J. Environ. Sustain. Sci. 1 (2026) 71-80

Contents lists available at AcademiansEdu

Journal of Environmental and Sustainability Science

journal homepage: https://academiansedu.org/jiess/

Green Hydrogen as a Catalyst for Sustainable Energy Transition: A Comparative Analysis of Technological, Policy, and Spatial Dimensions

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A R T I C L E I N F O

Article history:
Received: 24 March 2026
Received in revised form: 16 April 2026
Accepted: 04 May 2026
Available online: 18 June 2026

Keywords:
green hydrogen, renewable energy, energy transition, water electrolysis, sustainability, policy framework, spatial planning, decarbonization

A B S T R A C T

The global imperative to decarbonize energy systems has positioned green hydrogen as a cornerstone of the sustainable energy transition. Produced through water electrolysis powered by renewable electricity, green hydrogen offers a zero-carbon energy carrier capable of decarbonizing hard-to-abate industrial sectors, enabling long-duration energy storage, and enhancing energy security. This study presents a comprehensive comparative analysis of green hydrogen development across four distinct contexts: Kenya, Türkiye, India, and the Canadian province of Newfoundland and Labrador. Through an integrative framework examining technological readiness, policy architecture, resource endowment, and spatial sustainability, the research identifies both universal challenges and context-specific pathways for green hydrogen deployment. The findings reveal that while green hydrogen production technologies—particularly alkaline, PEM, and solid oxide electrolysis—have matured significantly, their commercial viability remains constrained by high capital costs, renewable electricity requirements, and infrastructure deficits. Policy analysis demonstrates that comprehensive national hydrogen strategies, demand-side incentives, and international cooperation frameworks are critical enablers, yet implementation gaps persist between ambition and execution. Spatial assessment of water stress and renewable energy potential in Türkiye reveals that high renewable potential regions coincide with severe water scarcity, necessitating seawater-based electrolysis approaches. The Kenyan case illustrates the importance of aligning green hydrogen development with existing renewable energy infrastructure and industrial decarbonization priorities. India's National Green Hydrogen Mission exemplifies large-scale ambition with targets of 5 million metric tonnes annually by 2030, while Newfoundland and Labrador's wind-to-hydrogen projects demonstrate the strategic value of proximity to European markets. The study concludes that successful green hydrogen deployment requires integrated approaches that simultaneously address technological innovation, policy coherence, infrastructure investment, spatial sustainability, and stakeholder engagement.

1. Introduction

The convergence of climate change imperatives, energy security concerns, and technological innovation has catalyzed an unprecedented transformation of global energy systems. Fossil fuels, which have powered industrial development for over two centuries, are increasingly recognized as unsustainable due to their contribution to greenhouse gas emissions, air pollution, and geopolitical instability. The Paris Agreement's ambition to limit global temperature rise to 1.5°C above pre-industrial levels requires nothing less than a fundamental restructuring of how energy is produced, distributed, and consumed (IPCC, 2018).

Renewable energy technologies—solar photovoltaic, wind power, hydropower, and geothermal—have experienced remarkable growth, with costs declining dramatically and deployment accelerating worldwide. However, the intermittent nature of solar and wind generation presents a persistent challenge: how to store energy for periods when the sun does not shine and the wind does not blow. Battery storage, while effective for short-duration applications, faces limitations in scalability, duration, and material requirements for long-term and seasonal storage (Dawood et al., 2020).

Hydrogen has emerged as a compelling solution to this challenge. As an energy carrier, hydrogen possesses high gravimetric energy density and can be stored for extended periods, transported through pipelines or shipping, and converted back to electricity or heat through combustion or fuel cells (Staffell et al., 2019). When produced through water electrolysis using renewable electricity, hydrogen is termed "green hydrogen" and offers a near-zero carbon footprint throughout its lifecycle (Glenk & Reichelstein, 2019).

The versatility of green hydrogen extends across multiple sectors. In transportation, hydrogen fuel cells offer longer ranges and faster refueling than battery electric vehicles, making them particularly suitable for heavy-duty trucks, buses, maritime vessels, and aviation (Kovač et al., 2021). In industry, green hydrogen can replace fossil fuels in high-temperature processes such as steel manufacturing, cement production, and chemical processing, sectors that are difficult to electrify directly (Vogl et al., 2018). In power systems, hydrogen enables long-duration energy storage and sector coupling, linking electricity, heating, and transportation networks (Götz et al., 2016).

Despite its potential, green hydrogen currently accounts for less than one percent of global hydrogen production, with the vast majority derived from fossil fuels through steam methane reforming and coal gasification (IEA, 2024). The gap between potential and realization reflects persistent challenges: high production costs, substantial renewable electricity requirements, hydrogen storage and transportation constraints, infrastructure deficiencies, and policy uncertainty (Ajanovic & Haas, 2020).

This study addresses these challenges through a comparative analysis of green hydrogen development across four diverse contexts: Kenya, Türkiye, India, and Newfoundland and Labrador (Canada). Each context offers unique insights into the opportunities and obstacles facing green hydrogen deployment. Kenya possesses abundant renewable energy resources and has established a green hydrogen strategy but faces infrastructure and investment constraints. Türkiye has committed to net-zero emissions by 2053 and is developing a hydrogen strategy, yet faces significant water stress that complicates electrolysis siting. India has launched an ambitious National Green Hydrogen Mission with substantial financial outlays and targets. Newfoundland and Labrador benefits from exceptional wind resources and proximity to European markets, with multiple commercial-scale projects under development.

The research objectives are threefold: (1) to synthesize current knowledge on green hydrogen production technologies, applications, and sustainability implications; (2) to analyze policy frameworks and implementation strategies across diverse national and regional contexts; and (3) to develop an integrated framework for assessing the spatial, environmental, and economic dimensions of green hydrogen deployment. The study employs a mixed-methods approach combining systematic literature review, policy analysis, and spatial assessment using geographic information systems and fuzzy logic modeling.

