



Green Hydrogen: Revolutionizing the Energy Landscape

Abdulgader Alsharif^{1*}, Mohamed Belrzaeg², Hassnen S. Snoussi³

^{1,3} Department of Electric and Electronic Engineering, College of Technical Science Sabah, Sabha, Libya

² Department of Mechanical and Industrial Engineering, Faculty of Engineering, Bani Waleed University, Bani Walid, Libya

الهيدروجين الأخضر: إحداث ثورة في مشهد الطاقة

عبدالقادر الشريف^{1*}، محمد بالرازق²، حسن سنوسي الزين³
^{3,1} قسم الهندسة الكهربائية والإلكترونية، كلية العلوم التقنية صباح، Sabha، ليبيا
² قسم الهندسة الميكانيكية والصناعية، كلية الهندسة، جامعة بني وليد، بني وليد، ليبيا

*Corresponding author: alsharifutm@gmail.com

Received: May 09, 2026

Accepted: July 18, 2026

Published: July 18, 2026

Abstract:

Green hydrogen, produced through water electrolysis powered by renewable electricity, has emerged as a critical pillar of the global energy transition. This article provides a comprehensive review of green hydrogen production technologies, applications, economic viability, and policy frameworks based on the latest 2025–2026 data. Global low-emissions hydrogen production reached nearly 1 Mt in 2025, with installed electrolysis capacity doubling to surpass 4 GW. Capital spending on low-emissions hydrogen projects reached nearly USD 7 billion in 2025, nearly double the 2024 level. Despite significant progress, challenges including high production costs (USD 2.7–6.4/kg unsubsidized globally in 2025), infrastructure gaps, and policy uncertainty continue to impede widespread adoption. This review analyzes the current state of green hydrogen technologies, presents comparative performance data across electrolyzer platforms, examines sectoral applications, and discusses the policy interventions required to unlock the full potential of green hydrogen as a cornerstone of sustainable energy systems.

Keywords: Green Hydrogen, Electrolysis, Renewable Energy, Decarbonization, Energy Storage, Fuel Cells, Levelized Cost of Hydrogen

الملخص

برز الهيدروجين الأخضر، الذي يُنتج عبر التحليل الكهربائي للماء باستخدام الكهرباء المتجددة، كركيزة أساسية في تحول الطاقة العالمي. يقدم هذا المقال مراجعة شاملة لتقنيات إنتاج الهيدروجين الأخضر، وتطبيقاته، وجدواه الاقتصادية، وأطر السياسات ذات الصلة، استناداً إلى أحدث بيانات عامي 2025-2026. بلغ الإنتاج العالمي للهيدروجين منخفض الانبعاثات قرابة المليون طن متري في عام 2025، مع تضاعف قدرة التحليل الكهربائي المركبة لتتجاوز 4 جيجاوات. كما وصل الإنفاق الرأسمالي على مشاريع الهيدروجين منخفض الانبعاثات إلى ما يقارب 7 مليارات دولار أمريكي في 2025، أي ما يقرب من ضعف مستواه في 2024. ورغم التقدم الكبير، لا تزال تحديات مثل ارتفاع تكاليف الإنتاج (2.7-6.4 دولار/كجم بدون دعم عالمياً في 2025)، والفجوات في البنية التحتية، وعدم اليقين السياسي تعوق الاعتماد الواسع النطاق. يحلل هذا المقال الوضع الحالي لتقنيات الهيدروجين الأخضر، ويقدم بيانات أداء مقارنة لمنصات المحطات الكهربائية، ويدرس التطبيقات القطاعية، ويناقش التدخلات السياسية اللازمة لإطلاق الإمكانيات الكاملة للهيدروجين الأخضر كحجر زاوية لأنظمة الطاقة المستدامة..

الكلمات المفتاحية: الهيدروجين الأخضر، التحليل الكهربائي، الطاقة المتجددة، إزالة الكربون، تخزين الطاقة، خلايا الوقود، التكلفة المستوية للهيدروجين.

Introduction

The global energy sector remains heavily reliant on fossil fuels, leading to escalating greenhouse gas emissions and the depletion of finite natural resources [14]. Global primary energy demand is forecasted to increase by 1.3% annually until 2040, driven by population growth, economic expansion, and technological advancements [12]. Fossil fuels currently account for approximately 85% of global energy consumption and are the primary

contributors to greenhouse gas emissions, with over 36 billion tons of CO₂ released annually [12]. These challenges underscore the necessity of accelerating the transition toward sustainable, resilient, and cost-effective energy alternatives [14].

In this context, green hydrogen has emerged as a promising solution for decarbonizing energy systems. Produced through water electrolysis powered by renewable energy sources, green hydrogen offers a sustainable alternative to fossil fuels and is poised to play a pivotal role in the transition to a low-carbon economy [12]. As a flexible and zero-emission energy carrier, hydrogen has significant potential to reduce emissions across multiple sectors, including transportation, industry, power generation, and heating [14].

Global hydrogen demand grew almost 3% in 2025 to surpass 100 Mt, concentrated in traditional uses in industry and refining [9]. However, low-emissions hydrogen including green hydrogen currently accounts for less than 1% of global hydrogen demand, highlighting the substantial scaling challenge ahead [2][7].

