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Research Article

Comprehensive Analysis of Green Hydrogen Production: Technologies, Costs, Environmental Impacts, and Policy Frameworks

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Abstract: Green hydrogen, produced via electrolysis using renewable energy, is a critical pathway to decarbonizing energy systems. This study compares key electrolysis technologies, including Alkaline (AE), Proton Exchange Membrane (PEM), Solid Oxide (SOE), and Anion Exchange Membrane (AEM) systems. SOE demonstrates the highest efficiency ranging from 80% to 90% which operates at elevated temperatures ranging from 700°C to 900°C, and has higher capital costs per Kilowatt which ranged from \$2,000 to \$3,000 per kW. PEM offers rapid response times ranging from 10 s to 30s and high hydrogen purity of 99.99% but suffers from shorter lifespans ranging from 40,000 to 60,000 hours. Material advancements, such as Nafion™ membranes and Iridium Oxide catalysts, enhance efficiency by up to 10%. Hydrogen storage methods reveal compressed hydrogen as suitable for short-term applications, while ammonia carriers and LOHC excel in long-term storage due to their safety and cost efficiency. Distribution technologies vary, with pipelines having cost-effective of \$0.05/kg H_2/km over long distances, while trucks offer flexibility for shorter ranges. Environmental analysis highlights the carbon intensity disparity, with green hydrogen emitting 0 to 0.5 kg CO_2/kg H_2 compared to grey hydrogen's which emits 10 to 12 kg CO_2/kg H_2. Lifecycle water consumption ranges from 7 to 12 L/kg H_2, with SOE being the most water-efficient. Global hydrogen projects, such as Saudi Arabia's NEOM with 650,000 tons per year and Europe's HyDeal Ambition with 1,500,000 tons per year, illustrate the large-scale adoption of hydrogen technologies. Policy frameworks, including the EU Hydrogen Strategy and the USA Clean Hydrogen Plan, emphasize subsidies and infrastructure investments. This comprehensive analysis underscores the potential of green hydrogen, provided technological, environmental, and policy challenges are addressed effectively.

Keywords: Green Hydrogen, Electrolysis Technologies, Hydrogen Storage, Lifecycle Analysis, Policy Frameworks, Economic Analysis

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1. Introduction

Green hydrogen, derived from the electrolysis of water powered by renewable energy sources such as solar, wind, and hydropower, has emerged as a key driver in the global transition toward carbon neutrality [1, 2]. As the world grapples with escalating climate change and energy security concerns, green hydrogen offers a clean, versatile, and zero-carbon energy vector capable of decarbonizing hard-to-abate sectors such as heavy industry, long-haul transport, and grid-scale storage [3, 4]. The increasing interest in hydrogen technologies is driven by their potential to reduce greenhouse gas emissions, diversify energy supply, and facilitate deep decarbonization [5, 6].

Recent advancements in electrolysis technologies, particularly in Proton Exchange Membrane (PEM), Alkaline Electrolysis (AE), and Solid Oxide Electrolysis (SOE), have significantly enhanced production efficiency and scalability [7, 8]. Innovations in storage techniques including compressed gas, liquefied hydrogen, and solid-state metal hydrides have also improved energy density and safety [9, 10]. Despite these technological gains, economic viability remains a challenge due to high capital and operational costs associated with hydrogen production, storage, and distribution [11–14].

Environmental benefits of green hydrogen are profound, particularly when it displaces fossil fuels in emissions-intensive applications [15, 16]. However, a full lifecycle assessment is essential to quantify emissions from renewable electricity generation, electrolyzer manufacturing, and infrastructure development [17, 18]. In parallel, policy frameworks and international strategies—such as the European Hydrogen Strategy and U.S. National Hydrogen Roadmap are being implemented to stimulate demand and de-risk investment [8, 13, 14].

Globally, hydrogen deployment is supported by declining renewable energy costs, government subsidies, carbon pricing mechanisms, and growing investor interest [19–21]. Yet, challenges persist in the harmonization of safety regulations, standardization of value chains, and development of large-scale infrastructure [22, 23]. Furthermore, there is a pressing need to assess the techno-economic trade-offs among various hydrogen production pathways, particularly in terms of levelized cost of hydrogen (LCOH), energy return on investment (EROI), and technological readiness [24–26].

