Solar versus Electrolysis Methods for Green Hydrogen Production: A Meta-Analysis of Efficiency, Yield, and Cost Performance

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Abstract—

The global transition to sustainable energy systems has accelerated interest in green hydrogen production, with solar and electrolysis methods emerging as leading technological pathways. However, systematic comparative evidence across multiple performance dimensions remains limited, creating challenges for evidence-based technology selection decisions.

This study aims to compare the effectiveness of solar and electrolysis methods for green hydrogen generation through systematic review and meta-analysis, examining efficiency, hydrogen yield, and levelized cost of hydrogen (LCOH) across recent scientific literature.

A comprehensive literature search was conducted across multiple databases (Web of Science, Scopus, PubMed, IEEE Xplore, ScienceDirect) for studies published from 2015-2025. Data were extracted and standardized using established conversion factors for efficiency (%), hydrogen yield (kg/day), and cost (USD/kg). Statistical analyses used Mann-Whitney U tests due to assumption violations, with effect sizes calculated using Cohen's conventions.

Forty-seven studies met the inclusion criteria, providing 8-20 studies per outcome measure. Electrolysis methods demonstrated significantly higher efficiency (55.8% vs 19.4%, $p = 0.001$, large effect $r = 0.62$) and more consistent, lower costs ($5.09 vs $8.03/kg, $p < 0.10$, medium effect $r = 0.335$). No statistically significant difference was found in hydrogen yield despite solar methods showing 14.72 times higher geometric mean, indicating that deployment scale influences yield more than technology choice.

Electrolysis methods currently offer superior consistency and commercial readiness, while solar approaches show potential for breakthrough performance under optimal conditions. The findings suggest that diversified technology portfolios may optimize adoption of green hydrogen across countries, with technology selection depending on specific application requirements, risk tolerance, and local conditions rather than technological superiority.

Keywords— Green hydrogen production, Meta-analysis, Electrolysis technologies, Solar hydrogen systems, Renewable energy comparison.

I. INTRODUCTION

The global green hydrogen market has experienced unprecedented growth, with production capacity reaching 0.3 million tons annually in 2022 and projections indicating expansion to 38 million tons by 2030 (International Energy Agency, 2023). Leading developed economies have established ambitious targets: Germany aims for 5 GW electrolyzer capacity by 2030, Japan targets 3 million tons of hydrogen imports annually, and Australia plans 1.7 GW of renewable hydrogen projects, while developing nations including India (5 million tons production target), Brazil (18 GW planned capacity), and South Africa (500 MW electrolyzer installations) are rapidly scaling their hydrogen capabilities (Hydrogen Council, 2024).

The factors affecting green hydrogen production effectiveness vary significantly across technological approaches, with numerous studies demonstrating diverse performance characteristics. Solar-based hydrogen generation studies by Ahmad et al. (2025) and Li et al. (2023) have examined photoelectrochemical and photovoltaic-electrolysis systems showing efficiency ranges of 4-35%, while electrolysis research by Kumar (2024), Shaban (2024), and Muhammad et al. (2025) has investigated alkaline, PEM, and solid oxide technologies demonstrating 60-95% conversion efficiencies. Cost effectiveness studies across different regions have revealed varying economic performance, with Vartiainen et al. (2022) reporting European costs of €1.0-2.7/kg, Abdelsalam (2024) finding Middle Eastern costs of $6.78/kg, and Selvam (2025) documenting global ranges of $3.2-7.1/kg for different technological configurations.

Meta-analysis is a systematic quantitative synthesis methodology that enables strong statistical comparison of heterogeneous research findings by standardizing diverse experimental conditions, measurement protocols, and outcome reporting formats. This approach can be used to overcome the limitations of individual studies and provide evidence-based insights into the relative effectiveness of competing technologies.

There is extensive existing research on the performance drivers and factors affecting the effectiveness of green hydrogen production over recent years across different countries, but limited research exists in comparing the systematic performance differences between solar and electrolysis methods. Most studies have focused on individual technologies or specific applications within single geographic contexts, creating knowledge gaps in comparative technology assessment. Recent changes in materials science, system integration approaches, and manufacturing scale economies have led to significant shifts in the relative performance patterns of solar and electrolysis hydrogen production technologies.

A systematic comparative study can help emerging economies such as India, Brazil, and South Africa make informed technology selection decisions for their national hydrogen strategies, thereby contributing to accelerated clean energy transition and economic development through optimal resource allocation toward the most effective technological pathways.

It is essential to understand how various performance factors impact hydrogen production effectiveness across different technological approaches in comparison to established benchmarks, enabling governments, policy advisors, and organizations working toward clean energy deployment to understand technological similarities and dissimilarities for informed policy decisions. It is equally important to study the evolving performance characteristics and changing technological advantages as both solar and electrolysis methods undergo rapid development. To the best of the researcher's knowledge, there is very limited research that systematically compares the effectiveness of solar hydrogen production methods with electrolysis approaches using standardized meta-analytical techniques.

Therefore, this study aims to investigate the factors affecting green hydrogen production effectiveness and the extent to which different technological approaches demonstrate superior performance, comparing solar and electrolysis methods for recent technological developments through comprehensive meta-analysis.

More specifically, the study addresses the following research questions:

- RQ1: What are the comparative efficiency levels between solar and electrolysis methods for green hydrogen production?
- RQ2: To what extent do hydrogen yield capacities differ between solar and electrolysis technological approaches?
- RQ3: What are the differences in levelized cost of hydrogen (LCOH) between solar and electrolysis methods across different studies and contexts?

The paper is organized as follows. The next section deals with an in-depth literature review of green hydrogen production technologies and their comparative assessment worldwide. The next section discusses the research methodology adopted for systematic review and meta-analysis. This is followed by the findings of the statistical analysis conducted using data from 47 studies across solar and electrolysis methods. The conclusions from the findings are presented next. Finally, the discussion section discusses the practical inferences of the study, limitations and further scope for research..

II. LITERATURE REVIEW

2.1 Green Hydrogen:

Green hydrogen has become an essential part of the world energy transition as hydrogen made by electrolysis from renewable energy sources, with little or no carbon emissions (Chiroșcă et al., 2024). The term was initially officially coined by the National Renewable Energy Laboratory, which applied renewable hydrogen as a synonym for green hydrogen production from renewable sources (NREL, 1995). The International Renewable Energy Agency (IRENA, 2019) considers green hydrogen a near-zero carbon production path employing renewable electricity for water electrolysis, separating it from gray hydrogen from fossil fuels and blue hydrogen with the help of carbon capture technologies.

The rationale behind the development of green hydrogen is based on several reasons. According to Gondal et al. (2018), hydrogen can be a good alternative to fossil fuels because of political, economic, and ecological benefits, whereas Kakoulaki et al. (2021) demonstrate that the technical potential of renewable energy sources such as wind, solar, and hydro is adequate to supply present electricity demand and extra demand for the production of green hydrogen. This abundance of renewable materials places green hydrogen as a scalable response to energy security needs as well as climate mitigation goals (Raman et al., 2022).

The strategic relevance of hydrogen towards deep decarbonization has been underscored by several researchers. Parra et al. (2019) and Maestre et al. (2021) emphasize how hydrogen has the potential to be an integral component of holistic hybrid renewable energy systems, allowing for higher system integration and robustness. The "Hydrogen Economy" idea has undergone revived interest, fueled by international sustainability needs, decreasing costs of renewables, and fast technological progress (Yap et al., 2023; Østergaard et al., 2020; IRENA, 2023). Bibliometric studies demonstrate exponential growth in hydrogen research during the last decade, both indicating scientific attention and policy pressure (Kar et al., 2022; Kourougianni et al., 2024).

Green hydrogen production synergizes across several Sustainable Development Goals, most importantly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), by providing energy access with reduced environmental footprint (Armaroli & Barbieri, 2021). Green hydrogen growth in the market is mainly fueled by industrial sectors that are hard to decarbonize such as steel, chemicals, transport, and energy storage applications (Oliveira et al., 2021)

2.2 Current State and Challenges:

Despite its potential, the current global hydrogen production landscape remains dominated by fossil fuel-based methods. The International Energy Agency (2023) reports that gray hydrogen production results in over 900 million tonnes of CO_2 emissions annually, representing 2.5% of global emissions. Only 0.7% of hydrogen production (approximately 1 Mt out of 95 Mt total) comes from low-emission methods, primarily blue hydrogen with carbon capture technologies. Production from water electrolysis using renewable electricity remains below 0.1 Mt annually, highlighting the significant scale-up challenge ahead (IEA, 2023).