The main contributions of this article are: (1) a comprehensive analysis of green hydrogen production technologies with up-to-date performance metrics; (2) a detailed classification framework for hydrogen production pathways; (3) quantitative assessment of economic trends and cost trajectories; (4) evaluation of sectoral applications with real-world project data; and (5) a critical review of policy frameworks and future outlook. The remainder of this article is organized as follows: Section 2 presents the classification of hydrogen production methods. Section 3 reviews electrolysis technologies and recent advancements. Section 4 analyzes the economic landscape and cost trends. Section 5 examines applications across transportation, industry, and power generation. Section 6 discusses policy frameworks and challenges. Section 7 provides the future outlook, and Section 8 concludes the review.

1. Hydrogen Classification Framework

Hydrogen itself is colorless, but a widely adopted color-coded typology has emerged to differentiate production pathways based on their techno-economic and environmental characteristics [15][16]. Table I summarizes the primary hydrogen classifications.

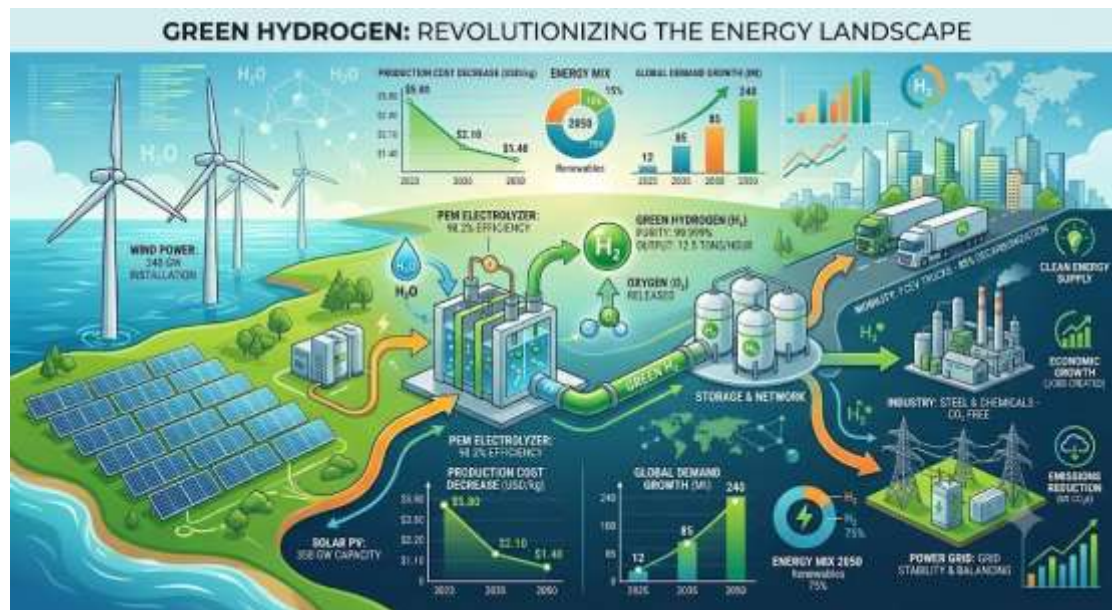


Figure 1: Green Hydrogen: Revolutionizing the Energy Landscape

Table 1: Classification of Hydrogen Production Pathways [12][15][11][16]

Color	Production Method	Feedstock	Emissions Profile	Cost (USD/kg)
Grey	Steam methane reforming (SMR)	Natural gas	High CO ₂ emissions (≤11.3 kg CO ₂ e/kg H ₂)	1.0–2.5
Blue	SMR with carbon capture and storage	Natural gas	Reduced emissions (≤3.38 kg CO ₂ e/kg H ₂)	1.5–3.0

Green	Water electrolysis powered by renewables	Water + renewable electricity	Near-zero emissions (≤ 0.45 kg CO ₂ e/kg H ₂)	2.7–6.4
Turquoise	Methane pyrolysis	Natural gas	Low emissions (solid carbon byproduct)	2.0–4.0
Pink	Electrolysis powered by nuclear energy	Water + nuclear electricity	Near-zero emissions	3.0–5.0

Hydrogen Production Pathways: Color Spectrum & Key Metrics				
Color	Production Method	Feedstock	Emissions Profile	Cost (USD/kg)
 Grey	 Steam methane reforming (SMR)	 Natural gas	 High CO ₂ emissions (≤ 11.3 kg CO ₂ e/kg H ₂)	 \$ 1.0–2.5
 Blue	 SMR with carbon capture and storage (CCS)	 Natural gas	 Reduced emissions (≤ 3.38 kg CO ₂ e/kg H ₂)	 \$ 1.5–3.0
 Green	 Water electrolysis powered by renewables	 Water + renewable electricity	 Near-zero emissions (≤ 0.45 kg CO ₂ e/kg H ₂)	 \$ 2.7–6.4
 Turquoise	 Methane pyrolysis	 Natural gas	 Low emissions (solid carbon byproduct)	 \$ 2.0–4.0
 Pink	 Electrolysis powered by nuclear energy	 Water + nuclear electricity	 Near-zero emissions	 \$ 3.0–5.0
*Note: Costs and emissions are illustrative and can vary based on technology, location, and scale.				

