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GREEN HYDROGEN IN THE GLOBAL ENERGY TRANSITION

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Abstract

The global energy transition has intensified the search for low-carbon solutions capable of decarbonizing sectors that are difficult to electrify, such as heavy industry, long-distance transport, and large-scale energy storage. In this context, green hydrogen has emerged as a strategic energy carrier, although its large-scale deployment remains constrained by economic, technological, and institutional barriers. This study aims to analyze the role of green hydrogen in the global energy transition through a structured literature review, with particular attention to production technologies, system integration, and implications for developing countries. Methodologically, the study adopts a qualitative and deductive approach based on a critical review of contemporary scientific and institutional literature, focusing on peer-reviewed articles, international reports, and policy documents published in recent years. The results indicate that advances in electrolyze technologies, the integration of hydrogen systems with renewable energy sources, and the use of modeling and simulation tools have significantly improved the technical feasibility of green hydrogen. However, high capital costs, infrastructure limitations, regulatory uncertainty, and limited technical capacity continue to restrict its diffusion, especially in developing economies. The study concludes that green hydrogen represents a relevant component of long-term decarbonization strategies, but its effective contribution to the energy transition depends on coordinated public policies, investment frameworks, technological innovation, and international cooperation.

Keywords: Developing Countries; Electrolysis; Energy Transition; Green Hydrogen; Renewable Energy Systems.

Resumo

A transição energética global intensificou a busca por soluções de baixo carbono capazes de promover a descarbonização de setores de difícil eletrificação, como a indústria pesada, o transporte de longa distância e o armazenamento de energia em larga escala. Nesse contexto, o hidrogênio verde emerge como um vetor energético estratégico, embora sua difusão em larga escala ainda enfrente barreiras econômicas, tecnológicas e institucionais. O objetivo deste estudo é analisar o papel do hidrogênio verde na transição energética global por meio de uma revisão de literatura estruturada, com ênfase nas tecnologias de produção, na integração de sistemas e nas implicações para países em desenvolvimento. Metodologicamente, o estudo adota uma abordagem qualitativa e dedutiva, baseada na análise crítica de literatura científica e institucional contemporânea, incluindo artigos revisados por pares, relatórios internacionais e documentos de políticas públicas publicados nos últimos anos. Os resultados indicam que os avanços nas tecnologias de eletrólise, a integração de sistemas de hidrogênio com fontes renováveis e o uso de ferramentas de modelagem e simulação têm ampliado a viabilidade técnica do hidrogênio verde. Entretanto, custos elevados de capital, limitações de infraestrutura, incertezas regulatórias e restrições de capacitação técnica ainda limitam sua expansão, especialmente em economias em desenvolvimento. Conclui-se que o hidrogênio verde constitui um componente relevante das estratégias de descarbonização de longo prazo, mas sua efetiva contribuição para a transição energética depende da articulação entre políticas públicas, mecanismos de investimento, inovação tecnológica e cooperação internacional.

Palavras-chave: Eletrólise; Hidrogênio Verde; Países em Desenvolvimento; Sistemas de Energia Renovável; Transição Energética.

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INTRODUCTION

The global energy transition toward carbon neutrality has intensified the search for low-carbon solutions capable of decarbonizing sectors that are difficult to electrify directly, such as steelmaking, heavy transport, refining, and fertilizer production. In this context, green hydrogen has emerged as a strategic energy carrier, as it enables the conversion of renewable electricity into a versatile fuel and industrial feedstock, supporting deep emission reductions across multiple sectors of the economy.

Despite its potential, the large-scale deployment of green hydrogen remains constrained by economic, technological, and institutional barriers. Historically higher production costs compared to fossil-based hydrogen, infrastructure requirements for storage and transport, and regulatory uncertainties have limited its diffusion, particularly in developing economies. These challenges coexist with recent advances in electrolyzer efficiency, hybrid renewable–hydrogen systems, and modeling and simulation tools, which have improved the techno-economic feasibility of green hydrogen projects and renewed interest in its strategic role within energy systems.

