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A Multi-Criteria Decision-Making Approach for Green Hydrogen Production via Renewable Energy Sources

Medine Türkmen*, Serap Ulusam Seçkiner

*[1]*Industrial Engineering, Engineering Faculty, Gaziantep University, Gaziantep, Türkiye*

*Corresponding author: mt9006@mail2.gantep.edu.tr
Orcid No: https://orcid.org/0009-0007-6842-2049

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Abstract: The global transition toward cleaner energy systems has intensified interest in green hydrogen as a sustainable and low-emission alternative to fossil-based fuels. However, selecting the most appropriate hydrogen production method remains a complex decision-making challenge due to the interplay of technical, economic, environmental, and social factors. This study applies the Analytic Hierarchy Process (AHP), a widely recognized multi-criteria decision-making (MCDM) approach, to systematically evaluate and rank various green hydrogen production technologies. A hierarchical framework was developed incorporating critical criteria such as investment cost, operational efficiency, environmental sustainability, and technological maturity. Expert judgments were used to assign relative weights to each criterion, and competing alternatives were assessed accordingly. The AHP analysis identified RW-Biomass: Bio Photolysis as the most favorable hydrogen production method, achieving the highest overall priority score (0.102), indicating its strong performance across the selected evaluation criteria. These results highlight the method's potential in aligning sustainability goals with practical energy planning, providing valuable insights for decision-makers in shaping future hydrogen strategies. The study confirms the effectiveness of AHP in delivering structured, transparent, and evidence-based assessments in the context of sustainable energy development.

Keywords: Green Hydrogen; Multi-Criteria Decision Making (MCDM); Analytic Hierarchy Process (AHP); Sustainability; Hydrogen Production Technologies;

1 Introduction

The ongoing global shift toward low-carbon energy systems has underscored the pivotal role of hydrogen in achieving long-term climate and energy goals. As nations strive to reduce emissions across the power, transport, and industrial sectors, hydrogen emerges as a promising alternative energy carrier. Among various production routes, green hydrogen produced via the electrolysis of water powered by renewable electricity offers significant environmental benefits due to its near-zero greenhouse gas emissions. It has been increasingly recognized as a vital element in decarbonization pathways and a central contributor to climate neutrality targets (Cetinkaya et al. 2012).

Nonetheless, technical, economic, and infrastructural barriers remain challenging the realization of green hydrogen's full potential. The variability of renewable energy sources, substantial capital investment for electrolysis infrastructure, and the lack of hydrogen transport and storage systems hinder its large-scale deployment (Valente et al. 2016). In this context, developing comprehensive and robust planning strategies is crucial to strike a balance between environmental performance, economic viability, and production scalability.

Strategic planning for hydrogen systems must address conflicting objectives under uncertain and dynamic conditions. This complexity necessitates the adoption of the MCDM methods capable of integrating diverse performance indicators such as energy efficiency, environmental footprint, production cost, technological maturity, and social acceptance. Previous studies have demonstrated that life cycle-based evaluations are effective in quantifying environmental and economic impacts of hydrogen production technologies (Valente et al. 2016), while decision-support frameworks can assist stakeholders in ranking alternatives based on sustainability criteria (Cetinkaya et al. 2012).

Li et al. (2020) further contribute to this field by proposing a novel MCDM framework that incorporates objective grey relational analysis (GRA) with DEMATEL for determining criteria weights. Their approach eliminates the reliance on subjective expert evaluations by using data-driven methods to establish interrelationships among criteria. This hybrid methodology enhances the objectivity of sustainability assessments and provides a clearer prioritization of hydrogen production technologies. Their work also highlights the necessity of evaluating environmental, economic, technological, and sociopolitical dimensions to guide decision-makers toward selecting the most sustainable pathways.

This study aims to explore how green hydrogen production planning can be optimized by systematically evaluating production alternatives using an integrated multi-criteria framework. By applying tools such as AHP and integrating expert judgments with quantitative performance metrics, the research seeks to identify viable options that balance capacity, cost, and environmental objectives.

From a theoretical perspective, this study extends the application of MCDM approaches in green hydrogen planning. Practically, it offers a structured, reproducible evaluation model to assist policymakers and industry stakeholders in making informed, balanced decisions aligned with broader sustainability goals.

The methodological approach used to implement this evaluation framework is presented in the next section, with a focus on the AHP model design, criteria weighting, and alternative assessment procedures.

