

# Hydrogen as a Clean Energy Vector: Technologies, Challenges, and Prospects in Developing Economies

Al-ameen I. Tihamiyu

Department of Mechanical Engineering, University of Ilorin, Nigeria.

Email: [tihamiyualameen@ymail.com](mailto:tihamiyualameen@ymail.com)

## **Abstract**

The global transition toward low-carbon energy systems has intensified interest in hydrogen as a clean and versatile energy vector. Hydrogen offers significant potential for decarbonizing sectors that are difficult to electrify, including heavy industry, transportation, and large scale energy storage. For developing economies, hydrogen presents both opportunities for sustainable growth and challenges related to cost, infrastructure, and policy frameworks. This review examines hydrogen energy technologies with a focus on their applicability in developing regions. Key hydrogen production pathways, including grey, blue, and green hydrogen, are discussed alongside storage, transportation, and utilization technologies such as fuel cells and industrial hydrogen applications. The paper further analyzes the major technical, economic, and institutional barriers limiting hydrogen deployment in developing economies, including high capital investment, inadequate infrastructure, and limited technical capacity. Regional perspectives and emerging initiatives are highlighted to illustrate current progress and lessons learned. Finally, future prospects and strategic recommendations are presented, emphasizing the role of renewable based green hydrogen in supporting energy security, industrial decarbonization, and sustainable development in developing countries.

## **Keywords**

Hydrogen energy, clean energy, developing economies, energy transition, renewable energy

## **Introduction**

Global energy systems are undergoing a major transition driven by increasing energy demand, climate change concerns, and the urgent need to reduce greenhouse gas emissions [1–3]. Fossil fuels continue to dominate the energy mix in many developing economies, contributing to environmental degradation, energy insecurity, and economic vulnerability due to price volatility [26].

Hydrogen has emerged as a promising clean energy vector because of its high energy content, flexibility, and ability to produce zero emissions at the point of use when generated from renewable sources [4,6]. Hydrogen can be applied across multiple sectors, including power generation, transportation, and industrial processes, while also serving as an effective energy storage medium for intermittent renewable energy sources [6,7].

Despite these advantages, hydrogen deployment in developing economies remains limited due to high costs, infrastructure gaps, weak policy frameworks, and limited technical capacity [27,28]. This review therefore examines hydrogen technologies, associated challenges, and future prospects with a focus on developing economies.

## **Hydrogen as an Energy Vector**

Hydrogen is classified as an energy vector rather than a primary energy source because it must be produced using other forms of energy [5]. Its significance lies in its ability to store, transport, and deliver energy in a clean and flexible manner. When utilized in fuel cells, hydrogen produces electricity with water as the only by-product, making it environmentally attractive [22].

Hydrogen possesses a high gravimetric energy density, although its low volumetric energy density presents storage and transportation challenges [19]. Nevertheless, its versatility allows application across diverse sectors, including electricity generation, transportation, and industrial processes such as ammonia and steel production [6,23].

For developing economies, hydrogen offers additional benefits such as enhanced energy security, reduced dependence on imported fossil fuels, and improved utilization of local renewable energy resources [27,28]. These attributes position hydrogen as a strategic component of long-term sustainable energy planning.

## **Hydrogen Production Technologies**

Hydrogen production technologies significantly influence the environmental and economic performance of hydrogen energy systems. These technologies are commonly categorized based on their carbon footprint and feedstock source [4,10].

### **Grey, Blue, and Green Hydrogen**

Grey hydrogen is produced mainly through steam methane reforming of natural gas, it remains the most widely used method due to its low cost and technological maturity; however, it generates substantial carbon dioxide emissions [4,8]. Blue hydrogen incorporates carbon capture and storage technologies to reduce emissions, but its deployment in developing economies is limited by high capital costs and infrastructure constraints [11].

Green hydrogen, produced through renewable powered electrolysis, offers near zero lifecycle emissions and aligns with global decarbonization targets [13,27]. Declining renewable energy costs are improving the feasibility of green hydrogen in developing regions with abundant solar and wind resources [1,30].

### **Electrolysis Technologies**

Water electrolysis technologies include alkaline electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis [14,15]. Alkaline electrolysis is the most mature and cost effective option, making it suitable for large scale applications in developing economies [13].

Proton exchange membrane electrolysis provides higher efficiency and operational flexibility but is associated with higher capital costs and material requirements [15]. Solid oxide electrolysis offers high efficiency due to high operating temperatures but remains largely at the demonstration stage [16].

### **Hydrogen Production from Biomass and Waste**

Hydrogen production from biomass and organic waste offers an alternative pathway with strong relevance for developing economies [17]. These technologies support waste management while producing useful energy carriers. However, challenges such as feedstock variability, technical complexity, and lower system efficiencies limit large scale adoption [18].

