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Sustainable Hydrogen Generation: Pathways to a Clean Energy Transition

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Abstract: ***Green hydrogen production refers to the generation of hydrogen using renewable and sustainable energy sources. This approach offers a viable pathway to decarbonization by significantly reducing greenhouse gas emissions and minimizing dependence on fossil fuels. A major advantage of green hydrogen lies in its environmentally friendly process, which avoids the direct release of harmful pollutants or greenhouse gases. However, to fully realize these benefits, it is essential to evaluate the entire hydrogen supply chain, including production, storage, transportation, and end-use applications. As a clean energy carrier, hydrogen plays a pivotal role in global strategies aimed at achieving net-zero emissions by 2050. This review highlights current techniques for green hydrogen production, explores their role in promoting a cleaner environment and sustainable energy systems, and provides an overview of the outlook and energy transition potential. Furthermore, it offers new insights and future research directions to accelerate the development and unlock the potential of green hydrogen technologies.***

Keywords: Green hydrogen energy; hydrogen production; energy transition; clean energy; perspective of green hydrogen

1. Introduction

The transition toward a decarbonized global energy system has placed renewable-energy-powered green hydrogen at the forefront of sustainable energy research. Green hydrogen production, driven by renewable resources, is increasingly recognized as a viable pathway to mitigate greenhouse gas (GHG) emissions and environmental pollution, thereby supporting the goals of the Paris Agreement [1,2]. As fossil fuels continue to dominate the global energy mix, their non–zero-carbon nature has prompted urgent exploration of alternative solutions. To achieve climate neutrality, a drastic shift from fossil-fuel dependence to low-carbon, efficient, and sustainable energy systems is required. Projections suggest that more than 90% of global CO_2 emissions must be reduced, with renewable energy contributing approximately 41% of this reduction [3,4].

Hydrogen (H_2) has emerged as a promising energy carrier due to its versatility, cost-effectiveness, and potential to enable a low-carbon society [5–7]. Beyond its role in energy storage and consumption, hydrogen is increasingly integrated into multiple sectors—including power generation, transportation, industry, and residential applications—underscoring its relevance for deep decarbonization [10–12]. The COVID-19 pandemic further accelerated the recognition of hydrogen technologies as strategic tools to strengthen economic resilience under ambitious climate policies [8, 9].

Recent years have witnessed a surge in global initiatives and investments aimed at advancing hydrogen technologies, largely motivated by declining costs of renewable-energy-derived hydrogen and the urgent need to curb GHG emissions [3,13]. Although hydrogen can be produced from various feedstocks such as coal, natural gas, bioenergy, and solar-driven processes, green hydrogen—generated via water electrolysis powered by renewable energy—has gained particular prominence for its minimal environmental footprint [15,16]. By 2050, global demand for green hydrogen could reach 530 million tonnes annually, potentially displacing ~10.4 billion barrels of oil (equivalent to ~37% of pre-pandemic global oil production) and creating a market worth $300 billion while generating nearly 400,000 jobs [18,19].

Hydrogen production is commonly classified by color codes based on feedstocks and carbon intensity: grey hydrogen (from natural gas via steam reforming, with CO_2 emissions released), blue hydrogen (natural gas with carbon capture), brown/black hydrogen (from coal gasification), and green hydrogen (from renewable-powered electrolysis) [20–22]. Among these, green hydrogen stands out as the most sustainable option, aligning closely with the United Nations' Sustainable Development Goal 7 (Affordable and Clean Energy) [23,24].

Given this context, the present review provides a comprehensive analysis of green hydrogen production technologies and their role in shaping a sustainable global energy economy. Specifically, it highlights the potential pathways, current progress, and future perspectives of the green hydrogen economy (GHE) in addressing energy challenges and achieving decarbonization targets. The structure of the paper is as follows: Section 2 analyzes the role of green hydrogen in the energy transition, Section 3 outlines production techniques, Section 4 discusses future perspectives and challenges, and Section 5 concludes with recommendations for research and policy directions.