Investment trends indicate growing recognition of hydrogen's strategic importance. Hydrogen technologies represented approximately 5% of global clean energy research and development budgets in 2021, with public investment increasing by 35% to reach $1.3 billion USD (IEA, 2022). By 2022, this research area had grown to 7.5% of clean energy technology budgets, which is an indication of accelerating policy support and commercial interest (IEA, 2023). These investments have made Green Hydrogen Energy Systems central elements in sustainable energy and climate mitigation strategies (Kourougianni et al., 2024).

However, significant technical and economic challenges persist. Dincer and Acar (2015) note that green hydrogen technologies are not readily accessible with reasonable effectiveness and cost, citing studies showing photovoltaic electrolysis costs exceeding $5/kg for hydrogen with energy efficiencies below 5%. Nevertheless, technological improvements and declining renewable energy costs are steadily reducing production costs (Islam et al., 2024; Reda et al., 2024).

The technological maturity varies significantly across different green hydrogen production approaches. While some electrolysis technologies have reached commercial deployment, many solar-based hydrogen production methods remain at laboratory or pilot scales, creating disparities in performance validation and cost assessment (Chiroșcă et al., 2024).

2.3 Green Hydrogen Production Technologies:

2.3.1 Electrolysis Technologies:

Water electrolysis is the most mature approach for green hydrogen production, using electricity to split water molecules into hydrogen and oxygen (IEA, 2019). Three primary electrolysis technologies have emerged as leading candidates for commercial deployment.

Alkaline Electrolysis (AEL) is the most mature electrolysis technology, using liquid alkaline electrolytes, typically potassium hydroxide (KOH), operating at temperatures between 60-80°C (Schmidt et al., 2017). Alkaline systems benefit from lower material costs due to the absence of noble metal catalyst requirements, using stainless steel electrodes instead (Buttler & Spliethoff, 2018). The technology operates at current densities ranging from 100-300 mA/cm² with single cell voltages of 1.7-

1.8 V, and can achieve lifespans exceeding 100,000 hours with appropriate maintenance (Domenech et al., 2021). Current investment expenses range from 500-1000 €/kW with operation and upkeep costs of 2-6% annually.

Proton Exchange Membrane Electrolysis (PEME) uses solid polymer electrolytes with high proton conductivity, enabling higher current densities around 1,000 mA/cm² and rapid response to power fluctuations in the millisecond range (Schmidt et al., 2017). This technology features high modularity and compactness through zero-gap architecture and Membrane-Electrode Assembly (MEA) design, making it suitable for coupling with variable renewable electricity sources (Buttler & Spliethoff, 2018). However, PEME systems require expensive noble metal catalysts (platinum, iridium) and have higher stack costs, with investment costs ranging from 600-1300 €/kW and operation and maintenance costs of 3-5% annually (Domenech et al., 2021).

Solid Oxide Electrolysis (SOEC) operates at high temperatures (500-850°C) using solid ceramic electrolytes, typically yttria-stabilized zirconia, achieving higher electrical efficiencies through combined heat and electricity utilization (Bhandari et al., 2014). SOEC systems can operate above 1,000 mA/cm² with single cell voltages around 1.3 V, though durability challenges remain with continuous operation limited to approximately 10,000 hours due to thermal cycling effects (Domenech et al., 2021). The technology remains at early development stages with higher investment costs estimated above 2000 €/kW.

2.3.2 Solar-Based Hydrogen Production:

Solar hydrogen production covers multiple technological approaches that directly use solar energy for hydrogen generation. The historical development of solar hydrogen research traces back to early work by Lodhi (1987) on high-temperature water dissociation, thermochemical water splitting, and photolysis processes. Later classifications by Lodhi (2004) identified solar, sea/ocean, hydro, wind, and nuclear energy as primary green sources for hydrogen production, with potential feedstocks including fresh water, seawater, hydrogen sulfide, and biomass (Dincer & Acar, 2015).

Solar hydrogen production methods can be categorized based on their primary energy conversion mechanism and feedstock requirements. These approaches include photoelectrochemical water splitting, concentrated solar power thermochemical processes, photovoltaic-powered electrolysis systems, and biomimetic artificial photosynthesis techniques (Miltner et al., 2010; Alstrum-Acevedo et al., 2005). Each approach has distinct advantages in terms of direct solar energy utilization and unique challenges related to efficiency, scalability, and cost-effectiveness.

2.4 Comparative Studies and Performance Assessment:

Limited systematic comparative analysis exists between solar and electrolysis methods for green hydrogen production, despite the importance of such comparisons for technology selection and policy development. Most existing studies focus on individual technologies or specific applications within single geographic contexts, creating knowledge gaps in cross-technology performance assessment.

Studies examining photovoltaic electrolysis systems have reported variable performance characteristics depending on system integration, scale, and operating conditions. While some research shows competitive efficiency potential, cost analyses consistently indicate challenges in achieving economic competitiveness with conventional hydrogen production methods (Dincer & Acar, 2015). The variability in reported performance metrics across different studies suggests significant influence of experimental conditions, measurement methodologies, and system boundaries on comparative assessments.

Electrolysis technologies benefit from more extensive commercial deployment and standardized performance reporting, facilitating more consistent comparative analysis. However, differences in system integration, renewable electricity sources, and operational profiles lead to variability in real-world performance.

Lack of comparable frameworks in consideration creates challenges for evidence-based technology choice. Various studies use different definitions of efficiency, methods of calculation of costs, and boundaries of performance, making quantitative comparison between solar and electrolysis methods difficult.

2.5 Research Gaps and Meta-Analysis Motivation:

Recent research identifies a few significant gaps in comparative green hydrogen technology evaluation. In the first place, the failure to systematically quantitatively synthesize findings across studies constrains the potential to make strong conclusions regarding relative technology performance. Specific studies might be subject to certain experimental conditions, regional contexts, or methodological decisions that are not indicative of wide-scale technology potential.

Second, the dynamics of very fast technological progress in solar as well as electrolysis solutions imply that performance standards set in previous research may no longer be indicative of current performance capability. Recent breakthroughs in materials science, systems integration, and scale-up of production mean new comparative estimates reflecting latest technological advancements are needed.

Third, most studies concentrate on individual performance metrics like cost or efficiency without systematic assessment across multiple outcome measures. Large-scale technology selection calls for comprehension of efficiency-yield capacity-economic performance trade-offs, which individual studies hardly cover.

Fourth, the variability of measurement units, reporting standards, and system boundaries between studies poses difficulties in direct comparison. Standardization is required to facilitate meaningful cross-study synthesis and meta-analytical strategies.

Lastly, geographic and economic context differences profoundly impact cost-effectiveness and performance of technology, but little research considers these factors in comparative evaluations. It is vital to understand variations in performance across varying deployment contexts for guiding technology selection decisions in various global markets.

These gaps in research highlight the call for systematic review and meta-analysis methods that would integrate quantitative evidence from a variety of heterogeneous studies, harmonize different outcome measures, and yield strong statistical contrasts between solar and electrolysis approaches. These analysis processes can help guide evidence-based decisions on technology choices and highlight areas of research investment needs

III. METHODOLOGY

The research applied a systematic review and meta-analysis design in comparing the efficiency of solar and electrolysis technologies in producing green hydrogen. The study adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) to maintain methodological soundness and transparency (Page et al., 2021).

A comparative effectiveness research strategy was taken to present evidence-based advice for technology choice in green hydrogen production.

Extensive literature searching was done in several electronic databases such as Web of Science, Scopus, PubMed, IEEE Xplore, and ScienceDirect. The search term used included the following keywords and Boolean operators:

- **Hydrogen production:** ("hydrogen production" OR "hydrogen generation" OR "H2 production")
- **Solar methods:** ("solar hydrogen" OR "photoelectrochemical" OR "PEC" OR "photovoltaic electrolysis" OR "PV electrolysis" OR "solar-to-hydrogen" OR "thermochemical water splitting")
- **Electrolysis methods:** ("water electrolysis" OR "electrolyzer" OR "alkaline electrolysis" OR "PEM electrolysis" OR "solid oxide electrolysis" OR "SOEC")
- **Green hydrogen:** ("green hydrogen" OR "renewable hydrogen" OR "clean hydrogen")
- **Performance metrics:** ("efficiency" OR "yield" OR "cost" OR "LCOH" OR "levelized cost")

The search was limited to peer-reviewed journal articles, conference proceedings, and technical reports published between 2015 and 2025 to capture recent technological developments while maintaining sufficient temporal scope. No language restrictions were initially applied, though non-English articles were excluded during screening if adequate translation resources were unavailable.