2. Literature Review

2.1 Green Hydrogen Production Technologies

Green hydrogen is produced through the electrolysis of water, a process in which electrical energy splits water molecules into hydrogen and oxygen. The electrochemical reaction is represented as:

$$2H_2O \rightarrow 2H_2 + O_2$$

The environmental performance of green hydrogen depends critically on the source of electricity powering the electrolyzer. When powered by renewable energy sources—solar, wind, hydro, or geothermal—the production process generates negligible greenhouse gas emissions (Squadrito et al., 2023).

Four main electrolysis technologies have emerged, each with distinct characteristics, advantages, and limitations:

Alkaline Water Electrolysis (AWE) represents the most mature and commercially deployed technology. AWE utilizes an alkaline electrolyte, typically potassium hydroxide, to facilitate ionic conduction between electrodes. Key advantages include relatively low capital costs, long operational lifetimes, and proven reliability under continuous operation. However, AWE systems exhibit slower dynamic response, limiting their effectiveness when integrated with variable renewable electricity generation (Dash et al., 2023). Recent advancements have focused on improving current density and reducing ohmic losses through advanced electrode materials and cell designs (Chauhan & Ahn, 2023).

Proton Exchange Membrane (PEM) Electrolysis has gained considerable attention due to its compact design, high operational efficiency, rapid start-up capability, and excellent compatibility with intermittent renewable energy sources. PEM systems employ a solid polymer electrolyte membrane that allows selective proton transport while preventing gas crossover, producing high-purity hydrogen. The technology's primary limitation is the high cost of noble metal catalysts (platinum and iridium) and membrane materials required for efficient operation (Arsad et al., 2024). Research efforts are directed toward developing low-cost catalyst alternatives and improving membrane durability (Gong, 2021).

Solid Oxide Electrolysis Cells (SOEC) represent a promising approach for future hydrogen production. Operating at temperatures between 700°C and 900°C, SOEC systems achieve superior electrical efficiency by utilizing thermal energy in addition to electricity during water decomposition. This high-temperature operation enables the use of cheaper catalyst materials and potentially integrates with industrial waste heat sources. However, long-term material degradation, thermal stress, and high manufacturing costs continue to limit commercial deployment (Schwarze et al., 2023).

Anion Exchange Membrane (AEM) Electrolysis is an emerging technology that combines the advantages of alkaline and PEM systems. AEM electrolyzers use non-precious metal catalysts and offer potentially lower costs while maintaining the operational flexibility of PEM systems. However, the technology remains in early development stages, with challenges related to membrane stability and performance at commercial scales (Kourougianni et al., 2024).

Recent comprehensive reviews have systematically examined these technologies, analyzing their fundamental principles, material challenges, and prospects for large-scale deployment (A Comprehensive Review of Green Hydrogen Technology, 2025; A Critical Review of Green Hydrogen Production by Electrolysis, 2025). The consensus emerging from this literature is that while no single technology dominates across all applications, ongoing innovation in catalyst materials, membrane development, and system integration is steadily improving efficiency and reducing costs.

2.2 Sustainability Dimensions of Green Hydrogen

The sustainability case for green hydrogen rests on three pillars: environmental, economic, and social.

Environmental sustainability is the most compelling argument for green hydrogen. Unlike fossil fuel-based hydrogen production, which generates significant carbon dioxide emissions, green hydrogen produced via renewable-powered electrolysis achieves near-zero lifecycle emissions (Valente et al., 2021). Life cycle assessment studies have consistently demonstrated that green hydrogen outperforms alternative production pathways across multiple environmental indicators, including greenhouse gas emissions, air pollutants, and resource depletion (Bhandari et al., 2014). However, the environmental performance depends on the renewable energy source, water availability, electrolyzer manufacturing processes, equipment recycling, and transportation infrastructure (Olaitan et al., 2024).

Economic sustainability encompasses production costs, job creation, and energy security implications. The cost of green hydrogen is primarily determined by renewable electricity prices, electrolyzer capital costs, capacity utilization, and financing conditions (BloombergNEF, 2024). Declining renewable electricity costs and electrolyzer manufacturing improvements are expected to reduce green hydrogen production costs substantially, with many analysts projecting competitiveness with fossil-based hydrogen before 2035 in many regions (IRENA, 2023). The economic case is further strengthened by the potential for job creation across the hydrogen value chain, from renewable energy generation to electrolyzer manufacturing, infrastructure development, and end-use applications (Sharma et al., 2023).

Social sustainability encompasses public acceptance, energy equity, and community impacts. Public perception of hydrogen safety remains a significant concern, with many viewing hydrogen as dangerous and explosive (Kovač et al., 2021). Addressing these concerns requires transparent communication, safety demonstrations, and community engagement. Energy equity considerations are equally important: hydrogen technology has the potential to worsen energy inequality if it favors certain companies or geographical areas disproportionately (Reyes et al., 2023). Ensuring fair access and benefits for all communities is essential for socially sustainable hydrogen development.

Recent research has emphasized the importance of integrated sustainability assessment frameworks that simultaneously evaluate environmental, economic, and social dimensions. Studies by Jena et al. (2023) have demonstrated the value of such frameworks for comparing renewable and conventional energy systems, highlighting the need for comprehensive evaluation approaches that go beyond narrow technical or economic metrics.

2.3 Global Policy Landscape

The policy environment for green hydrogen has evolved rapidly, with numerous countries establishing national hydrogen strategies, financial incentives, and regulatory frameworks. According to the International Energy Agency (IEA, 2025), 112 demand-side policies have moved forward since 2024, frequently in the form of grants and sectoral quotas. Legislated policies could trigger demand for nearly 6 million tonnes per annum of low-emissions hydrogen by 2030, while government demand targets add up to 9.5 million tonnes per annum; production targets are in the range of 27-33 million tonnes per annum.

The European Union has established one of the most comprehensive policy frameworks, building on the European Green Deal and the Fit for 55 package. The REPowerEU roadmap (2025-2027) introduces new legislative measures to accelerate the transition toward clean energy, with ambitious targets for hydrogen production and consumption (European Commission, 2020). The Renewable Energy Directive is being implemented through phased obligations for industry from 2026 to 2030, with remaining hydrogen demand to meet the 42% target by 2030 supported through incentives.

