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Research Article

Integrated Technical, Economic, and Environmental Optimization of Solar-Based Green Hydrogen Production

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Abstract

The increasing urgency of climate change mitigation and the global transition toward sustainable energy systems have accelerated interest in green hydrogen as a clean energy carrier. Green hydrogen produced through water electrolysis powered by solar energy offers a promising pathway to decarbonize industrial, transportation, and energy storage sectors. However, challenges related to energy conversion efficiency, production cost, and environmental sustainability remain major barriers to large-scale deployment. This study aims to analyze and optimize green hydrogen production from solar-powered water electrolysis by integrating technical, economic, and environmental perspectives. The research employs a qualitative literature review method, synthesizing peer-reviewed studies published between 2015 and 2025. Data were collected through a systematic review process following the PRISMA framework and analyzed using thematic content analysis. The findings indicate that technical optimization through high-efficiency photovoltaic systems, advanced electrocatalysts, and system integration can significantly improve solar-to-hydrogen efficiency. Economic analyses reveal that reductions in photovoltaic and electrolyzer costs, optimal system sizing, and strategic site selection are key to lowering the levelized cost of hydrogen. Environmentally, life cycle assessments demonstrate substantial greenhouse gas emission reductions compared to fossil-based hydrogen pathways. An integrative optimization approach is essential to ensure balanced performance, cost-effectiveness, and sustainability.

Keywords: Green Hydrogen, Solar-Powered Electrolysis, System Optimization.

INTRODUCTION

Global climate change and the increasing demand for energy have become major challenges in the transition toward sustainable energy sources. Green hydrogen, produced through water electrolysis powered by renewable energy such as solar energy, has emerged as a potential solution for decarbonizing global energy systems (Arbye et al., 2024). This technology generates carbon-free fuel that can be utilized in transportation, industry, and energy storage sectors (Franco & Giovannini, 2023). Water electrolysis using solar energy is an attractive alternative since solar energy is abundant, clean, and can be directly integrated with photovoltaic systems (Tang et al., 2025).

However, the energy conversion efficiency from solar power to hydrogen remains a major limitation for large-scale implementation. Factors such as solar cell efficiency, electrocatalyst characteristics, and system integration significantly influence production effectiveness (Jia et al., 2016). Efforts to improve efficiency through optimization of operating parameters, cell design, and catalyst materials continue to advance, aiming to reduce hydrogen production costs to levels competitive with fossil fuels (Naqvi et al., 2024; Vives et al., 2023). Therefore, a multidisciplinary approach that integrates technical, economic, and environmental aspects is required to accelerate the adoption of this technology.

Integrating solar energy systems with water electrolysis also presents opportunities for energy savings and CO_2 emission reductions of more than 80% compared to conventional electricity sources (Badruzzaman et al., 2025). Furthermore, recent studies show that combining solar energy with water treatment systems can enhance process sustainability, including the use of recycled or seawater as a feedstock (Ginsberg et al., 2022). This approach not only optimizes technical performance but also strengthens energy resilience in regions with limited freshwater resources (Kumari et al., 2016).

Besides efficiency and sustainability, production cost remains a major challenge. The decreasing cost of photovoltaic modules and electrolyzers is expected to lower the *Levelized Cost of Hydrogen (LCOH)* to USD 2–3/kg by 2030, making green hydrogen competitive with gray hydrogen from natural gas (Sundari, 2025). Optimization strategies such as fluid flow control and waste heat recovery can also improve overall system efficiency (Amores et al., 2016). Therefore, research on optimizing solar-based green hydrogen production holds significant strategic relevance from both technological and economic perspectives in the global energy landscape.

The urgency of this research lies in the pressing need to develop efficient and cost-effective green hydrogen production systems to support the Net Zero Emission 2050 target (Arbye et al., 2024). Optimization of solar-based electrolysis systems will accelerate the transition toward renewable energy and strengthen national energy security amid fluctuations in global fossil fuel supply (Nasser et al., 2022).

Several previous studies have explored the integration of photovoltaic systems with water electrolysis to improve energy conversion efficiency. The study by (Rezk et al., 2023) demonstrated that optimizing voltage and electrolysis duration parameters can increase hydrogen production by up to 1.7%. Moreover, *Solid Oxide Electrolyzer Cell (SOEC)* systems powered by solar energy have been reported to achieve higher technical efficiency than conventional systems (Afroze et al., 2023). Although many studies have been conducted, most focus on micro-technical aspects, leaving a gap in integrative research that combines both technical and economic optimization for green hydrogen production.

