

Article

Techno-Enviro-Economic-Based Comparative Analysis of Hydrogen Production Pathways Using AHP-TOPSIS Framework

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Abstract

Hydrogen is essential for decarbonising energy systems, yet optimal production pathways remain debated. This study presents a comprehensive techno–enviro–economic assessment of 17 hydrogen production methods. The assessment results were used to identify the optimal hydrogen production methods under a Multicriteria Decision Analysis (MCDA) framework using an integrated analytical hierarchy process (AHP)–technique for order preference by similarity to ideal solution (TOPSIS) framework. Eight criteria were evaluated—energy efficiency, technology readiness level (TRL), production rate, CO₂ emissions, water consumption, CAPEX, OPEX, and levelised cost of hydrogen (LCOH). AHP-derived criterion weights were energy efficiency: 34%, TRL: 18%, production rate: 10%, CO₂ emissions: 4%, H₂O consumption: 8%, LCOH: 4%, CAPEX: 13%, and OPEX: 8%—with an acceptable consistency ratio (CR = 0.06). Data gaps were addressed using multiple linear regression. TOPSIS rankings identified Steam Methane Reforming (SMR, $C_i = 0.77$) as the most viable pathway, followed by Solid Oxide Electrolysis Cell (SOEC, $C_i = 0.76$), and Proton Exchange Membrane (PEM, $C_i = 0.71$). Emerging photolytic and biological pathways ranked lowest because of their low TRLs and economics. Under the adopted criteria and weighting scheme, SMR+CCS demonstrated short-term transition potential while electrolysis pathways provide long-term sustainability. The framework offers policymakers and industry a replicable decision-support tool for developing hydrogen strategies.

Keywords: hydrogen production; AHP-TOPSIS; multi-criteria decision making; techno–enviro–economic analysis; energy transition



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1. Introduction

Hydrogen has emerged as a promising clean energy carrier with great potential to address global energy challenges and mitigate climate change [1–3]. As the world transitions towards sustainable energy systems, hydrogen production methods have come under increased scrutiny due to their adaptability and potential to reduce carbon footprints [4–6]. Currently, around 95% of global hydrogen output is derived from fossil fuel-based processes, with steam methane reforming (SMR) representing the dominant

technology [7–9]. However, reliance on carbon-intensive pathways, such as SMR, raises significant sustainability and environmental concerns [7,9,10].

To address these challenges, alternative hydrogen production technologies have been developed and optimised in recent years. Thermochemical processes, such as coal gasification, biomass gasification, advanced reforming techniques, and methane pyrolysis, have shown potential in reducing carbon intensity [11–13]. Electrolytic methods, including alkaline water electrolysis (AWE), proton exchange membrane (PEM) electrolysis, and solid oxide electrolysis cells (SOEC), are widely recognised for their ability to produce low-carbon hydrogen when coupled with renewable electricity [14–16]. In parallel, emerging photolytic and biological pathways, such as photocatalytic water splitting, photoelectrochemical systems, photobiological processes, and dark fermentation, continue to receive research attention [17–20]. Each of these technologies offers unique advantages but also faces challenges regarding efficiency, scalability, environmental performance, and cost-effectiveness [6,21,22].

Carbon capture and storage (CCS) integration with conventional hydrogen production, particularly SMR, has also been proposed as a pathway to reduce carbon emissions while retaining cost competitiveness. For example, ref. [23] reported that integrating CO₂ capture with SMR can cut emissions by up to 90% with only a 13% increase in hydrogen production costs. Similarly, refs. [24,25] found that SMR with CCS offers an important transitional pathway for blue hydrogen, although cost and energy penalties remain. These strategies highlight the potential of CCS-enabled fossil-based systems to reduce environmental impacts while maintaining economic viability [26,27].

As the global energy transition progresses, comprehensive techno–enviro–economic assessments of hydrogen production pathways have become essential for informing investment decisions, shaping energy policy, and guiding research and innovation priorities [28–30]. Such evaluations not only help identify trade-offs among cost, efficiency, and environmental sustainability but also support the development of a hydrogen economy aligned with climate goals [3,21,31]. In this context, improving the efficiency and environmental performance of hydrogen production remains critical to scaling sustainable hydrogen production at a global level [8,32,33].

This study contributes to this effort by applying a multi-criteria decision-analysis (MCDA) framework to compare 17 hydrogen production pathways across technical, environmental, and economic dimensions. The Analytic Hierarchy Process (AHP) was employed to derive criterion weights for the evaluation criteria, while the technique for order preference by similarity to ideal solution (TOPSIS) was applied to rank the alternatives, providing a structured and replicable methodology for identifying the most viable hydrogen production options [34–37].

2. Methodology

The methodology used in this study to evaluate, compare, and select the best hydrogen production pathways is the technique for order preference by similarity to ideal solution based on multi-criteria decision analysis (TOPSIS-MCDA). This methodology is effective for handling problems involving multiple conflicting criteria, making it suitable for comparing hydrogen production pathways.

Seventeen hydrogen production pathways were selected, grouped into thermochemical (e.g., steam methane reforming, autothermal reforming, partial oxidation of methane) and CCUS integrated options, electrolytic (alkaline water electrolysis, proton exchange membrane, solid oxide electrolysis cell), photolytic (photoelectrochemical and photobiological), and biological (dark-fermentation and photo-fermentation).

Eight criteria were identified from the literature: energy efficiency, technological readiness level (TRL), production rate, carbon emissions, water consumption, capital expenditure (CAPEX), operational expenditure (OPEX), and levelised cost of hydrogen (LCOH).

Data were sourced from published literature and industry reports to ensure that comparable technical, environmental, and economic parameters were extracted for each hydrogen production pathway. Where multiple values were available, representative data from peer-reviewed studies were selected to construct a consistent comparative decision matrix. Economic data (CAPEX, OPEX, and LCOH) were extracted from the cited literature and reported as presented in the original studies, as the objective of this work was a comparative assessment of hydrogen production pathways rather than a detailed techno-economic cost normalisation. Missing values were estimated using multiple linear regression based on the assumption that the completeness and logical relevance of certain criteria, such as technology readiness level (TRL), energy efficiency, and levelised cost of hydrogen (LCOH), influence or correlate reasonably with the performance, environmental impact, and cost structure of the hydrogen production technologies. This method was also preferred over simpler techniques (e.g., mean or median substitution) due to its ability to maintain the variability and structure of the data, and over more complex models, such as machine learning, due to ease of implementation and interpretability within the research scope.

The Analytic Hierarchy Process (AHP) was employed to derive the relative weights of the eight evaluation criteria using Saaty's 1–9 fundamental scale of pairwise comparisons. The pairwise comparison matrix was developed by the authors through a structured synthesis of published literature and industry reports on hydrogen production technologies, with the relative importance of each criterion assessed in the context of the study objective of identifying the most suitable hydrogen production pathway from technical, environmental, and economic perspectives. The pairwise comparison matrix was subsequently normalised, and the criteria weights were obtained from the normalised matrix. To ensure the logical consistency of the judgments, the Consistency Ratio (CR) was calculated, yielding a value of 0.06, which is below the acceptable threshold of 0.10 and therefore indicates acceptable consistency. The derived weights were subsequently incorporated into the TOPSIS framework to rank the hydrogen production pathways.