Germany, Japan, and Australia have emerged as leaders in green hydrogen development, utilizing public-private partnerships and policy support to drive progress. Germany has established hydrogen valleys—integrated hubs of hydrogen production and consumption—while Australia has leveraged its vast solar resources to produce hydrogen for both domestic use and export (Béres et al., 2024). These initiatives highlight the scalability and versatility of green hydrogen as a global energy solution.

The United States has implemented production tax credits and investment incentives through the Inflation Reduction Act, while the United Kingdom has established a hydrogen business model and allocation rounds for electrolytic hydrogen production. South Korea and Japan have focused on hydrogen as a strategic energy source, with Japan aiming to meet 40% of its total energy demand from green hydrogen by 2050 (Alvera, 2021).

International cooperation has emerged as a critical dimension of hydrogen policy. The Breakthrough Agenda provides a global collaborative framework comprising commitments, an annual process, and services to the international community. The Hydrogen Council, comprising major energy companies, has played a key role in coordinating industry perspectives and advocating for supportive policies. Bilateral agreements, such as the Canada-Germany declaration of intent for green hydrogen exports, demonstrate the growing importance of international hydrogen trade (Adams, 2023).

2.4 Research Gaps and Contribution

Despite the growing body of literature on green hydrogen, significant gaps remain. First, most studies focus on specific aspects—production technologies, economic feasibility, or policy frameworks—without integrating these dimensions within a comprehensive sustainability framework. Second, the spatial dimensions of green hydrogen deployment, particularly the relationship between renewable energy potential and water availability, have received limited attention. Third, comparative analyses across diverse national and regional contexts are relatively rare, limiting the transferability of insights.

This study addresses these gaps through an integrative framework that examines technological, policy, spatial, and sustainability dimensions across four distinct contexts. By comparing Kenya, Türkiye, India, and Newfoundland and Labrador, the research identifies both universal challenges and context-specific pathways, contributing to a more nuanced understanding of green hydrogen's role in the sustainable energy transition.

3. Methodology

3.1 Research Design and Approach

This study employs a mixed-methods research design combining systematic literature review, policy analysis, and spatial assessment. The integrative approach enables examination of green hydrogen development across multiple dimensions—technological, policy, spatial, and sustainability—while accommodating the diverse data sources and analytical requirements of each dimension.

The research is structured around four case studies representing distinct national and regional contexts:

1. **Kenya**: A developing economy with abundant renewable energy resources, a green hydrogen strategy, and significant agricultural and industrial decarbonization needs.
2. **Türkiye**: An emerging economy with ambitious net-zero targets, developing hydrogen strategy, and significant water stress constraints.
3. **India**: A major developing economy with the world's most ambitious green hydrogen targets and substantial financial commitments.
4. **Newfoundland and Labrador**: A subnational jurisdiction with exceptional wind resources, proximity to European markets, and multiple commercial-scale projects under development.

3.2 Data Sources and Collection

Data were collected from multiple sources to ensure comprehensiveness and triangulation:

Academic Literature: Systematic searches were conducted in Scopus, Web of Science, and Google Scholar using keywords including "green hydrogen," "renewable energy," "water electrolysis," "hydrogen policy," and "energy transition." The search was limited to peer-reviewed articles, review papers, and book chapters published between 2015 and 2026.

Policy Documents: National hydrogen strategies, energy plans, and regulatory frameworks were collected from government websites, international organizations (IEA, IRENA, UN), and policy databases.

Project Documentation: Environmental impact assessments, project announcements, and company reports were collected for hydrogen projects under development.

Spatial Data: Water stress projections (Aqueduct 4.0, World Resources Institute) and renewable energy potential data (Global Solar Atlas, Global Wind Atlas) were collected for spatial assessment.

3.3 Spatial Assessment Framework

For the spatial assessment component, a geographic information systems (GIS) approach was employed using ArcGIS Pro. The assessment integrated water stress and renewable energy potential indicators through fuzzy logic modeling.

Water Stress Assessment: Water stress projections for 2030 and 2050 under three scenarios—business-as-usual (SSP3-RCP7.0), optimistic (SSP1-RCP2.6), and pessimistic (SSP5-RCP8.5)—were obtained from the Aqueduct 4.0 database. Data were processed at the HydroBASINS Level 6 sub-basin scale.

Renewable Energy Assessment: Solar irradiation, photovoltaic power potential, wind speed, and wind power density data were obtained from the Global Solar Atlas and Global Wind Atlas.

Fuzzy Logic Modeling: Fuzzy linear membership functions were applied to each criterion based on established thresholds (Table 1). The fuzzy GAMMA operator with $\gamma = 0.90$ was used to integrate criteria and produce spatial index maps (Sekeroglu, 2024).

Table 1. Criteria and Membership Functions for Spatial Assessment

Criteria	Data Source	Membership Function
Water stress (%)	Aqueduct 4.0	$\mu x=0$: $x<20\%$; $\mu x=(0,1)$: $20\%\leq x<40\%$; $\mu x=1$: $x\geq 40\%$
Solar irradiation (kWh/m²-day)	Global Solar Atlas	$\mu x=0$: $x<4.5$; $\mu x=(0,1)$: $4.5\leq x<5$; $\mu x=1$: $x\geq 5$
Photovoltaic potential (kWh/kWp)	Global Solar Atlas	$\mu x=0$: $x<3.5$; $\mu x=(0,1)$: $3.5\leq x<4$; $\mu x=1$: $x\geq 4$
Wind speed (m/s)	Global Wind Atlas	$\mu x=0$: $x<5$; $\mu x=(0,1)$: $5\leq x<7$; $\mu x=1$: $x\geq 7$
Wind power density (W/m²)	Global Wind Atlas	$\mu x=0$: $x<200$; $\mu x=(0,1)$: $200\leq x<400$; $\mu x=1$: $x\geq 400$

3.4 Analytical Framework

The analysis integrates findings across four dimensions:

1. **Technological Readiness**: Assessment of electrolysis technologies, production costs, and infrastructure requirements.
2. **Policy Architecture**: Analysis of national hydrogen strategies, regulatory frameworks, and financial incentives.
3. **Spatial Sustainability**: Evaluation of resource availability, water stress, and land use implications.
4. **Implementation Pathways**: Identification of barriers, opportunities, and context-specific strategies.