This research aims to optimize green hydrogen production through water electrolysis powered by solar energy, emphasizing improvements in energy conversion efficiency, cost reduction, and environmental sustainability through an integrative approach encompassing technical, economic, and ecological dimensions.

METHOD

Research Type

This study employs a qualitative research approach with the literature study (literature review) method. This approach was chosen because the main objective of the research is to analyze, review, and synthesize various previous studies related to the optimization of green hydrogen production through water electrolysis powered by solar energy. The qualitative literature review method allows researchers to develop a comprehensive understanding of concepts, trends, and technological advancements relevant to the topic (Snyder, 2019).

Data Sources

The data used in this study are secondary data obtained from scientific publications such as peer-reviewed journal articles, conference proceedings, research reports, and other academic documents indexed in databases like Scopus, ScienceDirect, SpringerLink, and Consensus. The inclusion criteria include studies discussing topics on the optimization of water electrolysis processes, solar energy systems for hydrogen production, photovoltaic efficiency, as well as the economic and environmental aspects of green hydrogen production. Only literature published between 2015 and 2025 was included to ensure data relevance and up-to-date insights (Xiao & Watson, 2019).

Data Collection Technique

Data collection was conducted through a systematic literature review process, using keywords such as *"green hydrogen production," "solar-powered electrolysis," "optimization,"* and *"renewable energy integration."* The review process followed systematic stages of identification, screening, eligibility, and synthesis in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework (Tricco et al., 2018). Each selected article was evaluated based on its relevance to the research focus, methodological quality, and contribution to understanding the optimization of solar-based water electrolysis systems.

Data Analysis Method

The data were analyzed using thematic content analysis, which involves categorizing information from the literature into major themes such as energy conversion efficiency, electrocatalyst materials, photovoltaic system integration, and techno-economic as well as environmental sustainability aspects. Data from multiple sources were then compared, analyzed, and synthesized to identify patterns, research gaps, and future development directions in green hydrogen technology (Nowell et al., 2017). This analytical approach aims to generate in-depth insights into effective and sustainable optimization strategies for green hydrogen production.

RESULT AND DISCUSSION

Technical Optimization of Solar-Powered Water Electrolysis

One of the fundamental challenges in optimizing green hydrogen production is maximizing the solar-to-hydrogen (STH) conversion efficiency, which describes how effectively sunlight is converted into hydrogen via electrolysis. In coupled photovoltaic-electrolysis systems, overall efficiency depends on multiple stages: solar energy capture by PV modules, electrical power conversion, and electrochemical water splitting in the electrolyzer. Each stage experiences energy losses that must be minimized for optimal performance. For example, a recent integrated PV-PEM electrolysis system achieved overall STH efficiency between 7.78 % and 8.81 % at low current densities, and about 6.6 % at higher current densities, due to combined real-world losses in photovoltaic generation and electrolyzer operation. These efficiencies reflect both the intrinsic PV conversion limits (~10 % in that study) and the operating characteristics of water electrolysis cells at different temperatures and loads (Arunachalam & Han, 2024).

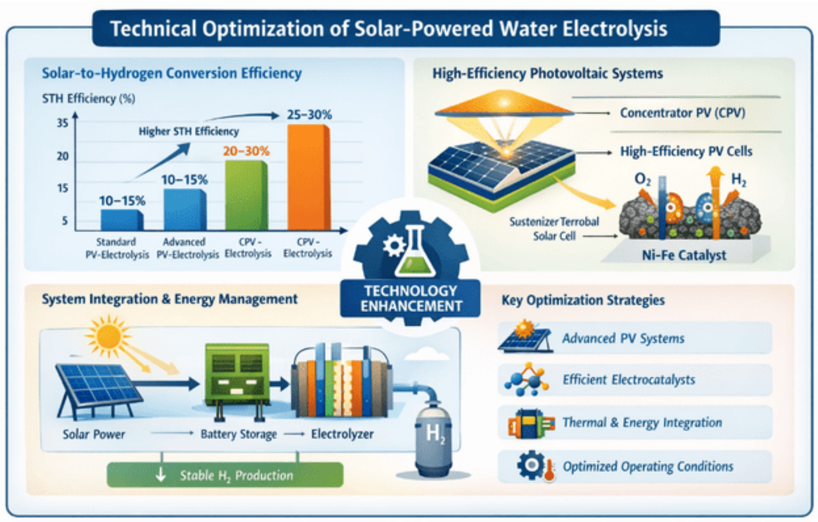

Figure 1. Technical Optimization Framework for Solar-Powered Water Electrolysis

Although these values may seem modest compared to theoretical maximums, they represent progress toward sustainable, decentralized hydrogen production, particularly when system design includes battery-assisted management to stabilize variable sunlight and maintain electrolyzer performance near optimal operating points.