Figure 2 : Classification of Hydrogen Production Pathways

Grey hydrogen, produced via steam methane reforming without carbon capture, remains the most cost-effective option but carries a high carbon footprint [15]. Blue hydrogen employs the same SMR process but incorporates carbon capture, utilization, and storage (CCUS) to reduce emissions by up to 90% [15]. Green hydrogen, derived from renewable-powered electrolysis, offers the lowest emissions but faces higher production costs and infrastructure hurdles [15†L9-L11][15]. Emerging forms, including turquoise (methane pyrolysis), pink (nuclear-powered electrolysis), and white (naturally occurring hydrogen), present novel opportunities and challenges [6][16].

The transition from grey to green hydrogen represents a fundamental shift in the energy paradigm. However, as of 2025, global hydrogen production remains dominated by unabated fossil fuels, with low-emissions hydrogen accounting for only slightly more than 1% of global production [7].

2. Electrolysis Technologies and Advancements

2.1 Overview of Electrolyzer Technologies

Green hydrogen production relies on water electrolysis, a process that utilizes electricity from renewable sources to split water into hydrogen and oxygen. Several electrolyzer technologies have reached varying levels of maturity, each with distinct performance characteristics, cost structures, and operational requirements. Table II presents a comparative analysis of the major electrolyzer technologies.

Table 2: Comparative Analysis of Electrolyzer Technologies[17][12]

Parameter	Alkaline (AWE)	PEM	SOEC	AEM
Maturity	Commercial	Commercial	Early commercial	Pre-commercial
Electrical efficiency	60–65%	70–75%	80–85%	60–70%
Energy consumption (kWh/kg H ₂)	43–50	43–50	<40	45–55
Operating temperature	60–80°C	50–80°C	700–900°C	50–80°C
Dynamic response	Slow	Fast	Slow	Moderate
Capital cost (USD/kW)	800–1,500	1,500–2,500	>2,500	1,000–2,000
Scalability	High (MW–GW)	Moderate	Moderate	Moderate
Suitability for variable RE	Limited	Excellent	Limited	Moderate

Alkaline Water Electrolyzers (AWE) represent the most mature and widely deployed technology, offering cost-effective large-scale production [17]. However, their limited dynamic response makes them less suited for integration with variable renewable energy sources such as solar and wind [17].

Proton Exchange Membrane (PEM) Electrolyzers provide high efficiency and excellent load flexibility, making them particularly advantageous for integration with intermittent renewable sources [17][17]. The average energy consumption for PEM electrolysis ranges from 43 to 50 kWh per kg of hydrogen, comparable to alkaline systems, but PEM offers superior dynamic response for grid-balancing applications [17]. The higher capital costs of PEM systems (USD 1,500–2,500/kW) remain a barrier to widespread deployment [17].

Solid Oxide Electrolysis Cells (SOECs) demonstrate superior electrical efficiency of up to 85%, compared to 75% for PEM and 65% for alkaline systems, though they require high operating temperatures (700–900°C) [17]. SOECs are particularly promising when coupled with high-temperature heat sources from industrial processes [17].

Anion Exchange Membrane (AEM) Electrolyzers represent an emerging technology that shows promise for cost reduction through the use of non-precious metal catalysts and less corrosive operating conditions [5][17]. However, durability improvements are still required before commercial-scale deployment [17].

2.2 Recent Advancements.

Recent advancements in electrolyzer technologies have focused on improving efficiency, scalability, and renewable energy integration. Key innovations include:

1. Advanced electrode materials: Research into non-precious metal catalysts, transition metal dichalcogenides, layered double hydroxides, and metal-free carbon-based systems has shown promise in reducing costs while maintaining performance [12][6].
2. Machine learning optimization: ML techniques are being increasingly applied to optimize electrolyzer operation, electrode materials, and system integration, collectively enhancing the efficiency, scalability, and cost-effectiveness of hydrogen production [12].
3. Hybrid electrolysis approaches: Hybrid water electrolysis coupled with value-added chemical synthesis at the anode addresses the sluggish kinetics and limited economic value of conventional oxygen evolution reactions [2].
4. Direct coupling with renewables: Studies have evaluated the performance of solar and wind-based electrolysis systems, focusing on hydrogen production rates, energy consumption, and system stability under varying environmental conditions [2].
5. Waste-derived electrocatalysts: Recent reviews have evaluated catalysts derived from biomass, shell waste, plastics, electronic waste, and spent batteries for hydrogen evolution and oxygen evolution reactions, presenting a circular engineering strategy for water electrolysis [2].

Despite these advancements, high costs of noble-metal catalysts and material durability remain key barriers to widespread green hydrogen adoption [12].

3. Economic Landscape and Cost Analysis

3.1 Current Cost Structure

The economics of green hydrogen production remain a critical barrier to widespread adoption. Table 3 presents a comprehensive cost analysis based on 2025–2026 data.