From a scientific and policy perspective, the rapid expansion of publications on green hydrogen has resulted in a diverse but fragmented body of literature. Existing studies often focus on specific technologies, applications, or regional experiences, such as electrolyzer performance, system integration, or export strategies. However, there remains a need for a structured synthesis that consolidates these contributions and critically examines how technological developments, system modeling approaches, and contextual factors interact, particularly in the case of developing countries, which combine high renewable potential with structural constraints.

Recent studies published in the Boletim de Conjuntura (BOCA) emphasize that the diversification of energy sources through renewable technologies is a central pillar of public policy responses to climate change, highlighting the strategic role of integrated energy planning, regulatory frameworks, and long-term policy coordination in national energy transitions. This perspective reinforces the relevance of emerging energy vectors, such as green hydrogen, as part of broader decarbonization strategies aimed at increasing system resilience and reducing dependence on fossil fuels. Energy diversification in developing economies is strongly conditioned by public policy design, institutional capacity, and long-term governance structures. These factors are particularly relevant for emerging energy carriers such as green hydrogen, whose large-scale deployment requires not only technological readiness but also stable regulatory frameworks, investment incentives, and coordinated national strategies aligned with climate objectives.

Based on this context, the research problem guiding this study can be formulated as follows: how does the contemporary literature characterize the role of green hydrogen in the global energy transition, with respect to its technological foundations, system integration approaches, and relevance for developing countries? Addressing this question requires a comprehensive review capable of organizing dispersed findings, identifying converging trends, and highlighting persistent barriers reported across different strands of the literature.

Accordingly, the main objective of this study is to analyze the role of green hydrogen in the global energy transition through a structured literature review. Specifically, the study aims to: (i) examine the fundamental concepts and characteristics associated with green hydrogen; (ii) analyze the main electrolysis technologies and system-integration approaches discussed in the literature; and (iii) identify opportunities, barriers, and strategic implications for the adoption of green hydrogen in developing countries, with emphasis on emerging and developing economies.

Methodologically, the study adopts a qualitative and deductive literature review approach, based on the critical analysis of contemporary scientific publications and institutional reports. The study draws on peer-reviewed journal articles, international agency reports, and policy documents that address green hydrogen from technological, economic, and systemic perspectives, without claiming the development of original empirical models or experimental results. Narrative and scoping-oriented literature reviews remain relevant tools for synthesizing fragmented bodies of knowledge, particularly in interdisciplinary fields where empirical evidence is dispersed across multiple domains. This approach is especially suitable for examining the systemic role of green hydrogen in the global energy transition.

This text has been structured as follows. Section 2 presents the fundamental concepts and key characteristics of green hydrogen. Section 3 discusses production technologies, focusing on electrolysis systems and approaches to system modeling and integration with renewable energy sources. Section 4 examines opportunities and challenges for green hydrogen deployment in developing countries. Finally, the concluding section synthesizes the main findings, outlines the limitations of the study, and proposes directions for future research.

FUNDAMENTAL CONCEPTS AND CHARACTERISTICS OF GREEN HYDROGEN

Hydrogen has long been recognized as a strategic energy carrier capable of supporting the transition toward low-carbon energy systems due to its versatility and potential for integration across multiple sectors (SEGOVIA-HERNÁNDEZ *et al*., 2025). Its relevance has increased substantially in the context of climate-neutrality targets, particularly in applications where direct electrification faces technical or economic limitations. Traditionally, hydrogen has been widely used in refining, fertilizer production, chemical processes, and metallurgy, with global demand exceeding 70 million tonnes per year.

Recent studies emphasize that green hydrogen should be understood not merely as a fuel substitute, but as a systemic energy carrier capable of linking the power, industrial, transport, and chemical sectors. This cross-sectoral role enables sector coupling and enhances flexibility in energy systems with high shares of variable renewable generation (STAFFELL *et al*., 2019; DAWOOD *et al*., 2020; GLENK; REICHELSTEIN, 2019; BLANCO *et al*., 2022; PARRA *et al*., 2023; IRENA, 2023).

However, the vast majority of this production is still based on fossil fuels, resulting in significant greenhouse gas emissions (GREEN HYDROGEN COALITION, 2020; IEA, 2024).

Green hydrogen, produced through water electrolysis powered exclusively by renewable energy sources, emerges as a low-emission alternative capable of substantially reducing the carbon footprint of existing hydrogen applications and enabling new decarbonization pathways (WORLD BANK; ESMAP, 2020). By decoupling hydrogen production from fossil fuels, this route aligns with international climate objectives and supports the integration of renewable electricity into broader energy and industrial systems (IRENA, 2023).