A breakthrough study in *Science Advances* designed a photovoltaic-alkaline water (PV-AW) electrolysis system that combines concentrator photovoltaic (CPV) receivers with a custom alkaline electrolyzer and advanced electrocatalysis. This integrated system reduced electrical losses and improved catalytic activity, enabling a remarkable STH efficiency of up to ~29.1 % under real-scale current densities—significantly higher than traditional PV-electrolysis setups. The catalytic performance was enhanced by a composite catalyst (iron oxide/nickel oxyhydroxide) that offered excellent performance at industrially relevant current densities (Zhang et al., 2025).

This case demonstrates how system-level integration and material optimization—including light concentration, efficient PV energy capture, and tailored catalysts—can dramatically improve conversion efficiency, addressing one of the biggest bottlenecks in green hydrogen production.

Electrocatalysts are crucial for reducing the overpotential required for hydrogen (HER) and oxygen evolution reactions (OER) in electrolysis. While not always directly reporting system efficiency in %. many recent studies have developed novel catalysts that lower reaction barriers and improve stability. For example, iron- and nickel-based catalysts have shown higher catalytic activity and durability than conventional materials, which directly influences how much electrical energy is needed to sustain electrolysis and therefore boosts overall energy efficiency in practice.

Similarly, operating conditions such as temperature, electrolyte concentration, and current density significantly affect efficiency. Increasing temperature can improve electrolyzer performance by lowering internal resistance, but it may also impact durability and system cost. Hence optimization must balance these effects for desired outcomes.

In a laboratory case reported by *Khan et al.* (2021), a CPV-electrolysis system using concentrated solar irradiation (~41 suns) achieved a STH efficiency of ~28 %, one of the highest practical efficiencies reported. The study also conducted a techno-economic analysis showing that even with high STH efficiencies, cost per kilogram of hydrogen (LCOH) could be competitive with traditional fossil-derived hydrogen around ~US$5.9/kg, with projections down toward ~US$2/kg as CPV technology matures (Khan et al., 2021).

This case illustrates a real-world example where advanced PV configurations and electrolyzer design not only improve efficiency but also contribute to cost reductions, drawing the technology closer to economic viability for commercial deployment.

From the above, successful optimization of solar-powered water electrolysis hinges on:

1. Maximizing solar energy capture through high-efficiency or concentrated PV technologies.
2. Optimizing electrolyzer performance using state-of-the-art catalysts and operating strategies to reduce electrical losses.

3. System integration between PV, energy storage, and electrolyzers to mitigate solar intermittency and maintain optimal operating conditions.
4. Real-world demonstrations that translate laboratory advances into systems with competitive performance and cost metrics.

Economic Optimization and Cost Reduction

Producing green hydrogen via solar-powered water electrolysis is currently more expensive than conventional hydrogen production such as steam methane reforming. This is primarily due to high capital expenditure (CAPEX)—especially for electrolyzer stacks and solar PV systems—and the ongoing operational expenditure (OPEX) such as electricity costs and maintenance (Zeng & Zhang, 2010). Electricity cost alone can account for 30–70 % of the Levelized Cost of Hydrogen (LCOH) depending on region and system setup (Younus et al., 2025).