Table 3: Green Hydrogen Cost Analysis(2026–2025)

Parameter	Value	Source
Global unsubsidized LCOH (2025)	USD 2.7–6.4/kg	BMI/Fitch Solutions [11]
US green hydrogen price (Q1 2026)	USD 5.00/kg	Expert Market Research [1]
European LCOH (future scenario)	3–4 €/kg	RePEc [1]
Optimized system LCOH	1.59–3.49 USD/kg	MDPI [20]
Saudi Arabia green hydrogen hub	USD 2.41/kg	IEEE Xplore [14]
Grey hydrogen cost	USD 1.0–2.5/kg	Fuel Journal [12]
Blue hydrogen cost	USD 1.5–3.0/kg	Market estimates
Projected LCOH (high-solar regions, 2030)	USD 1.50–2.50/kg	Mordor Intelligence [10]

The unsubsidized levelized cost of green hydrogen exhibits significant regional disparities, ranging from USD 2.7/kg in regions with abundant renewable resources to over USD 6.4/kg in less favorable locations [11†L7-L8].

Electricity prices are the dominant cost driver, accounting for more than two-thirds of total hydrogen production costs under high-price conditions [1].

A techno-economic optimization study of grid-tied green hydrogen hubs in Saudi Arabia identified Jubail as the optimal location with a hydrogen cost of USD 2.41/kg, an energy cost of USD 0.0245/kWh, and a payback period of 9.8 years [14]. The net energy metering scheme evaluated in this study could earn USD 14.25 million annually from grid exports while achieving a 97% greenhouse gas emission reduction against the grid-only baseline [14].

3.2 Investment Trends

Capital spending on low-emissions hydrogen projects reached nearly USD 7 billion in 2025, nearly double the 2024 level and equal to 0.7% of global investment in energy supply [8]. Investment in electrolysis overtook investment in CCUS-based hydrogen, thanks to a stronger pipeline, higher capital intensity, and faster project progress [8]. Electrolysis could account for approximately 70% of nearly USD 10 billion in anticipated investment in 2026 [8].

China and Europe lead committed electrolysis projects, with China accounting for more than 60% of capacity by 2026 and 25% of estimated investment. Europe represents less than 20% of capacity but 45% of investment, reflecting higher capital expenditure per unit of capacity [8]. Over 85% of investment targets existing hydrogen uses in industry and refineries, or hydrogen-based fuels [8].

International public finance for low-emissions hydrogen in emerging economies grew from a negligible level in 2022 to approximately USD 3.3 billion in cumulative commitments to governments by the first quarter of 2026 [8]. Project-level international public finance reached approximately USD 650 million cumulatively by Q1 2026, mainly for project preparation and reducing financing costs [8].

3.3 Electrolyzer Manufacturing and Market Dynamics

Global nameplate electrolyzer capacity reached 61–63 GW per year in 2025, but only 2.15 GW was operating, creating a significant oversupply [10]. This oversupply forced European alkaline prices down to USD 2,407/kW and PEM to USD 2,547/kW [10]. Chinese vendors control more than half of the installed factory capacity and are exporting modules below cost to maintain market share, impairing Western manufacturers' margins [10].

Electrolyzer manufacturing is entering a consolidation phase due to slow market development [7]. While China leads electrolysis manufacturing thanks to low costs and experience with large projects, signs of consolidation are also emerging there due to unsustainable domestic competition driven by excess capacity and offers below manufacturing costs [7]. As a response, many manufacturers are looking to expand markets outside of China [7].

3.4 Cost Reduction Trajectories

Substantial cost reductions are expected toward 2034, underpinned by manufacturing scale-up and electrolyzer standardization [11†L9-L10]. As hardware costs deflate, the unsubsidized levelized cost of green hydrogen is projected to fall toward USD 1.50–2.50 per kilogram in high-solar regions by 2030, potentially overtaking blue hydrogen ranges burdened by escalating carbon-capture charges (USD 80–150 per tonne by 2030) [10][5].

Aggressive policy incentives are expected to drive green hydrogen cost parity with grey hydrogen in key markets [11]. The price war in electrolyzer manufacturing is accelerating final investment decisions across the Middle East and India, two locations with abundant low-priced renewable electricity [10]. However, plummeting module prices are squeezing working-capital lines for smaller OEMs, raising the prospect of further sector consolidation [10].

4. Applications Across Sectors

4.1 Transportation

Green hydrogen offers transformative potential for decarbonizing transportation, particularly in segments where battery-electric options face limitations [13]. Hydrogen fuel cells provide longer ranges and faster refueling compared to battery-electric alternatives, making them particularly suitable for heavy-duty vehicles, trains, and maritime vessels [13][3].



Figure 3: hydrogen Applications: Status and Key Developments.

Fuel cell electric vehicle stock grew 20% in 2025 to almost 130,000 vehicles, driven by truck sales in China and a rebound in car sales in Korea [9]. Policies in these countries are the main drivers behind a projected tripling of stock by 2030, with trucks and buses accounting for approximately 60% and 30% of hydrogen use, respectively [9].

Life cycle assessment studies highlight the environmental benefits of hydrogen fuel cells over traditional engines, even with current grid emission factors [3]. Integration of hydrogen fuel cell vehicles could achieve greenhouse gas reductions ranging from 53% to near-total decarbonization, depending on the scenario [3].