3.1 Inclusion Criteria:

Studies were included if they met the following criteria:

- **Technology focus:** Investigated solar-based or electrolysis-based hydrogen production methods
- **Quantitative data:** Reported numerical values for at least one primary outcome measure (efficiency, hydrogen yield, or LCOH)
- **Study type:** Experimental studies, modeling studies, techno-economic analyses, or technology demonstrations
- **Data quality:** Provided sufficient methodological detail to assess data reliability
- **Scope:** Focused on green hydrogen production using renewable energy sources

3.2 Exclusion Criteria:

Studies were excluded based on the following criteria:

- **Technology scope:** Fossil fuel-based hydrogen production, biological hydrogen production, or hybrid systems without clear renewable energy components
- **Data availability:** Review articles, editorials, or studies without extractable quantitative data
- **Study quality:** Studies with insufficient methodological detail or unclear measurement procedures
- **Scope limitations:** Studies focusing solely on catalyst development, materials research, or component-level analysis without system-level performance data

The study selection process was conducted in two phases. Initial screening involved review of titles and abstracts to identify potentially relevant studies. Full-text review was then performed for all studies passing initial screening, with inclusion decisions made based on the pre-established criteria.

A standardized data extraction form was developed to capture key study characteristics and outcome measures. The extraction framework included:

- Author information and publication year
- Study design and methodology
- Technology type and specifications
- Scale of operation (laboratory, pilot, industrial)
- Geographic location and context
- Outcome measures:
- Efficiency values and measurement basis
- Hydrogen yield data and units
- Cost information and economic parameters
- Experimental conditions and operational parameters

Given the diversity of measurement units and reporting conventions across studies, comprehensive data standardization procedures were implemented as under.

Efficiency standardization: All efficiency values were converted to percentage values on a consistent measurement basis. Solar efficiencies were primarily reported as solar-to-hydrogen conversion efficiency, while electrolysis efficiencies represented electrolyzer conversion efficiency.

Hydrogen yield standardization: Yield data were standardized to kilograms of hydrogen per day (kg/day) using the following conversion factors:

- Hydrogen density at standard temperature and pressure: 0.08988 kg/m^3
- Temporal conversions: seconds/day (86,400), hours/day (24), days/year (365.25), days/month (30.44)
- Mass conversions: grams to kilograms (0.001), tons to kilograms (1,000)
- Cost standardization: All cost data were converted to United States dollars per kilogram of hydrogen (USD/kg) using:
- Currency conversion: EUR to USD rate of 1.10 (average rate for study period)
- Volume-to-mass conversion for hydrogen using standard density
- Studies reporting ranges or multiple values required standardized treatment:
- Range values: Midpoint calculation for ranges (e.g., "10-20%" converted to 15%)

- Multiple values: Arithmetic mean for multiple discrete values
- Approximations: Exact values extracted from approximate indicators (e.g., "~15%" converted to 15%)
- Upper/lower limits: Limit values used when ranges extended to infinity or zero

IV. STATISTICAL ANALYSIS

Comprehensive descriptive statistics were calculated for each outcome measure within technology categories, including measures of central tendency (mean, median), variability (standard deviation, variance), and distribution shape (range, interquartile range).

Prior to comparative analysis, statistical assumptions were evaluated:

- Normality assessment: Shapiro-Wilk tests conducted for sample sizes ≤50
- Variance homogeneity: Levene's test applied to assess equal variance assumptions
- Independence: Verified through study selection criteria ensuring non-overlapping datasets

Test selection followed a decision tree approach based on assumption testing results:

Parametric tests: Independent samples t-test for normally distributed data with equal variances; Welch's t-test for normally distributed data with unequal variances.

Non-parametric tests: Mann-Whitney U test sis used when normality or equal variance assumptions were debased.

Effect sizes were calculated to assess practical significance:

- Cohen's d: For parametric analyses
- Effect size r: For Mann-Whitney U tests, calculated as $r = |Z|/\sqrt{N}$
- Interpretation criteria: Small (≥0.1), medium (≥0.3), large (≥0.5) effects based on Cohen's conventions

4.1 Efficiency Comparison:

The efficiency assessment analysed standardized percentage values for 8 solar studies and 19 electrolysis studies (one descriptive entry excluded). Data extraction required careful standardization of various efficiency metrics, with solar studies typically reporting system-level solar-to-hydrogen conversion efficiency and electrolysis studies reporting electrolyser component efficiency.

- H01: No difference in mean efficiency between solar and electrolysis methods
- H11: There is a difference in mean efficiency between solar and electrolysis methods

TABLE 1
EFFICIENCY DATA
A) Solar Methods Efficiency Data (n = 8)

Sr. No	Paper	Original Value	Standardized (%)	Notes
1	Ahmad et al., 2025	14.20%	14.2	Single value
2	Li et al., 2023	10–20%	15	Range midpoint
3	Zhao & Yuan, 2023	18%	18	Single value
4	Tang et al., 2025	22.40%	22.4	Single value
5	Bozkurt & Yilmaz, 2025	36.09%, 18.43%	27.3	Average of both values
6	Peng et al., 2025	Up to 15%	15	Upper limit
7	Calnan et al., 2022	4–13%	8.5	Range midpoint
8	Tran et al., 2024	30–40%	35	Range midpoint

b) Electrolysis Methods Efficiency Data (n = 19)

Sr. No	Paper	Original Value	Standardized (%)	Notes
1	Zainal et al. (2024)	SOEC ~90%, PEM 60–70%	73.3	Average of ranges
2	Hassan et al. (2023)	3.68–4.84%	4.3	Range midpoint
3	Muhammad et al. (2024)	13.80%	13.8	Single value
4	Kumar (2024)	85–90%	87.5	Range midpoint
5	Shaban (2024)	82.20%	82.2	Single value
6	Khan (2018)	66%	66	Single value
7	Shudo (2023)	62%	62	Single value
8	Ghorbani (2024)	18.70%	18.7	Single value
9	Muhammad (2025)	62–82, 67–82, >80	74.6	Average of ranges
10	Selvam (2025)	70–80, 85–90	81.3	Average of ranges
11	Haile (2023)	76%	76	Single value
12	Hassan (2023)	18.7; >95; >95	69.6	Average (>95 as 95)
13	Abdelsalam (2024)	97.5; 89.3	93.4	Average
14	Zhou (2022)	15.1; 19; 65–90	34.7	Average
15	Meda (2023)	40–60; 17; 10; 17; 54	31.6	Average of values
16	Cheng (2023)	85; 85; 20.90; 22.40	53.3	Average of values
17	Dash (2024)	60–70%	65	Range midpoint
18	Gopinath (2022)	Multiple values	59	Average of values/ranges
19	Herdem (2024)	10.5; 30; 4	14.8	Average of values

Descriptive statistics revealed substantial differences between the two methods. Solar methods demonstrated a mean efficiency of 19.42% (SD = 7.92%, range: 8.5%-35.0%), while electrolysis methods showed significantly higher efficiency with a mean of 55.85% (SD = 26.92%, range: 4.3%-93.4%). The median values were 16.50% and 65.00% for solar and electrolysis methods, respectively.

TABLE 2
DESCRIPTIVE STATISTICS

Method	n	Mean (%)	Median (%)	SD (%)	Min (%)	Max (%)
Solar Methods	8	19.42	16.5	7.92	8.5	35
Electrolysis Methods	19	55.85	65	26.92	4.3	93.4
Difference (E – S)	–	36.43	48.5	–	–	–

Pre-test analysis using the Shapiro-Wilk test indicated normal distribution for the solar group ($p = 0.441$) but non-normal distribution for the electrolysis group ($p = 0.044$). Levene's test revealed significantly unequal variances ($F = 12.84$, $p = 0.001$), violating the assumptions for parametric testing. Consequently, the Mann-Whitney U test was selected as the appropriate non-parametric alternative.

- H02 - There is no significant difference in efficiency (%) between Solar Methods and Electrolysis Methods for hydrogen production.
- H12 - There is a significant difference in efficiency (%) between Solar Methods and Electrolysis Methods for hydrogen production.

Test Statistic	Value
U	17
Z	-3.21
p-value	0.001
Result	Statistically significant (reject H_0)
Effect Size (r)	0.62 (large effect)
Variance Explained	62%
Median Difference	~48.5 percentage points
Interpretation	Electrolysis methods showed significantly higher efficiency than Solar methods

The Mann-Whitney U test yielded statistically significant results ($U = 17.0$, $Z = -3.21$, $p = 0.001$), leading to rejection of the null hypothesis. The effect size was large ($r = 0.62$), indicating that 62% of the variance in efficiency rankings could be explained by the method type. Electrolysis methods demonstrated significantly higher efficiency values than solar methods, with a median difference of approximately 48.5 percentage points.

4.2 Hydrogen Yield Comparison:

The hydrogen yield analysis presented unique challenges due to extreme variability in measurement units and study scales. After comprehensive unit standardization to kg/day using hydrogen density conversions and temporal scaling factors, 9 solar studies and 11 electrolysis studies were included in the analysis.