2.1. Mathematical Implementation of AHP

2.1.1. Pairwise Comparison Matrix

A pairwise comparison matrix was constructed to represent the relative importance of the eight evaluation criteria. For n criteria, the reciprocal comparison matrix is expressed as

$$A = [a_{ij}]$$

where

$$A = \begin{bmatrix} 1 & a_{12} & a_{13} & \cdots & a_{1n} \\ a_{21} & 1 & a_{23} & \cdots & a_{2n} \\ a_{31} & a_{32} & 1 & \cdots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \cdots & 1 \end{bmatrix} \quad (1)$$

and where

A = pairwise comparison matrix,

a_{ij} = the relative importance of criterion i compared with criterion j .

$$a_{ji} = \frac{1}{a_{ij}} \quad (2)$$

Judgments are typically assigned using Saaty's 1–9 scale.

For example, if criterion i is considered five times more important than criterion j , then $a_{ij} = 5$, and the reciprocal comparison becomes $a_{ji} = \frac{1}{5}$.

This reciprocal relationship ensures consistency within the pairwise comparison matrix and reduces redundant comparisons during the AHP weighting process.

2.1.2. Normalisation of the Pairwise Comparison Matrix

The pairwise comparison matrix is normalised by dividing each element by the sum of its column:

$$r_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}} \quad (3)$$

where

r_{ij} = normalised value.

The normalisation process converts the pairwise comparison values into dimensionless quantities so that all criteria can be compared on a common scale.

2.1.3. Criteria Weights

The priority weight for each criterion is obtained by averaging the normalised values across each row:

$$w_i = \frac{1}{n} \sum_{j=1}^n r_{ij} \quad (4)$$

where

w_i = the weight of criterion i ,

r_{ij} = normalised value of the matrix element,

n = number of criteria.

These weights indicate the relative importance of each evaluation criterion in the decision-making process. The resulting priority weights are subsequently used as weighting factors in the TOPSIS analysis.

2.1.4. Consistency Index

To ensure logical consistency in the pairwise comparisons, the Consistency Index (CI) is calculated as

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (5)$$

where

λ_{max} = maximum eigenvalue of the matrix,

n = number of criteria.

2.1.5. Consistency Ratio

The consistency ratio (CR) evaluates the acceptability of the judgements:

$$CR = \frac{CI}{RI} \quad (6)$$

where

CR = random consistency Index,

CRA comparison matrix is considered acceptable if

$CR < 0.10$, indicating that the judgements are sufficiently consistent.

2.2. Mathematical Implementation of TOPSIS

2.2.1. Decision Matrix Construction

The decision matrix X is structured as

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (7)$$

where

x_{ij} = Performance of the i -th pathway under the j -th criterion,

m = Number of pathways,

n = Number of criteria.

2.2.2. Normalisation of the Decision Matrix

The normalised matrix R is calculated using Equation [34].

$$r_{ij}(x) = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}, i = 1, \dots, n; j = 1, \dots, m. \quad (8)$$

where

r_{ij} = normalized value of x_{ij} .

Vector normalisation removes the influence of differing measurement units among the evaluation criteria.

2.2.3. Weighted Normalised Decision Matrix

The weighted normalised matrix V is obtained using Equation [34].

$$v_{ij} = w_j \cdot r_{ij}$$

$$w_j = \text{Weight of the } j\text{-th criterion} \left(\sum_{j=1}^n w_j = 1 \right) \quad (9)$$

where

w_i = the weight of criterion i ,

r_{ij} = normalized value of x_{ij} .

Each normalised criterion is multiplied by its corresponding AHP weight to obtain the weighted normalised decision matrix.

2.2.4. Determination of Ideal and Negative-Ideal Solutions

The positive ideal solution (PIS) and negative ideal solution (NIS) are determined by Equations (10) and (11):

$$A^+ = \{ \max(v_{ij}) | j \in J^+; \min(v_{ij}) | j \in J^- \} \quad (10)$$

$$A^- = \{ \min(v_{ij}) | j \in J^+; \max(v_{ij}) | j \in J^- \} \quad (11)$$

where

J^+ = set of benefit criteria,

J^- = set of cost criteria.

The positive ideal solution represents the best attainable criterion values, whereas the negative ideal solution represents the least desirable criterion values.

2.2.5. Calculation of Separation Measures

The Euclidean distances from the PIS and NIS for each pathway are given by Equations (12) and (13).

$$S_i^+ = \sqrt{\sum_{j=1}^n (v_{ij} - A_j^+)^2} \quad (12)$$

$$S_i^- = \sqrt{\sum_{j=1}^n (v_{ij} - A_j^-)^2} \quad (13)$$

where

S_i^+ = separation from (PIS),

S_i^- = separation from (NIS).

2.2.6. Relative Closeness to Ideal Solution

The relative closeness C_i of each alternative (pathway) to the ideal solution will be obtained from Equation [37].

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-} \quad (14)$$

$0 \leq C_i \leq 1$; higher CI indicates better performance.

where

C_i = Relative Closeness Coefficient.

2.2.7. Ranking of Alternatives

Alternatives are ranked based on their CI values, with higher values indicating higher preference.

The overall methodological procedure adopted in this study is illustrated in Figure 1.

2.3. Data Collection and Preprocessing

Data for each criterion and production pathway were sourced from peer-reviewed publications and industry reports.

2.3.1. Data Completion Using Regression Analysis

In the process of compiling the decision matrix for the evaluation of hydrogen production pathways, it was observed that some criterion values were missing for some of the specific alternatives. These missing entries included production rate, CO₂ emissions, water consumption, capital expenditures (CAPEX), and operational expenditures (OPEX). Since a complete decision matrix is required to implement the selected TOPSIS procedure, these gaps were addressed systematically using a multiple linear regression model. The specific hydrogen production pathways with missing values and the variables estimated using the regression models are summarised in Table 1.

A multiple linear regression model was chosen for imputing missing values based on its ability to predict dependent variables using available independent variables. The decision was informed by the completeness and logical relevance of certain criteria, such as technology readiness level (TRL), energy efficiency, and levelised cost of hydrogen (LCOH). These variables were used as independent variables, based on the assumption that they influence or correlate reasonably with the performance, environmental impact, and cost structure of the hydrogen production technologies.

This method was also preferred over simpler techniques (e.g., mean or median substitution) due to its ability to maintain the variability and structure of the data, and over more complex models, such as machine learning, due to ease of implementation and interpretability within the research scope.