4.2 Industry

The industrial sector represents a critical opportunity for green hydrogen deployment, serving both as a clean feedstock and as a reducing agent in carbon-intensive processes [13]. Table 4 summarizes key industrial applications.

Table 4: Green Hydrogen Applications in Industry

Application	Sector	Key Developments
Steel production	Primary steelmaking	HYBRIT project (Sweden); ArcelorMittal green hydrogen combustion in Spain [18]
Ammonia production	Chemicals	Green ammonia plants; 1.5 Mt/year projected by 2028 [19]
Methanol production	Chemicals	Green hydrogen as clean feedstock [13]
Refining	Petroleum	Primary sector for low-emissions hydrogen adoption [9]
Fertilizer production	Agriculture	Supportive policies in Europe and India driving adoption [9]

In steel production, green hydrogen serves as a reducing agent for direct reduced iron to make green virgin iron [18]. A techno-economic assessment of hydrogen integration at the Taranto integrated steelworks in southern Italy found that integrating green hydrogen could achieve deep decarbonization by cutting emissions by over 90%, with a base-case levelized hydrogen cost of 3.6 EUR/kg and green steel production cost of 653 EUR/t [18].

Green hydrogen-based ammonia production through the Haber-Bosch process offers a near-term pathway for decarbonizing fertilizer production [19]. The world's largest green hydrogen and ammonia plant, utilizing an off-grid renewable system, is projected to produce 1.5 million tons of green ammonia annually by 2028 [19].

Refining and industry remain the main sectors in which low-emissions hydrogen adoption is taking place. Based on projects that have at least reached a final investment decision, 2.5 Mt is expected to be produced and consumed in refineries and industrial facilities by 2030 [9].

4.3 Power Generation and Energy Storage\

Green hydrogen plays a crucial role in energy storage and grid balancing by converting surplus renewable energy into hydrogen, which can be stored and reconverted into electricity during peak demand periods [13]. Key applications include:

1. Long-duration energy storage: Green hydrogen can be stored in large quantities, allowing for long-term energy storage and facilitating the integration of intermittent renewable energy sources into the grid.
2. Fuel cells for power generation: Hydrogen fuel cells provide flexible, clean electricity generation for stationary applications [13].
3. Gas turbine co-firing: Green hydrogen can be blended with natural gas or used in dedicated hydrogen gas turbines for power generation [13].
4. Grid balancing: Hydrogen production can absorb excess renewable generation during periods of oversupply, providing demand-side flexibility.

Progress in the power sector remains slow and concentrated in Japan and Korea. In Japan, policy support has helped projects to reach investment decisions, whereas changing policy priorities in Korea have led to a more cautious outlook than in previous years [9].

4.4 Notable Large-Scale Projects

Several large-scale green hydrogen projects exemplify the global momentum behind green hydrogen deployment [12]:

Table 5: Flagship Green Hydrogen Projects

Project	Location	Capacity	Status
NEOM Green Hydrogen Project	Saudi Arabia	4 GW RE + 220 kt H ₂ /year	80% complete; commercial production expected Q4 2026 [22]
HyDeal España	Spain	67 GW solar + 9.5 GW electrolysis	Planned
Hydrogen Lab Bremerhaven	Germany	Research/demonstration	Operational [5]
ENVISION Green Hydrogen Plant	China	1.5 Mt ammonia/year by 2028	Under construction [19]

The NEOM Green Hydrogen Project in Saudi Arabia has reached over 80% completion across all components as of Q1 2025. The 4 GW solar and wind power generation assets are scheduled for completion by mid-2026, followed by the commissioning of the electrolyzers [22]. The facility will integrate up to 4 GW of solar and wind power to produce up to 600 tonnes per day of carbon-free hydrogen, which will be converted to green ammonia for transport and export [22]. Commercial production is expected to commence in the fourth quarter of 2026 with a capacity of 220 ktonnes per annum [22].

5. Policy Frameworks and Challenges

5.1 Policy Landscape

Supportive policies and regulations are essential to incentivize the production and use of green hydrogen. A total of USD 41 billion in public funding has been identified in policy updates made since the Global Hydrogen Review 2025 [21]. Table 6 summarizes key policy initiatives.