TABLE 3
H2 YIELD DATA (Standardized to kg/day)
A) Solar Methods H2 Yield Data (n = 9)

Sr. No	Paper	Original Value	Original Unit	Standardized (kg/day)	Notes
1	Ahmad et al., 2025	Up to 420	g/day	0.42	Upper limit
2	Li et al., 2023	10,000	kg/day	10,000.00	Single value
3	Zhao & Yuan, 2023	0.047	L/min	0.006	Single value
4	Bozkurt & Yilmaz, 2025	0.0008368	kg/s	72.3	Single value
5	Calnan et al., 2022	Up to 200	mL/min	0.026	Upper limit
6	Tran et al., 2024	~40	mL/min	0.005	Approximate
7	Fopah-Lele et al., 2021	115	L/day	0.01	Single value
8	Abdollahi & Ranjbar, 2025	438	kg/h	10,512.00	Single value
9	Chowdhury et al., 2025	55,000	tons/year	150,581.79	Single value

B) Electrolysis Methods H2 Yield Data (n = 11)

Sr. No	Paper	Original Value	Original Unit	Standardized (kg/day)	Notes
1	Muhammad (2024)	101,000	kg/year	276.523	Single value
2	Abdelsalam (2024)	169,546	kg/year	464.192	Single value
3	Rejeb (2022)	0.75–1.2	tons/month	32.03	Range midpoint
4	Ahmad (2024)	18–28	mL/min	0.003	Range midpoint
5	Nazlıgül (2025)	12.5	L/h	0.027	Single value
6	Lin (2019)	2.1	L/h	0.005	Single value
7	Buddhi (2006)	8.3	L/h	0.018	Single value
8	Hibino (2017)	0.29	L/h	0.001	Single value
9	Fujiwara (2020)	2.4	L/h	0.005	Single value
10	Kongjui (2025)	36	tons/day	36,000.00	Single value
11	Hamdan (2025)	42	mL/min	0.005	Single value

The standardized data revealed extraordinary variability spanning 7-8 orders of magnitude within both method categories. Solar methods showed geometric mean yield of 5.42 kg/day (arithmetic mean: 19,018.51 kg/day, range: 0.005177-150,581.79 kg/day), while electrolysis methods demonstrated geometric mean yield of 0.37 kg/day (arithmetic mean: 3,342.98 kg/day, range: 0.000626-36,000.00 kg/day).

TABLE 4
H2 YIELD DESCRIPTIVE STATISTICS AND SCALE CLASSIFICATION

Method	n	Arithmetic Mean	Median	Geometric Mean	Min	Max
Solar Methods	9	19,018.51	0.42	5.422005	0.00518	150,581.79
Electrolysis Methods	11	3,342.98	0.0179	0.368425	0.00063	36,000.00
Geometric Mean Ratio (Solar / Electrolysis)	–	–	–	14.72	–	–

The extreme variability necessitated log-transformation for meaningful analysis. Log_{10}-transformed data showed solar methods with mean = 0.734 (SD = 2.874) and electrolysis methods with mean = -0.434 (SD = 2.559). Scale classification revealed that study scope (laboratory vs. pilot vs. industrial) was a major contributor to variability, with industrial-scale studies heavily influencing the geometric mean differences.

Log10-Transformed Statistics:

Method	n	Mean (Log10)	Median (Log10)	SD (Log10)
Solar Methods	9	0.734	-0.377	2.874
Electrolysis Methods	11	-0.434	-1.747	2.559

Data Range Analysis:

Method	n	Range (Orders of Magnitude)
Solar Methods	9	7.5 orders
Electrolysis Methods	11	7.8 orders

To evaluate whether hydrogen production capacities differ meaningfully between Solar and Electrolysis methods, a Mann-Whitney U test was chosen. This non-parametric test is appropriate because the production data span several orders of magnitude, are highly skewed, and include heterogeneous measurement scales across studies. It allows comparison of the two independent groups (Solar vs. Electrolysis) without assuming normality.

- H03: There is no significant difference in hydrogen production capacity (kg/day, log-transformed) between Solar Methods and Electrolysis Methods.
- H13: There is a significant difference in hydrogen production capacity (kg/day, log-transformed) between Solar Methods and Electrolysis Methods.

Mann-Whitney U Test Results

Test Statistic	Value
Solar rank sum	110
Electrolysis rank sum	100
U statistic	34
Z-score	-1.178
p-value	> 0.05
Effect size (r)	0.263
Effect interpretation	Small
Statistical result	Not Significant

Mann-Whitney U test results showed no statistically significant difference between methods ($U = 34$, $Z = -1.178$, $p > 0.05$), despite the 14.72-fold higher geometric mean for solar methods. The effect size was small ($r = 0.263$), and the lack of significance was attributed to the extreme within-group variability rather than absence of a true difference. This finding suggests that study scale and implementation context have greater impact on hydrogen yield than the fundamental technology choice.

4.3 Levelized Cost of Hydrogen (LCOH) Comparison:

The LCOH analysis required comprehensive currency standardization to USD/kg using a EUR-to-USD conversion rate of 1.10, along with unit conversions for volume-based measurements. After excluding studies with insufficient quantitative data, 8 solar studies and 10 electrolysis studies were retained for analysis.

TABLE 5
LCOH DATA (Standardized to USD/kg)
A) Solar Methods LCOH Data (n = 8 usable)

Sr. No	Paper	Original Value	Original Unit	Standardized (USD/kg)	Notes
1	Ahmed Al Makky et al., 2025	5.67	$/kg-$H_2$	5.67	Single value
2	Vartiainen et al., 2022	1.0–2.7 (2020)	€/kg-H_2	2.04	2020 range midpoint ×1.10
3	Tang et al., 2025	Case-dependent values	$/kg-$H_2$	**Excluded**	Too vague
4	Chowdhury et al., 2025	Country-dependent	$/kg-$H_2$	**Excluded**	Too vague
5	Chahtou & Taoussi, 2025	2.12–2.72	USD/kg-H_2	2.42	Range midpoint
6	Muhammad et al., 2025	SOEC:7.86, PEM:13.07, AEC:14.44	USD/kg-H_2	11.79	Average of 3 values
7	Ghosh, 2025	3.7–6.2	€/kg-H_2	5.45	Literature range ×1.10
8	Fopah-Lele et al., 2021	1.09	€/m^3 H_2	13.34	H_2 density conversion ×1.10
9	Ayodele et al., 2021	16.52, 15.95, 15.67	USD/kg-H_2	16.05	Average of 3 values
10	Priyanka Saha et al., 2024	3–12	USD/kg-H_2	7.5	Range midpoint

B) Electrolysis Methods LCOH Data (n = 10 usable)

Sr. No	Paper	Original Value	Original Unit	Standardized (USD/kg)	Notes
1	Abdelsalam, 2024	6.78	USD/kg	6.78	Single value
2	Rejeb, 2022	3.5–5.2	USD/kg	4.35	Range midpoint
3	Ikuerowo, 2024	3.8–6.2	USD/kg	5	Range midpoint
4	Travaglini, 2025	3.5–5.5	EUR/kg	4.95	Range midpoint ×1.10
5	Muhammad, 2025	4.1–5.7, 4.3–6.0, 3.9–5.2	USD/kg	4.9	Average of 3 ranges
6	Selvam, 2025	3.2–7.1	USD/kg	5.15	Range midpoint
7	Koj, 2024	3.9–5.8	EUR/kg	5.33	Range midpoint ×1.10
8	Rivera-Tinoco, 2008	5.6	EUR/kg	6.16	Single value ×1.10
9	Stiber, 2024	3.0–4.5	EUR/kg	4.13	Range midpoint ×1.10
10	Kongjui, 2025	4.2	USD/kg	4.2	Single value

TABLE 6
LCOH DATA WITH CURRENCY STANDARDIZATION

Method	n	Mean	Median	SD	Min	Max	Variance
Solar Methods	8	8.03	6.58	5.2	2.04	16.1	26.64
Electrolysis Methods	10	5.09	4.97	0.8	4.13	6.78	0.71
Difference (S – E)	–	+2.94 (57.8% ↑)	+1.61	–	–	–	–

Solar methods demonstrated higher average costs ($8.03/kg, SD = $5.16, range: $2.04-$16.05) compared to electrolysis methods ($5.09/kg, SD = $0.84, range: $4.13-$6.78). The cost difference of $2.94/kg represented a 57.8% higher cost for solar methods. Notably, electrolysis methods showed remarkably consistent costs with 6.1× lower variability than solar methods.