1) Overview of Green Hydrogen Production

Hydrogen is a versatile energy carrier with applications spanning energy storage, power generation, industrial processes, and transportation via fuel cell vehicles. Among the different production pathways, green hydrogen—derived from renewable energy sources—has gained particular importance as nations pursue sustainable energy targets (SETs) and transition toward a low-carbon economy.

The production of green hydrogen typically requires substantial inputs of renewable electricity and water resources. Consequently, regions with abundant renewable energy potential and access to reliable water supplies are considered optimal for large-scale deployment. Nevertheless, the economic competitiveness of green hydrogen compared to fossil-fuel-based alternatives remains a critical challenge. Achieving cost parity will depend on technological innovation, efficiency improvements, and significant reductions in capital and operational costs.

Policy frameworks and regulatory support are equally important in accelerating the adoption of green hydrogen. Governments can play a pivotal role by enabling large-scale manufacturing, ensuring consistent renewable energy availability, stimulating demand for hydrogen and its derivatives, and establishing robust storage and transportation infrastructure [25]. Such measures are essential to foster market confidence and create favorable conditions for scaling up production.

To assess the progress and research trends in this field, a bibliometric analysis of more than 100 publications from Google Scholar and Web of Science databases was conducted. Visualization of keyword co-occurrence networks using VOSviewer highlights the evolution of research focus over time. As illustrated in Fig. 1, the red cluster (lower left) represents initial stages of development in green hydrogen research, the blue cluster (upper center) signifies the intermediate phase, and the green cluster (lower right) reflects recent emphasis on hydrogen-related terms. Further, temporal mapping in Fig. 2 indicates that research activity from 2016 to 2019 was primarily clustered in the blue segment (lower left), while the maroon cluster (upper right) captures the intensified focus between 2020 and 2023. These findings underscore the growing global interest in green hydrogen technologies, particularly in recent years, driven by climate targets and rapid technological advancements.

2) Energy Transition with Green Hydrogen

Green hydrogen technologies are increasingly recognized as a cornerstone of the global energy transition. A key advantage lies in their capacity for energy storage, particularly through electrolysis, which enables the conversion of surplus renewable energy generated during low-demand periods into hydrogen. This hydrogen can be stored in gaseous, liquid, or solid-state forms depending on the end-use or export requirements, and later reconverted into electricity using fuel cells. Such flexibility facilitates the integration of intermittent renewable resources like solar and wind into the grid, thereby enhancing system stability and lowering the overall cost of renewable energy deployment.

Several hard-to-abate sectors—including long-haul transport, chemicals, and the iron and steel industries—stand to benefit from clean hydrogen adoption. These industries face persistent challenges in decarbonization, yet hydrogen offers a technically viable and scalable solution. Hydrogen-fueled vehicles also promise co-benefits such as improved air quality and greater energy security. At the system level, large-scale hydrogen storage, whether underground or aboveground, enhances reliability and supports energy demand flexibility, highlighting its central role in a resilient, low-carbon economy [26].