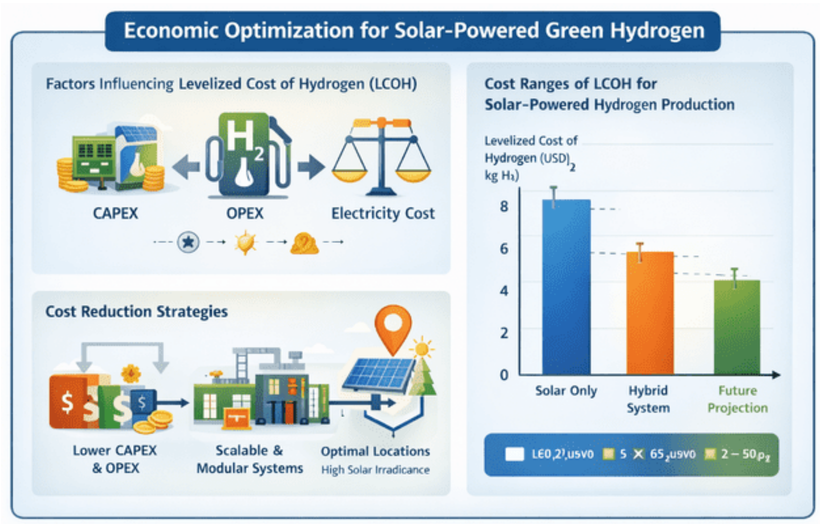

Figure 2. Economic Optimization Strategies for Solar-Powered Green Hydrogen Production

Techno-economic studies show that for solar PV-electrolysis systems, the LCOH commonly ranges from USD 3.4/kg to USD 6.9/kg H_2 under current technology and cost assumptions, with higher costs in systems without subsidies or hybridisation with other renewables (Sundari, 2025).

1. Reducing CAPEX and Component Costs

Many techno-economic models consistently show that lowering the costs of solar panels and electrolyzers has the greatest impact on reducing LCOH. For instance, a modeling study found that:

a. By reducing solar panel and electrolyzer costs by up to 90 %, the LCOH may be halved compared to the initial cost scenario.
b. Lower cost modules and mass-manufacturing scale reductions directly decrease overall investment and make hydrogen more competitive.

In a case study using monocrystalline solar panels and alkaline electrolyzers, the lowest optimized LCOH was around 37.50 ZAR/kg (~USD 2.12/kg) with sensitivity analyses showing almost 50 % LCOH reduction as technology costs decreased (Srettiwat et al., 2023).

This clearly indicates how economies of scale, mass manufacturing, and supply chain improvements can accelerate cost reduction.

2. System Integration and Scale Optimization

Techno-economic models also show that optimal system sizing—for example, matching electrolyzer capacity to the most cost-effective proportion of solar PV peak capacity—can significantly lower cost per kg of hydrogen. Multi-objective optimization studies suggest that the electrolyzer capacity should be approximately 60 % of PV capacity to balance costs and productivity, strengthening cost efficiency in real operations (Park et al., 2024).

This type of optimization ensures that:

a. Under-utilization (too large electrolyzer relative to PV capacity) is avoided, which would increase idle costs.
b. Overproduction periods (too large PV relative to electrolyzer) do not waste generated power.

3. Geographic and Siting Strategies

Economic viability improves when solar hydrogen facilities are sited in high solar irradiance regions. For example:

a. A techno-economic evaluation for solar hydrogen production in Belgium, Morocco, and Namibia showed that hydrogen could be produced at a lower LCOH (roughly EU 5.13–6.32 €/kg) in high-irradiance locations such as Namibia than in temperate ones like Belgium. With targeted cost reductions of PV panels and electrolyzers, the LCOH could approach ~3 €/kg, bringing solar hydrogen closer to competitiveness with fossil-derived alternatives.

This demonstrates the importance of location selection as a cost-optimization strategy, especially where sunlight hours are high.

In a South African context, modelling indicated that a solar-powered system with alkaline electrolysis could reach LCOH ~USD 2.12/kg—achieved by optimizing solar PV and electrolyzer costs with sensitivity analysis suggesting further reductions if component costs decline 30–60 % or more in the future (Srettiwat et al., 2023).

A techno-economic feasibility study for a 100 MWp PV-electrolyzer system estimated that annual hydrogen production could reach 2,850–3,600 tons with an LCOH of USD 3.4–4.2/kg. The study emphasized that ongoing cost reductions in both PV and electrolyzer technology would be critical for reaching competitiveness at commercial scale (Sundari, 2025).