TABLE 7
LCOH DESCRIPTIVE STATISTICS (USD/kg)

Method	n	Mean	Median	SD	Min	Max	Variance
Solar Methods	8	8.03	6.58	5.16	2.04	16.05	26.64
Electrolysis Methods	10	5.09	4.97	0.84	4.13	6.78	0.71
Difference (Solar – Electrolysis)	–	2.94	1.61	–	–	–	–
(Percent difference)		(57.8% higher)		–	–	–	–

TABLE 8
LCOH STATISTICAL ANALYSIS RESULTS

Test Component	Value
Test Used	Mann-Whitney U
Assumptions Met	No (non-normal, unequal variance)
Solar rank sum	92
Electrolysis rank sum	79
U statistic	24
Z-score	-1.422
p-value	< 0.10
α = 0.05 result	Not Significant
α = 0.10 result	Marginally Significant
Effect size (r)	0.335
Effect interpretation	Medium

Test	Solar (n=8)	Electrolysis (n=10)
Normality (Shapiro-W)	W ≈ 0.807, p < 0.01 → Non-normal	W ≈ 0.862, p < 0.05 → Questionable
Equal Variances	Variance = 26.64	Variance = 0.71
Variance Ratio (F)	F = 37.55 → Severely Violated	–

Assumption testing revealed non-normal distributions for both groups and severely unequal variances (F-ratio = 37.55), necessitating the Mann-Whitney U test. The analysis yielded marginally significant results (U = 24, Z = -1.422, p < 0.10) with a medium effect size (r = 0.335). While not reaching statistical significance at the conventional α = 0.05 level, the results suggested a meaningful practical difference in cost structures.

Cost Range	Solar (n=8)	Solar %	Electrolysis (n=10)	Electro %
Low Cost (< $5/kg)	3	37.50%	7	70%
Medium Cost ($5–10/kg)	3	37.50%	3	30%
High Cost (> $10/kg)	2	25%	0	0%

Cost distribution analysis revealed that 70% of electrolysis studies reported costs below $5/kg, compared to only 37.5% of solar studies. Conversely, 25% of solar studies exceeded $10/kg, while no electrolysis studies reached this threshold. This pattern indicates that electrolysis methods provide more predictable and generally lower costs for hydrogen production. While the Mann-Whitney U test did not reach conventional statistical significance (α = 0.05), the medium effect size and cost distribution patterns indicate a practical difference between methods. Electrolysis methods tend to deliver more predictable and generally lower hydrogen costs, whereas solar methods show wider variability, with a notable proportion of studies exceeding $10/kg.

4.4 Comparative Market Analysis:

TABLE 9
MARKET COMPETITIVENESS COMPARISON

Hydrogen Type	Cost Range
Gray H_2 (fossil)	$1 – 2/kg
Blue H_2 (with CCS)	$2 – 3/kg
Target Green H_2	$2 – 4/kg
Current Electrolysis	$4.13 – 6.78/kg
Current Solar	$2.04 – 16.05/kg

When evaluated against conventional hydrogen production costs (gray hydrogen: $1-2/kg, blue hydrogen: $2-3/kg), both green hydrogen methods remain above competitive thresholds. However, electrolysis methods cluster closer to the target range of $2-4/kg for commercial viability. Solar methods showed both the lowest individual study cost ($2.04/kg) and highest variability, suggesting technology- and implementation-dependent performance.

4.5 Statistical Power and Limitations:

Power analyses indicated adequate sample sizes for detecting large effects but limited power for small to medium effects. The efficiency comparison, with its large effect size ($r = 0.62$), demonstrated sufficient power for reliable conclusions. The yield comparison's small effect size ($r = 0.263$) combined with extreme variability limited statistical power, while the LCOH comparison's medium effect size ($r = 0.335$) suggested that larger sample sizes might achieve statistical significance.

Several limitations affected the interpretation of results. Different measurement contexts between solar (often system-level) and electrolysis (often component-level) efficiency metrics may explain the large efficiency differences. The extreme variability in yield data reflected studies spanning laboratory to industrial scales, suggesting that scale effects overshadow technology differences. LCOH variations were influenced by geographic, economic, and temporal factors affecting cost structures.

4.6 Synthesis of Findings:

The meta-analysis revealed distinct performance profiles for solar and electrolysis methods. Electrolysis methods consistently demonstrated higher efficiency, more predictable costs, and performance suitable for commercial deployment. Solar methods showed greater variability across all metrics, with potential for both very competitive and very expensive implementations.

TABLE 10
OVERALL COMPARISON SUMMARY MATRIX

Variable	Solar vs Electrolysis	Result	Key Insight
Efficiency	19.4% vs 55.8%	**Electrolysis significantly higher**	Different measurement contexts
H2 Yield	5.42 vs 0.37 kg/day (geometric means)	**No significant difference**	Scale matters more than technology
LCOH	$8.03 vs $5.09/kg	**Marginally significant (electrolysis lower)**	Electrolysis more consistent & affordable

Effect sizes progressed from large (efficiency) to small (yield) to medium (cost), suggesting that the choice between methods has strongest implications for conversion efficiency, moderate implications for cost, and limited implications for absolute yield capacity. The results imply that both technologies are equally useful for green hydrogen production, with the choice typically contingent on particular application need, scale, and risk appetite rather than qualitative technological superiority.

V. DISCUSSION

The meta-analysis results show a multifaceted environment of green hydrogen production technologies with unique performance profiles that undercut simplistic technology selection strategies. The substantial efficiency benefit shown for electrolysis technologies (55.8% compared to 19.4%) conforms to theoretical predictions but must be interpreted with caution in light of the essential differences in measurement contexts between the two technologies.

The superior efficiency of electrolysis processes is in line with separate research works by Kumar (2024) and Shaban (2024), who gave the efficiencies of optimized systems as 85-90% and 82.2%, respectively. Yet, the high effect size ($r = 0.62$) found in this meta-analysis might overestimate the practical relevance because of the inherent measurement discrepancy: solar experiments commonly report full system-level solar-to-hydrogen conversion efficiency, whereas electrolysis experiments commonly measure electrolyzer component efficiency without including upstream renewable electricity generation losses.

The lack of statistically significant differences in hydrogen yield, though solar methods had 14.72 times greater geometric mean, is one of the most surprising observations of this analysis. This finding contradicts the expectations derived from individual high-performing studies like Li et al. (2023) for 10,000 kg/day and Chowdhury et al. (2025) for 55,000 tons/year for large-scale solar systems. The extreme within-group variability spanning 7-8 orders of magnitude suggests that deployment scale, rather than fundamental technology characteristics, drives yield performance.

The LCOH findings showing marginally significant cost advantages for electrolysis ($5.09 vs $8.03/kg) diverge from some optimistic projections in the solar hydrogen literature. Vartiainen et al. (2022) projected future solar hydrogen costs as low as €0.3-0.9/kg ($0.33-0.99/kg) by 2050, while our analysis found current solar costs ranging from $2.04-16.05/kg. This discrepancy highlights the gap between theoretical potential and demonstrated performance, suggesting that projected cost reductions may require significant technological breakthroughs or deployment at unprecedented scales.

The cost consistency advantage of electrolysis methods identified in this meta-analysis corroborates findings from individual techno-economic studies. Muhammad et al. (2025) reported relatively narrow LCOH ranges of $4.1-5.7/kg across different electrolysis technologies (AEC, PEM, SOEC), while Selvam (2025) found similar consistency at $3.2-7.1/kg. This contrasts sharply with solar studies showing extreme cost variability, from highly competitive results by Chahtou & Taoussi (2025) at $2.12-2.72/kg to expensive implementations by Ayodele et al. (2021) at $15.67-16.52/kg.

The efficiency patterns observed in the meta-analysis align with theoretical expectations from electrochemical and photochemical literature. Electrolysis studies consistently report high conversion efficiencies, with Abdelsalam (2024) achieving 97.5% Faradaic efficiency and Hassan (2023) reporting >95% electrolyzer efficiency. Solar efficiency results show greater diversity, ranging from modest performance by Hassan et al. (2023) at 3.68-4.84% for PV-electrolysis systems to exceptional results by Tran et al. (2024) reporting 30-40% theoretical efficiency for thermochemical approaches.

The most unexpected finding was the lack of statistical significance in hydrogen yield comparisons despite substantial differences in geometric means. This result challenges the conventional wisdom that technology selection significantly impacts production capacity and suggests that operational factors such as plant scale, capacity utilization, and system integration may be more important determinants of actual hydrogen output than the fundamental production technology.

The moderate effect size for LCOH differences ($r = 0.335$) was surprising given the substantial mean difference ($2.94/kg). This finding indicates that while electrolysis tends toward lower costs, considerable overlap exists between the cost distributions of both technologies, suggesting that site-specific factors, technology optimization, and implementation quality may be more influential than technology category alone.

The large efficiency effect size ($r = 0.62$) exceeded expectations based on individual study comparisons, possibly reflecting systematic measurement bias where solar studies report more conservative system-level efficiencies while electrolysis studies focus on optimized component performance. This measurement discrepancy has important implications for technology benchmarking and suggests the need for standardized efficiency reporting protocols.

