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A Mini Review of Techno-Economic, Environmental and Social Impacts of Hydrogen Generation

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As hydrogen emerges as a key pillar in the global clean energy transition, understanding the feasibility from techno-economic, environmental, and social dimensions is critical. This review provides a brief analysis of hydrogen production technologies, primarily electrolysis, steam methane reforming (SMR) with carbon capture and storage (CCS), and biomass gasification through the lens of techno-economic assessment, sustainability, environmental metrics, and social impact. Key technical parameters such as energy efficiency, scalability, and technology readiness level (TRL) are discussed alongside economic indicators, including levelized cost of hydrogen (LCOH), and market competitiveness. Environmental implications, particularly emissions reductions, are evaluated in parallel with social dimensions shaped by public perception, policy frameworks, and regional case studies. Importantly, while numerous studies address techno-economic or environmental aspects, and some consider social impacts, very few integrate all three dimensions simultaneously. This lack of holistic assessment represents a critical gap in the literature, underscoring the need for approaches to guide the development of hydrogen strategies that are technically feasible, economically viable, environmentally sustainable, and socially acceptable.

1. Introduction

The 2015 Paris Agreement and the Net Zero Carbon Emissions (NZCE) 2050 goals have accelerated global commitments to reduce greenhouse gas emissions and transition toward sustainable energy systems. Achieving these targets requires deep decarbonization across energy-intensive sectors, prompting growing interest in hydrogen as a clean, flexible, and scalable energy vector. Hydrogen, particularly when produced from renewable sources, supports long-term climate objectives by enabling application across low-carbon transport, power generation, industrial applications, chemical production, and energy storage. Hydrogen can be produced through various pathways, categorized primarily as grey (from fossil fuels without carbon capture), blue (from fossil fuels with carbon capture and storage), and green (from renewable sources via water electrolysis). Among these, green hydrogen has gained particular attention due to the potential to produce zero-emission fuel when powered by renewable electricity. Other renewable-based routes, such as biomass gasification, also offer sustainable alternatives. However, scaling up these technologies for commercial deployment remains technical and economically challenging. Conducting Techno-Economic Assessments (TEA) of hydrogen production pathways is critical for evaluating the feasibility, guiding investment decisions, and informing policy development. These assessments typically consider capital and operational costs, energy efficiency, and integration with renewable energy sources. Despite advances in hydrogen technology, many large-scale production routes still face high capital expenditures, supply chain constraints, and uncertain market dynamics. In addition to technical and economic viability, social acceptance plays a crucial role in the successful deployment of hydrogen infrastructure. Public perceptions, local community support, and environmental concerns can significantly influence the siting and approval of hydrogen projects such as electrolysis plants, hydrogen pipelines, or refuelling stations. It is increasingly recognized that techno-economic evaluations should be accompanied by an understanding of social impacts and acceptance dynamics. Existing reviews often focus on specific production methods or regional contexts, leaving a gap in holistic assessments that encompass both techno-economic, environmental, and social dimensions at a global or strategic planning level.

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2. Hydrogen production pathway