Hydrogen as an Energy Carrier

From an energetic perspective, hydrogen is characterized by a high gravimetric energy density of approximately 33.3 kWh per kilogram, which is nearly three times higher than that of conventional liquid fuels such as gasoline (GREEN HYDROGEN COALITION, 2020). This attribute makes hydrogen particularly attractive for applications in which weight is a critical constraint, including heavy-duty transport, maritime operations, aviation-related fuels, and large-scale stationary storage.

In addition to its energy density, hydrogen can be converted into electricity through fuel cells with high efficiency and zero local emissions, producing only water vapor as a byproduct. This conversion pathway has been increasingly explored in hybrid energy systems and microgrids, where hydrogen complements batteries by enabling long-duration and seasonal energy storage, thereby enhancing system resilience and flexibility under high shares of intermittent renewable generation (LEE *et al*., 2024).

Seasonal storage capability represents a key systemic advantage of hydrogen. Unlike conventional electrochemical storage technologies, which are generally optimized for short-duration applications, hydrogen enables the storage of surplus renewable energy over weeks or months. This feature is particularly relevant in regions with strong seasonal variability in solar and wind resources, allowing energy systems to balance supply and demand over longer time horizons and reduce renewable curtailment (SEGOVIA-HERNÁNDEZ *et al*., 2025; IRENA, 2023).

Classification of Hydrogen Production Pathways

Hydrogen production pathways are commonly classified according to the primary energy source and the associated environmental impact. This color-based classification, although simplified, is widely used in the literature and policy documents to distinguish production routes and their emission profiles (IEA, 2024).

Gray hydrogen is predominantly produced through steam methane reforming, emitting between 8 and 12 kg of CO_2 per kilogram of hydrogen produced. Brown hydrogen, derived from coal or lignite gasification, represents the most carbon-intensive pathway. Blue hydrogen follows a similar process to gray hydrogen but incorporates carbon capture and storage technologies; its environmental performance depends strongly on capture efficiency, methane leakage rates, and the long-term integrity of storage sites (SEGOVIA-HERNÁNDEZ *et al*., 2025).

Emerging pathways include turquoise hydrogen, produced via methane pyrolysis, which generates solid carbon as a byproduct but remains at early stages of technological development. In contrast, green hydrogen refers exclusively to hydrogen produced via water electrolysis powered by renewable electricity sources such as solar, wind, hydro, biomass, or biogas. This pathway is characterized by the absence of direct CO_2 emissions and is widely regarded as the most sustainable option for achieving deep decarbonization in the long term (GREEN HYDROGEN COALITION, 2020; WORLD BANK; ESMAP, 2020).

International organizations and certification frameworks increasingly emphasize the importance of additionality and traceability in defining green hydrogen, requiring that the electricity used for electrolysis originate from renewable sources that would not otherwise have been generated. This alignment with sustainability standards is critical for accessing premium markets and ensuring the credibility of green hydrogen value chains (IEA, 2024; IRENA, 2023).

Environmental and Systemic Benefits

The replacement of fossil-based hydrogen with green hydrogen offers substantial environmental benefits. Estimates indicate that substituting current gray hydrogen production with green hydrogen could avoid hundreds of millions of tonnes of CO_2 emissions annually, particularly in sectors such as ammonia, methanol, steelmaking, and refining, which are considered among the most difficult to decarbonize (GREEN HYDROGEN COALITION, 2020; IEA, 2024).

Beyond emission reduction, green hydrogen provides systemic benefits that enhance its strategic relevance within energy transitions. One key advantage is its ability to support the expansion of renewable energy systems. Electrolyzers can operate flexibly during periods of excess renewable generation, absorbing electricity that would otherwise be curtailed and converting it into a storable energy carrier. This function increases overall system efficiency and improves the economic performance of renewable assets.

Green hydrogen also contributes to energy security by diversifying energy supply options and reducing dependence on imported fossil fuels. For countries with abundant renewable resources, domestic hydrogen production can strengthen resilience against price volatility and geopolitical risks associated with conventional energy markets (WORLD BANK; ESMAP, 2020; IRENA, 2023).

