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Challenges and future directions for green hydrogen development

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Abstract

Green hydrogen has been increasingly recognized as a critical solution for decarbonization in various sectors, including transportation, heavy industry, and energy storage. However, its widespread adoption is currently hindered by several obstacles, including high production costs, insufficient infrastructure, and inadequate differentiation from fossil fuel-derived hydrogen. To promote the green hydrogen economy, targeted policy actions are necessary. These include creating a climate-oriented market foundation, ensuring long-term resilience through diversified supply chains, and offering robust financial incentives. Addressing these challenges is essential for unlocking green hydrogen's potential and achieving global carbon neutrality targets.

Keywords: *green hydrogen, emissions reduction, policy actions, infrastructure, energy transition*

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1. Introduction

The role of hydrogen in the global energy transition has been extensively discussed in the recent literature [1, 2]. However, while hydrogen and its derivatives are projected to constitute only 3.9% of the global energy mix by 2050, far below the 15% target set by the Paris Agreement [3], substantial obstacles remain in realizing this potential. Key challenges include high production costs, lack of infrastructure, and difficulties in differentiating green hydrogen from fossil fuel-derived alternatives.

For instance, current production costs of green hydrogen exceed 5 USD/kg [4], making it less competitive compared to fossil fuel-derived hydrogen, which costs around 1–2 USD/kg [5]. However, with technological advancements and economies of scale, green hydrogen production costs are expected to fall to 3 USD/kg by 2030, according to an IRENA report [6]. Additionally, green hydrogen's carbon abatement cost ranges from 500 to 1250 USD/tCO_2, while fossil hydrogen is typically lower, reflecting a significant cost disparity.

2. Materials and methods

This study synthesizes existing literature and reports on the challenges and potential of green hydrogen technologies. Comprehensive reviews of recent publications, government reports, and market analyses were conducted to identify key barriers to the adoption of green hydrogen. In addition to qualitative analysis, quantitative data were collected from reputable sources, such as International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and Hydrogen Council, to provide a robust empirical foundation.

Data on infrastructure, production costs, and policy frameworks were analyzed to support the findings.

3. Results

Our analysis reveals several critical challenges to the widespread adoption of green hydrogen, as well as emerging opportunities. The following sections provide both qualitative and quantitative data:

3.1. Cost of green hydrogen production

The cost of green hydrogen production remains a major challenge. According to an IRENA report [6], green hydrogen production costs range from USD 5 to USD 6 per kilogram, significantly higher than gray hydrogen, which is priced around USD 1.5 per kilogram. As shown in **Table 1**, production costs for green hydrogen are expected to decrease to 3 USD/kg by 2030, largely driven by falling renewable energy costs and advancements in electrolysis technologies.

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Table 1 • Green hydrogen production cost (2019–2030).

Year	Green hydrogen production cost (USD/kg)	Gray hydrogen production cost (USD/kg)
2019	5.50	1.50
2020	5.40	1.50
2021	5.20	1.50
2022	5.00	1.50
2023	5.00	1.50
2024	4.80	1.50
2025	4.50	1.50
2026	4.30	1.50
2027	4.10	1.50
2028	3.90	1.50
2029	3.60	1.50
2030	3.00	1.50

Note: Data were calculated by the authors' team.

3.2. Infrastructure limitations

The current global hydrogen infrastructure is limited, with only about 4500 km of dedicated hydrogen pipelines [6]. As shown in **Table 2**, the lack of refueling stations and hydrogen transportation systems remains a barrier to market adoption. Expanding infrastructure is essential for up-scaling green hydrogen production and facilitating its use in sectors like transportation and industry.

3.3. Market differentiation

The lack of established certification standards for green hydrogen complicates market differentiation. **Table 3** demonstrates the cost comparison between gray and green hydrogen production and outlines the potential economic advantages of green hydrogen once its market receives clear certification standards.