4. Results

4.1 Technological Readiness and Innovation

The review of green hydrogen production technologies reveals significant progress and persistent challenges. Alkaline electrolysis remains the most commercially mature technology, with installed capacity exceeding 1 GW globally and capital costs ranging from $500-1,000/kW (IEA, 2024). PEM electrolysis has experienced rapid growth, with costs declining to $1,000-1,500/kW, driven by manufacturing scale-up and membrane improvements. SOEC technology, while demonstrating superior efficiency (up to 90%), remains at pilot scale with costs exceeding $2,000/kW.

Recent innovations are addressing key technological barriers. Advances in catalyst materials—including non-precious metal alternatives for PEM systems and perovskite-based materials for SOEC—are reducing costs and improving durability (Arsad et al., 2024). Membrane-free electrolyzer designs and advanced cell architectures are emerging as promising approaches for next-generation systems (Advancements of innovative water electrolyzers for hydrogen production, 2025).

Artificial intelligence and digital technologies are transforming hydrogen production and management. AI-enabled optimization can improve electrolyzer performance, forecast renewable electricity generation, and reduce operational costs (Ahmed et al., 2024). Machine learning algorithms can predict hydrogen production capacity based on regional geographic conditions, enabling more accurate project planning (Chew et al., 2023). Digital twins and predictive maintenance systems are enhancing operational reliability and extending equipment lifetimes.

Table 2. Comparison of Electrolysis Technologies

Technology	Maturity	Efficiency (%)	Capital Cost ($/kW)	Advantages	Limitations
Alkaline (AWE)	Commercial	60-70	500-1,000	Low cost, long life	Slow response
PEM	Commercial	65-75	1,000-1,500	Fast response, compact	High catalyst cost
SOEC	Pilot	80-90	>2,000	High efficiency	High temperature, degradation
AEM	Demo	60-75	1,500-2,500	Low-cost catalysts	Limited durability

4.2 Policy Architecture and Implementation

The policy analysis reveals a diverse landscape of national hydrogen strategies, regulatory frameworks, and financial incentives.

Kenya has emerged as a regional leader in green hydrogen policy. The country launched its Green Hydrogen Strategy and Roadmap in 2023, followed by guidelines for green hydrogen and its derivatives in 2024 (Kenya's Guidelines on Green Hydrogen and Its Derivatives, 2025). The strategy aligns with Kenya's Vision 2030 and its commitment to achieve 100% clean energy by 2030. Key policy priorities include leveraging renewable energy resources (geothermal, solar, wind) for hydrogen production, decarbonizing industrial sectors (fertilizer production, transportation), and positioning Kenya as a regional hydrogen hub (Towards a green H2 economy: Kenya Country Report, 2025). The government has committed approximately $1 billion for green hydrogen investments, focusing on fertilizer and ethanol production and transportation decarbonization.

Türkiye has defined policy goals in the "Türkiye Hydrogen Technologies Strategy and Roadmap" under the National Energy Plan and its 2053 net-zero emission commitment. The 2025 Investment Action Plan targets industry and green energy, guiding legislation, regulation, and infrastructure for hydrogen production, safety, and implementation (Türkiye's 2025 investment action plan targets industry, green energy, 2025). A 500-km green hydrogen pipeline linking the Aegean and Marmara regions has been proposed, with capacity to transport up to 600 kilotons of green hydrogen annually (Proposal submitted for 500-km green hydrogen pipeline, 2025). The strategy emphasizes domestic electrolyzer manufacturing, safety standards, and alignment with EU environmental regulations.

India has launched the National Green Hydrogen Mission (NGHM) with an outlay of ₹19,744 crore ($2.4 billion). The mission aims to make India a global hub for green hydrogen production, usage, and export, targeting 5 million metric tonnes of annual production by 2030 (Government of India, 2023). Progress as of November 2025 includes 18 companies awarded cumulative production capacity of 862,000 tonnes per annum under the incentive scheme (Progress of National Green Hydrogen Mission, 2025). The Green Hydrogen Certification Scheme of India was launched in April 2025 to establish a transparent framework for certification. Three major ports have been recognized as green hydrogen hubs, and five pilot projects with 37 vehicles and 9 refueling stations have been sanctioned (Three Major Ports Recognised as Green Hydrogen Hubs, 2025).

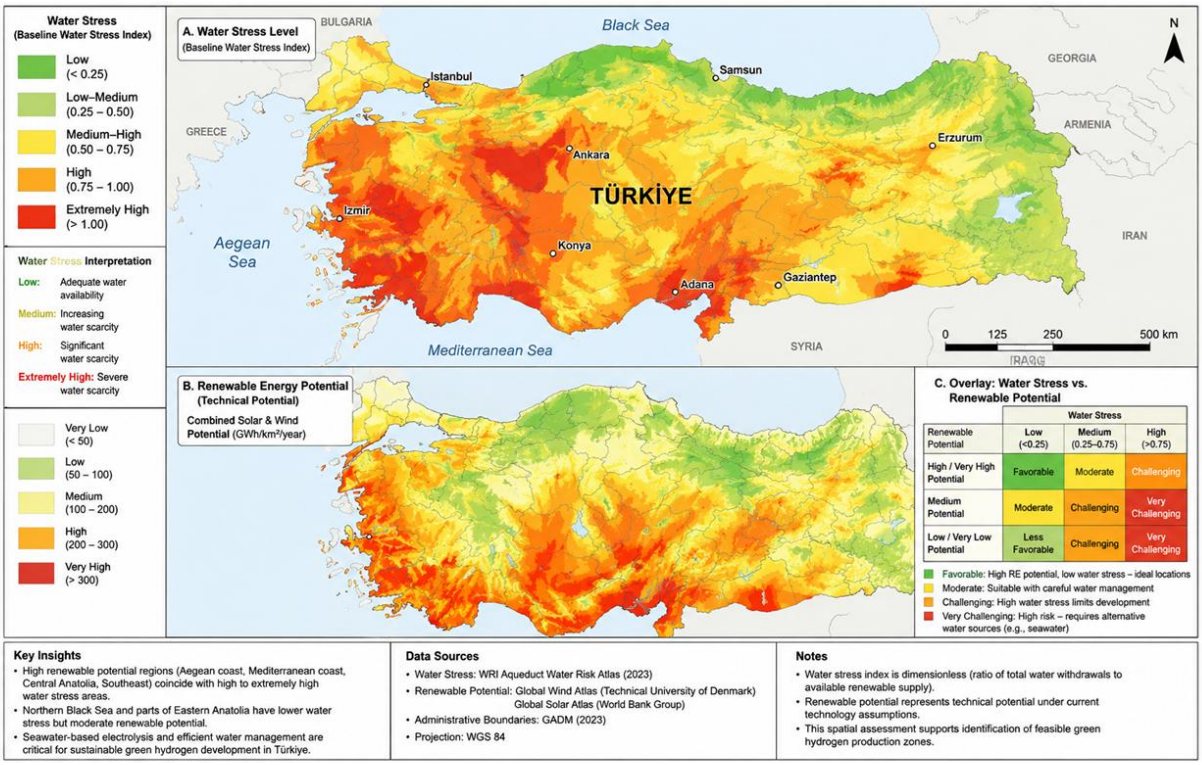
Newfoundland and Labrador has benefited from Canada's national hydrogen strategy, which outlines a vision for hydrogen in Canada's economy by 2050. The province has emerged as a focal point for wind-to-hydrogen development, with six companies pursuing projects: EverWind NL Company, Exploits Valley Renewable Energy Corporation, Toqlukuti'k Wind and Hydrogen, World Energy GH2 Ltd., Argentia Renewables LP, and North Atlantic Refining Limited (Minister Crocker Provides Update on Renewable Energy Projects, 2025). Project Nujio'qonik (World Energy GH2) aims to produce approximately 210,000 tonnes of green hydrogen annually (1.2 million tonnes of green ammonia), with first production targeted for 2025 (Project Nujio'qonik, Canada, 2024). The province's proximity to Europe and existing renewable energy grid provide competitive advantages.