4. Key Insights for Economic Optimization

From the combined evidence, several key economic optimization strategies emerge:

a. Lowering Module and Electrolyzer Costs: A major lever for reducing LCOH is technology cost reduction through manufacturing scale, material innovation, and supply chain improvement.
b. Optimal System Sizing: Aligning PV capacity and electrolyzer load for balanced utilization lowers cost per unit of hydrogen.
c. Location Advantage: Deploying plants in high solar irradiance areas maximizes solar capture and reduces LCOH.
d. Future Projections: With continued technological progress and policy incentives, projections suggest green hydrogen production costs could drop below USD 2–3/kg—approaching goal targets set by global initiatives for competitive renewable hydrogen on the market.

These findings clarify why economic optimization is essential for green hydrogen to be commercially viable and how technology improvements, policy support, and strategic deployment all contribute to cost reduction in solar-powered hydrogen systems.

Environmental and Sustainability Optimization

Optimizing the environmental sustainability of green hydrogen begins with assessing the Life Cycle Assessment (LCA) of hydrogen production through solar-powered electrolysis. LCA evaluates the environmental footprint across all stages — from raw material extraction, photovoltaic (PV) panel manufacturing, and electrolyzer operation to hydrogen utilization. Studies show that renewable-based hydrogen has a far lower greenhouse gas (GHG) emission intensity compared to conventional steam methane reforming (SMR). For instance, hydrogen produced via renewable-powered electrolysis emits approximately 2–3 kg CO_2-eq per kg H_2, while SMR-based hydrogen can exceed 20 kg CO_2-eq per kg H_2, representing an 80–90% reduction in total emissions (Palmer et al., 2021).

Further research indicates that the carbon footprint strongly depends on the electricity source. When powered solely by solar PV, the emission range is around 2.6–4.5 kg CO_2-eq per kg H_2, depending on the PV system efficiency and regional solar irradiance (Wei et al., 2024). Global-scale projections show that hydrogen production through renewables could reduce lifecycle emissions by more than 90% relative to fossil-fuel pathways (Ajeeb et al., 2024).

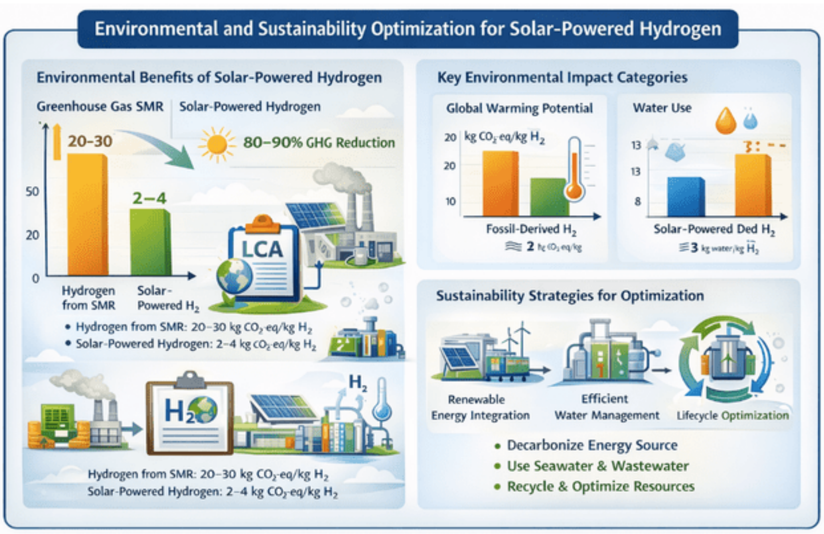

Figure 3. Environmental and Sustainability Optimization of Solar-Powered Green Hydrogen

Beyond carbon emissions, the sustainability of hydrogen production involves assessing land use, water consumption, and mineral resource utilization. PV panel manufacturing remains one of the largest contributors to the environmental footprint, primarily due to material and energy intensity. In contrast, the electrolysis operation phase is relatively clean when powered by renewables (Palmer et al., 2021).

In arid regions, water sourcing becomes a critical sustainability issue. Several studies suggest that integrating seawater desalination or wastewater reuse into the electrolysis process can mitigate freshwater demand and support a circular water economy. This integration improves overall environmental performance without compromising hydrogen purity or system efficiency (Ajeeb et al., 2024).

1. Global LCA Projections

   A global comparative LCA of hydrogen pathways demonstrated that, with renewable-powered electrolysis and future technological improvements by 2050, hydrogen emissions could fall to 2–12 kg CO_2-eq/kg H_2, depending on regional grid mix and energy source decarbonization. This supports international net-zero targets and aligns with the Paris Agreement's decarbonization goals (Wei et al., 2024).