From a developmental perspective, green hydrogen creates opportunities for regional economic development, particularly in countries with high solar and wind potential. The establishment of hydrogen value chains can stimulate investment, create skilled employment, and foster technological learning, while enabling participation in emerging international markets for hydrogen and its derivatives, such as green ammonia and methanol (WORLD BANK; ESMAP, 2020).

In this sense, green hydrogen is increasingly viewed not only as a technological solution but also as a systemic component of sustainable development strategies. Its successful integration depends on coordinated advances in technology, infrastructure, regulation, and institutional capacity, especially in developing economies seeking to align decarbonization objectives with broader socioeconomic goals (SEGOVIA-HERNÁNDEZ *et al*., 2025; IEA, 2024).

PRODUCTION TECHNOLOGIES: ELECTROLYTIC SYSTEMS AND SYSTEM MODELING

The production of green hydrogen depends fundamentally on the performance, efficiency, and integration of electrolysis systems with renewable energy sources. Recent advances in electrolyzer technologies, power electronics, and computational modeling have significantly improved the technical and economic prospects of green hydrogen, particularly in contexts characterized by variable renewable generation (SEGOVIA-HERNÁNDEZ *et al*., 2025; IEA, 2024).

As a result, the literature increasingly emphasizes not only individual component performance but also system-level optimization and dynamic operation.

Water Electrolysis Technologies

Water electrolysis is an electrochemical process in which water molecules are split into hydrogen and oxygen through the application of electrical energy. When this electricity is supplied exclusively by renewable sources, the resulting hydrogen is classified as green and is associated with minimal life-cycle emissions (GREEN HYDROGEN COALITION, 2020; WORLD BANK; ESMAP, 2020). Among the available technologies, alkaline electrolyzers, proton exchange membrane electrolyzers, and solid oxide electrolyzer cells represent the most relevant pathways discussed in the contemporary literature.

Alkaline electrolyzers are the most mature and widely deployed technology, with decades of industrial experience. They are characterized by relatively low capital costs, long operational lifetimes, and robust performance under steady operating conditions. However, their lower current density and limited dynamic response reduce their suitability for direct coupling with highly intermittent renewable sources, unless complemented by buffering strategies or auxiliary storage systems (IEA, 2024). Despite these limitations, alkaline systems remain economically attractive for large-scale hydrogen production in contexts with stable electricity supply.

Proton exchange membrane electrolyzers have gained increasing attention due to their high power density, compact design, and fast dynamic response. These characteristics make PEM systems particularly suitable for integration with variable renewable energy sources such as solar and wind, as they can operate efficiently under fluctuating load conditions (LEE *et al*., 2024). Nevertheless, their reliance on noble metal catalysts, such as platinum and iridium, raises concerns regarding cost, material availability, and long-term scalability. Ongoing research efforts aim to reduce catalyst loading or develop alternative materials to address these challenges (IEA, 2024).

Solid oxide electrolyzer cells operate at high temperatures, typically between 700 and 900°C, allowing them to achieve higher thermodynamic efficiencies by utilizing thermal energy in addition to electricity. This characteristic makes SOEC technology particularly attractive for integration with industrial processes that generate waste heat, potentially reducing overall energy consumption (SEGOVIA-HERNÁNDEZ *et al*., 2025). However, SOEC systems remain at lower levels of technological maturity and face challenges related to material degradation, system complexity, and high capital costs, which currently limit their large-scale deployment (IRENA, 2023).

Comparative reviews indicate that alkaline, PEM, and solid oxide electrolyzers present distinct trade-offs in terms of efficiency, dynamic response, capital costs, and scalability. While alkaline systems remain dominant in large-scale industrial applications, PEM electrolyzers are increasingly favored for renewable-coupled systems due to their operational flexibility, and SOEC technologies are explored for high-temperature industrial integration (BUTTLER; SPLIETHOFF, 2018; ACAR; DINCER, 2019; BUTTLER; SPLIETHOFF, 2020).

System Modeling and Simulation of Hydrogen Production

Recent modeling-based studies demonstrate that advanced control strategies and high-resolution simulations are essential for optimizing electrolyzer operation under intermittent renewable supply. Approaches based on model predictive control, hybrid optimization, and digital twins have been shown to reduce renewable curtailment, extend component lifetime, and improve overall system efficiency (GABRIELLI *et al*., 2020; PARRA *et al*., 2021).

