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A Comprehensive Review of Green Hydrogen: Electrolyzer Technologies, Applications, and Barriers to Large-Scale Deployment

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ABSTRACT

Green hydrogen is a zero emission fuel produced by splitting H2O into hydrogen and oxygen using renewable electricity sources like solar, wind, hydrocarbon via Luther LASIS. It acts as a clean energy carrier for decarbonizing heavy industries come on long and transport and shipping push up because this process does not emit CO2, green hydrogen is considered an important option for reducing greenhouse gas emissions and supporting global climate goals. This review presents an overview of green hydrogen production technologies, with focus main types of electrolyzers: alkaline, proton exchange membrane and solid oxide electrolyzer. The advantages, limitations, efficiency and current development status of these technologies are discussed in a clear comparative manner. The review also highlights key challenges facing large scale adaptation of green hydrogen, including high production cost, dependence on renewable electricity, storage and transportation difficulties and the need for supporting infrastructure. In addition, potential applications of green hydrogen in power generation industrial sectors such as steel and chemical production and transportation are examined. Overall, the study shows that although green hydrogen is still at an early stage of deployment, continued technological progress, cost reductions and Strong policy support could make it a crucial component of a sustainable and low carbon energy system.

Keywords: Green Hydrogen; Renewable Energy; Water Electrolysis; Electrolyzer Technologies: Decarbonization; Hydrogen Storage In; Energy Transition; Sustainable Energy.

INTRODUCTION

Green hydrogen has emerged as a promising energy vector in the global transition toward low carbon and sustainable energy systems. It is produced through the electrolysis of water using electricity generated from renewable energy sources such as solar, wind, hydropower resulting in near -zero greenhouse gas emissions during production. Unlike conventional hydrogen production pathways, which rely heavily on fossil fuels and contribute significantly to CO2 emissions, green hydrogen offers a clean alternative aligned with international climate of migration goals[1-3].

The increasing penetration of intermittent renewable energy sources as highlighted the need for efficient energy storage and sector coupling solutions. Green hydrogen are addresses this challenges by enabling large scale and long term energy storage while facilitating Decarbonization across multiple sectors, including power generation, transportation and energy intensity industries such as steel, chemical and refining[4-5].

Furthermore, hydrogen can be converted into directives such as ammonia or synthesis fuels, expanding its applicability and in case of transport.

Despite its considerable potential the widespread deployment of Green hydrogen is constrained by high production costs, limited electrolyzer capacity and infrastructure challenges and Resource requirements particularly H2O and renewable electricity availability. Consequently ongoing research and policy efforts focus on technological advancements, cost reduction strategies and systems integration approaches to enhance the feasibility and scalability of green hydrogen technologies[6].

This review article examines current status of green hydrogen production technologies, recent advancements techno economic Challenges and future prospects.

Green Hydrogen Production Technologies

Green hydrogen is primarily produced through Water electrolysis, a process that uses electricity from renewable energy source to split water into hydrogen and oxygen.

Depending on the electrolyte material, operating conditions and system design, several electrolysis technologies has been developed[7].

Alkaline Water Electrolysis (AWE)

Alkaline water electrolysis (AWE) is the most mature and commercially established technology for hydrogen production via water electrolysis that Splits water into high purity hydrogen and oxygen using direct current electricity and an aqueous electrolyte [typically 25 to 40% KOH or NaOH]. It has been employed at industrial scale for several decades and continues to play a significant Role in large scale green hydrogen generation due to robustness, relatively low cost and reliance on earth abundant materials[8-9].

Principle of Operation:-

In alkaline water electrolysis, water is decomposed into hydrogen and oxygen in an electrochemical cell containing a liquid alkaline electrolyte, typically KOH or NaOH. The electrolyte facilitates the transport of hydroxide ions between the electrodes; porous diaphragm separates the anode and cathode to prevent product gas mixing[10].

The electrochemical reactions are

Cathode (Hydrogen Evolution Reaction):

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Anode (Oxygen Evolution Reaction):

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

Overall Reaction:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

System Configuration and Operating Conditions:

AWE systems typically consist of multiple electrolysis cells assembled into stacks, along with balance -of-plant components such as electrolyte circulation ULDE, gas seperators and head Exchanges[11].