2 Materials and Method

This study adopts a structured, three-stage methodology to evaluate green hydrogen production alternatives under multiple criteria using the AHP model. The approach integrates expert judgment with quantitative analysis to ensure a robust and context-specific decision framework. The methodology comprises the following phases:

- **Analytic Hierarchy Process (AHP):** Identification of the alternatives, criteria, and the hierarchical structure based on an extensive review of relevant literature and consultations with domain experts.
- **Data Gathering:** Collection of pairwise comparison judgments and performance evaluations from experts through structured questionnaires to determine criteria weights and alternative performance.
- **Sensitivity Analysis:** Evaluation of how variations in the criteria weights affect the final rankings of alternatives to examine the robustness of the decision-making model.

Each stage of the methodology is elaborated in the following subsections.

2.1 Analytic Hierarchy Process (AHP)

The AHP, developed by Saaty (1980), provides a systematic approach for solving multi-criteria decision problems by decomposing the decision into a hierarchy of goals, criteria, sub-criteria, and alternatives.

- **Goal:** Optimal selection of green hydrogen production method,
- **Criteria/Sub-criteria:** Cost, efficiency, sustainability, and technology readiness,
- **Alternatives:** Different hydrogen production pathways, such as electrolysis, biomass gasification, and photolysis.

This hierarchical structure enables structured comparison and prioritization of alternatives based on consistent and traceable logic. In line with Russo and Camanho (2015), the hierarchical structure in this study was constructed as shown in Fig 1.

The selection and formulation of criteria were guided by an extensive literature review and validated through expert consultation. Russo and Camanho (2015) emphasize the importance of contextual relevance, measurability, and clarity in criteria design, which was carefully observed in this study.

The decision-making framework incorporated a diverse range of hydrogen production pathways as shown in Fig 2, including conventional fossil-based processes, renewable biomass conversion methods, and advanced water-splitting technologies. These alternatives were selected to reflect the full spectrum of current technological options.

Particular emphasis was placed on ensuring a balanced representation of both mature and emerging technologies, thereby allowing for a comprehensive evaluation across economic, environmental, and technical dimensions. This inclusive selection supports a robust comparative analysis aligned with multi-criteria decision-making methodologies.

This study employed AHP to identify the most suitable production method through a multi-criteria evaluation that aligns technical, environmental, and economic considerations. Four main criteria were identified, each with multiple sub-criteria, and fourteen alternatives were identified for this model as shown in Table 1.