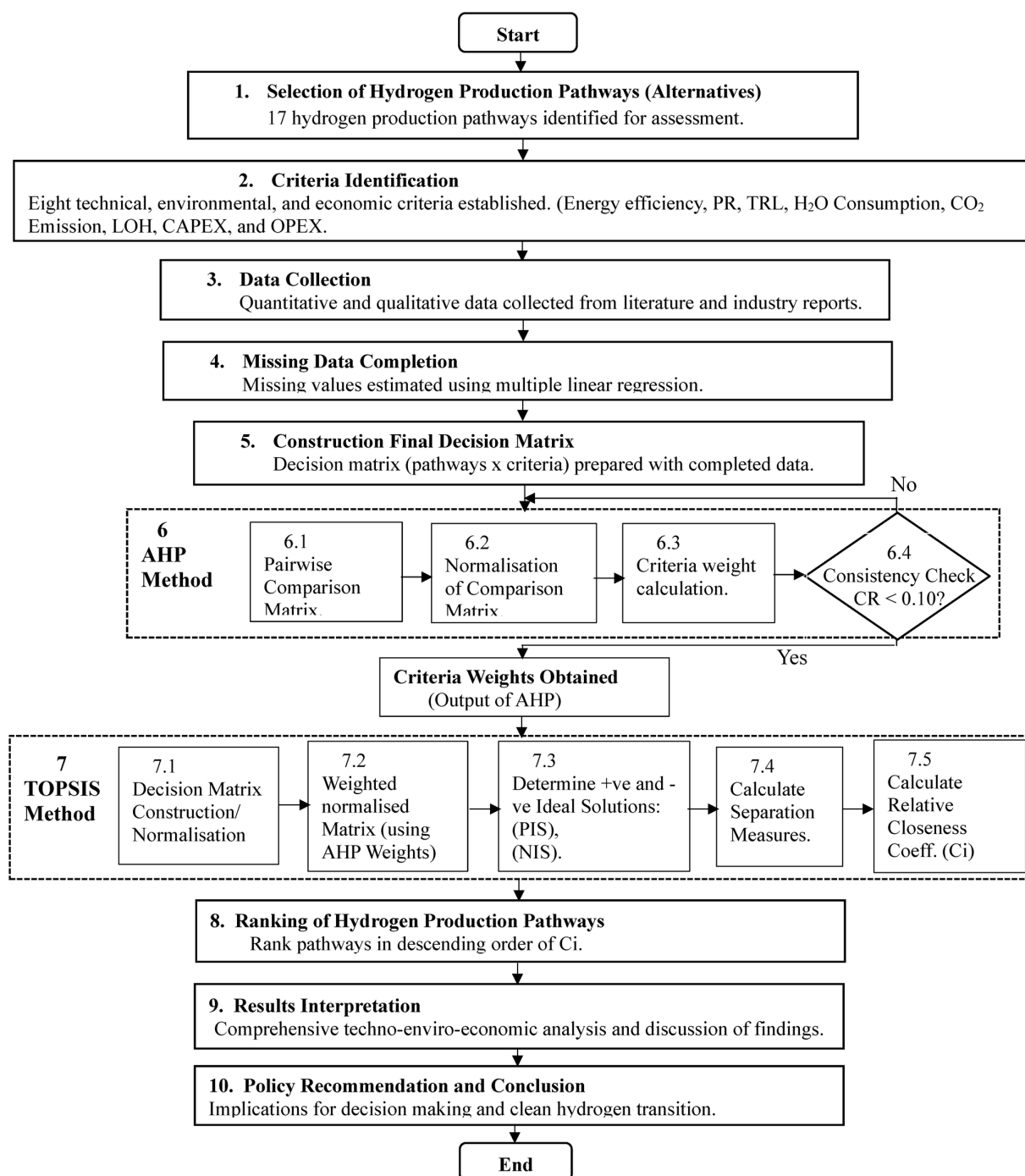


Figure 1. Flowchart of the integrated AHP-TOPSIS framework for techno–enviro–economic evaluation and ranking of hydrogen production pathways.

Table 1. Summary of data completion with regression analysis.

S/N	Criterion	Method Estimates
1	Production Rate	Estimated for SOEC, PEC, PB, PF, and DF.
2	CO ₂ Emission	Estimated for PEC, PB, PF, and DF.
3	Water Consumption	Estimated for POX, Biomass Gasification+CCUS, Methane Pyrolysis, SOEC, PEC, PB, PF, and DF.
4	CAPEX	Estimated for POX, MP, PB, and DF.
5	OPEX	Estimated for ATR, ATR+CCUS, POX, MP, AWE, PEM, SOEC, PEC, PB, and DF.

2.3.2. Regression Model Formulation and Execution

The general form of the regression model is given as

$$Y = \beta_0 + \beta_1(TRL) + \beta_2(Energy\ Efficiency) + \beta_3(LCOH) + \varepsilon \quad (15)$$

where

Y is the dependent variable (production rate, CO₂ emissions, water consumption, CAPEX, and OPEX), β_0 is the intercept, β_1 , β_2 , and β_3 are the regression coefficients, and ε is the error term.

Each missing criterion was modelled independently. That is, five separate regression models were developed, one each for production rate, CO₂ emissions, water consumption, CAPEX, and OPEX. The regression analyses were performed using Microsoft Excel's Data Analysis Toolpak, and the resulting models were used to compute the missing values for the relevant alternatives. The statistical performance of each regression model was evaluated using statistics as summarised in Table 2. Although the p -values of the regression models exceeded 0.05 in most cases, indicating that the relationships were not statistically significant at the 95% confidence level, the models were employed solely as a pragmatic data imputation approach to estimate missing values where alternative data sources were unavailable. Compared with simple mean or median imputation, the regression models provided structured, criteria-informed estimates that preserved the completeness of the decision matrix required for the AHP-TOPSIS analysis. The R^2 values ranged from 0.09 to 0.77, indicating modest explanatory powers across the models. Accordingly, the regression-estimated values should be interpreted with caution and are intended only to support the comparative multi-criteria decision-making framework rather than to establish predictive relationships. In applying the regression models, only the deterministic components (intercept and regression coefficients) were used to compute point estimates for the missing values. The residual (error) term was excluded because the objective was to obtain consistent estimates for the dataset completion rather than to quantify prediction uncertainty.

Table 2. Statistics of performance of the regression models used for data imputation.

Variable	Observation	R ²	Adjusted R ²	F-Statistic	p -Value
Production Rate	12	0.22	−0.07	0.77	0.545
CO ₂ Emission	13	0.77	0.69	9.98	0.003
H ₂ O Cons.	9	0.70	0.52	3.82	0.091
CAPEX	13	0.09	−0.21	0.30	0.823
OPEX	7	0.23	−0.54	0.30	0.827

2.3.3. Summary of Data Completion

The hydrogen production pathways that contained missing data and the corresponding variables estimated using the regression models are presented below.