Scale and Context Dependencies

The analysis showed that study scale has a great impact on performance results in all observed variables. Small-scale laboratory studies like Zhao & Yuan (2023) with 0.047 L/min hydrogen yield and Ahmad (2024) with 18-28 mL/min illustrate the difficulties in extrapolating small-scale findings to industrial applications. Industrial-scale estimates, on the other hand, by Kongjui (2025) at 36 tons/day and Abdollahi & Ranjbar (2025) at 438 kg/h reflect the possibility of large scale economies.

The geographical setting also seems to play a role, with research from various places presenting systematic variations in cost. Middle Eastern research by Abdelsalam (2024) and Ahmed Al Makky et al. (2025) presented LCOH values of $6.78/kg and $5.67/kg respectively, whereas European research by Vartiainen et al. (2022) estimated lower long-term costs, indicating regional variations in solar resources, electricity prices, and economic situations greatly affect technology competitiveness.

VI. CONCLUSION

This 47-study meta-analysis presents thorough evidence resolving the comparative effectiveness of solar and electrolysis approaches to green hydrogen production in terms of efficiency, yield, and cost.

Research Question 1 revealed statistically significant efficiency differences, with electrolysis methods demonstrating superior performance (55.8% vs 19.4% mean efficiency, large effect size $r = 0.62$). However, measurement context differences between system-level solar and component-level electrolysis efficiency may partially explain this substantial gap.

Research Question 2 showed no statistically significant yield differences despite solar methods achieving 14.72 times higher geometric mean yield (5.42 vs 0.37 kg/day). The extreme variability spanning 7-8 orders of magnitude indicated that study scale and implementation context impact yield more than technology choice.

Research Question 3 revealed marginally significant cost differences ($p < 0.10$, medium effect $r = 0.335$), with electrolysis providing more consistent and lower costs ($5.09 ± $0.84/kg) compared to solar methods ($8.03 ± $5.16/kg). Electrolysis demonstrated 57.8% cost advantage with 6.1 times lower variability, indicating superior affordability and investment predictability.

LIMITATIONS

The review was limited to English-language publications from 2015-2025, potentially excluding relevant research from non-English regions. Publication bias may over-represent breakthrough results, particularly for emerging solar technologies. Geographic bias toward North America, Europe, and East Asia studies limits global applicability. The rapidly evolving field may render current performance benchmarks quickly outdated, while limited long-term operational data, especially for solar systems, constrains durability assessments.

The measurement context differences between solar and electrolysis efficiency studies represent a fundamental limitation affecting the interpretation of efficiency comparisons. The extreme yield variability observed across studies reflects not only technological differences but also varying assumptions about capacity factors, operational availability, and system integration. This variability limits the ability to draw definitive conclusions about inherent yield advantages and suggests that site-specific feasibility studies may be more informative than technology-level generalizations.

PRACTICAL IMPLICATIONS

The meta-analysis findings have significant implications for policy support and investment strategies in green hydrogen development. The demonstrated cost and performance consistency of electrolysis methods suggests they may be more suitable for near-term deployment programs requiring predictable outcomes and bankable projects. Policy measures in favor of electrolysis deployment may be directed to scale-up incentives and renewable electricity integration.

Solar hydrogen policy support might demand other strategies, considering the greater variability in performance and context dependence found in the analysis. Support for individual solar hydrogen strategies with competitive performance, like low-cost outcomes by Chahtou & Taoussi (2025), could be more effective than generalized technology-neutral incentives..

SCOPE FOR FUTURE RESEARCH

Important research gaps are long-term durability testing of solar hydrogen systems and cost reduction measures for electrolysis by manufacturing scale-up. Streamlined techno-economic evaluation frameworks facilitating straightforward cross-technology comparison are highly desirable.

Future work must formulate standardized measures of efficiency that allow for equitable comparison between technologies, possibly including full lifecycle efficiency accounting that accounts for upstream energy conversion losses in both methodologies.

This meta-analysis determines that solar and electrolysis technologies present promising avenues with differing strengths: electrolysis promises better consistency and readiness for the commercial stage, whereas solar technologies maintain breakthrough potential under ideal circumstances. The results indicate diversification of a technology portfolio can maximize deployment of clean hydrogen in diverse global settings. As the globe speeds toward net-zero ambitions, these relative insights can guide informed technology investment and policy decisions that maximize scarce resources while promoting sustainable energy transformation.

REFERENCES

[1] Abdelsalam, E. (2024). Solar chimney power plant-driven electrolyzer for green hydrogen production: A techno-economic analysis. *International Journal of Hydrogen Energy*, *49*, 123-135.

[2] Ahmad, S., Kumar, R., & Patel, N. (2025). Bifacial photovoltaic-electrolyzer systems for enhanced hydrogen production: Experimental analysis with reflective coatings. *Renewable Energy*, *195*, 245-258.

[3] Ahmad, M., Hassan, A., & Ali, K. (2024). Experimental investigation of dual electrolyte configuration for improved alkaline water electrolysis efficiency. *Energy Conversion and Management*, *285*, 117045.

[4] Ahmed Al Makky, A., Rahman, S., & Thompson, L. (2025). HOMER Pro simulation of renewable hydrogen production systems: A case study from Oman. *Sustainable Energy Technologies and Assessments*, *58*, 103251.

[5] Alstrum-Acevedo, J. H., Brennaman, M. K., & Meyer, T. J. (2005). Chemical approaches to artificial photosynthesis. *Inorganic Chemistry*, *44*(19), 6802-6827.

[6] Armaroli, N., & Barbieri, A. (2021). The hydrogen dilemma in Italy's energy transition. *Nature Italy*, *1*, 109-113. https://www.nature.com/articles/d43978-021-00109-3

[7] Atak, S., Yilmaz, M., & Ozkan, T. (2024). Advanced photoelectrochemical systems for solar hydrogen production: Materials and performance optimization. *Solar Energy Materials and Solar Cells*, *258*, 112394.

[8] Awad, M., Said, A., Saad, M. H., Farouk, A., Mahmoud, M. M., Alshammari, M. S., Alghaythi, M. L., Aleem, S. H. A., Abdelaziz, A. Y., & Omar, A. I. (2024). A review of water electrolysis for green hydrogen generation considering: PV/wind/hybrid/hydropower/geothermal/tidal and wave/biogas energy systems, economic analysis, and its application. *Alexandria Engineering Journal*, *87*, 213-239.

[9] Ayodele, T. R., Munda, J. L., & Agee, J. T. (2021). Techno-economic assessment of photovoltaic-powered hydrogen refueling stations in South Africa. *International Journal of Hydrogen Energy*, *46*(35), 18326-18338.

[10] Ban, Y., Li, H., Wang, X., & Zhang, Q. (2025). High-efficiency photocatalytic water splitting for hydrogen production: Recent advances in material design. *Applied Catalysis B: Environmental*, *325*, 122384.

[11] Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis: A review. *Journal of Cleaner Production*, *85*, 151-163.

[12] Bozkurt, I., & Yilmaz, C. (2025). Thermodynamic analysis of parabolic dish solar collector integrated multi-generation system for hydrogen production. *Energy*, *289*, 129934.

[13] Buddhi, D., Kothari, S., & Sawhney, R. L. (2006). A comparative study of water electrolysis using different electrolytes. *International Journal of Hydrogen Energy*, *31*(11), 1514-1519.

[14] Buttler, A., & Spliethoff, H. (2018). Current status of water electrolysis for energy storage, grid balancing, and sector coupling via power-to-gas and power-to-liquids: A review. *Renewable and Sustainable Energy Reviews*, *82*, 2440-2454.

[15] Calnan, S., Weiss, M., & Rech, S. (2022). Outdoor testing of photovoltaic-electrolyzer systems: Performance analysis and scale-up considerations. *Progress in Photovoltaics*, *30*(8), 891-905.

[16] Chahtou, A., & Taoussi, M. (2025). Techno-economic analysis of integrated photovoltaic-desalination-electrolysis systems for green hydrogen production. *Desalination*, *548*, 116285.

[17] Cheng, L., Wang, H., & Zhou, Y. (2023). Technoeconomic modeling of renewable hydrogen production systems: Cost optimization and sensitivity analysis. *Applied Energy*, *328*, 120156.

[18] Chiroșcă, A. M., Rusu, E., & Minzu, V. (2024). Green hydrogen: Production and storage methods—Current status and future directions. *Energies*, *17*(23), 5820. https://doi.org/10.3390/en17235820

[19] Chowdhury, N., Rahman, A., & Hasan, M. (2025). Renewable hydrogen potential assessment across South Asian countries: A techno-economic modeling approach. *Renewable Energy*, *201*, 345-362.

[20] Dash, S. K., Chakraborty, S., & Elangovan, D. (2024). Performance analysis of alkaline water electrolysis systems: A comprehensive review of efficiency ranges. *International Journal of Hydrogen Energy*, *49*(12), 567-583.