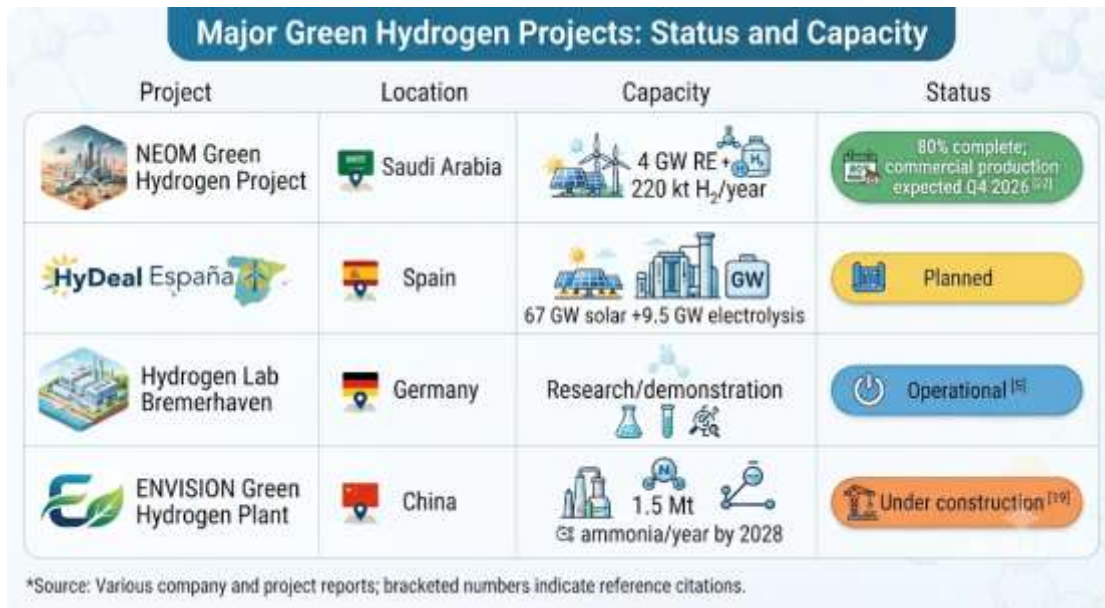


Figure 4: Major Green Hydrogen Policy Initiatives

Table 6: Major Green Hydrogen Policy Initiatives

Policy/Program	Region	Key Features
Inflation Reduction Act (45V)	United States	Up to USD 3/kg production tax credit; start construction before Jan 2028 [10]
European Hydrogen Bank	EU	€1.3 billion auction for hydrogen production; €2.9 billion Net-Zero Technologies call [4]
SIGHT Scheme	India	USD 2.4 billion for electrolysis manufacturing and production incentives [10]
Renewable Energy Directive	EU	42% renewable hydrogen target by 2030; mandate starts 2027 with 4% target [4]
China National Energy Administration	China	41 clean-hydrogen pilot projects approved for preferential loans and subsidies [4]
Algeria Finance Law 2026	Algeria	Exemptions from customs duties and taxes on electrolyzers and solar panels [4]

The U.S. Inflation Reduction Act's 45V credit of up to USD 3 per kilogram for low-carbon hydrogen has become a global benchmark that Europe's Hydrogen Bank, India's SIGHT scheme, and Brazil's pending incentive framework now mirror [10]. These subsidies establish predictable revenue floors, permitting developers to secure non-recourse debt at lower spreads [10].

However, policy uncertainty remains a significant challenge. An accelerated sunset clause in the One Big, Beautiful Bill Act, which requires U.S. projects to start construction before January 1, 2028, prompted cancellations exceeding 4.9 Mtpa in 2025, underscoring persistent policy risk [10]. Multiple EU member states have announced support for electrolyzer manufacturing after a common framework for state aid was approved in 2025 [21].

5.2 Challenges to Widespread Adoption

Despite significant progress, several challenges continue to impede the widespread adoption of green hydrogen:

Table 7: Key Challenges and Mitigation Strategies

Challenge	Description	Mitigation Strategies
Cost	Green hydrogen (USD 2.7–6.4/kg) vs. grey (USD 1.0–2.5/kg) [12]	Scale-up, standardization, policy incentives [11]
Infrastructure	Lack of production, storage, and distribution networks	Public-private investment, hydrogen hubs [7]

Renewable energy scaling	Limited renewable capacity for dedicated electrolysis	Accelerated RE deployment, grid integration
Policy uncertainty	Changing priorities, delayed implementation	Long-term policy frameworks, cross-border coordination
Material durability	Catalyst degradation, membrane longevity	R&D into advanced materials [12]
Demand creation	Limited offtake agreements	Mandates, green procurement, carbon pricing [9]
Regulatory barriers	Complex permitting, certification gaps	Streamlined processes, ISO standard development [21]

- **Cost:** Currently, green hydrogen production is significantly more expensive than fossil fuel-based hydrogen due to the high cost of renewable electricity and electrolysis equipment. The cost gap remains substantial: green hydrogen costs USD 2.7–6.4/kg compared to USD 1.0–2.5/kg for grey hydrogen [12][11].
- **Infrastructure:** The development of a robust infrastructure for the production, storage, and distribution of green hydrogen is crucial. Investments in hydrogen refueling stations, pipelines, and storage facilities are required to support widespread adoption. One large project for production from fossil fuels with CCUS started operation in 2025, but several smaller projects have been postponed due to delays in CCUS infrastructure [7].
- **Demand and offtake:** New offtake agreements for low-emissions hydrogen reached 1.7 Mtpa in 2025, level with 2024 but down from 2.5 Mtpa in 2023 [21]. One-fifth of all new agreements were firm offtakes, concentrated in power generation, industry, and refining [9]. However, sluggish and uncertain policy implementation is failing to address the major barriers to adoption and preventing faster uptake [9]. Trade-oriented agreements were higher than agreements for domestic use for the first time in 2025 [9].
- **Project pipeline:** Committed production grew by 3%, reaching 4.3 Mt by 2030, which could increase to more than 6 Mt if projects with strong potential reach final investment decisions in 2026 or 2027 [7]. However, the project pipeline shrank by 10 Mt to 27 Mt by 2030, driven by delays expected after 2030, projects temporarily paused, and cancellations [7]. More than 100 GW of announced electrolysis capacity could lose any chance of being in operation by 2030 if investment decisions are not taken before the end of 2027 [7].
- **Grid integration challenges:** From 2030 onward, grid penalties could add USD 0.20–0.50/kg to hydrogen costs, eroding competitiveness versus blue hydrogen in gas-rich regions [10]. EU rules forcing hourly matching between renewable output and hydrogen production limit developers' ability to arbitrage cheap imports across bidding zones [10].