The regression models ensured that no data points were missing in the final decision matrix required for the TOPSIS-MCDA analysis; however, the imputed values and resulting rankings should be interpreted cautiously because of the limited statistical performance of the regression data. Table 3 presents the complete dataset after the regression models were applied, which serves as the final decision matrix for TOPSIS analysis.

Table 3. Decision matrix.

METHODS	TRL	Energy Eff. (%)	PR (Tons/Day)	CO ₂ Emission (kgCO ₂ /kgH ₂)	Water Consumption (L/kg)	LCOH (\$/kgH ₂)	CAPEX (\$/kW)	OPEX (\$/kW)
SMR	9.00 (a)	77.50 (b)	350.00 (c)	13.00 (d)	17.54 (e)	1.39 (f)	919.50 (g)	42.77 (h)
SMR+CCS	8.50 (a)	65.00 (b)	350.00 (c)	4.40 (d)	32.18 (e)	1.73 (f)	1637.00 (g)	49.11 (h)
ATR	9.00 (a)	67.50 (b)	607.00 (c)	10.50 (d)	7.40 (e)	1.34 (f)	939.00 (g)	244.90 *
ATR+CCS	8.00 (a)	64.00 (b)	607.00 (c)	2.80 (d)	24.22 (e)	2.02 (f)	1674.00 (g)	179.58 *
POX	9.00 (a)	65.00 (b)	750.00 (c)	10.50 (d)	16.38 *	1.48 (f)	1691.22 *	262.95 *
CG	9.00 (a)	79.50 (b)	650.00 (c)	22.99 (d)	31.00 (e)	1.92 (f)	2670.00 (g)	133.50 (h)
CG+CCS	6.50 (a)	67.00 (b)	650.00 (c)	4.87 (d)	49.44 (e)	2.01 (f)	3920.00 (g)	196.00 (h)
BG	8.00 (a)	42.50 (b)	264.00 (c)	2.50 (d)	16.28 (e)	1.91 (f)	1453.60 (g)	578.72 (h)
BG+CCS	7.00 (a)	35.00 (b)	75.45 (c)	−15.80 (d)	25.36 *	3.10 (f)	1716.53 (g)	336.17 (h)
MP	3.50 (a)	42.50 (b)	50.00 (c)	3.70 (d)	76.22 *	1.36 (f)	3204.48 *	−150.57 *
AWE	9.00 (a)	65.00 (b)	70.00 (c)	2.93 (d)	22.28 (e)	2.36 (f)	2000.00 (g)	279.87 *
PEM	9.00 (a)	80.00 (b)	50.00 (c)	2.37 (d)	17.52 (e)	4.95 (f)	2450.00 (g)	237.54 *
SOEC	6.50 (a)	89.00 (b)	171.01 *	1.49 (d)	58.11 *	4.50 (f)	2000.00 (g)	−76.13 *
PEC	4.00 (a)	10.00 (b)	−673.85 *	−53.70 *	45.84 *	8.86 (f)	1010.00 (g)	243.24 *
PB	3.00 (a)	5.00 (b)	−520.46 *	−46.56 *	57.99 *	7.05 (f)	1801.73 *	139.25 *
PF	4.00 (a)	0.10 (b)	−90.50 *	−28.20 *	46.30 *	3.16 (f)	1860.00 (g)	42.00 (h)
DF	5.00 (a)	70.00 (b)	60.10 *	−4.35 *	67.82 *	4.50 (f)	2899.34 *	−109.26 *

* Author's computation. Values marked with (*) were estimated using regression analysis as part of the data imputation procedure described in Section 2.3. These estimates were included solely to complete the comparative decision matrix and should be interpreted with caution, particularly where regression models exhibited limited statistical significance. (a) [38–41]. (b) [5,6,22,31,38,39,42–44]. (c) [2,39,42,43,45]. (d) [38,46–49]. (e) [50–53]. (f) [5,6,10,22,31,38,40–42,54–56]. (g) [2,4,31,46,48,55,57–61]. (h) [46,47]. Note: Negative production rate, CO₂ emission and OPEX values marked as regression estimates (Author's computation) are outputs of the regression-based imputation procedure and should be interpreted with caution. The negative CO₂ emissions reported for BG+CCS is derived from the literature and reflects its documented net-negative life cycle emissions.

It should be noted that, with the exception of the CO₂ emission value for BG+CCS, which was obtained directly from the literature and represents the net-negative life cycle emissions achievable through biomass carbon uptake and carbon capture and storage, several values in the decision matrix were estimated using regression analysis due to the unavailability of published data. These include CO₂ emission estimates for PEC, PB, PF, and DF, the production rate estimates for PEC, PB, and PF, and the OPEX estimates for methane pyrolysis (MP), SOEC, and DF. Some of these regression-derived estimates are negative. These negative values are mathematical outputs of the unconstrained regression models and should not be interpreted as physically negative hydrogen production rates, actual negative operating expenditures, or verified carbon-negative emissions for the affected technologies. Rather, they reflect the limitations of regression-based extrapolation under conditions of limited data availability. The regression estimates were retained to provide a complete and internally consistent decision matrix for the comparative AHP-TOPSIS analysis; therefore, the rankings of technologies with regression-imputed values should be interpreted with appropriate caution.

Table 2 summarises the statistical performance of the regression models used for data imputation. The models exhibited varying predictive performance, with R² values ranging from 0.09 to 0.77 and statistically significant relationships observed only for the CO₂ emission model ($p < 0.05$).

3. Results and Discussion

3.1. Results

The evaluation was carried out based on eight criteria: energy efficiency, technology readiness level (TRL), production rate (PR), carbon emissions, water consumption, levelised cost of hydrogen (LCOH), capital expenditure (CAPEX), and operational expenditure

(OPEX). The criteria were weighted using the analytical hierarchy process to determine their relative importance, after which the TOPSIS method was applied to rank seventeen hydrogen production methods accordingly.

3.1.1. Results of Analytical Hierarchy Process Analysis

The analytical hierarchy process method was used to determine the relative importance of the evaluation criteria through a pairwise comparison matrix. The priority weights were computed using the normalised eigenvector method (Equation (4)), while the consistency of the comparisons was verified using the consistency ratio formula (Equation (6)). The calculated criterion weights are presented in Figure 2.