4.3 Spatial Assessment: Water Stress-Renewable Energy Nexus

The spatial assessment for Türkiye reveals critical insights for green hydrogen planning. Under all scenarios for 2030 and 2050, the Eastern Black Sea region and Eastern Anatolia represent areas with low water stress (<10%), benefiting from favorable precipitation regimes and water resource diversity. However, a large portion of Türkiye faces severe water stress under future scenarios (Sekeroglu, 2026).

The 2030 scenarios identify Southern Marmara, the Aegean Region, the northern parts of the Mediterranean Region, Central Anatolia, and parts of Eastern and Southeastern Anatolia as high-risk areas. The 2050 scenarios indicate expansion of risk areas under business-as-usual and pessimistic conditions. Even under optimistic scenarios limiting global surface temperature rise, severe water stress is projected for the Aegean, Central Anatolia, and Mediterranean regions.

Figure 1. Spatial Distribution of Water Stress and Renewable Energy Potential in Türkiye



The spatial relationship between water stress and renewable energy potential reveals critical patterns. Areas characterized by high solar energy potential and high water stress are concentrated in the Aegean coasts, Southern Marmara, the Mediterranean Region, Southeastern Anatolia, and Central Anatolia. Regions with the highest wind potential—Southern Marmara (Balıkesir, Çanakkale) and the Aegean coasts—also experience considerable water stress.

These findings have significant implications for green hydrogen planning. The addition of energy-related water use to already increasing water stress may render freshwater-based electrolysis infeasible in high-potential regions. Seawater-based electrolysis emerges as a critical alternative for coastal regions. The presence of high renewable energy potential in coastal areas of Southern Marmara, the Mediterranean, and the Aegean regions strongly supports seawater-based green hydrogen as a sustainable pathway (Albatayneh et al., 2025).

4.4 Regional Case Studies: Implementation Pathways

Kenya: The Kenyan case illustrates the importance of aligning green hydrogen development with existing renewable energy infrastructure and industrial decarbonization priorities. Kenya's abundant geothermal, solar, and wind resources provide a strong foundation for green hydrogen production. The focus on fertilizer production and transportation decarbonization aligns with pressing national needs: reducing fertilizer import dependence and addressing urban air pollution. Key challenges include limited renewable energy infrastructure, technical expertise gaps, public skepticism about hydrogen safety, and financial barriers due to high initial investment costs (Odhiambo et al., 2025). The government's strategy of public-private partnerships and international collaboration addresses these challenges while leveraging Kenya's competitive advantages.

Türkiye: The Turkish case highlights the critical importance of spatial planning and water resource management. The coincidence of high renewable energy potential and severe water stress in key regions necessitates seawater-based approaches for environmental sustainability. The development of the Southern Marmara Hydrogen Coast Valley and the proposed 500-km hydrogen pipeline demonstrates progress toward an integrated hydrogen ecosystem (Sekeroglu, 2026).

Policy priorities include creating green hydrogen legislation, promoting domestic electrolyzer manufacturing, and supporting research and development. The alignment with EU environmental regulations provides a framework for quality and safety standards.

India: The Indian case demonstrates the potential of large-scale, government-led hydrogen initiatives. The National Green Hydrogen Mission's comprehensive approach—encompassing production incentives, demand creation, research and development, and enabling infrastructure—provides a model for ambitious hydrogen deployment. However, challenges remain: creating stable demand, ensuring competitive delivered costs, and developing bankable offtake opportunities across end-use sectors (Demand creation key to scaling India's green hydrogen economy, 2026). The Green Hydrogen Certification Scheme addresses the need for transparent certification, while port development and pilot projects demonstrate progress toward implementation.

Newfoundland and Labrador: The Newfoundland case illustrates the strategic value of exceptional renewable resources and proximity to markets. The province's abundant wind resources, existing renewable energy grid, and proximity to Europe provide competitive advantages for green hydrogen production and export (Pourvaziri et al., 2026). The six projects under development represent one of the most concentrated hydrogen development efforts globally. However, challenges include environmental impacts on sensitive ecosystems, water use for electrolysis, infrastructure requirements, and community acceptance (Mercer et al., 2017; Hogan, 2025). The projects' emphasis on environmental impact assessment, Indigenous engagement, and community consultation addresses these challenges.

5. Discussion

5.1 Integrating Technological, Policy, and Spatial Dimensions

The findings from the four case studies reveal both universal patterns and context-specific variations in green hydrogen development. Several key themes emerge from the comparative analysis.