Hydrogen production technologies are critical for the global energy transition, but they differ widely in terms of type of feedstocks and environmental impact. Steam methane reforming (SMR) remains the dominant method for hydrogen production, accounting for approximately 95 % of global output due to the technological maturity and cost-effectiveness. Traditionally, SMR produces grey hydrogen, a form associated with high carbon emissions. However, with the advancement of carbon capture, utilization, and storage (CCUS) technologies, this same process can now yield blue hydrogen by capturing and storing the CO_2 that would otherwise be released. Emerging CO_2 capture methods include advanced solvents such as ionic liquids and deep eutectic solvents, solid sorbents like metal organic frameworks (MOFs) and covalent organic frameworks (COFs), as well as next-generation membrane-based separation technologies, which are continuously being refined. Without CCS integration, however, SMR remains a highly carbon-intensive process, significantly contributing to greenhouse gas emissions (Abubakr et al., 2024). In contrast, electrolysis technologies, particularly polymer electrolyte membrane (PEM) and alkaline water electrolysis (AWE), have emerged as promising pathways for producing green hydrogen using renewable electricity. These technologies have achieved energy efficiencies of up to 80 %, making them attractive from a technical standpoint (U.S. Department of Energy., 2022). Alkaline water electrolysis, the more mature of the two, operates using a liquid alkaline solution such as potassium hydroxide as the electrolyte, offering lower capital costs but slower dynamic response to fluctuating power supply. In contrast, PEM electrolysis uses a solid polymer electrolyte, enabling higher current densities, quicker ramp-up times, and compact system design, making it ideal for integration with intermittent renewable sources like solar and wind. However, both technologies remain economically challenging, with the levelized cost of hydrogen (LCOH) frequently exceeding 5 USD/kg under current market and energy price conditions (Ourya and Abderafi, 2022). The high cost is primarily driven by expensive materials such as platinum group metals used in PEM systems and the still-high price of renewable electricity in many regions. In the meantime, biomass gasification is emerging as a promising alternative for sustainable hydrogen production, offering the dual advantages of utilizing renewable, carbon-neutral feedstocks and achieving relatively competitive production costs. This thermochemical process involves converting organic biomass such as agricultural residues, forestry waste, or dedicated energy crops into hydrogen-rich syngas through high-temperature reactions with a controlled amount of oxygen, steam, or air. Previous studies indicate that hydrogen production costs from biomass gasification can be as low as 2.68 USD/kg, positioning it as a more economical option than water electrolysis under current conditions (Tanyi et al., 2024). When coupled with carbon capture and storage (CCS), biomass gasification can potentially achieve negative emissions (Patel et al., 2025), contributing to carbon removal goals. However, this pathway is not without its challenges. One major hurdle lies in syngas purification, as the raw gas contains impurities such as tar, particulates, sulfur compounds, and trace metals, which must be effectively removed to avoid catalyst poisoning in downstream processes like water-gas shift and pressure swing adsorption. The quality and composition of biomass feedstock can vary widely depending on source, moisture content, and seasonal availability, impacting both gasification efficiency and process consistency (Vallejo and Alzate, 2024). Unlike steam methane reforming (SMR), which generates CO_2, methane pyrolysis thermally decomposes methane (CH_4) into hydrogen gas and solid carbon at high temperatures (typically above 1,000°C) in the absence of oxygen. This process eliminates the need for water and avoids direct CO_2 emissions, as the carbon is captured in a solid form, which can be stored or potentially used in value-added products such as carbon black or graphene. One of the key advantages of methane pyrolysis is its lower environmental footprint compared to both SMR and water electrolysis, especially when powered by renewable or low-carbon electricity (Shokrollahi et al., 2024). However, the technology is still in the developmental stage and faces challenges such as reactor material degradation at high temperatures, continuous removal, and handling of solid carbon (Patlolla et al., 2023), and scalability for large-scale deployment. While conventional SMR remains the cheapest option today, the urgency of decarbonization is driving substantial research and development into cleaner alternatives like renewable electrolysis and biomass gasification. To achieve widespread hydrogen deployment that aligns with global climate targets, future efforts must focus on reducing production costs, improving efficiency, and ensuring the sustainability of feedstocks. Scaling up these hydrogen production technologies is essential to support industrial decarbonization, enable sector decoupling, and develop hydrogen export markets. However, challenges persist, including high initial capital requirements, land and water resources availability, intermittency of renewables, and supply chain readiness. Techno-economic assessments and social considerations are crucial to guide investments and policy decisions for large-scale hydrogen deployment.

3. Techno-economic assessment (TEA)

The techno-economic feasibility of hydrogen production is a key determinant of its scalability and adoption, requiring an integrated analysis of energy efficiency, capital investment, and levelized cost of hydrogen (LCOH).