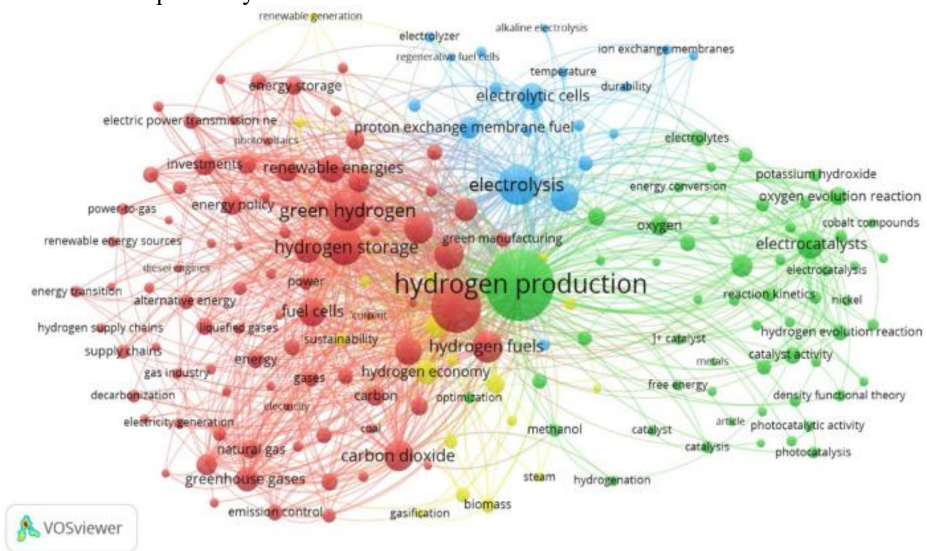

Figure 1: Keyword co-occurrence network of green hydrogen research highlighting major thematic clusters. The red cluster indicates early development themes, the blue cluster reflects intermediate research directions, and the green cluster represents recent focus on hydrogen-related advancements

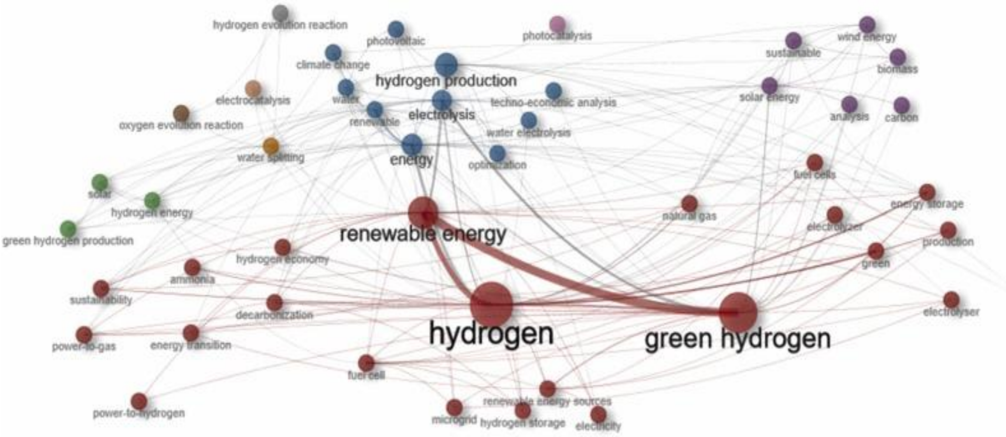

Figure 2: Temporal evolution of green hydrogen research keywords (2016–2023). The blue cluster illustrates trends from 2016 to 2019, while the maroon cluster signifies the intensified research emphasis between 2020 and 2023.

Beyond environmental benefits, the hydrogen transition offers substantial socio-economic opportunities. Development of hydrogen infrastructure, electrolyser manufacturing, fuel cell production, and related supply chains is projected to generate new employment, stimulate exports, and attract foreign investment. The sector's expansion is also expected to drive innovation in advanced materials, cost-effective fuel cells, and high-performance storage technologies. With ongoing technological progress, the scope of hydrogen applications is anticipated to broaden, supported by declining costs and efficiency gains in electrolysers and other enabling technologies.

Despite these advances, several techno-economic challenges remain before global hydrogen trade can achieve commercial viability. Large-scale deployment requires thorough analysis of production costs, transportation infrastructure, and market competitiveness across different regions. Projections suggest that by 2050, approximately 55% of traded hydrogen will be transported through repurposed natural gas pipelines, reducing costs and leveraging existing infrastructure [27,28]. Accordingly, scenario-based assessments of hydrogen production and distribution for 2030 and 2050 are essential for evaluating the global trade outlook.

Optimization of the hydrogen supply chain—including production, storage, transport, and end-use—will be critical to unlocking its full potential as a clean energy carrier. Additionally, integrating hydrogen topics into education, outreach, and workforce training can ensure the development of skilled labor, thereby strengthening the socio-economic foundations of the hydrogen economy. Governments across the world have already begun endorsing national hydrogen strategies to meet decarbonization targets, reduce GHG emissions, and position hydrogen as a key element of sustainable energy management. Table 1 summarizes ongoing investments and projects announced globally to accelerate the sector's growth.