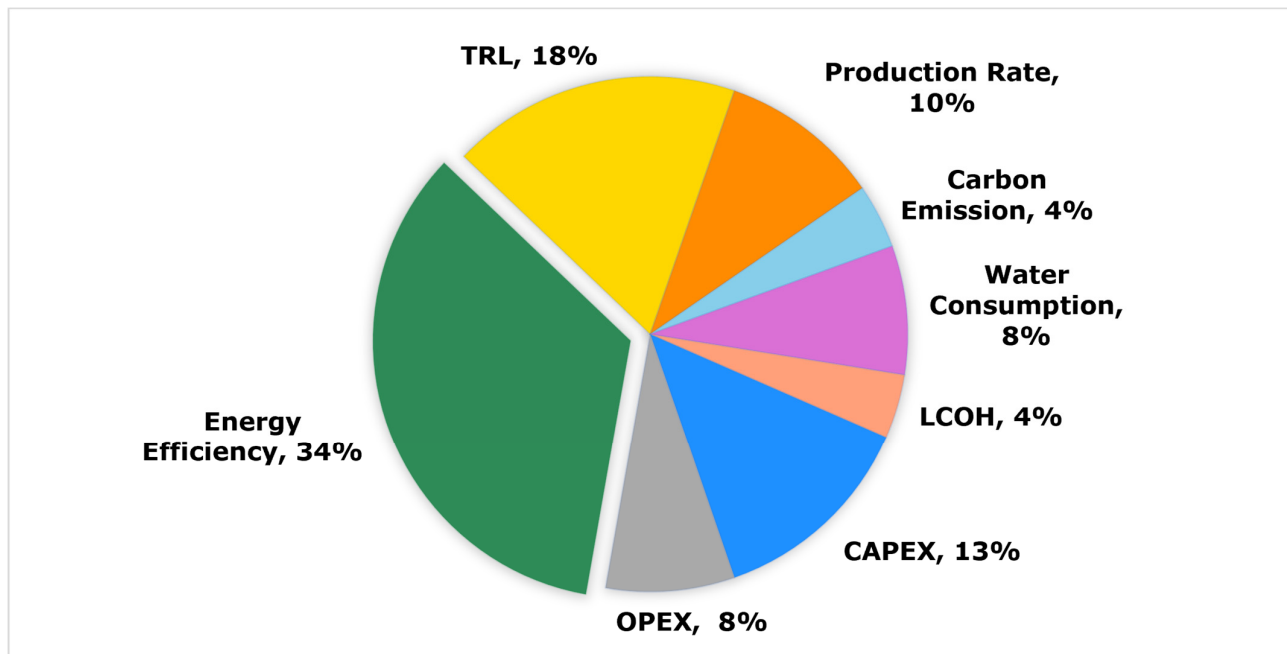


Figure 2. Relative weights of the evaluation criteria obtained using the analytical hierarchy process (AHP).

From the analytical hierarchy process-derived weights, energy efficiency emerged as the most critical criterion (34%), reflecting its significant role in sustainable hydrogen production. Technological readiness level (TRL) and capital expenditure (CAPEX) followed with 18% and 13%, respectively, emphasising the importance of technological feasibility and investment cost. Environmental concerns, such as carbon emissions and water consumption, had lower weights (4% and 8%, respectively), indicating they were considered less critical than economic and technical criteria in the decision-making process.

The weighting scheme adopted in this study reflects the specific objective of identifying hydrogen production pathways that provide balanced long-term technical, environmental, and economic performance rather than minimising production cost alone. Although hydrogen production cost remains a major barrier to large-scale commercialisation, the transition toward sustainable hydrogen systems also depends on factors such as energy efficiency, technology maturity, environmental performance, and operational feasibility. Consequently, the pairwise comparisons considered the combined importance of all selected criteria within the decision context, rather than prioritising any single economic indicator in isolation.

Previous multi-criteria studies have demonstrated that the selection and weighting of evaluation criteria vary according to the study objective, geographical context, and decision-maker priorities. For example, ref. [13] evaluated hydrogen production pathways

primarily using economic and environmental criteria, whereas more recent studies have adopted broader techno-economic and sustainability-based frameworks incorporating technological maturity, energy efficiency, environmental impact, and operational considerations. Recent AHP- and AHP-TOPSIS-based studies have further demonstrated that different weighting configurations may be appropriate depending on the intended application and policy context. Building upon these studies, the present work evaluates seventeen hydrogen production pathways using an integrated techno-enviro-economic framework that combines AHP for criteria weighting with TOPSIS for ranking the alternatives.

The prominence of energy efficiency in this study (34%) aligns with earlier AHP applications in energy systems, where efficiency was treated as a critical evaluation factor [62]. This outcome contrasts with [63], who applied AHP to hydrogen production methods and found CO₂ emissions (41.1%) to be the most influential criterion, followed by hydrogen production cost (23.7%) in one of its cases, the base case. Similarly, refs. [28,30] highlighted economic criteria, such as levelised cost of hydrogen and capital investment, as dominant factors. The divergence may be attributed to differences in study objectives. While earlier studies primarily sought to minimise environmental burden or production cost, the present work explicitly integrates sustainability and long-term viability, hence elevating energy efficiency as a decisive parameter.

The normalised pairwise comparison matrix for each criterion and the resulting criterion weights are presented in Table 4.

Table 4. Normalised pairwise comparison matrix.

Criteria	Energy EFF (%)	TRL	PR	CO ₂ Emission	H ₂ O Cons.	LCOH	CAPEX	OPEX	SUM	Criteria Weights	Criteria Weights (%)
Ener EF.	0.3723	0.4569	0.4110	0.2561	0.3659	0.2692	0.3516	0.2647	2.7476	0.34	34
TRL	0.1241	0.1523	0.2466	0.1829	0.2195	0.1923	0.1172	0.1765	1.4114	0.18	18
PR	0.0745	0.0508	0.0822	0.1098	0.0732	0.1154	0.2344	0.0882	0.8283	0.10	10
CO ₂ E.	0.0532	0.0305	0.0274	0.0366	0.0244	0.1154	0.0234	0.0294	0.3403	0.04	4
H ₂ O Con.	0.0745	0.0508	0.0822	0.1098	0.0732	0.1154	0.0586	0.0882	0.6526	0.08	8
LCOH	0.0532	0.0305	0.0274	0.0122	0.0244	0.0385	0.0391	0.0882	0.3134	0.04	4
CAPEX	0.1241	0.1523	0.0411	0.1829	0.1463	0.1154	0.1172	0.1765	1.0558	0.13	13
OPEX	0.1241	0.0761	0.0822	0.1098	0.0732	0.0385	0.0586	0.0882	0.6507	0.08	8
									8.00	1.00	100.00

The consistency-ratio calculation based on the weighted sum values and criterion weights as shown in Table 5.

Table 5. Calculating consistency ratio, CR.