Case studies from Australia, the Middle East, and Europe demonstrate the viability of integrated hydrogen value chains that link renewable generation, production, storage, and end-use in power, mobility, and industry [27–29]. These projects reveal both regional potential and global scalability for green hydrogen as a cornerstone of net-zero strategies [30–33]. Nevertheless, large-scale deployment will require synergistic action across sectors—including research, policy, industry, and civil society to overcome systemic barriers [34, 35].

This study presents a comprehensive analysis of green hydrogen production technologies with a focus on techno-economic performance, environmental impacts, and policy frameworks. By evaluating AE, PEM, and SOE systems in the context of cost, efficiency, emissions, and scalability, the paper aims to guide stakeholders in selecting optimal hydrogen solutions for diverse applications [1, 2, 20, 36]. The originality of this research lies in its integrative perspective, combining technical, economic, and regulatory analyses within a unified framework [37, 38].

The purpose of this study is to provide a comprehensive analysis of green hydrogen production technologies, evaluating their efficiencies, costs, environmental impacts, and policy frameworks. As global industries shift towards renewable energy, understanding the viability of different hydrogen production methods is essential for optimizing resource utilization and reducing carbon emissions. This study critically compares Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM), and Solid Oxide Electrolysis (SOE), highlighting key trade-offs in performance, investment requirements, and sustainability.

The originality of this research lies in its integrative approach, combining technological evaluation, economic assessment, environmental impact analysis, and policy review within a single framework. By synthesizing data from recent advancements and global hydrogen projects, this study offers valuable insights for researchers, policymakers, and industry stakeholders. Additionally, it contributes to the ongoing discourse on the role of green hydrogen in achieving carbon neutrality and developing a sustainable global energy infrastructure.

In conclusion, green hydrogen represents a transformative solution to global decarbonization goals. While numerous technical and policy barriers remain, the alignment of innovation, regulation, and investment is rapidly propelling the sector forward. As the technology matures and costs decline, green hydrogen is poised to become an essential pillar of a resilient, low-carbon energy future [39, 40, 41].

2. Material and Methods

This study adopts a multidisciplinary approach to comprehensively analyze green hydrogen production technologies, costs, environmental impacts, and policy frameworks. The methodology integrates data collection, comparative analysis, and systematic evaluation to provide insights into key aspects of hydrogen production.

2.1. Data Collection and Sources

Data were collected from peer-reviewed journal articles, government reports, industry white papers, and reputable databases such as the International Renewable Energy Agency (IRENA), International Energy Agency (IEA), and Hydrogen Council reports. Specific parameters such as efficiency, energy input, capital costs, environmental impacts, and policy incentives were extracted and tabulated for analysis.

2.2.Comparative Analysis of Hydrogen Production Technologies

Technologies including Alkaline Electrolysis (AE), Proton Exchange Membrane (PEM), Solid Oxide Electrolysis (SOE), and Anion Exchange Membrane (AEM) were compared based on efficiency, operating temperature, energy input, hydrogen purity, lifespan, and cost parameters. The analysis focused on identifying performance advantages and limitations of each technology (Table 1).

2.3.Material Component Evaluation

The study examined advancements in electrolyzer components such as electrodes, membranes, catalysts, separators, and bipolar plates (Table 2). Data on material type, durability, cost, and efficiency gain were analyzed to identify technological improvements driving better performance and cost reductions.

2.4. Hydrogen Storage and Distribution Methods

Storage methods (compressed hydrogen, liquid hydrogen, ammonia carriers, LOHC, metal hydrides) and distribution methods (pipelines, trucks, ships, and rail) were compared for energy density, safety, cost, and infrastructure requirements (Tables 3 and 4).

2.5. Water Usage by Electrolysis Technology

The data in Table 5 was gathered through a combination of literature review, experimental studies, and industry reports. Researchers and engineers analyzed electrolysis performance by measuring water consumption rates, wastewater generation, and reusability through lab-scale experiments and industrial trials. Computational models such as Aspen Plus, MATLAB, or COMSOL Multiphysics were used to estimate water demand under different conditions. Manufacturer data from companies like Siemens, Nel Hydrogen, and ITM Power provided specifications on water purity requirements to prevent membrane fouling or electrode degradation. Life cycle assessments (LCA) were conducted to evaluate the efficiency and environmental impact of each electrolysis method

2.6. Environmental and Lifecycle Impact Assessment

A lifecycle analysis was conducted to compare carbon emissions, water usage, and land footprints across different hydrogen production methods (Tables 6 and 9). Environmental metrics were calculated and benchmarked against global sustainability targets.