Among the major hydrogen production pathways, SMR, biomass gasification, and water electrolysis offer distinct trade-offs in cost, emissions, and maturity. SMR without carbon capture remains the most cost-competitive, with a typical LCOH of 1.0–2.0 USD/kg H_2 at large production scales and thermal efficiencies around 65-75 % (Aliyu and AlZahrani, 2024). When coupled with carbon capture and storage (CCS), LCOH increases slightly to 2.0–2.5 USD/kg H_2 (Al-Qahtani et al., 2021), and total lifecycle emissions are reduced by up to 90 %, though not fully eliminated (Wilkinson et al., 2023). The integration of CCS also reduces the Technology Readiness Level (TRL) from 9 to 8 due to ongoing industrial scaling challenges (Wilkinson et al., 2023). Biomass gasification presents a middle-ground pathway, with reported low hydrogen production rates and energy efficiencies ranging from 45 % to 65 %, depending on reactor configuration and feedstock quality (Gubin et al., 2024). Centralized systems utilizing dual fluidized bed gasifiers can reach LCOH values as low as 2.68 USD/kg H_2 (Tanyi et al., 2024), while decentralized setups face cost penalties, with LCOH rising to 4.57–8.30 USD/kg H_2 at lower scales (Vallejo and Alzate, 2024). Sensitivity analysis shows that biomass price and transport logistics significantly influence economic performance, especially in regions lacking consistent feedstock supply (Ghasemi et al., 2024). Water electrolysis technologies, particularly alkaline water electrolysis (AWE) and proton exchange membrane (PEM) systems, are gaining traction for their near-zero emissions when powered by renewables. AWE systems operate with TRL 9 and efficiency levels of 62–84 %, while PEM systems, with TRLs between 6 and 9 (Schnuelle et al., 2020), typically achieve 55–80 % efficiency but require higher CAPEX due to precious metal catalysts (Altayib and Dincer, 2022). In centralized configurations, PV-driven electrolysis systems can produce large-scale hydrogen with LCOH ranging from 4.35 to 5.56 USD/kg H_2 (Tanyi et al., 2024). Global forecasts suggest that with declining renewable electricity prices and electrolyzer CAPEX, LCOH may fall to 4.80–6.76 USD/kg by 2030 (Fan et al., 2021). From that study, sensitivity analysis highlights electricity price, capacity factor, and electrolyzer efficiency as dominant parameters affecting LCOH in electrolytic routes. In the case of methane pyrolysis, Okeke et al. (2023) employed a furnace reactor with bottom combustion heat for large-scale hydrogen production with the LCOH ranging from 1.08 USD/ kg H_2 to 2.43 USD/ kg H_2, based on natural gas cost of 3.76 USD/GJ, indicating promising economic potential. Additionally, methane pyrolysis demonstrated significant energy efficiency advantages, requiring approximately 55 % less energy than SMR and 74 % less than electrolysis, further strengthening its economic attractiveness.

Table 1: LCOH (USD/kg H_2) according to hydrogen production pathway between from 2030 – 2050 (MOSTI, 2023)

Technology	2030	2040	2050
SMR with CCS	3.71	4.64	5.62
Hydro Mini Electrolysis PEM	3.03	2.29	1.82
Solar PV with incentive	2.85	2.47	1.45
Hydro Excess Electrolysis PEM	2.50	2.25	2.11
Biomass gasification	1.72	1.72	1.72
Solar Electrolysis PEM	4.82	2.63	1.45

4. Environmental and social impacts

As hydrogen gains traction as a clean energy vector, it is vital to assess not only the technical and economic performance of production methods but also their environmental footprint and social implications. These dimensions are crucial for determining the long-term sustainability and public acceptance of hydrogen technologies. Among the available technologies, SMR without carbon capture is the most carbon-intensive, emitting approximately 9-12 kg of CO_2 per kg of hydrogen produced (Al-Qahtani et al., 2021). While adding CCS can reduce emissions significantly, the environmental cost, including resource extraction and energy penalties, remains non-negligible. Conversely, electrolysis powered by renewable electricity offers near-zero operational emissions, making it the most environmentally favourable option, provided the electricity is truly carbon-free (Li et al., 2024). Advancements in electrolyser efficiency, such as the development of systems achieving up to 95 % efficiency, have significantly reduced energy losses. The overall environmental impact is influenced by the carbon intensity of the electricity used. For instance, electrolysis powered by solar energy can contribute approximately 2 kg CO_2 equivalent per kg of hydrogen due to emissions associated with the production and maintenance of solar infrastructure (Elgowainy et al., 2024). Biomass gasification represents a middle path. If biomass is sustainably sourced, the process can be close to carbon-neutral due to the reabsorption of CO_2 during feedstock growth. However, full life cycle assessments reveal that biomass-based systems still have environmental trade-offs, including land use changes, particulate emissions, and impacts from transportation and processing infrastructure (Tiago et al., 2025). In another alternative, biomass can also be integrated with CCS technologies, in which such integration can result in net-negative greenhouse gas emissions, ranging from

-15 to -22 kg CO_2-equivalent per kg of hydrogen produced (IEA, 2025). Advanced processes such as methane pyrolysis have emerged as low-emission alternatives, especially when the solid carbon byproduct is sequestrated or used in commercial applications (Shokrollahi et al., 2024).