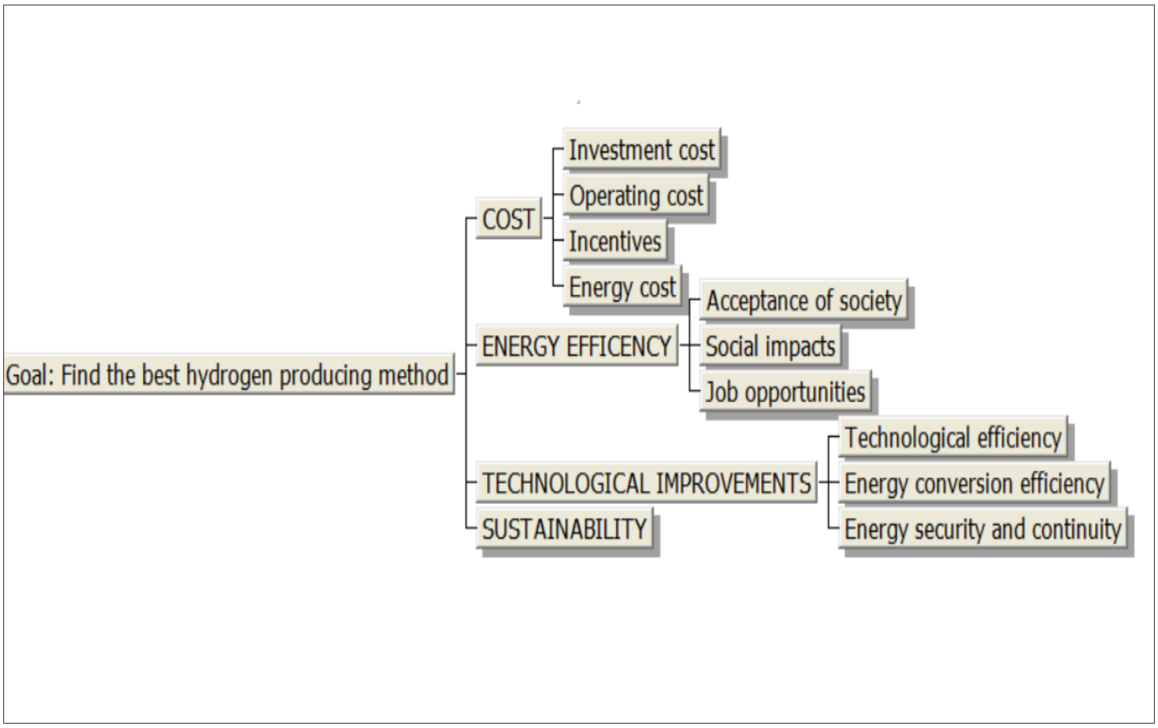

Fig. 1. The hierarchical structure of the AHP model

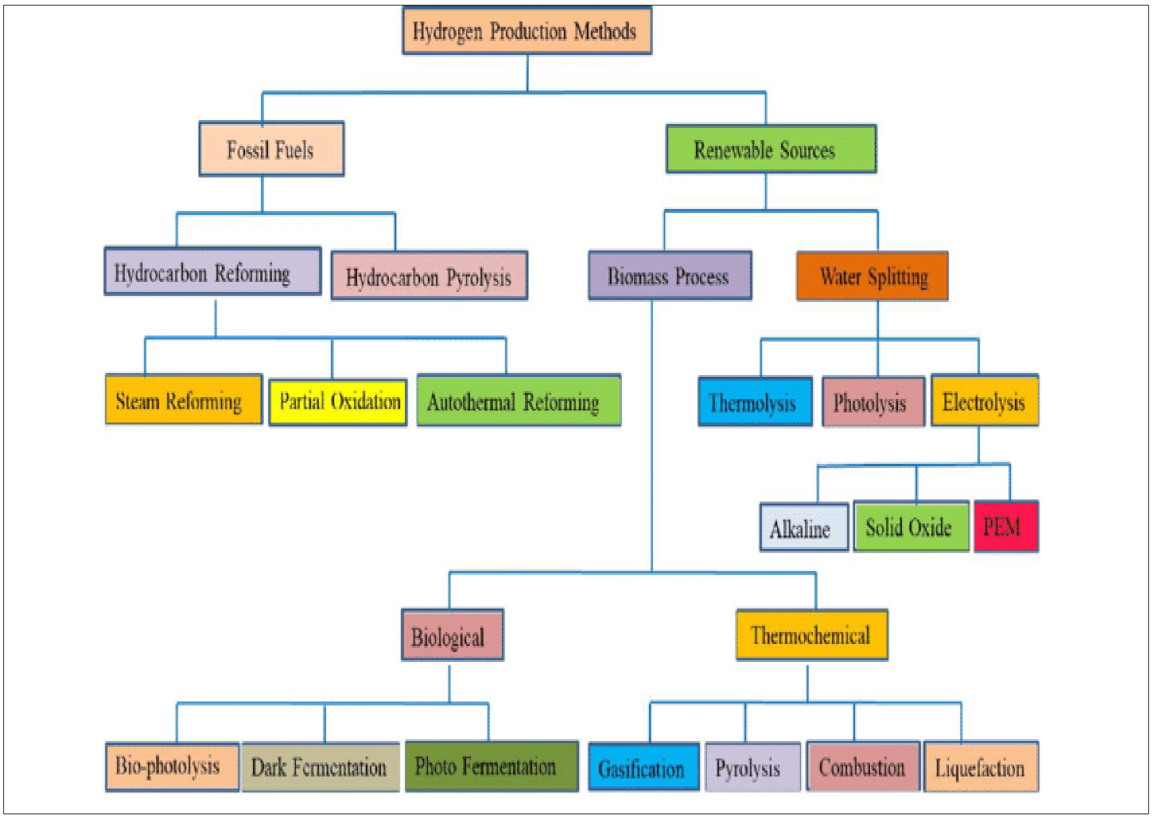

Fig. 2. Hydrogen Production Methods

Table 1 Criteria and Alternatives

Criteria and Sub-Criteria	Alternatives
Cost	**Fossil-Based**
• Investment Cost	• Steam Reforming
• Operating Cost	• Partial Oxidation
• Incentives	• Autothermal Reforming
• Energy Cost	• Hydrocarbon Pyrolysis
Technological Improvements	**Renewable-Biomass- Based**
• Technological Efficiency	• Bio-Photolysis
• Energy Conversion Efficiency	• Dark Fermentation
• Energy Security and Continuity	• Photo-Fermentation
Energy Efficiency	• Thermochemical Pyrolysis
• Social Acceptance	• Gasification
• Job Opportunities	• Combustion
• Social Impacts	• Liquefaction
Sustainability	**Renewable- Water Splitting**
	• Electrolysis
	• Thermolysis
	• Photolysis