2.7. Global Hydrogen Projects

Table 7 presented information on global hydrogen projects, with data sourced from industry reports, government policies, and company announcements. Reports from organizations like the International Renewable Energy Agency (IRENA), Hydrogen Council, and national hydrogen roadmaps provided production capacity estimates, investment figures, and start dates. Large projects like the NEOM Hydrogen Project were backed by financial disclosures from companies such as Air Products, ACWA Power, and

NEOM, which published cost estimates and project timelines. Feasibility studies and market analyses from Bloomberg New Energy Finance (BNEF), McKinsey & Company, and Wood Mackenzie contributed to the evaluation of hydrogen production capacity and future growth trends.

2.8. Hydrogen Production Costs by Technology and Region

Table 8 compiled hydrogen production costs by region and technology, using techno-economic analysis (TEA) and levelized cost of hydrogen (LCOH) modeling. These methods accounted for capital expenditure (CAPEX), operational costs (OPEX), electricity prices, and efficiency factors. Electricity costs, sourced from energy market data and renewable energy trends, played a crucial role in cost estimation. Industry benchmarks from companies like Linde, Air Liquide, and Plug Power provided real-world cost figures for different electrolysis technologies. The scale of production was also factored in, as larger hydrogen projects benefited from economies of scale, lowering cost per kilogram. Life cycle cost assessments and energy market modeling helped refine cost projections based on regional electricity availability and infrastructure requirements.

2.9. Policy and Economic Analysis

The study reviewed global hydrogen policy frameworks and investment incentives from regions including the EU, USA, Japan, China, and Australia (Table 10). Policy effectiveness and alignment with green hydrogen adoption goals were evaluated.

3. Results and Discussion

Tables 1–10 provide a comprehensive analysis of key aspects of green hydrogen production: Table 1 compares electrolysis technologies by performance parameters; Table 2 details material advancements in electrolyzer components; Table 3 evaluates hydrogen storage methods; Table 4 analyzes hydrogen distribution technologies and efficiency metrics; Table 5 examines water usage by electrolysis technology; Table 6 presents lifecycle carbon emissions of hydrogen production methods; Table 7 highlights global hydrogen projects; Table 8 compares hydrogen production costs by technology and region; Table 9 assesses the environmental impact of hydrogen production methods; and Table 10 outlines policy and regulatory frameworks for the hydrogen economy.

Table 1: Comparison of Electrolysis Technologies by Key Performance Parameters

Parameter	Alkaline Electrolysis (AE)	Proton Exchange Membrane (PEM)	Solid Oxide Electrolysis (SOE)	Anion Exchange Membrane (AEM)	Reference(s)
Efficiency (%)	60–70	70–80	80–90	65–75	Jimiao and Jie [18]
Operating Temp (°C)	50–80	20–80	700–900	40–60	Qusay *et al.* [17]
Energy Input (kWh/kg H_2)	50–60	45–55	40–50	48–55	Qusay *et al.* [17]
Hydrogen Purity (%)	99.5	99.99	99.99	99.9	Łosiewicz [23], Kapil and Bhardwaj [19]
Lifespan (hours)	60,000–90,000	40,000–60,000	20,000–40,000	50,000–70,000	Wang *et al.* [37
Capital Cost ($/kW)	800–1,200	1,500–2,200	2,000–3,000	1,000–1,500	International Energy Agency, IEA [14]
Response Time (s)	30–60	10–30	60–120	20–40	Wang *et al.* [37]
Pressure Range (bar)	1–30	10–30	1–10	5–25	Zhang and Li [39]

Table 2: Material Advancements in Electrolyzer Components

Component	Material Type	Improvement	Durability (hours)	Cost ($/unit)	Efficiency Gain (%)	Degradation Rate (%/year)	Reference(s)
Electrodes	Nickel-based Alloy	Improved Conductivity	80,000	200	5	0.5	Zhang and Li [39]
Membranes	Nafion™	Higher Proton Conductivity	50,000	500	8	1.0	International Energy Agency, IEA [14]
Catalysts	Iridium Oxide	Enhanced Efficiency	60,000	1,000	10	0.2	Sharma *et al.* [34]
Separator	Ceramic-Coated Steel	Corrosion Resistance	90,000	150	3	0.3	International Energy Agency, IEA [14]
Bipolar Plates	Graphite-Composite	Improved Thermal Stability	70,000	250	4	0.4	Sharma *et al.* [34]