3.4. Policy gaps

The lack of integrated policy frameworks remains a significant challenge. Current hydrogen policies mainly focus on road transport, neglecting industrial and heavy-duty applications. According to the Hydrogen Council [7], countries with holistic hydrogen policies can expect an increase in green hydrogen adoption by over 25% by 2030.

Table 3 • Cost comparison between green and gray hydrogen (2024).

Hydrogen type	Production cost (USD/kg)
Green hydrogen	5.00
Gray hydrogen	1.50

Note: Data were calculated by the authors' team.

4. Discussion

As green hydrogen holds great promise for achieving decarbonization goals, several dimensions—technical, economic, and social—must be addressed. The high production costs, infrastructure gaps, and policy shortcomings need targeted interventions to unlock green hydrogen's full potential.

4.1. Comparative analysis of existing literature

A thorough review of recent studies [1, 5] reveals a consensus on the need to scale up green hydrogen production through cost reduction strategies, including subsidies and long-term government support. However, a comparative analysis shows a lack of consensus on the optimal strategies for achieving these goals. **Table 4** compares cost reduction trajectories for green hydrogen as projected by different reports [2, 6, 8].

Table 4 • Projected green hydrogen cost reduction (2024–2030).

Year	IEA projection (USD/kg)	IRENA projection (USD/kg)	Hydrogen council projection (USD/kg)
2024	5.00	5.50	4.50
2025	4.80	5.30	4.30
2026	4.60	5.00	4.10
2027	4.40	4.80	3.90
2028	4.20	4.60	3.70
2029	4.00	4.40	3.50
2030	3.00	3.00	3.00

Note: Data were calculated by the authors' team.

4.2. Infrastructure development

Developing hydrogen infrastructure is vital for market adoption. Several recent studies highlight the need for coordinated efforts between governments and the private sector to expand pipeline networks and establish hydrogen refueling stations [9, 10].

Table 2 • Global hydrogen infrastructure (2024).

Infrastructure element	Current status	Estimated growth (2024–2030)	Barriers to expansion
Hydrogen pipelines	4500 km (global total)	12,000 km (by 2030)	High cost, lack of policy coordination
Hydrogen refueling stations	1000 stations	10,000 stations (by 2030)	Limited investment, regulatory hurdles
Hydrogen storage facilities	200 facilities	1000 facilities (by 2030)	Land availability, technology maturity
Hydrogen distribution networks	Limited (mainly local)	National and international (by 2030)	Infrastructure complexity, cost-sharing challenges

Note: Data were calculated by the authors' team.

4.3. Mineral supply vulnerabilities

The reliance on critical minerals for electrolysis technologies is another challenge. As noted by several studies [11–16], securing stable supply chains for materials such as nickel and platinum group metals is crucial for sustaining green hydrogen production at scale.

5. Conclusions

Green hydrogen represents a transformative opportunity for decarbonizing various sectors, particularly transportation and heavy industry. However, significant challenges—such as high production costs, limited infrastructure, and a lack of differentiation—must be addressed to realize its full potential. As demonstrated in **Table 5**, achieving a reduction in production costs to below 3 USD/kg is essential for green hydrogen to compete with fossil hydrogen.

Table 5 • Global hydrogen production vs. demand (2024–2030).

Year	Global hydrogen production (million tonnes)	Global hydrogen demand (million tonnes)
2024	90	120
2025	95	125
2026	100	130
2027	105	135
2028	110	140
2029	115	145
2030	120	150

Note: Data were calculated by the authors' team.

Policymakers must prioritize green hydrogen in climate strategies, focusing on integrated policy frameworks, financial incentives, and infrastructure development. By addressing these challenges, green hydrogen can play a crucial role in achieving global decarbonization targets and contributing to a sustainable energy future.

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Author contributions

The author confirms sole responsibility for this work. The author approves of this work and takes responsibility for its integrity.

Conflict of interest

The author declares no conflicts of interest.

Data availability statement

Data supporting these findings are available within the article, at https://doi.org/10.20935/AcadEnergy7564, or upon request.

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