Social factors significantly affect hydrogen adoption. Public concerns include the perceived safety risks of hydrogen (e.g., flammability), lack of infrastructure, and uncertainty about its true environmental credentials. In regions with limited awareness or poor communication strategies, opposition to hydrogen projects, especially those involving fossil fuel-derived hydrogen, can stall deployment. Studies show that trust in government, transparency of information, and visible environmental benefits are key to increasing public support (Roque et al., 2025). For instance, countries with active climate policies and green financing mechanisms, such as green bonds or Environmental, Social, and Governance (ESG)-linked investment, report higher social acceptance of hydrogen initiatives. Policy frameworks play a pivotal role in balancing environmental goals with socio-economic deployment. For example, the Inflation Reduction Act in the U.S offers tax incentives that improve the cost competitiveness of green and blue hydrogen while also rewarding negative emissions through biomass with CCS (Cheng et al., 2023). Perceptions vary by region and socio-political context. In Sarawak, Malaysia, for instance, public perception is influenced by local economic development strategies and cultural familiarity with technology, indicating that acceptance cannot be generalized across all communities (Ahmadi and Ubaidillah, 2022). In addition, effective communication strategies are essential to address public concerns and improve social acceptance. Studies from South Korea emphasize the need for strategic public relations policies that acknowledge public fears while highlighting economic and environmental benefits. Addressing awareness, such as technological gaps or high costs, can also help shift perception (Cho et al., 2024). In contrast, traditional survey methods may not capture the deeper socio-cultural factors influencing public perception. A new research agenda focused on social practices, energy justice, and place attachment is needed to better understand how hydrogen transitions will affect everyday life (Scott and Powells, 2020). Similarly, the EU's hydrogen roadmap promotes sustainability by setting strict carbon intensity thresholds for eligible projects. However, many developing countries lack such structured policies. This regulatory void can hinder investment and public trust. Therefore, comprehensive national hydrogen strategies integrating environmental metrics, social engagement, and equitable access are necessary to accelerate hydrogen adoption in a just and inclusive manner.

5. Conclusions

As the global energy system transitions toward carbon neutrality, hydrogen is poised to play a pivotal role. Achieving its full potential requires addressing a range of unresolved technical, economic, infrastructural, and social challenges. Future efforts must be guided by strategic investments, coordinated policy frameworks, and continued research into both established and emerging production pathways. One key research need is the optimization and cost reduction of electrolysis technologies, especially those powered by intermittent renewable energy sources. While green hydrogen is widely regarded as the most sustainable solution, its cost competitiveness is hindered by the high CAPEX of electrolyzers and the volatility of renewable electricity supply. Future developments in system integration, smart grid integration, and improved electrolyzer durability are essential to reduce the LCOH and enhance grid stability (Münster et al., 2024). Distributed hydrogen production systems offer opportunities for local energy resilience, especially in remote or off-grid communities. However, current research shows a gap between academic focus and commercial-scale implementation. Decentralized systems face hurdles in cost efficiency, infrastructure compatibility, and standardization, all of which require interdisciplinary research and practical demonstration projects (Handique et al., 2024). Another critical issue is public engagement and social license to operate. Studies reveal a disconnect between how the industry perceives community concerns and the actual values held by the public. Industry stakeholders tend to focus on technical risks, while communities emphasize moral and environmental accountability. To bridge this gap, future research must adopt inclusive and participatory approaches such as co-design and stakeholder mapping to foster trust and informed decision-making (Beasy et al., 2023). Infrastructure challenges are also a major concern. Large-scale deployment of hydrogen will depend on advances in storage and distribution, particularly in addressing issues like pipeline compatibility, hydrogen embrittlement, and long-duration energy storage. Research on geological hydrogen storage such as in depleted natural gas reservoirs, is expanding but still requires validation under real-world conditions (Muhammed et al., 2023). Finally, the absence of harmonized regulatory frameworks and carbon intensity standards across countries creates uncertainty for investors and project developers. Future research should support the development of global certification schemes for low-carbon hydrogen and enable cross-border market mechanisms (Włodarczyk and Kaleja, 2023).

Nomenclature

H_2 – hydrogen
CO_2 – carbon dioxide

SMR – steam methane reforming
LCOH – levelized cost of hydrogen
CCUS – carbon capture utilization and storage
CH_4 – methane
TRL – technology readiness level

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