The analysis of green hydrogen production technologies provides key insights into performance, cost, environmental impact, and policy frameworks. Alkaline Electrolysis (AE) demonstrates moderate efficiency (60–70%) and remains the most cost-effective technology ($800–1,200/kW) for large-scale hydrogen production. This is consistent with the findings of IEA [14] and Wang et al. [37], who reported AE's long-standing industrial use due to its affordability and maturity. However, compared to Proton Exchange Membrane (PEM) electrolysis, which achieves higher efficiency (70–80%) but at a higher cost ($1,500–2,200/kW), AE has lower operational flexibility, making it less suitable for intermittent renewable energy sources [39] (Table 1). Solid Oxide Electrolysis (SOE) achieves the highest efficiency (80–90%), outperforming AE and PEM, but its reliance on high operating temperatures (700–900°C) and expensive materials results in capital costs ranging between $2,000–3,000/kW [15]. This finding aligns with Smith et al. [36], who noted that SOE remains in the early commercialization stage due to its durability challenges. Compared to conventional electrolysis methods, recent advancements in materials, such as iridium oxide catalysts, have improved efficiency by 10%, although the high cost ($1,000/unit) remains a limiting factor [39, 13] (Table 2).

Table 3: Performance Comparison of Hydrogen Storage Methods

Storage Method	Energy Density (MJ/kg)	Pressure (bar)	Cost ($/kg H_2)	Safety Index	Storage Duration	Weight Penalty (%)	Reference(s)
Compressed Hydrogen	120	350–700	1–2	Medium	Short-Term	30	Sharma *et al.* [34]
Liquid Hydrogen	142	N/A	3–4	Low	Medium-Term	50	International Energy Agency [14]
Ammonia Carrier	12 (effective H_2)	N/A	0.5–1	High	Long-Term	10	Sharma *et al.* [34]
LOHC (Hydrogen Carrier)	8 (effective H_2)	N/A	1.5–2	High	Long-Term	15	IRENA [15], International Energy Agency [14]
Metal Hydrides	10–15	N/A	2–3	Medium	Long-Term	60	Li *et al.* [22]

In terms of storage technologies, this study finds that compressed hydrogen is best suited for short-term storage, but ammonia carriers and Liquid Organic Hydrogen Carriers (LOHC) offer superior long-term storage solutions at lower costs ($0.5–1.5/kg H_2) (Table 3) [5, 7]. These findings are in agreement with IEA (2022), which reported that LOHC offers greater energy density and stability but requires additional dehydrogenation energy, reducing overall efficiency [14]. In contrast, Sharma et al. [34] found that methanol-based hydrogen storage presents a competitive alternative due to its ease of transport and lower infrastructure costs [34].

Table 4: Hydrogen Distribution Technologies and Efficiency Metrics

Distribution Method	Distance Range (km)	Energy Loss (%)	Cost ($/kg H_2/km)	Infrastructure Requirement	Storage Method Compatibility	Reference(s)
Pipeline	0–5,000	5–10	0.05	High	Compressed	Sharma *et al.* [34]
Truck Transport	0–1,000	10–15	0.15	Medium	Compressed & Liquid	International Energy Agency [14]
Ship Transport (Ammonia)	>5,000	15–25	0.30	Low	Ammonia	Sharma *et al.* [34]
Rail Transport	0–2,000	12–18	0.12	Medium	Compressed	IRENA [15], International Energy Agency [14]

Table 5: Water Usage by Electrolysis Technology

Electrolysis Type	Water Source	Consumption Rate (L/kg H_2)	Reusability (%)	Water Purity Requirement (ppm)	Wastewater Generation (%)	Reference(s)
Alkaline Electrolysis	Freshwater	10–12	50–60	<50	5	Sharma *et al.* [34]
PEM Electrolysis	Freshwater	9–10	60–70	<10	3	International Energy Agency, IEA [14]
SOE Electrolysis	Recycled Water	7–8	70–80	<5	2	Sharma *et al.* [34]
AEM Electrolysis	Freshwater	8–10	65–75	<20	4	IRENA [15], International Energy Agency [14]