High-resolution simulations, often based on hourly or sub-hourly time steps, enable the assessment of system performance over a full year of operation, capturing seasonal variability and operational constraints. These models support optimized sizing of electrolyzers and associated components, allowing researchers and practitioners to minimize capital expenditures while maintaining target hydrogen production levels (IEA, 2024). They also provide a basis for evaluating key performance indicators such as system efficiency, capacity factor, and levelized cost of hydrogen.

Advanced control strategies represent another important application of modeling. Techniques such as model predictive control, fuzzy logic, and data-driven approaches have been employed to regulate electrolyzer operation under fluctuating renewable input, improving efficiency and reducing component stress (LEE *et al*., 2024). In parallel, the concept of digital twins—virtual replicas of physical systems—has gained prominence as a means of monitoring performance, predicting degradation, and optimizing maintenance strategies, thereby extending system lifetime and reducing operational costs (SEGOVIA-HERNÁNDEZ *et al*., 2025).

Simulation platforms such as MATLAB/Simulink, TRNSYS, HOMER, and Modelica are widely used in the literature to analyze hybrid renewable–hydrogen systems. Comparative studies indicate that these tools enable consistent long-term performance assessments and support techno-economic evaluations across a wide range of configurations, including off-grid and grid-connected systems (MÖLLER; KRAUTER, 2022).

Integration with Renewable Energy Systems

The integration of electrolyzers with renewable energy systems is a defining feature of green hydrogen production. In hybrid configurations, electrolyzers operate as flexible loads that absorb excess renewable electricity during periods of high generation, thereby reducing curtailment and enhancing overall system efficiency (WORLD BANK; ESMAP, 2020; IRENA, 2023).

Solar photovoltaic systems present diurnal and seasonal generation patterns that require careful alignment with electrolyzer operating profiles. PEM electrolyzers, in particular, are well suited to follow rapid changes in solar output due to their fast response characteristics. Wind-based systems, characterized by higher short-term variability, similarly benefit from electrolyzer technologies capable of dynamic operation and from advanced control strategies that smooth power fluctuations (LEE *et al*., 2024).

Power electronics play a critical role in enabling this integration. AC–DC and DC–DC converters ensure compatibility between variable renewable generation and electrolyzer voltage and current requirements, while maximum power point tracking strategies enhance overall system efficiency. Thermal management and water supply also represent essential design considerations, as electrolyzer performance and durability depend on stable operating conditions and access to purified water—factors that are sometimes underestimated in simplified analyses (IEA, 2024).

At the system level, the inclusion of electrolyzers can improve microgrid stability by providing controllable demand that mitigates rapid fluctuations in renewable output. This function is particularly valuable in isolated or weak grids, where hydrogen systems can contribute to both energy storage and grid-balancing services (SEGOVIA-HERNÁNDEZ *et al*., 2025).

Overall, the literature indicates that the technical viability of green hydrogen production is increasingly shaped by the intelligent integration of electrolyzers with renewable energy systems and by the use of advanced modeling and control tools. These developments have reduced operational risks and improved economic performance, reinforcing the role of green hydrogen as a complementary component of renewable-based energy systems (IEA, 2024; IRENA, 2023).

GREEN HYDROGEN IN DEVELOPING COUNTRIES

Developing countries occupy a strategically important position in the emerging global hydrogen economy due to the combination of abundant renewable energy resources, relatively low marginal costs for renewable expansion, and the potential for associated industrial development. International reports and recent studies highlight that regions with high solar irradiation and favorable wind regimes may achieve competitive conditions for large-scale green hydrogen production, particularly when coupled with declining renewable energy costs and technological learning effects (WORLD BANK; ESMAP, 2020; IEA, 2024; IRENA, 2023).

Beyond export-oriented strategies, green hydrogen also presents relevant opportunities for domestic energy transitions in developing economies. Its application can support the decarbonization of existing industrial activities, enhance energy security, and reduce dependence on imported fossil fuels. At the same time, the development of hydrogen value chains can generate employment, stimulate technological learning, and foster integration into emerging low-carbon global markets (IRENA, 2023; WORLD BANK; ESMAP, 2020).