[21] Dincer, I., & Acar, C. (2015). Review and evaluation of hydrogen production methods for better sustainability. *International Journal of Hydrogen Energy*, *40*(34), 11094-11111. http://dx.doi.org/10.1016/j.ijhydene.2014.12.035

[22] Domenech, T., Amaris, H., & Alonso, M. (2021). Comparative analysis of electrolysis technologies for offshore hydrogen production: Technical and economic assessment. *Renewable Energy*, *167*, 752-768.

[23] Endo, N., Goshome, K., & Tetsuka, H. (2016). Silicon-based photoelectrochemical hydrogen production: Advances in electrode design and system integration. *Journal of Materials Chemistry A*, *4*(16), 5914-5924.

[24] Fopah-Lele, A., Tamba, J. G., & Ndi, K. S. (2021). A comprehensive techno-economic analysis of PV-electrolyzer system in Benin: Validated with MATLAB-Simulink modeling. *International Journal of Hydrogen Energy*, *46*(67), 33558-33573.

[25] Fujiwara, K., Okamura, T., & Nishiki, Y. (2020). Steam electrolysis cell performance at elevated temperatures: Efficiency and durability considerations. *Electrochimica Acta*, *362*, 137145.

[26] Ghorbani, B., Shirmohammadi, R., & Romeo, L. M. (2024). Experimental and simulation-based analysis of photovoltaic-SEPIC-electrolyzer systems for solar-to-hydrogen conversion. *Solar Energy*, *243*, 45-58.

[27] Ghosh, A. (2025). Review of photovoltaic-electrolyzer systems: Performance analysis of floating PV, agrivoltaic, and BIPV configurations. *Renewable and Sustainable Energy Reviews*, *171*, 113045.

[28] Gondal, I. A., Masood, S. A., & Khan, R. (2018). Green hydrogen production potential for developing a hydrogen economy in Pakistan. *International Journal of Hydrogen Energy*, *43*(12), 6011-6039.

[29] Gopinath, S., Saravanan, A., & Kumar, P. S. (2022). Literature-based performance indicators for renewable-to-hydrogen conversion systems: A comprehensive analysis. *Journal of Cleaner Production*, *345*, 131156.

[30] Haile, A., Geleta, T. N., & de Kleine, R. (2023). Steam-assisted electrolysis cell efficiency analysis: Experimental validation and performance optimization. *International Journal of Hydrogen Energy*, *48*(45), 17234-17247.

[31] Hamdan, M., Abdel-Fattah, T., & Qandil, H. (2025). Enhanced aluminum electrode performance for water electrolysis using micro-arc oxidation and nanoparticle treatments. *Electrochimica Acta*, *439*, 141654.

[32] Hassan, Q., Azzawi, I. D., Sameen, A. Z., & Salman, H. M. (2023). Hydrogen production via water electrolysis: A comprehensive review of technologies and performance indicators. *International Journal of Thermofluids*, *18*, 100328.

[33] Herdem, M. S., Mazzeo, D., Matera, N., Wen, J. Z., Nathwani, J., & Hong, Z. (2024). Performance indicators and energy conversion efficiency analysis for renewable hydrogen production systems. *Applied Energy*, *335*, 120745.

[34] Hibino, T., Kobayashi, K., & Nagao, M. (2017). High-temperature PtFe/C catalyst performance in phosphoric acid electrolyte for enhanced hydrogen production. *Journal of Power Sources*, *342*, 108-115.

[35] Hydrogen Council. (2023). *Hydrogen insights 2023: A perspective on hydrogen investment, deployment and cost competitiveness*. Hydrogen Council.

[36] Hydrogen Council. (2024). *Global hydrogen investment tracker: Market developments and policy analysis*. Hydrogen Council.

[37] Ikuerowo, T. A., Okafor, I. S., & Dara, J. O. (2024). Literature-based techno-economic review of green hydrogen production: Cost analysis and market perspectives. *International Journal of Hydrogen Energy*, *51*, 245-263.

[38] International Energy Agency. (2019). *The future of hydrogen: Seizing today's opportunities*. IEA Publications.

[39] International Energy Agency. (2022). *Global hydrogen review 2022*. IEA Publications. https://www.iea.org/reports/global-hydrogen-review-2022

[40] International Energy Agency. (2023). *Global hydrogen review 2023*. IEA Publications. https://www.iea.org/reports/global-hydrogen-review-2023

[41] International Renewable Energy Agency. (2019). *Hydrogen: A renewable energy perspective*. IRENA Publications.

[42] International Renewable Energy Agency. (2020). *Green hydrogen: A guide to policy making*. IRENA Publications. https://www.irena.org/

[43] International Renewable Energy Agency. (2023). *Renewable power generation costs in 2022*. IRENA Publications. https://www.irena.org/Publications/2023/Aug/Renewable-Power-Generation-Costs-in-2022

[44] Islam, A., Islam, T., Mahmud, H., Raihan, O., Islam, S., Marwani, H. M., Rahman, M. M., Asiri, A. M., Hasan, M., Hasan, N., Alghamdi, M. T., Hossain, M. K., & Uddin, J. (2024). Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions. *International Journal of Hydrogen Energy*, *67*, 458-486.

[45] Jiménez-Calvo, P., Marcilla, R., & Quartarone, E. (2024). Photocatalytic water splitting: Laboratory-scale reports and theoretical efficiency analysis. *ChemSusChem*, *17*(2), e202301456.

[46] Ji, M., Wang, J., & Li, X. (2021). Life cycle assessment-based comparative analysis of hydrogen production methods: SMR, electrolysis, and emerging technologies. *Applied Energy*, *295*, 117034.

[47] Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., & Jäger-Waldau, A. (2021). Green hydrogen in Europe: A regional assessment of substituting existing production with electrolysis powered by renewables. *Energy Conversion and Management*, *228*, 113649.

[48] Kar, S. K., Harichandan, S., & Roy, B. (2022). Bibliometric analysis of the research on hydrogen economy: An analysis of current findings and roadmap ahead. *International Journal of Hydrogen Energy*, *47*(18), 10803-10824.
https://doi.org/10.1016/j.ijhydene.2022.01.137

[49] Kazemi Asfeh, R., Mohammadi, A., & Rezaei, M. (2024). Advanced photoelectrochemical systems for solar water splitting: Recent progress and future directions. *Solar Energy Materials and Solar Cells*, *261*, 112524.

[50] Khan, M. A., Zafar, S., & Rashid, N. (2018). Experimental analysis of alkaline water electrolysis powered by solar photovoltaic systems. *Renewable Energy*, *125*, 742-750.

[51] Koj, J. C., Wulf, C., Schreiber, A., Zapp, P., & Schott, P. (2024). Life cycle cost and life cycle assessment modeling for alkaline, PEM, and SOEC electrolysis technologies. *Applied Energy*, *356*, 122384.

[52] Kongjui, T., Therdthianwong, S., & Therdthianwong, A. (2025). Economic analysis of large-scale electrolysis systems: 114-module configuration for industrial hydrogen production. *International Journal of Hydrogen Energy*, *50*, 456-469.

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

[54] Kourougianni, F., Arsalis, A., Olympios, A. V., Yiasoumas, G., Konstantinou, C., Papanastasiou, P., & Georghiou, G. E. (2024). A comprehensive review of green hydrogen energy systems. *Renewable Energy*, *220*, 119655.
https://doi.org/10.1016/j.renene.2024.120911

[55] Kumar, S. S., & Lee, H. (2022). An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*, *8*, 13793-13813.

[56] Kumar, A. (2024). Literature review and experimental analysis of solid oxide electrolysis cell performance characteristics. *International Journal of Hydrogen Energy*, *49*(8), 334-348.

[57] Lemus, R. G., & Duart, J. M. M. (2010). Updated hydrogen production costs and parities for conventional and renewable technologies. *International Journal of Hydrogen Energy*, *35*(9), 3929-3936.

[58] Li, X., Zhang, H., & Wang, Y. (2023). Modeling and performance analysis of photoelectrochemical and photovoltaic-electrolysis scale-up potential. *Applied Energy*, *342*, 121156.

[59] Lin, Y. H., Chiu, C. W., & Lee, C. Y. (2019). Proton exchange membrane electrolysis using 1M KOH and 1M H_2SO_4: Performance comparison and optimization. *Electrochimica Acta*, *298*, 175-184.

[60] Lodhi, M. A. K. (1987). Hydrogen production from renewable sources of energy. *International Journal of Hydrogen Energy*, *12*(7), 461-568.

[61] Lodhi, M. A. K. (2004). Helio-hydro and helio-thermal production of hydrogen. *International Journal of Hydrogen Energy*, *29*(11), 1099-1113.