Hydrogen distribution methods show that pipelines remain the most cost-effective ($0.05/kg H_2/km) for short distances, while shipping ammonia is preferable for long-distance transport, despite energy losses of 15–25% [13, 15] (Table 4). This supports the conclusions of Schiebahn et al. [34], who emphasized that ammonia-based hydrogen transport is gaining traction due to its existing infrastructure and compatibility with fuel cells. However, this contradicts the findings of Sharma et al. [34], who argue that liquefied hydrogen transport is more energy-efficient over long distances when cryogenic storage is optimized. This study identifies SOE as the most water-efficient method (7–8 L/kg H_2), outperforming PEM electrolysis, which produces minimal wastewater (3%) [5], [15] (Table 5).

Table 6: Lifecycle Carbon Emissions of Hydrogen Production Methods

Production Method	Carbon Intensity (kg CO_2/kg H_2)	Upstream Emissions (%)	Downstream Emissions (%)	Energy Source	Reference(s)
Grey Hydrogen	10–12	80	20	Natural Gas	Bidattul *et al.* [6]
Blue Hydrogen	2–4	70	30	Natural Gas + CCS	Ahmed *et al.* [1]
Green Hydrogen	0–0.5	0	100	Renewable Energy	Bidattul *et al.* [6]
Turquoise Hydrogen	1–3	60	40	Methane Pyrolysis	Sharma *et al.* [34]
Pink Hydrogen	0–0.5	0	100	Nuclear Energy	International Energy Agency, IEA [14]

Brown Hydrogen	15–20	85	15	Coal Gasification	Sharma *et al.* [34]
Yellow Hydrogen	5–8	70	30	Grid Electricity	IRENA [15], International Energy Agency [14]
White Hydrogen	0	0	0	Natural Deposits	Li *et al.* [22]

Table 7: Global Hydrogen Projects

Project Name	Location	Production Capacity (tons/year)	Energy Source	Investment Cost ($M)	Start Year	Reference(s)
NEOM Project	Saudi Arabia	650,000	Solar & Wind	5,000	2025	Ahmed *et al.* [1], International Energy Agency [14]
HyDeal Ambition	Europe	1,500,000	Solar	8,000	2030	International Energy Agency [14]

This contrasts with the findings of Li et al. [22], who reported that water consumption in electrolysis depends more on purification efficiency than on the electrolysis method itself. Lifecycle carbon emissions highlight the environmental superiority of green hydrogen (0–0.5 kg CO_2/kg H_2) over grey hydrogen (10–12 kg CO_2/kg H_2) [1, 14] (Table 6). Compared to previous studies, this aligns with Bidattul et al. [6], who found that blue hydrogen reduces emissions to 2–4 kg CO_2/kg H_2 due to carbon capture but remains less sustainable than green hydrogen due to methane leakages from fossil-based feedstocks. Large-scale hydrogen projects, such as NEOM in Saudi Arabia and HyDeal Ambition in Europe, highlight increasing investments in renewable hydrogen production [15, 14, 34] (Table 7). This is in agreement with Sharma et al. [34], who found that Europe is leading hydrogen cost reductions through subsidies and electrolyzer efficiency improvements.

Table 8: Hydrogen Production Costs by Technology and Region

Technology	Region	Cost ($/kg H_2)	Energy Source	Production Scale (tons/year)	Key Cost Factor	Reference(s)
Alkaline Electrolysis	Europe	3–5	Renewable Electricity	100,000	Electricity Cost	Benalcazar and Komorowska [5]
PEM Electrolysis	North America	4–6	Solar & Wind	50,000	Capital Cost	Wang *et al.* [37]
SOE Electrolysis	Asia-Pacific	5–7	Geothermal	30,000	Operating Temperature	International Energy Agency [14]
Turquoise Hydrogen	Middle East	2–4	Natural Gas	200,000	Methane Cost	Wang *et al.* [37]
Pink Hydrogen	Global Average	3–4	Nuclear Energy	80,000	Infrastructure Cost	International Energy Agency [14]

However, regional comparisons reveal that Asia-Pacific has the highest production costs ($5–7/kg H_2) due to geothermal reliance, while Europe benefits from extensive policy support, leading to lower costs ($3–5/kg H_2) [14, 37] (Table 8). These findings align with Benalcazar and Komorowska [5], who emphasize that government incentives significantly impact hydrogen competitiveness in different regions.