Priority Applications

One of the most frequently discussed applications in the literature concerns off-grid and isolated systems, particularly in remote regions that currently rely on diesel generators. Hybrid systems combining renewable generation, batteries, electrolyzers, hydrogen storage, and fuel cells have been identified as viable alternatives for reducing fuel transportation costs, improving local air quality, and enhancing energy reliability. When logistical costs and environmental externalities are considered, green hydrogen-based solutions may become economically competitive in such contexts, especially with the support of targeted financing instruments and public policies (WORLD BANK; ESMAP, 2020; CANADA H2BC, 2024).

Heavy-duty mobility and mining operations represent another priority application. Fuel-cell vehicles and hydrogen-powered equipment offer advantages in terms of driving range, refueling time, and operational flexibility when compared with battery-electric alternatives, particularly in applications involving long duty cycles and harsh operating conditions. Developing countries with significant mining and extractive sectors, such as Chile, Peru, South Africa, and Brazil, have been identified as promising early adopters of green hydrogen technologies in this domain, aligning decarbonization objectives with corporate sustainability strategies (IEA, 2024).

Energy-intensive industries, including steelmaking, ammonia production, and refining, constitute some of the largest potential sources of demand for green hydrogen in developing economies. In the steel sector, the direct reduced iron route combined with electric arc furnaces and powered by green hydrogen has been identified as a pathway capable of reducing emissions by up to 95% compared to coal-based production routes (LEDARI, 2023; STEELWATCH, 2024). Similarly, the production of green ammonia using renewable hydrogen offers a route to decarbonize fertilizer supply chains while enabling participation in international markets for low-carbon chemical products (SALEHMIN *et al*., 2025).

Green hydrogen also plays a role in grid balancing and long-duration energy storage. In electricity systems with high shares of variable renewable generation, hydrogen enables seasonal storage and supports system flexibility beyond the capabilities of conventional battery technologies. Modeling studies demonstrate that integrating electrolyzers and hydrogen storage can reduce renewable curtailment, improve asset utilization, and enhance system resilience at both local and national scales (IRENA, 2023).

Barriers and Structural Challenges

Despite these opportunities, the literature consistently identifies a set of interconnected barriers that constrain the large-scale deployment of green hydrogen in developing countries. Among the most prominent challenges is the high capital cost associated with electrolyzers, compression and storage infrastructure, and transport systems. Although declining renewable energy costs and technological improvements have reduced the levelized cost of hydrogen in recent years, green hydrogen remains more expensive than fossil-based alternatives in many regions, necessitating policy support mechanisms such as subsidies, contracts for difference, and public procurement schemes (IEA, 2024).

Infrastructure limitations represent another critical constraint. The development of hydrogen transport and storage systems—including pipelines, port facilities, and conversion routes such as ammonia or liquid organic hydrogen carriers—requires substantial investment and long-term planning. The selection of appropriate carriers involves trade-offs related to energy density, safety, reconversion efficiency, and regulatory requirements, which pose additional challenges for countries with limited logistical and institutional capacity (ZHAO, 2025; AMMONIA ENERGY ASSOCIATION, 2024).

Institutional and technical capacity gaps further complicate hydrogen deployment. Many developing countries lack specialized regulatory frameworks, trained personnel, and planning capabilities necessary to design, operate, and oversee complex hydrogen systems. International cooperation, technology transfer, and targeted training programs are therefore emphasized as essential components of sustainable hydrogen strategies, reducing the risk of external dependency and ensuring safe and efficient system operation (WORLD BANK; ESMAP, 2020).

Regulatory uncertainty and the absence of harmonized certification standards also limit market access. International hydrogen trade increasingly depends on the ability to demonstrate the renewable origin of electricity, additionality, and lifecycle emission performance. Countries without clear certification schemes may face barriers to entry in premium markets, underscoring the importance of aligning national frameworks with international standards proposed by organizations such as IEA and IRENA (IEA, 2024; IRENA, 2023).

From an innovation policy perspective, the effectiveness of technological transitions depends not only on research and development efforts but also on the coherence and implementation of innovation policies (CARVALHO; CUSTÓDIO; PAMPLONA, 2025). This finding is particularly relevant for green hydrogen, as limitations in policy coordination, financing mechanisms, and institutional design can significantly delay technological diffusion, especially in developing countries.