First, technological readiness is advancing but commercialization gaps persist. While electrolysis technologies have matured significantly, particularly alkaline and PEM systems, the gap between technical potential and commercial viability remains substantial. High capital costs, renewable electricity requirements, and infrastructure deficits constrain deployment across all contexts. The green hydrogen accounted for less than one percent of global hydrogen production in 2024 (IEA, 2024), despite decades of research and development. This gap reflects the persistent challenge of transitioning from demonstration to commercial scale.

The technological pathway forward involves multiple strategies: reducing electrolyzer costs through manufacturing scale-up and innovation, improving efficiency through advanced materials and system integration, and developing hydrogen storage and transportation infrastructure. Recent projections suggest that global electrolyzer capacity could expand to nearly 520 GW by 2030 (Energy & Fuels, 2026), indicating significant momentum. However, the pace of renewable deployment and capital investment remain key constraints (Green hydrogen pathways for a net-zero future, 2026).

Second, policy architecture is critical but implementation gaps persist. All four contexts have established or are developing national hydrogen strategies, demonstrating policy commitment. However, the gap between policy ambition and implementation varies significantly. India's National Green Hydrogen Mission provides substantial financial resources and clear targets, while Kenya's strategy emphasizes alignment with existing renewable energy infrastructure. Türkiye's developing strategy and Newfoundland's project-based approach reflect different stages of policy development.

The effectiveness of policy interventions depends on several factors: demand-side incentives to create markets, supply-side support to reduce costs, regulatory frameworks to enable investment, and international cooperation to facilitate trade. The IEA (2025) notes that legislated policies could trigger demand for nearly 6 million tonnes per annum of low-emissions hydrogen by 2030, while government demand targets add up to 9.5 million tonnes per annum. However, achieving net-zero scenarios would require green hydrogen to make up 65 percent of global hydrogen output by 2035, up from just one percent today (IEA, 2025). This gap underscores the need for accelerated policy implementation.

Third, spatial sustainability is an underexplored but critical dimension. The spatial assessment for Türkiye reveals that high renewable energy potential regions coincide with severe water stress, challenging assumptions about the environmental sustainability of freshwater-based electrolysis. This finding has implications beyond Türkiye, as many regions with high renewable potential also face water scarcity. The water footprint of hydrogen production—approximately 9-10 liters of water per kilogram of hydrogen (Beswick et al., 2021)—becomes a critical constraint in water-stressed regions.

The solution lies in seawater-based electrolysis, which offers a sustainable alternative for coastal regions. Recent advances in direct seawater electrolysis and desalination technologies are making this approach increasingly feasible (Yu et al., 2025; Loomba et al., 2023). However, challenges remain: the complex composition of seawater can cause corrosion and pH fluctuations, while brine disposal from desalination can harm marine ecosystems (Liu et al., 2023). Further research and development are needed for commercial-scale implementation.

Fourth, context matters. The four case studies demonstrate that green hydrogen development must be tailored to local conditions: resource endowments, industrial structure, policy environment, and social context. Kenya's focus on fertilizer production and transportation aligns with pressing national needs. Türkiye's water stress necessitates seawater-based approaches. India's scale requires comprehensive policy frameworks and substantial investment. Newfoundland's wind resources and proximity to markets enable export-oriented development.

5.2 Theoretical Contributions

This study contributes to the theoretical understanding of green hydrogen development in several ways.

First, it provides an integrated framework for analyzing green hydrogen across technological, policy, spatial, and sustainability dimensions. Much of the existing literature examines these dimensions in isolation, limiting understanding of their interconnections. The integrative framework developed in this study demonstrates how technological readiness, policy architecture, spatial sustainability, and implementation pathways interact to shape green hydrogen outcomes. This framework can guide future research and inform policy development.

Second, the study advances understanding of the water-energy nexus in hydrogen planning. The spatial assessment methodology developed for Türkiye provides a replicable approach for identifying regions where water stress constrains hydrogen production. By making water availability visible as a spatial limitation, the framework enables more sustainable planning. The finding that seawater-based electrolysis offers a viable alternative in coastal regions has implications for hydrogen development in other water-stressed regions.

Third, the comparative analysis contributes to contextual theorizing. By examining green hydrogen development across four diverse contexts, the study demonstrates how universal challenges manifest differently depending on local conditions. This contextual understanding is essential for developing effective policies and strategies. The case studies reveal that while technological and policy solutions can be transferred, their effectiveness depends on adaptation to local resource endowments, institutional capacity, and social context.

5.3 Practical Implications

The findings have several practical implications for policymakers, industry, and researchers.

For policymakers, the study underscores the importance of comprehensive hydrogen strategies that address multiple dimensions simultaneously. Technology-focused policies must be complemented by demand-side incentives, infrastructure investment, and spatial planning. The water-energy nexus must be explicitly considered in hydrogen planning, with seawater-based approaches prioritized in water-stressed regions. International cooperation, including technology transfer, hydrogen certification, and trade agreements, will be essential for establishing global hydrogen markets.

The timing of policy interventions is critical. The IEA (2025) emphasizes that achieving net-zero scenarios requires accelerated action in the coming decade. Governments must move from strategy development to implementation, with clear targets, dedicated resources, and accountability mechanisms. The Breakthrough Agenda's framework for international cooperation provides a model for coordinated action.

For industry, the findings highlight the importance of strategic positioning along the hydrogen value chain. Opportunities exist in electrolyzer manufacturing, renewable energy development, hydrogen production, infrastructure, and end-use applications. The cost reduction trajectory for electrolyzers suggests that early movers may gain competitive advantages. However, the gap between policy ambition and market reality (Hydrogen markets face reality check in 2026, 2026) suggests that companies should maintain flexibility and diversify across applications and geographies.

For researchers, the study identifies several priority areas for future investigation. First, the water-energy nexus requires further research, including life cycle assessment of seawater-based electrolysis, optimization of water use in hydrogen production, and spatial planning methodologies. Second, the social dimensions of hydrogen deployment—public acceptance, energy equity, and community engagement—merit greater attention. Third, the integration of hydrogen with other energy system components—renewable electricity, energy storage, and sector coupling—requires systems-level analysis.