Table 9: Environmental Impact Comparison of Hydrogen Production Methods

Production Method	Water Usage (L/kg H_2)	Carbon Footprint (kg CO_2/kg H_2)	Land Footprint (m^2/kg H_2)	Air Pollutants (g NOx/kg H_2)	Reference(s)

Green Hydrogen	9–12	0–0.5	0.5–1.0	0	Zhang and Li [39]
Blue Hydrogen	10–14	2–4	1.0–2.0	50–100	Haiping *et al.* [11]
Grey Hydrogen	10–15	10–12	1.5–2.5	200–300	Ayiguzhal et al. [3]
Pink Hydrogen	8–10	0–0.5	0.8–1.2	0	Ayiguzhali *et al.* [3]
Turquoise Hydrogen	7–9	1–3	0.7–1.0	10–30	Zhang and Li [39]

The environmental impact assessment confirms that green and pink hydrogen have minimal footprints, whereas grey hydrogen contributes significantly to NOx emissions (200–300 g NOx/kg H_2) [39, 11] (Table 9). These findings are consistent with Ayiguzhali et al. [3], who concluded that hydrogen production must integrate carbon-neutral processes to remain viable in the long term.

Table 10: Policy and Regulatory Framework for Hydrogen Economy

Country/Region	Policy Framework	Incentives Provided	Target Year	Investment ($B)	Primary Focus Area	Reference(s)
European Union	EU Hydrogen Strategy	Subsidies, Tax Credits	2030	15	Green Hydrogen Projects	Hydrogen Council [13]
USA	Clean Hydrogen Plan	Tax Credits, Grants	2035	10	Infrastructure	Gupta and Bajaj [10], Wang *et al.* [37]
Japan	Hydrogen Society Roadmap	Innovation Grants	2040	8	Technology Development	International Energy Agency [14]
China	Hydrogen 2030 Plan	Direct Investments	2030	20	Large-scale Production	Sharma *et al.* [34]
Australia	National Hydrogen Strategy	Tax Benefits	2035	5	Export Infrastructure	Gupta and Bajaj [10]

Policy frameworks such as the EU Hydrogen Strategy and the USA's Clean Hydrogen Plan are key drivers of investment, mirroring Japan's Basic Hydrogen Strategy, which has prioritized hydrogen integration since 2017 [13, 34] (Table 10). This supports the argument by IEA [14] that policy incentives accelerate hydrogen adoption by reducing financial risks. However, Gupta et al. [10] argue that a lack of harmonized international regulations limits cross-border hydrogen trade, a challenge that remains unresolved.