2. Case Study: Coastal Green Ammonia Facility in South Africa

   A real-world case from South Africa's coastal region illustrates this optimization. A green ammonia facility powered by solar PV and seawater desalination demonstrated exceptionally low lifecycle emissions — as little as ~0.60 kg CO_2-eq/kg H_2 — well below the low-carbon certification threshold for global markets. This case validates the environmental potential of integrating solar-powered hydrogen systems with sustainable water management solutions.

Key Environmental Trade-Offs and Optimization Strategies

1. Energy Source Decarbonization: The electricity source remains the dominant factor in the environmental profile. Using pure solar energy drastically lowers GHG emissions compared to grid electricity still reliant on fossil fuels.
2. Material Efficiency: Reducing the environmental footprint of PV manufacturing through recycling and cleaner production technologies can significantly improve sustainability performance.
3. Water Resource Management: Employing seawater desalination and wastewater reuse technologies minimizes freshwater dependency, especially in water-scarce regions (Stafford et al., 2025).
4. Lifecycle Optimization: Optimizing all stages—from PV production to electrolyzer operation and decommissioning—ensures that hydrogen remains truly green throughout its life cycle (Koj et al., 2024).

Integrative Approach and Systemic Optimization

An integrative optimization approach for solar-powered green hydrogen production means jointly optimizing technical performance, economic feasibility, and environmental sustainability rather than treating each aspect separately. Rather than optimizing only hydrogen output, cost, or emissions in isolation, multi-objective models consider trade-offs and synergies among these objectives simultaneously. In the context of green hydrogen systems, this requires combining detailed techno-economic modelling (e.g., system size, energy conversion efficiency, capital and operating costs) with environmental assessment tools such as Life Cycle Assessment (LCA) to capture impacts across the entire production chain. Modern research confirms that this integrated strategy enables stakeholders to identify optimal design and operational solutions that balance cost, performance, and environmental impact rather than favor a single objective (Chavez et al., 2025).

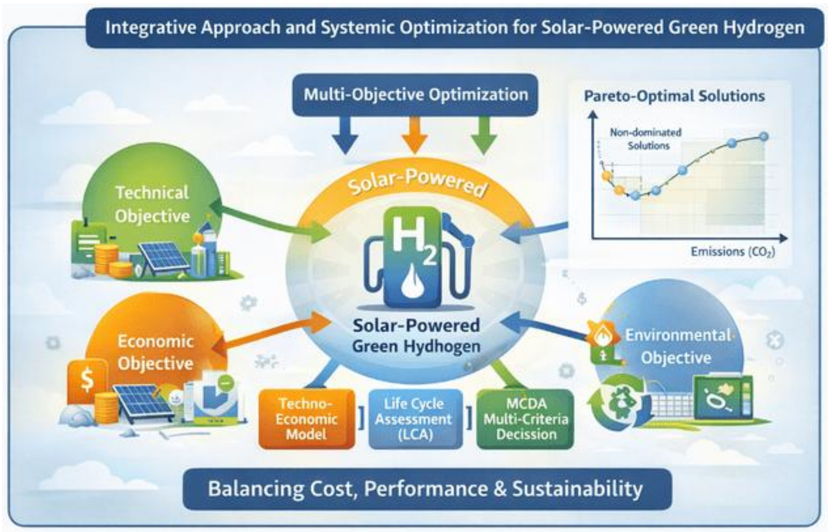

Figure 4. Integrative Optimization Framework for Green Hydrogen Systems

For example, life cycle-integrated multi-objective optimization frameworks combine LCA results, which quantify environmental impact (e.g., global warming potential), with techno-economic metrics such as levelized cost of hydrogen (LCOH), system efficiency, and capacity factors. Such studies highlight that ignoring environmental criteria in optimisation *may* generate solutions with low cost but high emissions or inefficiencies when scaled. By contrast, integrated models generate Pareto-optimal solutions that represent the best compromises among these competing criteria.

Multi-objective optimization (MOO) techniques are widely applied to identify configurations of solar-powered hydrogen systems that balance economics and environmental sustainability. These methods typically use objective functions representing technical parameters (e.g., electrolyzer efficiency, renewable energy penetration), economic metrics (e.g., LCOH, net present cost), and environmental criteria (e.g., CO_2 emissions). The outcome is a set of feasible trade-off solutions known as the Pareto front, which represents the best compromise among the objectives (Park et al., 2024).