Operating Parameters:

1. Temperature: 60–90°C

2. Pressure: Atmospheric to ~30 bar

3. Current density: 0.2 – 0.6 Acm²
4. Cell voltage: 1.8 – 2.4 V

Nickel based electrodes are commonly used due to their favorable catalytic Activity and corrosion resistance in alkaline Environment.

Advantages

High technological maturity and long operational lifetime

Lower capital cost compared to PEM electrolysis

Uses of non-precious, widely available materials.

Proven scalability to multi Megawatt industrial systems.

Limitations and Challenges

Lower current density compare to PEM systems, resulting in larger systems S1 Slower dynamic response to fluctuating renewable power inputs.

Risk of gas crossover through porous diaphragms it low loads.

Handling and Corrosions issues associated with concentrated alkaline electrolysis[12-15].

Role in Green Hydrogen Production:-

Due to its reliability, cost effectiveness And industrial readiness this alkaline water electrolysis is expected to remain a key technology for early and large scale green hydrogen development, particularly in applications with stable renewable power supply and len Stringent Dynamic responses requirements.

Proton Exchange Membrane (PEM) Electrolysis

PEM electrolysis employs a solid polymer electrolyte and operates under acidic conditions. If deceivers high current density, Compact design and fast response intermittent renewable power. Its main limitation is high cost due to the use precious metal catalysts Such as platinum and Indium[16-18].

Principle:-

PEM uses a solid polymer electrolyte membrane and operates under acidic conditions.

Anode:

$$H_2O \rightarrow \frac{1}{2}O_2 + 2H^+ + 2e^-$$

Cathode:

$$2H^+ + 2e^- \rightarrow H_2$$

Solid Oxide Electrolysis (SOE)

SOE operates get high temperatures [650-850 degree Celsius] using ceramic electrolysis. It offers high electrical efficiency and the possibility of utilizing industrial waste heat.

However material degradation and durability key challenges and the technology are still in early commercialization stages[19-21].

Operating temperature: 650–850°C Electrolyte: Ceramic oxide

Cathode:

$$H_2O + 2e^- \rightarrow H_2 + O^{2-}$$

Anode:

$$O^{2-} \rightarrow \frac{1}{2}O_2 + 2e^-$$

Advantages:-

- Very high electrical efficiency
- Potential integration with industrial was heat or nuclear/ Solar Thermal Energy.
- Lower electricity demand per unit of hydrogen.

Limitations:-

- ✓ High operating temperatures lead to material degradation.
- ✓ Limited Operational lifetime. Technology still a pilot and demonstration scale.

Anion Exchange Membrane Water Electrolysis (AEMWE)

AEM is an emerging technology combining features of alkaline Proton Exchange membrane electrolysis (PEM). It operates under alkaline conditions with a solid membrane and has potential for lower cost due to reduced reliance on node metals. Long-term Membrane stability is still under development[22].

Key Features:-

- ✓ Operating temperature: 40–70°C
- ✓ Electrolyte: Solid anion exchange membrane
- ✓ Catalyst: Potential use of non-noble metals

Cathode:

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$

Anode:

$$2OH^- \rightarrow \frac{1}{2}O_2 + H_2O + 2e^-$$

Advantages:

- Reduced reliance on precious metals
- Improved operational flexibility.
- Lower projected cost compared to PEM.

Limitations:

- Membrane stability and durability changes.
- Lower technology readiness level.
- Ongoing research and development required.

Photo electrochemical and Photocatalytical Water Splitting

Its aim to produce hydrogen directly from sunlight and water, eliminating the need for external electricity sources[23].

Photo Electrochemical Water Splitting

In this system, a semiconductor Photo Electrode is immersed in a electrolyte. Up on illumination, photons with energy equal to greater than the semiconductor land gap generate electron hole pairs. These charge carriers migrate to the surface and Participate in redox reactions[24].