2.2 Data Gathering

The pairwise comparisons were collected using Saaty's 1–9 fundamental scale to reflect the relative importance of each criterion concerning others. Data for criteria weights and alternative evaluations were collected through structured surveys conducted with domain experts, including academics and industry professionals in energy planning and hydrogen production. A total of 10 experts participated in the pairwise comparison process. The pairwise comparison matrix was constructed, and the priority weights were derived from the principal eigenvector. In Equation 1 was used to estimate weights:

$$A \cdot w = \lambda_{max} \cdot w \quad (1)$$

Where A is the pairwise comparison matrix, w is the eigenvector of weights, λ_{max} is the maximum eigenvalue of matrix A. To ensure consistency of expert judgments, the Consistency Ratio (CR) was calculated in Equation 2:

$$CR = \frac{CI}{RI}\ ,\ CI = \frac{\lambda max - n}{n-1} \quad (2)$$

Where CI is the random consistency index. A CR value below 0.10 was deemed acceptable (Saaty, 1980). For the alternative evaluations, experts provided performance scores for each hydrogen production method against each criterion. This data formed the decision matrix for final ranking calculations.

2.3 Sensitivity Analysis

To assess the robustness of the decision model, a sensitivity analysis was conducted by varying the weights of key criteria and observing the impact on the final rankings of the alternatives. This process identifies whether small changes in judgments or priorities result in significant shifts in outcomes. Such analyses are especially critical in energy planning studies, where uncertainty and evolving technological landscapes are common. As highlighted by Govindan and Jepsen (2016), sensitivity analysis in MCDM frameworks improves decision-maker confidence and enhances transparency in sustainable system assessments.

Following the implementation of the AHP model and synthesis of expert judgments, the subsequent section reports the results obtained and discusses their implications for green hydrogen production planning.

3 Results and discussion

In this study, AHP was applied to determine the most suitable hydrogen production method based on four main criteria: Cost, Energy Efficiency, Technological Improvements, and Sustainability. The AHP methodology allowed for the quantification of expert preferences and the prioritization of these criteria according to their relative importance. The performance of fourteen hydrogen production technologies was evaluated using these weighted criteria.

While the current results support Fossil-based hydrogen production methods, largely due to their cost-effectiveness, this does not necessarily reflect long-term sustainability goals. If future policies emphasize Sustainability or Technological Advancements, Renewable Water-Splitting and Biomass-based methods may rank higher. Therefore, a multi-scenario or dynamic weighting approach could be beneficial in strategic energy planning to accommodate shifts in policy or resource availability.

Based on the pairwise comparison matrix constructed using expert judgments, the following criterion weights were obtained:

- **Cost**: 52.52%
- **Energy Efficiency**: 19.77%
- **Technological Improvements**: 17.87%
- **Sustainability**: 9.84%

These results reveal that **Cost** is the most influential criterion in determining the optimal hydrogen production method, reflecting the economic sensitivity of current energy planning strategies. Using these weights, each alternative's overall AHP score was computed as the weighted sum of its performance across the four criteria. The alternative with the highest AHP score was Fossil-Steam Reforming, followed closely by Fossil-Partial Oxidation and Fossil-Autothermal Reforming. These alternatives generally exhibit low production costs and acceptable levels of efficiency, explaining their high ranking.