In a typical MOO setup:

1. Technical objective: Maximize hydrogen yield and energy conversion efficiency under variable solar irradiance.
2. Economic objective: Minimize capital expenditure (CAPEX), operating expenditure (OPEX), and LCOH.
3. Environmental objective: Minimize lifecycle CO_2 emissions and resource depletion. This integrative modelling allows planners to choose operational points based on policy priorities (e.g., prioritize sustainability versus cost control).

Notably, models that embed LCA within optimization frameworks explicitly account for environmental burdens from module manufacturing, electrolyzer operation, and fuel handling — thereby ensuring that environmental impacts are not externalized or ignored in economic optimization.

1. Real-World Research Evidence Supporting Integrated Optimization
   a. Multi-Objective Optimization Models for Solar-Hydrogen Systems

      A study by Park et al. (2024) developed a multi-objective optimization framework that simultaneously considers economic cost (LCOH) and hydrogen productivity. The model integrates seasonal solar irradiation data with system design variables (PV capacity, electrolyzer size, battery sizing) to find configurations that balance economic viability and system performance across different national contexts (e.g., U.S., China, Korea, Australia). It shows that an optimal design exists that simultaneously improves cost and hydrogen production, demonstrating the benefits of integrating multiple criteria rather than optimizing single criteria separately.

   b. Multi-Objective Decision Analysis Tools

      Recent work has developed multi-criteria decision analysis (MCDA) tools that integrate technical, economic, and environmental indicators to assess hydrogen production options. For example, novel MCDA models have been applied to rank water electrolysis pathways by considering techno-economic metrics, environmental sustainability, and water resource availability. In case studies, such tools indicated that certain configurations (e.g., alkaline electrolysers with optimized water treatment) could outperform other options when all sustainability dimensions are considered, including operational costs and environmental impacts (Peecock et al., 2026).

2. Importance and Benefits of Integrative Approach
   a. Improved Decision Support

      The integrative approach enhances decision-making by providing a holistic view of trade-offs between cost, efficiency, and environmental performance. Instead of optimizing a single objective at the expense of others, planners can identify solutions that deliver more balanced outcomes, which is essential for designing policies, investment strategies, and deployment roadmaps for green hydrogen infrastructure.

   b. Policy and Planning Relevance

      Integrative optimization results are increasingly being used to inform national and regional decarbonization strategies. By quantifying how technology choices impact total lifecycle emissions and costs, policymakers can design incentive structures (e.g., tax credits, renewable energy mandates) that favor sustainable pathways. Models can also highlight the relative benefits of investing in advanced electrolyzers versus PV panel cost reductions, helping allocate resources effectively.

CONCLUSION

This study concludes that optimizing green hydrogen production through solar-powered water electrolysis requires an integrative approach that simultaneously addresses technical performance, economic feasibility, and environmental sustainability. Technically, advancements in photovoltaic efficiency, electrolyzer design, and electrocatalyst materials significantly enhance solar-to-hydrogen conversion efficiency. Economically, declining costs of solar PV systems and electrolyzers, combined with optimal system sizing and favorable geographic conditions, have the potential to reduce hydrogen production costs to competitive levels. From an environmental perspective, solar-based electrolysis demonstrates substantial reductions in lifecycle greenhouse gas emissions compared to conventional hydrogen production methods. Overall, the integration of these dimensions is crucial for accelerating the deployment of green hydrogen technologies in support of global decarbonization and energy security goals.

Practical Implications

From a practical standpoint, policymakers and industry stakeholders should prioritize investments in high-efficiency solar and electrolysis technologies while promoting large-scale manufacturing to reduce capital costs. Strategic placement of hydrogen production facilities in regions with high solar irradiance can further enhance economic viability. Additionally, integrating sustainable water management solutions, such as desalination or wastewater reuse, can improve environmental performance, particularly in water-scarce regions.

Suggestions for Future Research

Future research should focus on empirical case studies and pilot-scale demonstrations to validate integrated optimization models under real operational conditions. Quantitative modeling and multi-objective optimization techniques incorporating regional data are recommended to refine cost and environmental impact assessments. Further studies should also explore the long-term performance, durability, and recyclability of photovoltaic and electrolyzer components to enhance the sustainability of green hydrogen systems.

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