6. Future Outlook

6.1 Growth Projections

The clean hydrogen market is expected to experience significant growth over the coming decade. According to Mordor Intelligence, the clean hydrogen market size in terms of production capacity is expected to grow from 2.25 Mtpa in 2025 to 4.5 Mtpa in 2026 and is forecast to reach 13.75 Mtpa by 2031, representing a compound annual growth rate of 25.03% over 2026–2031 [10].

Low-emissions hydrogen production is expected to register record growth in 2026, accounting for more than 1% of global production, strongly concentrated in China, Europe, and North America [7]. More than 2.5 GW of electrolysis capacity is under construction, targeting operation in 2026, with growth expected mostly in Europe (2 GW) [7].

The hydrogen sector has fundamentally shifted from planning to execution, with global operational production capacity expected to double in 2026 as industrial-scale projects come online [10]. By 2034, global green hydrogen capacity is projected to reach 8.9 million tonnes, with emerging economies expected to contribute 60% of this capacity. China leads at 1.06 million tonnes, followed by India (0.86 million tonnes) and Saudi Arabia (0.44 million tonnes) [10].

6.2 Technology Roadmap

Continued advancements in electrolyzer technologies are expected to drive efficiency improvements and cost reductions:

1. Alkaline electrolyzers will remain the workhorse for large-scale production, with ongoing improvements in electrode materials and system design.

2. PEM electrolyzers will gain market share in applications requiring rapid dynamic response and integration with variable renewables.
3. SOEC technology will advance toward commercial deployment, particularly in industrial settings where high-temperature heat is available.
4. AEM electrolyzers may emerge as a cost-competitive alternative once durability challenges are resolved.
5. Artificial intelligence and machine learning will play an increasing role in optimizing electrolyzer operation, predictive maintenance, and system integration [5].

6.3 Sectoral Outlook

Transportation: Fuel cell electric vehicle stock is projected to triple by 2030, with trucks and buses accounting for the majority of growth [9]. Hydrogen-based fuels will play an increasingly important role in maritime and aviation decarbonization, though policy drivers remain critical [9].

Industry: Green hydrogen adoption in steel production, ammonia synthesis, and refining will accelerate as cost parity approaches and carbon pricing mechanisms strengthen. Deep decarbonization of industrial processes through green hydrogen integration could achieve emissions reductions exceeding 90% in some applications [18].

Power generation: Grid integration of green hydrogen will expand as renewable curtailment increases and long-duration storage requirements grow. However, competition with battery storage for grid-balancing applications may limit hydrogen's role in some markets [10].

7. Conclusion

Green hydrogen represents a transformative solution for the global energy transition, offering a clean, versatile, and sustainable pathway to decarbonize multiple sectors of the economy. The past year has witnessed significant progress: installed electrolysis capacity doubled to surpass 4 GW, investment in low-emissions hydrogen projects reached nearly USD 7 billion, and global hydrogen demand surpassed 100 Mt. Major projects such as NEOM are approaching commercial operation, and electrolyzer technologies continue to advance in efficiency and scalability.

However, substantial challenges remain. The cost gap between green and grey hydrogen persists (USD 2.7–6.4/kg vs. USD 1.0–2.5/kg), infrastructure development lags behind project announcements, and policy uncertainty continues to impede final investment decisions. The project pipeline has contracted, and many announced projects face the risk of cancellation if investment decisions are not made soon.

Overcoming these challenges will require continued collaboration between governments, industries, and research institutions. Supportive policies including production tax credits, procurement mandates, and streamlined permitting are essential to bridge the cost gap and create predictable revenue streams for project developers. Continued research and development into advanced electrolyzer materials, system integration, and artificial intelligence optimization will drive efficiency improvements and cost reductions.

The future outlook for green hydrogen remains promising. With projected costs falling toward USD 1.50–2.50/kg in high-solar regions by 2030 and the clean hydrogen market expected to grow at over 25% CAGR through 2031, green hydrogen is positioned to become increasingly competitive with fossil fuel alternatives. By addressing the remaining challenges through sustained investment, innovation, and policy support, green hydrogen can fulfill its potential as a cornerstone of sustainable energy systems, contributing to climate change mitigation, energy security, and a greener, more sustainable future.