Principal reactions:-

Photo anode (Oxygen Evolution Reaction):

$$H_2O + 2h^+ \rightarrow \frac{1}{2}O_2 + 2H^+$$

Photocathode (Hydrogen evolution reaction):

$$2H^+ + 2e^- \rightarrow H_2$$

Photo Catalytic Water Splitting

Photo Catalytic water splitting involves dispersing semiconductor catalytic particles in Water. When illuminated, the catalyst absorbs photon, generating electron hole pairs that drive hydrogen and oxygen evolution on the particle Surface[25].

Overall Reaction

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2$$

Advantages:

- Potentially low system complexity.
- Direct Utilization of solar energy.

Limitations:-

- Low conversion efficiency.
- Material stability sources.
- Currently limited laboratory scale research.

Recent Advancements in Green Hydrogen

Recent years have seen rapid technological progress and scaling effort in green hydrogen, Driven by the urgent need decarbonize energy systems and hard to abet industries innovations span electrolysis technologies, Digital Integration, large scale deployment Novel research directions enhancing efficiency lowering cost and expanding applicability[26].

Electrolyser Efficiency and Technology Breakthroughs

Advancement in electrolyser technologies is central to reducing the cost and energy intensity of green hydrogen production.

Improved catalyst and membrane materials new electrode and membrane designs are increasing energy efficiency and reducing reliance on precious metals [Iridium, Platinum], particularly for PEM and AEM systems. Novel membrane research including AL drive in materials Design, creating fluorine alternatives and expanding Material discovery[27].

Next generation Alkaline Systems 3rd generation Alkaline electrolyzers with advanced diaphragms and electrode structures show enhanced gas purity and reduced losses, pushing efficiency towards 75 – 80%.

High temperature and hybrid electrolysis: solid oxidic electrolytic cell [SOECS] operating at elevated temperatures can achieve theoretically efficiency of above 90% by leveraging waste heat and co-electrolysis of CO2 with water. Dynamic operation and renewable integration: Modern design allows Electrolysers to adjust quickly to interpretant power from solar and wind maximizing renewable utilization and lowering cost per kilogram of Hydrogen[28].

Digitalization and System Optimization

Data driven in tools and digital technologies are enhancing performance and control:

AI and Predictive Control: Artificial intelligence techniques help optimize electrolyzer operation, predictor renewable generation availability, Fine tube production cycles for cost minimization and reliability. Digital Twin and IOT platforms enable real time monitoring and predictive maintenance, improving uptime and efficiency.

Market Response Operation:- Research into advanced control strategies proposes that electrolyzers could participate in multiscale electricity markets, event selling excess electricity during high periods to reduce or offset net energy[29].

Large scale Projects and Industrial Deployment:-

Green hydrogen deployment is moving from pilots megawatt and gigawatt scale projects.

Industrial and Infrastructure Project:- Massive initiatives like the NUOM Green Hydrogen project in Saudi Arabia has on two integrated 3.9 GB of renewable capacity to produce hundreds of times of greenhouse daily ammonia and other derivatives.

Modular and scalable Plants:- Electrolyzers manufacturers are developing modular Architecture that can be scaled easily from small plants to gigawatts scale facilities, reducing lead times and capital expenditure[30].

Strategic Hub and policies:- Many governments are establishing dedicated hydrogen hubs backed by strategic policies and Incentives to encourage local manufacturing, R&D and larger scale deployment.

Novel Production Pathways

Emerging scientific approaches are pushing the boundaries of water heating and hydrogen synthesis full.

Alternative electrochemical methods:- Researchers has developed electrolysis method that reduces required voltage and energy input, significantly cutting costs and potentially increasing hydrogen yield, through challenges remain in scaling and stability.

Photo Electro chemical and solar driven systems:- Solar only water splitting devices Earth abundant materials are showing promises in direct sunlight to hydrogen corrosion, Which could reduce systems, dependence on grid electricity in remote areas[31].

Combine Process Innovations:- Concepts such as developed water electrolysis separate hydrogen and oxygen production stages to improve safely and reduce crossover losses, potentially lowering capital costs and Improving stack life.

Growth in Application and Value Chains

Green hydrogen derivatives:- Projects integrating hydrogen with down chemicals such as green ammonia and methanol are expanding market demand and creating value chains that improve economics of production.