Empirical studies and international assessments indicate that regulatory stability, access to concessional finance, and long-term offtake agreements are decisive for the viability of green hydrogen projects in developing countries. Case studies from Latin America, Africa, and Asia highlight that public–private coordination and institutional capacity building are as critical as technological readiness (HUENTELER *et al*., 2020; IEA, 2022; HANNA *et al*., 2023; PFLUGMANN; BLASIO, 2024).

Finally, financial and market risks pose significant challenges for project development. Large-scale hydrogen projects are exposed to uncertainties related to energy prices, demand evolution, regulatory changes, and technological performance. As highlighted in recent studies, innovative financing mechanisms—including blended finance, climate funds, long-term offtake agreements, and public–private partnerships—are often required to reach final investment decisions and reduce perceived risks for investors (IEA, 2024; AMMONIA ENERGY ASSOCIATION, 2024).

Overall, the literature suggests that while developing countries possess strong comparative advantages for green hydrogen production, the realization of this potential depends on coordinated action across policy, finance, infrastructure, and capacity-building domains. Addressing these barriers is critical to ensuring that green hydrogen contributes not only to global decarbonization goals but also to inclusive and sustainable development pathways in emerging economies (WORLD BANK; ESMAP, 2020; IRENA, 2023).

CONCLUSION

This study has analyzed the role of green hydrogen in the global energy transition through a structured review of the contemporary scientific and institutional literature. The results indicate that green hydrogen has consolidated itself as a relevant energy carrier for the decarbonization of sectors that are difficult to electrify, particularly heavy industry, long-distance transport, and large-scale energy storage. Advances in electrolysis technologies, the integration of hydrogen systems with renewable energy sources, and the use of modeling and simulation tools have significantly improved the technical feasibility of green hydrogen production, reinforcing its potential role within low-carbon energy systems. These findings directly address the objectives of this study by synthesizing the conceptual foundations, technological developments, and contextual challenges associated with green hydrogen deployment.”

The review also highlights that the strategic relevance of green hydrogen extends beyond its technological dimension. For developing countries, the literature points to a combination of comparative advantages—such as high solar and wind potential and opportunities for renewable expansion—alongside significant structural challenges. Applications in off-grid systems, heavy-duty mobility, mining operations, energy-intensive industries, and green ammonia production emerge as priority niches capable of catalyzing learning processes, reducing costs over time, and supporting broader decarbonization efforts.

However, the findings consistently show that the large-scale deployment of green hydrogen remains constrained by economic, infrastructural, regulatory, and institutional barriers. High upfront capital costs, limitations in transport and storage infrastructure, regulatory uncertainty, and gaps in technical and institutional capacity continue to restrict diffusion, particularly in developing economies. As emphasized in the literature, overcoming these barriers requires coordinated policy frameworks, long-term investment mechanisms, harmonized certification standards, and international cooperation to reduce risks and improve market conditions.

Regarding the limitations of this study, it should be noted that the analysis is based exclusively on secondary sources and does not include original empirical data or quantitative modeling. While this approach is appropriate for the objectives of a literature review, it may limit the depth of context-specific insights and the ability to capture rapidly evolving market dynamics. Additionally, although the review draws on a broad range of scientific and institutional references, the heterogeneity of methodologies and assumptions across studies may affect the comparability of results.

Future research could address these limitations by conducting empirical case studies of green hydrogen projects in developing countries, incorporating techno-economic modeling, life-cycle assessment, and policy analysis at national and regional scales. Further investigations into financing mechanisms, workforce development, and regulatory design would also contribute to a more comprehensive understanding of how green hydrogen value chains can be effectively implemented in different socioeconomic contexts.

In conclusion, green hydrogen should be understood not merely as a technological alternative, but as a systemic component of long-term sustainable development strategies. Its successful contribution to the global energy transition will depend on the alignment of technological innovation, public policies, investment frameworks, and international cooperation. When these elements are coherently articulated, green hydrogen can play a central role in reducing emissions, strengthening industrial competitiveness, and supporting inclusive development pathways, particularly in emerging and developing economies.

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