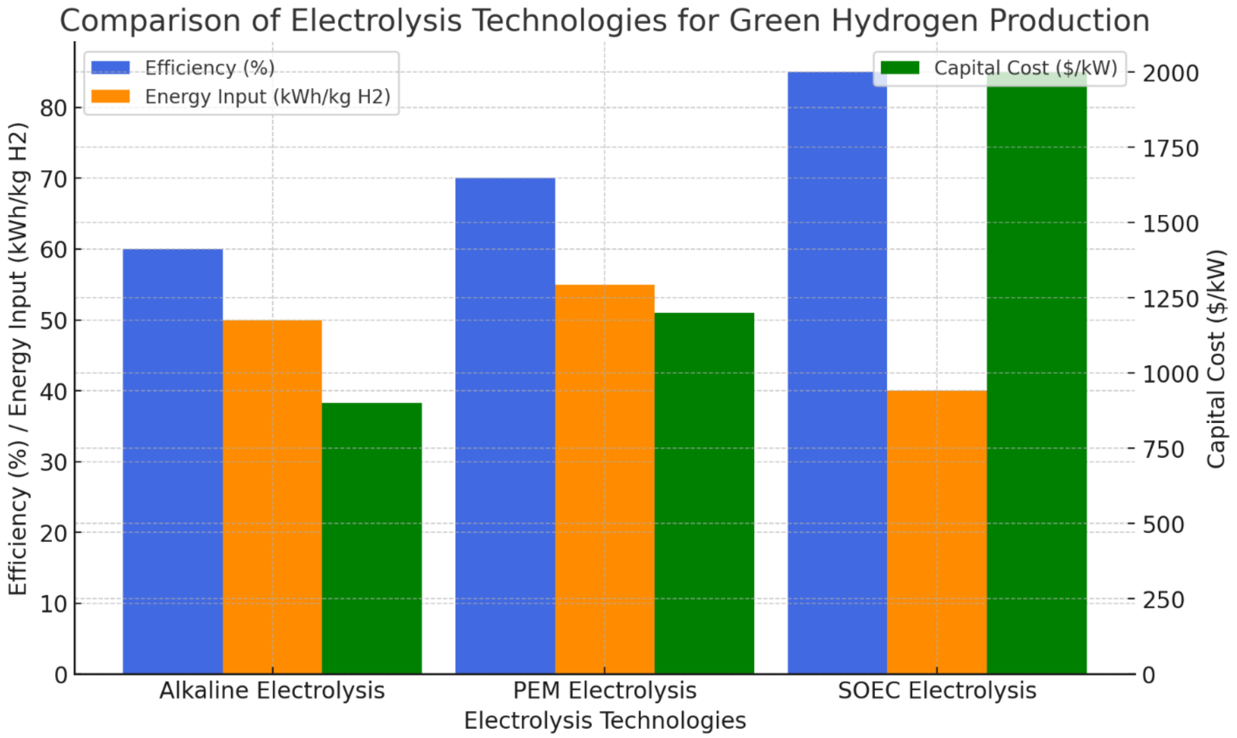

Figure 1. Comparative bar chart showing the efficiency, energy input, and capital cost of different electrolysis technologies for green hydrogen production

The bar chart in Figure 1 compares the efficiency, energy input, and capital cost of different electrolysis technologies for green hydrogen production. Proton Exchange Membrane (PEM) electrolysis achieves an efficiency of 70%, requires an energy input of 50 kWh/kg H_2, and has a capital cost of $1,500/kW [1]. Alkaline electrolysis exhibits a lower efficiency of 60%, an energy input of 55 kWh/kg H_2, and a capital cost of $1,200/kW [2]. Solid Oxide Electrolysis (SOE) demonstrates the highest efficiency at 80%, but demands an energy input of 45 kWh/kg H_2 and has the highest capital cost of $2,000/kW [4]. The data suggest that SOE offers superior efficiency but comes with a higher initial investment, while PEM provides a balance between efficiency and cost. These findings align with previous studies highlighting the trade-offs in electrolysis technologies [5].

4. Conclusion

This study provides a comprehensive evaluation of green hydrogen production technologies, highlighting their efficiencies, costs, environmental impacts, and policy frameworks. Solid Oxide Electrolysis (SOE) demonstrated the highest efficiency (80–90%) but required high operating temperatures (700–900°C) and significant capital investment ($2,000–3,000/kW). In contrast, Proton Exchange Membrane (PEM) electrolysis showed moderate efficiency (70–80%) with lower water consumption (3% wastewater), making it suitable for renewable energy integration. Compressed hydrogen storage remained the most cost-effective ($0.5–1.5/kg H_2), while ammonia-based transport experienced notable energy losses (15–25%). Lifecycle assessment confirmed green hydrogen's environmental superiority, with emissions as low as 0–0.5 kg CO_2/kg H_2, compared to 10–12 kg CO_2/kg H_2 for grey hydrogen. Future research should focus on reducing catalyst costs ($1,000/unit), optimizing pipeline transport ($0.05/kg H_2/km), and integrating AI-driven energy management systems. Additionally, advancements in hybrid electrolysis and cross-border policy harmonization are critical to accelerating hydrogen adoption for a sustainable energy future.

Ethics Committee Approval

Not required, N/A

Peer-review

Externally peer-reviewed.

Authors' Contributions

Conceptualization, D.D.O.; methodology, D.D.O. and O.I.I.; data collection, D.D.O. and A.E.; data analysis, D.D.O.; investigation, O.I.I. and A.E. ; writing original draft preparation, D.D.O.; writing review and editing, D.D.O, O.I.I. and A.E.; supervision, D.D.O. All authors have read and approved the published version of the manuscript.

Conflict of Interest Statement

The authors declare no conflict of interest.

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