5.4 Limitations and Future Research

Several limitations of this study should be acknowledged.

First, the case study selection, while diverse, is not exhaustive. The findings may not be generalizable to all contexts, and other regions may face different challenges and opportunities. Future research should expand the comparative analysis to include additional countries and regions, particularly in the Global South where hydrogen development is at earlier stages.

Second, the spatial assessment for Türkiye, while methodologically rigorous, is based on scenario projections that involve uncertainty. The Aqueduct 4.0 dataset provides valuable insights but relies on assumptions about climate change, economic development, and water management that may not materialize. Future research should incorporate multiple data sources and scenarios to enhance robustness.

Third, the study relies primarily on secondary data and document analysis. Primary data collection—including interviews with policymakers, industry representatives, and community members—would provide deeper insights into implementation challenges and stakeholder perspectives. Future research should incorporate qualitative methods to complement the quantitative and spatial analyses.

Fourth, the study focuses on production and supply-side dimensions of green hydrogen. Demand-side considerations—including end-use applications, market development, and consumer behavior—receive less attention. Future research should examine the demand side more comprehensively, including sector-specific applications and market creation strategies.

6. Conclusion

This study has examined green hydrogen as a catalyst for sustainable energy transition through a comparative analysis of technological, policy, spatial, and sustainability dimensions across four distinct contexts. The findings reveal both the transformative potential of green hydrogen and the persistent challenges that constrain its deployment.

The technological assessment demonstrates significant progress in electrolysis technologies, with alkaline and PEM systems achieving commercial maturity and SOEC and AEM technologies showing promise for future applications. However, the gap between technical potential and commercial viability remains substantial, with high capital costs, renewable electricity requirements, and infrastructure deficits constraining deployment. Continued innovation in catalyst materials, membrane development, and system integration is essential for cost reduction and performance improvement.

The policy analysis reveals a diverse landscape of national hydrogen strategies, regulatory frameworks, and financial incentives. Kenya, Türkiye, India, and Newfoundland and Labrador have all established or are developing hydrogen strategies, demonstrating policy commitment. However, implementation gaps persist between ambition and execution. The effectiveness of policy interventions depends on demand-side incentives, supply-side support, regulatory frameworks, and international cooperation. The IEA's finding that achieving net-zero scenarios requires green hydrogen to make up 65 percent of global hydrogen output by 2035 underscores the urgency of accelerated action.

The spatial assessment for Türkiye reveals critical insights for hydrogen planning. The coincidence of high renewable energy potential and severe water stress in key regions challenges assumptions about the environmental sustainability of freshwater-based electrolysis. Seawater-based electrolysis emerges as a critical alternative for coastal regions, with the potential to address water constraints while leveraging renewable energy resources. The spatial assessment methodology developed in this study provides a replicable approach for identifying regions where water stress constrains hydrogen production.

The comparative analysis across the four case studies demonstrates that green hydrogen development must be tailored to local conditions. Kenya's focus on fertilizer production and transportation aligns with pressing national needs. Türkiye's water stress necessitates seawater-based approaches. India's scale requires comprehensive policy frameworks and substantial investment. Newfoundland's wind resources and proximity to markets enable export-oriented development. These contextual variations underscore the importance of place-based approaches to hydrogen development.

The integrated framework developed in this study—encompassing technological readiness, policy architecture, spatial sustainability, and implementation pathways—provides a foundation for future research and policy development. By examining the interconnections among these dimensions, the framework enables more comprehensive analysis and more effective decision-making.

The path forward for green hydrogen involves multiple parallel strategies: accelerating electrolyzer cost reduction through innovation and scale-up, developing hydrogen storage and transportation infrastructure, creating markets through demand-side policies, integrating hydrogen with renewable energy systems, and ensuring spatial and environmental sustainability. International cooperation—including technology transfer, hydrogen certification, and trade agreements—will be essential for establishing global hydrogen markets.

In conclusion, green hydrogen stands as a critical component of the sustainable energy transition, offering a zero-carbon energy carrier capable of decarbonizing hard-to-abate sectors, enabling long-duration energy storage, and enhancing energy security. However, realizing its potential requires integrated approaches that simultaneously address technological innovation, policy coherence, infrastructure investment, spatial sustainability, and stakeholder engagement. The case studies examined in this study demonstrate that while challenges are significant, the opportunities are equally substantial. With concerted effort and strategic investment, green hydrogen can contribute meaningfully to global decarbonization and sustainable development.

References

Adams, T. A. (2023). How Canada can supply Europe with critical energy by creating a Trans-Atlantic energy bridge. *Canadian Journal of Chemical Engineering, 101*(4), 1729-1742.

Ajanovic, A., & Haas, R. (2020). On the future prospects and limits of hydrogen economy. *International Journal of Hydrogen Energy, 45*(41), 20709-20717.

Albatayneh, A., Al-Omary, M., Jaradat, M., Bdour, M., Al-Khasawneh, Y., Hindiyeh, M., & Aljarrah, R. (2025). Water-Energy Nexus Dilemma for hydrogen production in Water-Scarce regions. *Energy Nexus, 19*, 100463.

Alvera, M. (2021). *The Hydrogen Revolution: A Blueprint for the Future of Clean Energy*. Hadder & Stoughton.

Arsad, S. R., Arsad, A. Z., Ker, P. J., Hannan, M. A., Tang, S. G. H., Goh, S. M., et al. (2024). Recent advancement in water electrolysis for hydrogen production: A comprehensive bibliometric analysis and technology updates. *International Journal of Hydrogen Energy, 60*, 780-801.

Béres, R., Mararakanye, N., Auret, C., Bekker, B., & van den Broek, M. (2024). Analysing the prospects of grid-connected green hydrogen production in predominantly fossil-based countries—a case study of South Africa. *International Journal of Hydrogen Energy, 83*, 975-986.

Beswick, R. R., Oliveira, A. M., & Yan, Y. (2021). Does the green hydrogen economy have a water problem? *ACS Energy Letters, 6*(9), 3167-3169.

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production methods—A review. *Journal of Cleaner Production, 85*, 151-163.