A viable pathway to achieve the 1.5 °C climate scenario will require large-scale, cost-competitive hydrogen production supported by sufficient renewable electricity generation. Ensuring that renewable energy capacity dedicated to hydrogen does not compete with essential electricity demand will necessitate accelerated scaling of solar, wind, hydropower, and other renewable sources. As shown in Fig. 3, green hydrogen can be produced through

Table 1: List of large green hydrogen planned/ongoing projects

No.	Name of project	Country	Estimated cost	Estimated capacity of green hydrogen harvesting	References
1	NEOM	Saudi Arabia	$8.5 billion	1.2 M tonnes per year	[29, 30]
2	Asian Renewable Energy hub	Australia	–	1.75 M tonnes per year	[31]
3	Green Energy Oman	Oman	$10 billion	3.75 M tonnes per year	[31]
4	Reckaz	Kazakhstan	$40–50 billion	3 M tons per year	[31]
5	HyDeal Ambition	Spain	–	3.6 M tonnes per year	[31]
6	Western Green Energy Hub	Australia	$70 billion	20 M tonnes per year	[31]
7	Hy deal Ambition	West Europe	–	3.6 M tonnes per year	[31]
8	Sinopec	China	¥2.6 billion	3.5 M tonnes per year	[32]
9	–	India	$4.29 billion	5 M tonnes per year	[33]

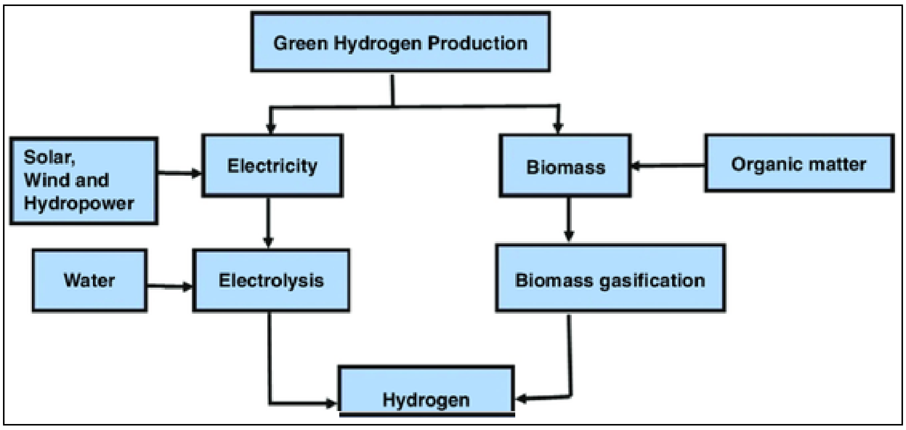

Figure 3: Potential pathway for producing hydrogen from green energy

multiple renewable routes, including biogas production from organic matter, biomass gasification, and electrolysis powered by photovoltaic (PV), concentrating solar power (CSP), wind, or hydropower resources. Electrolysis—the most mature technique—splits water molecules into hydrogen and oxygen according to the reaction:

$$H_2O + \text{energy} \rightarrow H_2 + \frac{1}{2} O$$

Emerging approaches, such as photoelectrochemical (PEC) water splitting, aim to harness solar radiation directly for hydrogen production. Although still at an early stage of development, PEC technologies show promise for sustainable, efficient hydrogen generation [35,36]. Similarly, biohydrogen production from algae has attracted growing interest, with certain species capable of releasing hydrogen as a metabolic by-product under specific conditions [37–41]. While not yet industrially mature, these pathways highlight the breadth of innovation under exploration.

Future cost reductions will depend on maximizing electrolyser utilization, developing seawater electrolysis technologies [42–45], and overcoming the intermittency of renewable supply. Collectively, these technological, infrastructural, and policy advancements will determine the extent to which green hydrogen fulfills its potential as a cornerstone of the clean energy transition.

The Perspective of Green Hydrogen Energy

The global shift toward clean energy places green hydrogen at the intersection of technological innovation, economic opportunity, and climate action. Its large-scale deployment requires coordinated efforts across governments, industries, research institutions, and communities. By diversifying energy sources, reducing greenhouse gas (GHG) emissions, and fostering sustainable growth, green hydrogen offers a transformative pathway toward achieving international decarbonization goals [14].