CW	0.3435	0.176	0.1035	0.0425	0.0816	0.039	0.1320	0.0813			
Criteria	Ener EF.	TRL	PR	CO ₂ Emission	H ₂ O Cons.	LCOH	CAPEX	OPEX	Weighted Sum Value (WSV)	Criteria Weights (CW)	WSV/ CW
Ener EF.	0.3435	0.5292	0.5175	0.2975	0.4080	0.2744	0.3960	0.2439	3.0100	0.3435	8.76
TRL	0.1145	0.1764	0.3105	0.2125	0.2448	0.1960	0.1320	0.1626	1.5493	0.1764	8.78
PR	0.0687	0.0588	0.1035	0.1275	0.0816	0.1176	0.2640	0.0813	0.9030	0.1035	8.72
CO ₂ E.	0.0491	0.0353	0.0345	0.0425	0.0272	0.1176	0.0264	0.0271	0.3597	0.0425	8.46
H ₂ O Con.	0.0687	0.0588	0.1035	0.1275	0.0816	0.1176	0.0660	0.0813	0.7050	0.0816	8.64
LCOH	0.0491	0.0353	0.0345	0.0142	0.0272	0.0392	0.0440	0.0813	0.3247	0.0392	8.28
CAPEX	0.1145	0.1764	0.0518	0.2125	0.1632	0.1176	0.1320	0.1626	1.1306	0.1320	8.56
OPEX	0.1145	0.0882	0.1035	0.1275	0.0816	0.0392	0.0660	0.0813	0.7018	0.0813	8.63

3.1.2. Results of TOPSIS Analysis

The technique for order preference by similarity to ideal solution method was applied using the weighted normalised matrix derived from the analytical hierarchy process weights. Each hydrogen production pathway was evaluated based on its relative closeness (Ci) to the ideal solution. Figure 3 is a bar chart showing the TOPSIS analysis result.

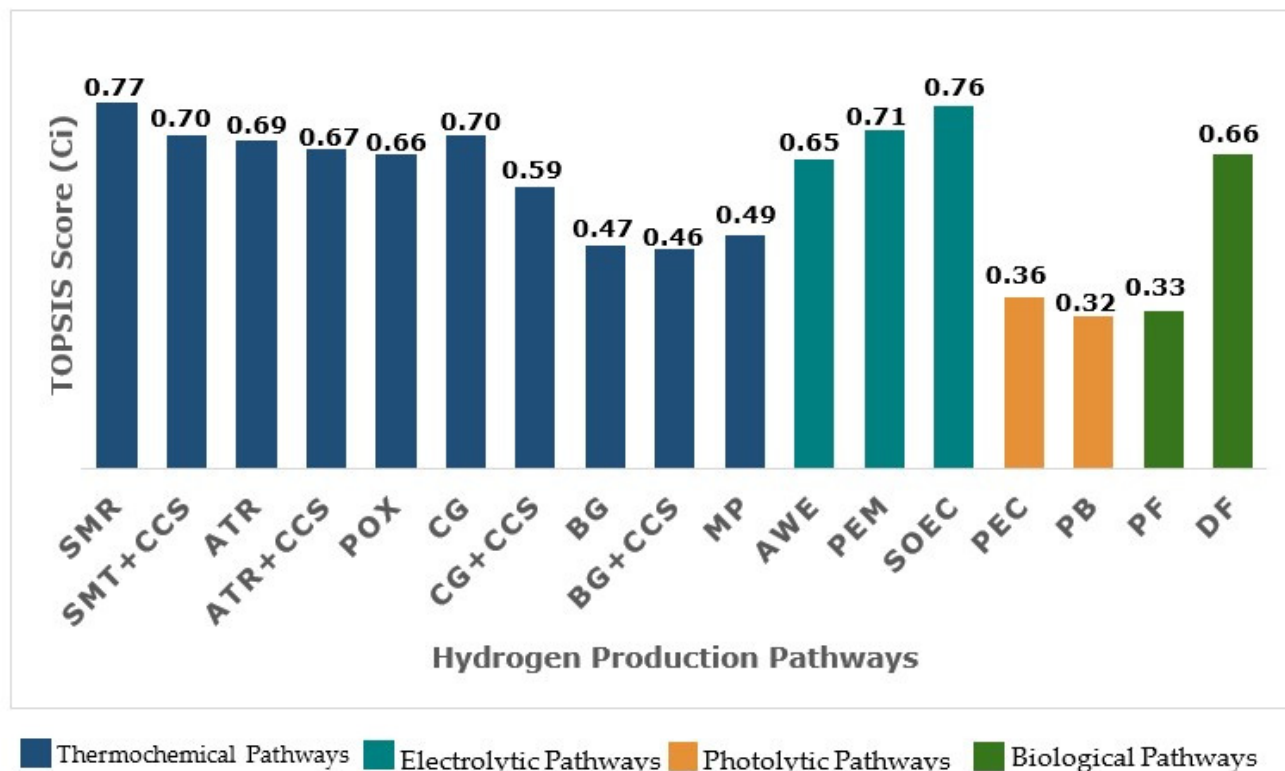


Figure 3. TOPSIS ranking of hydrogen production pathways based on relative closeness (Ci) value.

The TOPSIS analysis indicates that Steam Methane Reforming (SMR) is the most preferred hydrogen production method, mainly due to its balanced performance across cost, efficiency, and technological readiness. This result agrees with studies put forward by [9,63]. Solid Oxide Electrolysis (SOEC) and Proton Exchange Membrane Electrolysis (PEM) follow, with competitive scores due to their high efficiencies despite higher capital costs.

Biomass gasification with carbon capture and storage (BG+CCS) exhibited net-negative CO₂ emissions because the biomass feedstock absorbs atmospheric CO₂ during growth, while CO₂ generated during the gasification process is captured and permanently stored [64]. However, the extent of carbon removal depends on sustainable biomass sourcing, high CO₂ capture efficiency, and secure long-term geological storage [65]. Furthermore, large-scale deployment may be constrained by biomass availability and the additional capital and operating costs associated with carbon capture and storage [40,65].

Conversely, Photobiological (PB) and Photofermentation (PF) methods ranked lowest, primarily due to their low production rates, high costs, and limited maturity levels as presented in Figure 3. Table 6 presents the weighted normalised decision matrix and the computed relative closeness (Ci) scores for each hydrogen production pathway based on the TOPSIS method. A higher Ci value indicates closer proximity with the ideal solution. Steam Methane Reforming (SMR) ranked first with the highest Ci of 0.77, followed by Solid Oxide Electrolysis Cell (SOEC) and Proton Exchange Membrane (PEM) electrolysis. Pathways such as PEC, PF, and PB recorded the lowest Ci values, indicating poor performance across

multiple criteria, particularly in readiness level and economic feasibility. Table 6 highlights how each pathway compares across the techno–enviro–economic indicators.

Table 6. Calculating weighted normalised matrix and relative closeness.