BloombergNEF. (2024). *Hydrogen Economy Outlook 2024*. BloombergNEF.

Chauhan, D., & Ahn, Y. H. (2023). Alkaline electrolysis of wastewater and low-quality water. *Journal of Cleaner Production, 397*, 136613.

Chew, Y. E., Cheng, X. H., Loy, A. C. M., How, B. S., & Andiappan, V. (2023). Beyond the colours of hydrogen: opportunities for process systems engineering in hydrogen economy. *Process Integration and Optimization for Sustainability, 7*(4), 941-950.

Dash, S. K., Chakraborty, S., & Elangovan, D. (2023). A brief review of hydrogen production methods and their challenges. *Energies, 16*(3), 3.

Dawood, F., Anda, M., & Shafiullah, G. M. (2020). Hydrogen production for energy: An overview. *International Journal of Hydrogen Energy, 45*(7), 3847-3869.

European Commission. (2020). *A hydrogen strategy for a climate-neutral Europe*. European Commission.

Glenk, G., & Reichelstein, S. (2019). Economics of converting renewable power to hydrogen. *Nature Energy, 4*(3), 216-222.

Gong, J. (2021). A commentary of green hydrogen in MIT Technology Review 2021. *Fundamental Research, 1*(6), 848-850.

Götz, M., Lefebvre, J., Mörs, F., Koch, A. M., Graf, F., Bajohr, S., Reimert, R., & Kolb, T. (2016). Renewable power-to-gas: A technological and economic review. *Renewable Energy, 85*, 1371-1390.

Government of India. (2023). *National Green Hydrogen Mission*. Ministry of New and Renewable Energy.

Hogan, J. L. (2025). The legacy of the cod fishery collapse: understanding wind energy acceptance in Newfoundland through energy justice and place. *Energy Research & Social Science, 127*, 104274.

IEA. (2024). *Global Hydrogen Review 2024*. International Energy Agency.

IEA. (2025). *Policies – Global Hydrogen Review 2025*. International Energy Agency.

IPCC. (2018). *Global Warming of 1.5°C*. Intergovernmental Panel on Climate Change.

IRENA. (2023). *Green hydrogen cost reduction: Scaling up electrolysers to meet the 1.5°C climate goal*. International Renewable Energy Agency.

Jena, M. C., Mishra, S. K., & Moharana, H. S. (2023). Renewable energy sourcing to enhance sustainable manufacturing by using Madhab's EEE impact analysis model. *Global Journal of Energy Technology Research Updates*.

Kovač, A., Paranos, M., & Marciuš, D. (2021). Hydrogen in energy transition: A review. *International Journal of Hydrogen Energy, 46*(16), 10016-10035.

Kourougianni, F., Arsalis, A., Olympios, A. V., Yiasoumas, G., Konstantinou, C., Papanastasiou, P., et al. (2024). A comprehensive review of green hydrogen energy systems. *Renewable Energy, 231*, 120911.

Liu, G., Xu, Y., Yang, T., & Jiang, L. (2023). Recent advances in electrocatalysts for seawater splitting. *Nano Materials Science, 5*(1), 101-116.

Loomba, S., Khan, M. W., Haris, M., Mousavi, S. M., Zavabeti, A., Xu, K., et al. (2023). Nitrogen-doped porous nickel molybdenum phosphide sheets for efficient seawater splitting. *Small, 19*(18), 2207310.

Mercer, N., Sabau, G., & Klinke, A. (2017). "Wind energy is not an issue for government": barriers to wind energy development in Newfoundland and Labrador, Canada. *Energy Policy, 108*, 673-683.

Odhiambo, J. O., Ngugi, R., Onsumu, E., & Wachana, P. (2025). Pathways to green hydrogen production as a sustainable energy solution in Kenya by 2040. *Discover Energy, 5*, 37.

Olaitan, D., Bertagni, M., & Porporato, A. (2024). The water footprint of hydrogen production. *Science of the Total Environment, 927*, 172384.

Pourvaziri, Z., Sabau, G.-L., & Haghiri, M. (2026). Wind energy and green hydrogen production: a sustainable vision for the province of Newfoundland and Labrador, Canada. *Academia Green Energy, 3*.

Reyes, K. M. D., Bruce, K., & Shetranjiwalla, S. (2023). Green chemistry, life cycle assessment, and systems thinking: an integrated comparative-complementary chemical decision-making approach. *Journal of Chemical Education, 100*(1), 209-220.

Schwarze, K., Geißler, T., Nimtz, M., & Blumentritt, R. (2023). Demonstration and scale-up of high-temperature electrolysis systems. *Fuel Cells, 23*, 492.

Sekeroglu, A. (2024). Site selection for biomass-solar hybrid renewable energy facilities: Spatial modelling based on fuzzy logic-geographic information systems. *Renewable Energy, 237*, 121775.

Sekeroglu, A. (2026). Water stress-renewable energy nexus for green hydrogen: A spatial assessment framework in Türkiye. *International Journal of Energy Studies, 11*(2), 1007-1032.

Sharma, G. D., Verma, M., Taheri, B., Chopra, R., & Parihar, J. S. (2023). Socio-economic aspects of hydrogen energy: an integrative review. *Technological Forecasting and Social Change, 192*, 122574.

Squadrito, G., Maggio, G., & Nicita, A. (2023). The green hydrogen revolution. *Renewable Energy, 216*, 119041.

Staffell, I., Scamman, D., Velazquez Abad, A., Balcombe, P., Dodds, P. E., Ekins, P., Shah, N., & Ward, K. R. (2019). The role of hydrogen and fuel cells in the global energy system. *Energy & Environmental Science, 12*(2), 463-491.

Valente, A., Iribarren, D., & Dufour, J. (2021). Life cycle assessment of hydrogen energy systems: A review. *Renewable and Sustainable Energy Reviews, 143*, 110908.

Vogl, V., Åhman, M., & Nilsson, L. J. (2018). Assessment of hydrogen direct reduction for fossil-free steelmaking. *Journal of Cleaner Production, 203*, 736-745.

Yu, L., Ning, M., Wang, Y., Yuan, C., & Ren, Z. (2025). Direct seawater electrolysis for hydrogen production. *Nature Reviews Materials, 10*, 857-873.