References

- [1] IEA, "Production – Global Hydrogen Review 2026," International Energy Agency, Paris, 2026 .
- [2] IEA, "Investment and innovation – Global Hydrogen Review 2026," International Energy Agency, Paris, 2026 .
- [3] IEA, "Demand – Global Hydrogen Review 2026," International Energy Agency, Paris, 2026 .
- [4] [4]IEA, "Policy – Global Hydrogen Review 2026," International Energy Agency, Paris, 2026 .
- [5] Mordor Intelligence, "Clean Hydrogen - Market Share Analysis, Industry Trends & Statistics, Growth Forecasts (2026 - 2031)," 2026 .
- [6] JBMI/Fitch Solutions, "Diversified Incentives And Standardisation To Improve Green Hydrogen Price Competitiveness," Nov. 2025 .

- [7] Advancements in green hydrogen production: A comprehensive review of prospects, challenges, and innovations in electrolyzer technologies," *Fuel*, vol. 404, part B, art. 136251, Jan. 2026 .
- [8] [8]S. T. Fregene, "Application of Green Hydrogen in Transportation, Industry, and Power Generation: A Review," *J. Appl. Sci. Environ. Manage.*, vol. 29, no. 11, pp. 3507, 2025 .
- [9]]Optimization-Driven Multi-Aspect Planning of Grid-Tied Green Hydrogen Hubs in Saudi Arabia," in *Proc. IEEE Conf.*, Aswan, Egypt, Sep. 2025 .
- [10] Color-coded nomenclature of colorless hydrogen: which one is better?," *RSC Adv.*, 2025 .
- [11] A. Alsharif and W. A. A. Milad, "AI in Renewable Energy Forecasting: Bridging the Gap Between Data **Science and Energy**," *Eurasian Journal of Theoretical and Applied Sciences (EJTAS)*, pp. 36–56, 2025.
- [12]]Multidimensional Evaluation of Hydrogen Production Technologies: A Path to Sustainable Energy and Climate Resilience," *Eur. PMC*, Jun. 2025 .
- [13] Comparative Analysis of Alkaline, PEM, and Solid Oxide Electrolyzers for Green Hydrogen Production," *AIChE Proc.*, 2025 .
- [14] "Synergizing Renewable Energy and Electric Vehicles: An Experimental Analysis of Grid Integration, Charging Optimization, and Environmental Impact", *jibas*, vol. 1, no. 1, pp. 35–43, Jul. 2025, doi: 10.65421/jibas.v1i1.10.
- [15] Techno-Economic Assessment of Hydrogen Integration for Decarbonizing the Steel Industry: A Case Study," *MDPI*, Nov. 2025 .
- [16] M. Khaleel, Z. Yusupov, M. Gunesser, Y. N. Nassar, H. El-Khozondar, A. Ahmed, and A. A. Alsharif, "Towards Hydrogen Sector Investments for Achieving Sustainable Electricity Generation," **Solar Energy and Sustainable Development Journal**, vol. 13, no. 1, pp. 71-96, 2024.
- [17] Alsharif, A., Qassab, K. S. Q., Dobi, A., Ahmed, A. A., Alsharif, M. A., Almaktoof, A., & Imbamy, I. (2026). A Comprehensive Review of Energy Storage Batteries for Solar Energy Systems. *Journal of Insights in Basic and Applied Sciences*, 154-171.
- [18] "The Evolution and Impact of Open Source Systems: Governance, Sustainability, and Innovation in the Digital Age", *jshd*, vol. 1, no. 1, pp. 27–38, Jul. 2025, doi: 10.65421/jshd.v1i1.7.
- [19] Transitioning Ammonia Production: Green Hydrogen-Based Haber–Bosch and Emerging Nitrogen Reduction Technologies," *Res. Portal ULisboa*, Aug. 2025 .
- [20] Cost Analysis and Optimization of Green Hydrogen Production via Concentrating Solar Technologies and PEM Electrolyzer," *Mar.* 2026 .
- [21] From Electricity Prices to Hydrogen Costs: Evaluating Green Hydrogen Production Economics," Jan. 2026 .
- [22] Optimal Hybrid Energy System Sizing for Green Hydrogen Production: Scenario-Based Techno-Economic Approach," *MDPI*, Jan. 2026 .
- [23] NEOM Green Hydrogen Project," *ACWA Power*, 2025 .
- [24] ArcelorMittal adopts green hydrogen combustion at Spanish rolling mill," *European Hydrogen Observatory*, Nov. 2025 .
- [25] "Accelerating the Green Transition: An Experimental Study on the Integration of Renewable Energy with Electric Vehicle Infrastructure", *jibas*, vol. 1, no. 1, pp. 01–09, Jul. 2025, doi: 10.65421/jibas.v1i1.4.
- [26] A. Alsharif, "AI-Based Spatiotemporal Analysis of Solar and Wind Energy Potential Using Satellite and Ground Sensor Data," *Scientific Journal for Publishing in Health Research and Technology*, pp. 1–7, 2025.
- [27]]System efficiency analysis of direct coupled PV–PEM electrolyzer systems," *AIT Publications*, Jan. 2026.
- [28] "Design and Feasibility of a 50 MW Off-Grid Wind Energy System with Integrated Power Converters for the City of Alasaba, Libya ", *jibas*, vol. 2, no. 2, pp. 21–29, Apr. 2026, doi: 10.65421/jibas.v2i2.83.