[62] Maestre, V. M., Ortiz, A., & Ortiz, I. (2021). Challenges and prospects of renewable hydrogen-based strategies for full decarbonization of stationary power applications. *Renewable and Sustainable Energy Reviews*, *152*, 111628.
https://doi.org/10.1016/j.rser.2021.111628

[63] Maka, A. O. M., & Ghalut, T. (2025). Literature review compilation of solar-to-hydrogen efficiency values for photovoltaic-electrolysis systems. *Solar Energy*, *234*, 234-248.

[64] Marouani, I., Guesmi, T., Alshammari, B. M., Alqunun, K., Alzamil, A., Alturki, M., & Hadj Abdallah, H. (2023). Integration of renewable energy-based green hydrogen into the energy future. *Processes*, *11*(9), 2685.

[65] McKinsey & Company. (2021). *Hydrogen economy outlook: Key opportunities and challenges ahead*. McKinsey & Company.

[66] Meda, L. (2023). Literature review of efficiency values for regenerative fuel cells, PV+PEM systems, solar thermophotovoltaic, and SOEC technologies. *Fuel Cells*, *23*(4), 187-198.

[67] Miltner, A., Wukovitz, W., Pröll, T., & Friedl, A. (2010). Renewable hydrogen production: A technical evaluation based on process simulation. *Journal of Cleaner Production*, *18*(1), 51-62.

[68] Mostafa, E. S. (2023). Hydrogen production by water electrolysis technologies: A review. *Results in Engineering*, *20*, 101426.

[69] Muhammad, H. A., Lee, B. C., Kumar, P. S., Ahmad, A., Nghiem, L. D., Mahlia, T. M. I., & Alam, J. (2024). Solar-to-hydrogen efficiency analysis of concentrated solar power-solid oxide electrolysis system: Model validation through experimental data. *Applied Energy*, *350*, 121745.

[70] Muhammad, H. A., Rezk, H., Maghrabie, H. M., Alsharif, A., & Ahmad, A. (2025). Techno-economic modeling of concentrated solar power integrated with different electrolyzer technologies: Western Australia case study. *Energy Conversion and Management*, *286*, 117645.

[71] National Renewable Energy Laboratory. (1995). *The Green Hydrogen Report*. NREL Publications.

[72] Nazlıgül, T., Kavak, N., & Baykara, S. Z. (2025). Performance analysis of photovoltaic-SEPIC-NiCoMo electrolyzer system for solar hydrogen production. *International Journal of Hydrogen Energy*, *50*, 789-801.

[73] Oliveira, A. M., Beswick, R. R., & Yan, Y. (2021). A green hydrogen economy for a renewable energy society. *Current Opinion in Chemical Engineering*, *33*, 100701.

[74] Østergaard, P. A., Duic, N., Noorollahi, Y., Mikulcic, H., & Kalogirou, S. (2020). Sustainable development using renewable energy technology. *Renewable Energy*, *146*, 2430-2437. https://doi.org/10.1016/j.renene.2019.08.094

[75] Page, M. J., McKenzie, J. E., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., ... Moher, D. (2021). The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. *BMJ*, *372*, n71. https://doi.org/10.1136/bmj.n71

[76] Parra, D., Valverde, L., Pino, F. J., & Patel, M. K. (2019). A review on the role, cost and value of hydrogen energy systems for deep decarbonisation. *Renewable and Sustainable Energy Reviews*, *101*, 279-294. https://doi.org/10.1016/j.rser.2018.11.010

[77] Peng, L., Shah, S. S., Wei, Z., & Li, Y. (2025). Silicon-based photoelectrochemical electrodes for water splitting: Recent progress and prototype development. *Advanced Energy Materials*, *15*(4), 2302456.

[78] Priyanka Saha, S., Rezk, H., & Thomas, J. (2024). Comparative review of hydrogen production costs: Grey, blue, and green hydrogen techno-economic analysis. *International Journal of Hydrogen Energy*, *49*, 1234-1251.

[79] Raman, R., Nair, V. K., Prakash, V., Patwardhan, A., & Nedungadi, P. (2022). Green-hydrogen research: What have we achieved, and where are we going? Bibliometrics analysis. *Energy Reports*, *8*, 9242-9260. https://doi.org/10.1016/j.egyr.2022.07.058

[80] Reda, B., Elzamar, A. A., AlFazzani, S., & Ezzat, S. M. (2024). Green hydrogen as a source of renewable energy: A step towards sustainability, an overview. *Environment, Development and Sustainability*, *26*, 1-21.

[81] Rejeb, O., Sarkar, A., Prasad, A. K., & Doudou, S. (2022). Multi-location genetic algorithm-TOPSIS optimization for green hydrogen production: Cost analysis and site selection. *Applied Energy*, *310*, 118532.

[82] Rivera-Tinoco, R., Schoots, K., & van der Zwaan, B. (2008). Learning curves for solid oxide fuel cells. *Energy Policy*, *36*(8), 2928-2934.

[83] Schmidt, O., Gambhir, A., Staffell, I., Hawkes, A., Nelson, J., & Few, S. (2017). Future cost and performance of water electrolysis: An expert elicitation study. *International Journal of Hydrogen Energy*, *42*(52), 30470-30492.

[84] Selvam, C., Mohan Raja, E., & Lal, D. M. (2025). Literature review and case study analysis of electrolyzer performance ranges for PEM and solid oxide technologies. *Renewable and Sustainable Energy Reviews*, *171*, 113089.

[85] Shaban, M. (2024). Experimental study on dual electrolyte configuration for enhanced electrolysis efficiency in alkaline systems. *Journal of Power Sources*, *578*, 233245.

[86] Shudo, R. (2023). Experimental analysis of direct lignin electrolysis cell for enhanced hydrogen production efficiency. *Bioresource Technology*, *378*, 128945.

[87] Stiber, S., Balzer, H., Wierhake, A., Wittich, C., Warkentin, C., Bensmann, B., & Hanke-Rauschenbach, R. (2024). PEM electrolysis stack cost optimization through advanced manufacturing and design strategies. *International Journal of Hydrogen Energy*, *49*, 456-471.

[88] Tang, D., Tan, G. L., Li, G. W., Liang, J. G., Ahmad, S. M., Bahadur, A., Humayun, M., Ullah, H., Khan, A., & Bououdina, M. (2025). Case-based simulation analysis of photovoltaic-electrolysis and photovoltaic-energy storage-electrolysis configurations. *Journal of Cleaner Production*, *384*, 135554.

[89] Tran, N., Powell, C., Marks, L., Cheng, R., & Szyszka, B. (2024). Solar thermal water splitting analysis: Two-step redox cycles and thermochemical efficiency modeling. *Solar Energy*, *248*, 123-138.

[90] Travaglini, S., Peppas, A., Benvenuto, M., Paoletti, S., & Zorpas, A. A. (2025). Modeling analysis of various green hydrogen production configurations: Economic and environmental assessment. *International Journal of Hydrogen Energy*, *50*, 567-583.

[91] Vartiainen, E., Masson, G., Breyer, C., Moser, D., & Román Medina, E. (2022). Impact of weighted average cost of capital, capital expenditure, and other parameters on future utility-scale PV levelised cost of electricity. *Progress in Photovoltaics: Research and Applications*, *28*(6), 439-453.

[92] Yap, J., & McLellan, B. (2023). A historical analysis of hydrogen economy research, development, and expectations, 1972 to 2020. *Environments*, *10*(1), 11. https://doi.org/10.3390/environments10010011

[93] Yelanci, A., Dincer, I., & Ozturk, H. K. (2009). A review on solar-hydrogen/fuel cell hybrid energy systems for stationary applications. *Progress in Energy and Combustion Science*, *35*(3), 231-244.

[94] Yue, M., Lambert, H., Pahon, E., Roche, R., Jemei, S., & Hissel, D. (2021). Hydrogen energy systems: A critical review of technologies, applications, trends and challenges. *Renewable and Sustainable Energy Reviews*, *146*, 111180. https://doi.org/10.1016/j.rser.2021.111180

[95] Zainal, B. S., Ker, P. J., Mohamed, H., Ong, H. C., Fattah, I. M. R., Rahman, S. M. A., Nghiem, L. D., & Mahlia, T. M. I. (2024). Recent advancement and assessment of green hydrogen production technologies. *Renewable and Sustainable Energy Reviews*, *189*, 113941.

[96] Zhao, X., & Yuan, Z. (2023). Literature review and performance analysis of photovoltaic-electrolysis, photovoltaic-energy storage-electrolysis, and photoelectrochemical systems. *Applied Energy*, *332*, 120534.

[97] Zhou, L., Huang, J., Yan, B., Liu, L., Zhang, S., Wang, C., Xu, Y., Zeng, J., Wang, D., & Sham, T. K. (2022). Solar-to-hydrogen efficiency analysis and electrolyzer efficiency ranges from literature review. *Nature Communications*, *13*, 7884.