METHODS	TRL	En. Eff (%)	PR (Tons/Day)	CO ₂ Emission (kgCO ₂ /kgH ₂)	H ₂ O Cons. (L/kg)	LCOH (\$/kgH ₂)	CAPEX (\$/kW)	OPEX (\$/kW)	S+	S−	Ci	Rank
SMR	0.0541	0.1055	0.0019	0.0062	0.0083	0.0036	0.0135	0.0036	0.0391	0.1324	0.77	1
SMR+CCS	0.0511	0.0885	0.0019	0.0021	0.0152	0.0044	0.0241	0.0041	0.0486	0.1133	0.70	4
ATR	0.0541	0.0919	0.0034	0.0050	0.0035	0.0034	0.0138	0.0204	0.0535	0.1180	0.69	5
ATR+CCS	0.0481	0.0872	0.0034	0.0013	0.0114	0.0052	0.0246	0.0149	0.0534	0.1083	0.67	6
POX	0.0541	0.0885	0.0042	0.0050	0.0077	0.0038	0.0249	0.0219	0.0577	0.1101	0.66	7
CG	0.0541	0.1083	0.0036	0.0109	0.0146	0.0049	0.0393	0.0111	0.0533	0.1246	0.70	4
CG+CCS	0.0390	0.0912	0.0036	0.0023	0.0233	0.0051	0.0577	0.0163	0.0712	0.1017	0.59	9
BG	0.0481	0.0579	0.0015	0.0012	0.0077	0.0049	0.0214	0.0481	0.0923	0.0824	0.47	11
BG+CCS	0.0420	0.0477	0.0004	−0.0075	0.0120	0.0079	0.0253	0.0280	0.0881	0.0738	0.46	12
MP	0.0210	0.0579	0.0003	0.0018	0.0360	0.0035	0.0472	−0.0125	0.0897	0.0872	0.49	10
AWE	0.0541	0.0885	0.0004	0.0014	0.0105	0.0060	0.0294	0.0233	0.0583	0.1075	0.65	8
PEM	0.0541	0.1090	0.0003	0.0011	0.0083	0.0127	0.0361	0.0198	0.0503	0.1241	0.71	3
SOEC	0.0390	0.1212	0.0009	0.0007	0.0274	0.0115	0.0294	−0.0063	0.0430	0.1385	0.76	2
PEC	0.0240	0.0136	−0.0037	−0.0255	0.0216	0.0227	0.0149	0.0202	0.1196	0.0660	0.36	13
PB	0.0180	0.0068	−0.0029	−0.0221	0.0274	0.0180	0.0265	0.0116	0.1264	0.0595	0.32	15
PF	0.0240	0.0001	−0.0005	−0.0134	0.0218	0.0081	0.0274	0.0035	0.1286	0.0629	0.33	14
DF	0.0300	0.0953	0.0003	−0.0021	0.0320	0.0115	0.0427	−0.0091	0.0596	0.1142	0.66	7

3.2. Key Findings

Presented in this section are the key findings derived from the multi-criteria decision analysis (MCDA) conducted using the AHP-TOPSIS hybrid method. The evaluation focused on 17 hydrogen production pathways assessed against eight techno–enviro–economic criteria, including energy efficiency, technology readiness level (TRL), production rate, levelised cost of hydrogen (LCOH), carbon footprint, water consumption, capital expenditure (CAPEX), and operational expenditure (OPEX). The analysis provides a holistic comparison of hydrogen production alternatives to determine the most sustainable and viable options for clean energy utilisation.

3.2.1. Technical Perspective

From a technical standpoint, pathways such as Proton Exchange Membrane Electrolysis (PEM), Alkaline Water Electrolysis (AWE), and Steam Methane Reforming (SMR) exhibited relatively high scores in terms of energy efficiency and technological readiness level as shown in Table 6, which presents the weighted normalised decision matrix and relative closeness values obtained from the TOPSIS analysis. Solid Oxide Electrolysis demonstrated high energy efficiency and ranked second overall in the AHP-TOPSIS analysis. However, its TRL remains slightly below that of Steam Methane Reforming (SMR), the most commercially established hydrogen production pathway.

Conversely, technologies such as Photobiological (PB) and Photo Fermentation (PF) demonstrated low technological readiness level and production rates, reflecting their nascent stage of development, as shown in the TOPSIS results presented in Figure 3. These technologies, while promising from a research standpoint, currently lack the technical maturity required for large-scale deployment.

3.2.2. Environmental Perspective

Environmentally, water electrolysis technologies, such as alkaline water electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis cell, generally outperform fossil fuel-based processes in terms of carbon footprint, especially when powered by renewable electricity. These methods produce little to no direct CO₂ emissions, making

them favourable for decarbonisation efforts. The comparative environmental performance of these technologies can be observed in the decision matrix (Table 3) and their influence on the final ranking presented in Table 6 and Figure 3.

On the other hand, steam methane reforming and Coal Gasification, despite being mature and efficient, have high carbon emissions, unless coupled with carbon capture, utilisation, and storage. The addition of carbon capture, utilisation, and storage to steam methane reforming and autothermal reforming considerably reduced their carbon intensity but introduced additional costs and energy penalties. Methane Pyrolysis (MP) stood out for its ability to produce hydrogen with minimal CO₂ emissions without the need for CCUS, although it remains at a lower TRL. Water consumption in this study represents the amount of water consumed during hydrogen production. Water requirements vary among production pathways and include process water as well as water used for cooling and auxiliary operations. For electrolysis, actual plant water demand exceeds the theoretical stoichiometric requirement because additional water is required for purification, cooling, and other balance-of-plant operations. Likewise, thermochemical pathways may require water across upstream and downstream activities, including natural gas production, biomass cultivation, coal mining, steam generation, and carbon capture where applicable. At large production scales, freshwater availability may therefore become a significant constraint, particularly in water-stressed regions. Integrating hydrogen production with desalination, wastewater reuse, and water-recovery technologies can reduce pressure on freshwater resources and improve system sustainability [50–53,66,67].

3.2.3. Economic Perspective

In terms of economic viability, traditional methods such as steam methane reforming and autothermal reforming have demonstrated the lowest LCOH, making them currently the most cost-effective for hydrogen production, as shown in the economic parameters reported in the decision matrix in Table 3. However, this cost advantage is counterbalanced by their environmental drawbacks. Electrolysis technologies, while cleaner, are still associated with higher LCOH due to electricity costs and capital investment, especially in proton exchange membrane and solid oxide electrolysis systems. CAPEX and OPEX findings reported in Table 3 revealed that mature technologies such as steam methane reforming and alkaline water electrolysis have lower costs compared to advanced or emerging technologies, such as solid oxide electrolysis, photoelectrochemical, and photobiological technologies. Notably, proton exchange membrane and alkaline water electrolysis showed competitive OPEX when operated at scale, suggesting potential long-term economic benefits if upfront costs can be reduced through innovation or policy incentives.

3.2.4. Overall Ranking and Insights

The application of the TOPSIS method yielded a ranked list of alternatives, with Steam Methane Reforming (SMR) emerging as the top performer (see Figure 3), primarily due to its high TRL, low LCOH, and established infrastructure. Despite its environmental drawbacks, the economic and technical advantages of SMR give it a comparative edge under current conditions. This result is consistent with [9,17], who also reported SMR dominance in current practice.

