3.3 Solid Oxide Electrolysis (SOEC)

Ceramic electrolytes are used in solid oxide electrolysis, which takes place at temperatures between 700 and 1000°C. At higher temperatures, some of the energy needed is provided as heat, increasing overall efficiency. This technique is appropriate for industrial applications where waste heat is available and exhibits very high efficiency. High operating temperatures, however, have the potential to degrade materials and raise maintenance expenses. Efficiency range: 80–90%.

Comparison of Electrolysis Technologies

Type	Cost Level	Efficiency	Advantages	Limitations
Alkaline	Low	60–80%	Cheap and mature	Slow response
PEM	Medium–High	65–85%	Compact and fast	Expensive catalysts
Solid Oxide	High	80–90%	Very efficient	High temperature issues

4. Challenges in Green Hydrogen Production

High cost, energy losses, storage problems, transportation risks and lack of infrastructure restrict large-scale adoption.

4.1 High Production Cost

Electrolyzers, catalysts, and renewable electricity contribute to higher costs compared to fossil-based hydrogen. Current prices range between $3–8 per kg.

4.2 Energy Losses

Energy conversion losses occur during electrolysis, compression, and reconversion, reducing overall efficiency to approximately 60–70%.

4.3 Storage Difficulties

Hydrogen has very low density and requires compression or liquefaction. Liquefaction at −253°C consumes additional energy and increases cost.

4.4 Transportation Issues

Transportation through pipelines may cause leakage and embrittlement. Special tankers or cryogenic containers are necessary.

4.5 Infrastructure Limitations

Limited refueling stations, storage facilities, and regulatory frameworks hinder widespread implementation.

Major Challenges and Possible Solutions

Challenge	Cause	Possible Solution
High cost	Expensive equipment	Mass production
Energy loss	Conversion inefficiency	Improved catalysts
Storage	Low density gas	Compression or liquefaction
Transport	Leakage risk	Better pipelines
Infrastructure	Limited stations	Government support

5. Recent Technological Advancements

There is a lot of study being done on cost reduction and efficiency improvement. Nickel-iron, cobalt oxides, and nanostructured materials are examples of non-noble metal catalysts that have demonstrated encouraging results. Productivity is increased via large-scale electrolyser stacks, enhanced electrode designs, and advanced membranes. Better use of intermittent energy sources is made possible by the integration of hydrogen production with renewable power plants and smart grids. To speed up commercialisation, a number of nations have started hydrogen valleys and demonstration projects.

Rapid development is also being encouraged by national hydrogen missions, government programs, and incentives.

6. Applications of Green Hydrogen

Green hydrogen has diverse applications across multiple sectors:

- Fuel for fuel-cell vehicles
- Electricity generation in fuel cells
- Energy storage for renewable power
- Steel and fertilizer industries
- Aviation and maritime fuels
- Chemical synthesis such as ammonia and methanol

Sector	Use of Hydrogen
Transportation	Fuel cell vehicles
Power	Electricity generation and storage
Industry	Steel and ammonia production
Chemicals	Refineries and synthesis
Energy storage	Backup for renewables

7. Future Prospects

Global demand for hydrogen is expected to increase significantly over the coming decades. With large-scale manufacturing of electrolyzers and declining renewable energy costs, the price of green hydrogen is projected to decrease below $2 per kg by 2030.

Expansion of infrastructure, international collaboration, and supportive policies will further accelerate adoption. In countries such as India, green hydrogen can play a crucial role in sustainable industrial growth and energy independence.

8. Conclusion

Green hydrogen represents a promising pathway toward a sustainable and low-carbon energy future. It offers significant environmental advantages over conventional hydrogen production methods and supports renewable energy integration. Although challenges related to cost, storage, and infrastructure remain, ongoing technological advancements and policy support are expected to overcome these barriers. With continued research and investment, green hydrogen can become a key component of the global clean energy transition.

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