Transport and storage innovations:- Developments like large liquefied hydrogen carriers are facilitating global hydrogen trade and supporting Intern solar critical for global decarbonization[32].

Techno-Economic Challenges

Its significant potentials for deep decarbonization, green hydrogen faces several techno economical carriers that limit large scale commercialization and competitiveness with fossil based hydrogen.

High Production Cost

The cost of green hydrogen remains sustainably higher than grey hydrogen produced via steam methane reforming SMR the levelled cost of hydrogen is strongly influenced.

- ✓ High electricity consumption
- ✓ Renewable electricity price volatility
- ✓ Capital cost of electrolyzers
- ✓ Low capacity factors in renewable integrated systems

Capital Expenditure

Electrolyzer systems, particularly PEM and solid oxide technologies, require expensive components such as:

- ✓ Precious metal catalyst (Pt, Ir)
- ✓ High performance Membrane
- ✓ Power electronics and balance of plant systems

Efficiency and Energy Losses

Electrolysis efficiency typically ranges between 60 - 80%, meaning significant electrical energy is required per unit of hydrogen produced[33]. Additional losses occur during:

- Hydrogen compression or liquefaction
- Storage and transportation
- Reconversion to electricity

Infrastructure and Storage Costs

Hydrogen’s low volumetric energy density creates challenges in

- Compression [350-700] bar
- Liquefication [-253”c]
- Pipeline transport
- Storage materials and safety systems

Future Prospects of Green Hydrogen

Green hydrogen is expected to play portal role in achieving global decarbonization targets and transitioning towards a Sustainable Energy Systems. With rapid technological advancements, declining renewable electricity cost and supportive policy frameworks its long term outlook is highly promising[34].

Cost Reduction and Commercial Competitiveness

Largely Depends On Reductions:-

- Renewable electricity prices
- Electrolyzer capital cost through mass manufacturing
- Catalyst loading and use of non-precious materials
- Improved system efficiency and durability

Expansion of Industrial Applications

Green hydrogen is expected to expand beyond conventional refining and ammonia production into:-

- Green steel manufacturing (Direct reduced iron processes)
- Low carbon cement and chemicals
- Sustainable aviation fuels
- Green methanol and ammonia has energy carriers

Integration with Renewable Energy Systems

Green hydrogen will increasingly function:-

- ➢ A large scale, long duration energy storage medium
- ➢ A balancing tool for intermittent solar and wind power
- ➢ A key component in sector coupling (Power to gas, power to fuels)

Development of Hydrogen Infrastructure

- ✓ Dedicated hydrogen pipelines and storage systems
- ✓ Liquefied hydrogen shipping technologies
- ✓ Hydrogen hubs and industrial clusters
- ✓ Standardized safety and regulatory frameworks.

Technological Innovation

- ✓ Improve electrolyzer efficiency and lifetime
- ✓ Developed advanced material for membranes and catalysts
- ✓ Scale solid oxide and anion Exchange membrane technologies
- ✓ Enhance Solar driven hydrogen productions [PEC and photo catalyst]

Policy and Global Climate Commitments

National Hydrogen Strategies, carbon pricing mechanisms and international climate agreements are accelerating investments in green hydrogen. Long term policy stability and financial incentives will be critical for scaling and projects and attracting private investment[35].

CONCLUSION

Green hydrogen stands at the fore front of Global Decarbonization Strategies offering a scalable and Carbon neutral Hardware pro transform Energy, industrial and transport Systems.

Renewable powered water electrolysis provides the technological foundation, with alkaline and PEM systems driving Current deployment, while solid oxide, annual exchange membrane and Solar driven in approaches represent next, frontier of efficiency and system integration.

Despite rapid progress, achieving large scale adoption requires overcoming critical techno economic barriers; include high production cost, infrastructure gaps material constraints and system inefficienes. Addressing these challenges will depend on coordinated advances in Catalyst and membrane engineering manufacturing scale up renewable energy expansion and stable policy mechanisms.

With sustained innovation, strategic investment and cross sector integration, green hydrogen has a potential to evolve from a niche decarbonization option to a corner stone of resilient, net zero global energy economy.

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