Electrolysis pathways such as SOEC and PEM followed closely in the ranking, reflecting their superior efficiency and environmental performance. Their positions in the ranking are clearly illustrated in Figure 3 and supported by their relative closeness values in Table 6. This aligns with [14,37], who highlighted SOEC and PEM as promising technologies for long-term sustainability, even though they remain more expensive today. Reference [63] further reinforces this perspective, emphasising that electrolysis technologies, particularly

when powered with renewable energy, represent the most viable long-term option for decarbonised hydrogen production, despite current economic limitations. Interestingly, while previous studies often ranked alkaline water electrolysis (AWE) higher due to lower CAPEX and maturity [68], the present results placed SOEC above AWE, underscoring the decisive weight given to energy efficiency in this study's integrated AHP-TOPSIS framework.

Although SOEC ranked second overall owing to its superior energy efficiency and favourable environmental performance, several technical challenges continue to limit its widespread commercial deployment. SOEC operates at high temperatures (typically 700–900 °C), which improves electrical efficiency by utilising thermal energy but also accelerates material degradation, thermal stress, and component ageing. In addition, the technology depends on a reliable supply of low-cost renewable electricity and, where applicable, high-temperature heat sources to achieve its full efficiency potential. The high capital cost of specialised ceramic materials and concerns regarding long-term stack durability remain major barriers to large-scale deployment. Nevertheless, ongoing advances in materials engineering, stack design, and renewable energy integration are expected to improve the commercial competitiveness of SOEC, reinforcing its potential as a key technology for future low-carbon hydrogen production [40].

At the lower end, Photobiological and Photofermentation methods ranked lowest (see Figure 3 and Table 6) due to their poor efficiency, low TRL, and scalability challenges. Similar findings were reported by [29,46], who noted that these biological approaches remain at the experimental stage with limited near-term deployment potential.

Overall, the results highlight the trade-offs between technological maturity, economic feasibility, and environmental sustainability in hydrogen production. While fossil-based technologies such as SMR currently dominate due to cost and infrastructure advantages, the results also indicate that advanced electrolysis technologies represent the most promising long-term pathways for sustainable hydrogen production.

4. Conclusions

This study carried out a comprehensive techno–enviro–economic comparative analysis of hydrogen production pathways for clean energy utilisation, applying the AHP-TOPSIS multi-criteria decision-making framework to 17 alternatives. The conclusions are drawn directly from the results obtained after addressing the specific objectives.

From a technical assessment, Steam Methane Reforming (SMR) demonstrated the strongest viability due to its low cost, maturity, and widespread industrial application.

Solid Oxide Electrolysis Cell (SOEC) and Proton Exchange Membrane (PEM) electrolysis exhibited high energy efficiencies and compatibility with renewable integration. While PEM has achieved a high technology readiness, the comparatively lower technology readiness level of SOEC indicates that it is less technologically mature than PEM and SMR, which may affect its near-term commercial adoption. In contrast, Photobiological and Photofermentation methods performed poorly, reflecting their experimental stage and low scalability.

In terms of the environmental dimension, electrolysis-based technologies SOEC, PEM, and AWE outperformed fossil-based processes with near-zero emissions when powered by renewable energy. However, these pathways required high water input, which can be problematic in water-scarce regions. Fossil-based technologies such as SMR and Coal Gasification exhibited high emissions unless coupled with CCUS, though even with CCUS, residual emissions remain.

On the economic front, SMR and Autothermal Reforming (ATR) were the most cost-competitive pathways, with SMR having the lowest LCOH, CAPEX, and OPEX. Electrolysis

pathways, while environmentally superior, were associated with higher costs, primarily from electricity requirements and capital investment.

Although the findings provide valuable insights into the comparative performance of the evaluated hydrogen production pathways, they should be interpreted in light of certain limitations. The rankings were derived using literature-based data, fixed AHP criterion weights, and regression-imputed values for missing parameters. Consequently, the results represent a comparative decision-support framework and may vary with different datasets, weighting schemes, or methodological assumptions.

By integrating the technical, environmental, and economic results through the AHP-TOPSIS framework, SMR ranked first overall, followed by SOEC and PEM. Based on the adopted evaluation criteria and weighting scheme, SMR emerged as the most practical option for near-term hydrogen production because of its cost competitiveness and technological maturity, while electrolysis pathways, particularly SOEC and PEM, demonstrate strong long-term potential as renewable electricity becomes more accessible and these technologies continue to mature. The study therefore underscores the dual challenge of balancing economic feasibility with environmental sustainability and highlights the importance of policy, innovation, and investment to accelerate the transition toward low-carbon hydrogen pathways.

Building upon this work, future research could consider the following:

- i. Incorporating sensitivity and uncertainty analyses using Monte Carlo simulation or scenario-based approaches to evaluate the robustness of the AHP-TOPSIS rankings under variations in criterion weights and key economic and policy parameters.
- ii. Geographic contextualisation of the evaluation framework, for example, assessing the best-fit hydrogen technologies for specific regions by integrating geographical information system (GIS) based data on local renewable resources, water availability, and energy infrastructure into the MCDA approach.
- iii. Improving the accuracy of techno-economic datasets of emerging hydrogen production pathways, particularly those with limited industrial deployment.
- iv. Future studies should incorporate multi-temporal scenario analyses considering projected carbon pricing, renewable electricity costs, and equipment CAPEX reductions to assess how future market and policy changes may influence the competitiveness of hydrogen production pathways.

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Nomenclatures

AHP	Analytic Hierarchy Process
ATR	Autothermal Reforming
AWE	Alkaline Water Electrolysis

BG	Biomass Gasification
CAPEX	Capital Expenditure
CCS	Carbon Capture and Storage
CCUS	Carbon Capture, Utilisation, and Storage
CG	Coal Gasification
CI	Consistency Index
CR	Consistency Ratio
DF	Dark Fermentation
GIS	Geographical Information System
LCOH	Levelised Cost of Hydrogen
MCDA	Multi-Criteria Decision Analysis
MP	Methane Pyrolysis
NIS	Negative Ideal Solution
OPEX	Operating Expenditure
PB	Photobiological hydrogen production
PEC	Photoelectrochemical hydrogen production
PEM	Proton Exchange Membrane electrolysis
PF	Photofermentation
PIS	Positive Ideal Solution
POX	Partial Oxidation
PR	Production Rate
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolysis Cell
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
TRL	Technology Readiness Level

SYMBOLS

A	Pairwise comparison matrix
A_{ij}	Pairwise comparison value
A^+	Positive ideal solution
A^-	Negative ideal solution
C_i	Relative closeness to the ideal solution
N	Number of criteria or alternatives
R_{ij}	Normalised decision-matrix value
S_i^+	Distance from the positive ideal solution
S_i^-	Distance from the negative ideal solution
V_{ij}	Weighted normalised decision-matrix value
W_i	Criterion weight
X_{ij}	Performance of alternative I under criterion j
$\Lambda_{\max}$	Maximum eigenvalue
β_0	Regression intercept
$\beta_1 - \beta_3$	Regression coefficients
ε	Regression error term
R^2	Coefficient of determination

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