## **Suitability for Developing Economies**

Green hydrogen and biomass-based hydrogen represent the most sustainable long-term options for developing economies, particularly when supported by appropriate policy frameworks, capacity building, and international collaboration [27,28].

## **Hydrogen Storage and Transportation**

Efficient storage and transportation are critical to the widespread adoption of hydrogen energy systems. Common storage methods include compressed hydrogen gas, liquid hydrogen, and solid-state storage using metal hydrides [19–21]. Compressed gas storage is currently the most widely used due to its simplicity, although it requires high-pressure tanks and safety considerations [19].

Liquid hydrogen offers higher energy density but involves significant energy losses during liquefaction and requires advanced insulation technologies [20]. Solid-state storage, such as metal hydrides, provides safer storage at lower pressures but remains expensive and technologically complex [21].

For developing economies, limited infrastructure and high capital costs present major barriers to hydrogen storage and transportation. Decentralized hydrogen production and localized consumption may therefore offer more practical solutions in the near term [28].

## **Hydrogen Utilization Technologies**

Hydrogen can be utilized across several sectors, with fuel cells being the most prominent application. Fuel cells convert hydrogen directly into electricity with high efficiency and minimal environmental impact [22,23]. They are used in transportation, stationary power generation, and backup power systems.

In addition to fuel cells, hydrogen is widely used in industrial processes such as ammonia production, petroleum refining, and emerging low carbon steelmaking technologies [6]. Power to gas systems also allow hydrogen to be injected into natural gas grids or converted into synthetic fuels, improving renewable energy integration [13].

Despite their benefits, hydrogen utilization technologies face challenges related to cost, durability, and system integration, particularly in resource constrained settings [22].

## **Challenges in Developing Economies**

Several challenges hinder hydrogen adoption in developing economies. These include high capital investment requirements, inadequate infrastructure, limited access to financing, and weak policy and regulatory frameworks [27,28]. Technical skill shortages and limited research capacity further constrain local development and deployment of hydrogen technologies.

Safety concerns and low public awareness also affect acceptance, while competing development priorities may reduce government focus on hydrogen investments [25]. Addressing these challenges requires coordinated policy action, international partnerships, and targeted capacity building initiatives.

## **Future Prospects and Opportunities**

The future prospects for hydrogen in developing economies are increasingly positive due to falling renewable energy costs, technological advancements, and growing global interest in green hydrogen [1,30]. Many developing regions possess abundant renewable resources, positioning them as potential producers and exporters of green hydrogen.

Hydrogen deployment can support industrial decarbonization, job creation, energy access, and long-term economic growth [27]. Strategic planning, supportive policies, and investment in education and infrastructure will be critical to realizing these benefits.

## **Conclusion**

Hydrogen represents a promising clean energy vector capable of supporting sustainable energy transitions in developing economies. While significant challenges related to cost, infrastructure, and policy remain, advances in renewable energy and hydrogen technologies offer growing opportunities. By prioritizing green hydrogen pathways, strengthening institutional frameworks, and fostering international cooperation, developing economies can leverage hydrogen to enhance energy security, reduce emissions, and promote sustainable development.

## **Research Gaps and Recommendations**

Despite increasing global interest in hydrogen energy, several research gaps remain, particularly in the context of developing economies.

### **Research Gaps**

First, there is limited region specific data on hydrogen production potential in developing countries. Many existing studies focus on developed economies, making it difficult to accurately assess techno-economic feasibility under local conditions such as unstable power supply, high ambient temperatures, and limited infrastructure.

Second, there is insufficient research on small and medium scale hydrogen systems suitable for decentralized applications. Most studies emphasize large scale hydrogen production, which may not be practical for rural or semi urban areas in developing economies.

Third, limited attention has been given to lifecycle assessments and sustainability evaluations of hydrogen systems within developing-country contexts. Factors such as local material availability, supply chains, and end-of-life management are often overlooked.

Finally, policy, regulatory, and socio-economic dimensions of hydrogen deployment remain underexplored. Issues such as public acceptance, workforce development, safety standards, and financing mechanisms require more comprehensive investigation.

### **Recommendations**

Future research should prioritize localized techno-economic assessments that account for regional energy resources, infrastructure constraints, and market conditions. Emphasis should be placed on renewable based green hydrogen systems integrated with solar and wind energy.

Research efforts should also focus on developing cost effective, modular hydrogen technologies suitable for decentralized and off-grid applications. This approach would enhance energy access and support inclusive energy transitions.

From a policy perspective, governments in developing economies should establish clear hydrogen strategies, supportive regulatory frameworks, and incentives for private sector participation. International collaboration and technology transfer will be essential for capacity building and knowledge sharing.

Finally, investment in education and workforce development is critical to ensure the availability of skilled professionals capable of supporting hydrogen research, deployment, and maintenance.

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