Table 2: Breakdown of the potential of global green hydrogen production by region [46]

No.	Region	Estimated Energy Capacity (EJ)	Percentage (%)
1	Sub-Saharan Africa	2715	28.6
2	Middle East and North Africa	2023	21.3
3	North America	1314	13.8
4	Oceania (Australia)	1272	13.4
5	South America	1114	11.7
6	Rest of Asia	684	7.2
7	Northeast Asia	212	2.23
8	Europe	88	0.92
9	Southeast Asia	64	0.67

From an economic standpoint, green hydrogen presents significant opportunities for industrial growth, job creation, and energy diversification. Countries with abundant renewable resources are particularly well-positioned to leverage hydrogen exports, reduce reliance on fossil fuels, and stimulate economic development. For example, Table 2 outlines regional production potentials, with Sub-Saharan Africa (28.6%) and the Middle East and North Africa (21.3%) identified as the leading contributors due to their vast solar and wind capacities [46].

Technologically, green hydrogen acts as both a development catalyst and an enabler of renewable energy integration. Electrolysis, the most mature production pathway, benefits from ongoing advancements in efficiency, cost reduction, and material innovation. These developments not only reduce the cost of hydrogen generation but also enhance its role in balancing electricity grids with high shares of variable renewables. By mitigating renewable energy curtailment and providing long-term storage options, hydrogen strengthens energy system flexibility and resilience [42].

The momentum behind green hydrogen adoption is further reinforced by ambitious national policies and carbon-neutrality targets. Several countries—including the USA, Germany, Austria, Saudi Arabia, and China—have announced large-scale investments in hydrogen infrastructure, ranging from electrolyser deployment to storage and refueling networks [15,42]. As illustrated in Fig. 4, green hydrogen's applications span across multiple sectors, including industry, power generation, construction,

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and transportation, highlighting its versatility in supporting the energy transition.

Global projections emphasize its role in climate mitigation. Studies suggest that green hydrogen could contribute to reducing nearly 80 gigatonnes of CO_2 emissions by 2050, thereby supporting the 1.5 °C climate target and enabling net-zero pathways [48]. Realizing this potential, however, depends on geographic conditions and resource availability. Desert regions with high solar irradiation, for example, are well-suited for large-scale PV and CSP-driven hydrogen production. Such projects could supply domestic markets while generating export revenues, thus advancing both sustainability and economic development.

Despite these prospects, the economics of green hydrogen remain challenging. Initial investment costs—particularly those associated with renewable energy capacity, electrolysers, and storage infrastructure—are critical barriers. Achieving cost-competitiveness will require economies of scale, favorable financing mechanisms, and policy incentives. Green financing, in particular, should prioritize early-stage projects to accelerate market development and bring down levelized costs of hydrogen production [29,49].

Ultimately, green hydrogen represents a key lever in global energy transitions. By combining climate benefits with economic potential, it holds the promise of reshaping energy systems into more sustainable, resilient, and environmentally responsible structures. With continued investment, policy support, and technological innovation, green hydrogen could become a cornerstone of the clean energy future.

2. Conclusions

Green hydrogen has emerged as a pivotal element in the pursuit of global net-zero targets, offering a dual role as both an energy vector and a decarbonization strategy. Its ability to reduce greenhouse gas emissions, foster energy independence, and facilitate the transition to a low-carbon economy underscores its growing importance in sustainable energy systems.

Recent technological advances, particularly in renewable-energy-driven electrolysis, have improved the feasibility of large-scale green hydrogen production by lowering costs and enhancing efficiency. These developments position green hydrogen not only as a tool for environmental mitigation but also as a catalyst for economic growth, job creation, and global clean-energy trade.

However, key challenges remain before green hydrogen can achieve widespread deployment. Cost reduction, large-scale infrastructure development, and industrial integration are critical factors. Establishing a global hydrogen market, where nations with abundant renewable resources can export hydrogen as an energy commodity, could accelerate adoption and reduce reliance on fossil fuel imports.

Future efforts must prioritize the development of advanced, cost-effective electrolysers, efficient storage and transport solutions, and enabling policy frameworks. With coordinated investments and international collaboration, green hydrogen can play a transformative role in shaping a sustainable, low-carbon energy future.

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