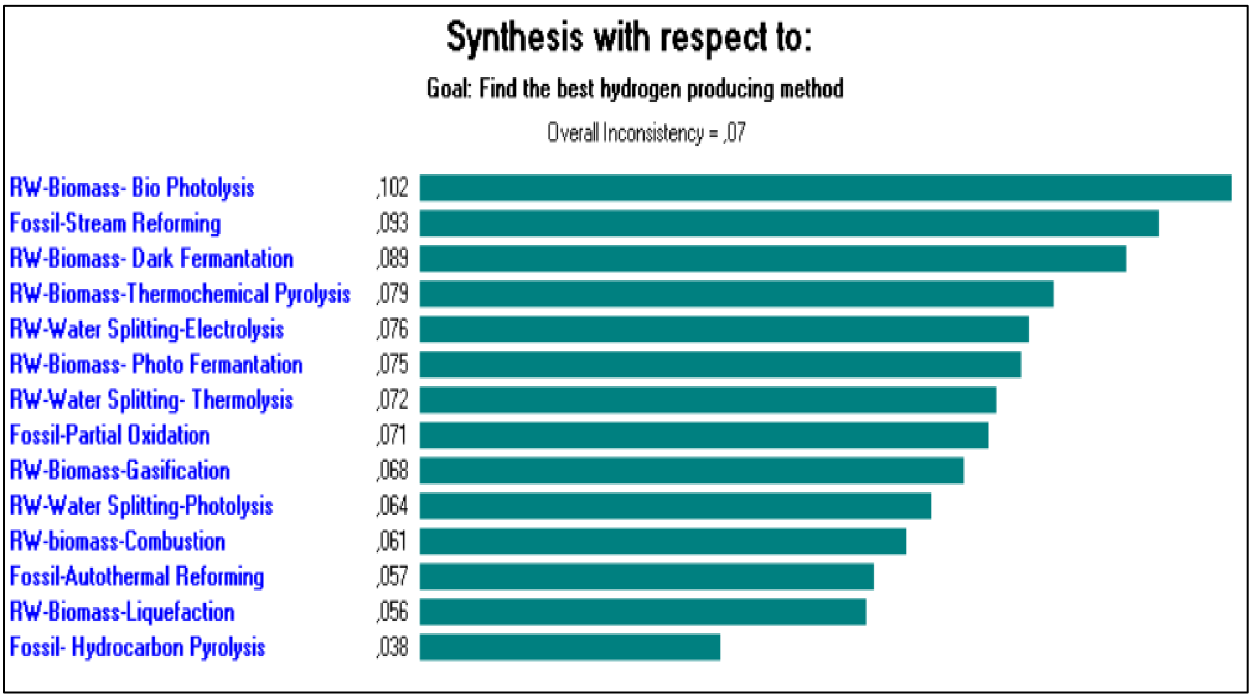

Fig. 3. The results of the AHP model

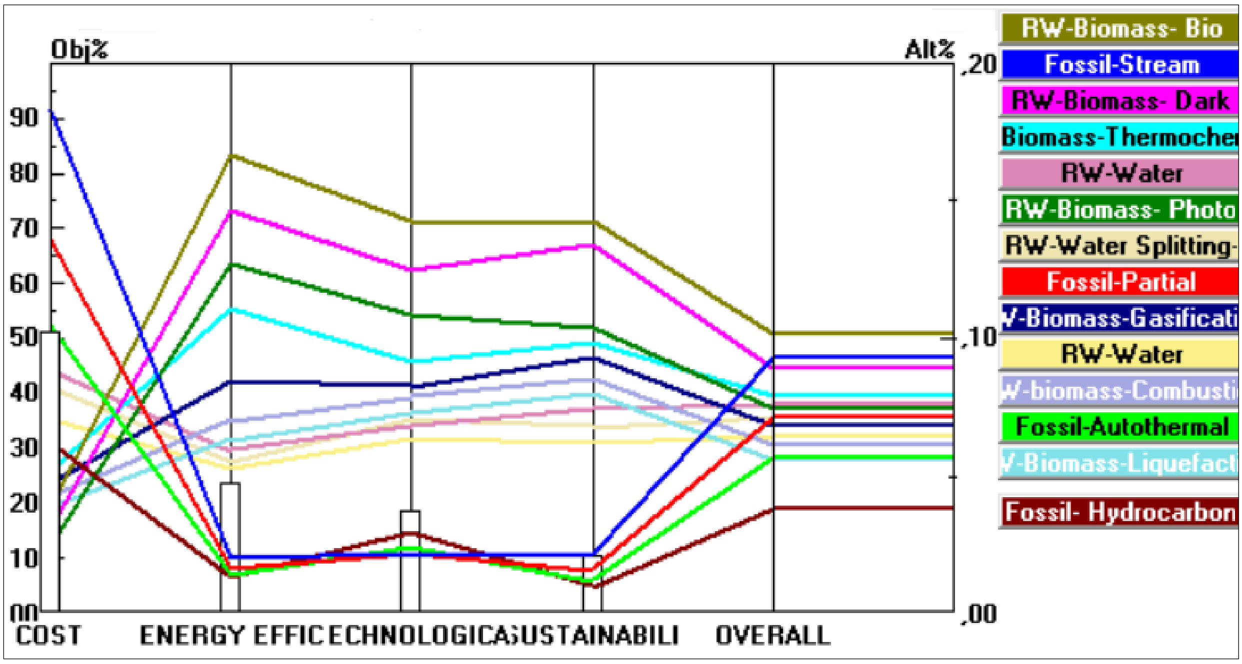

Fig. 4. Performance sensitivity analysis of the AHP model

As shown in Fig 3, RW-Biomass Bio Photolysis is ranked the highest with a weight of 0.102, suggesting it is the most preferred method when all considered criteria are aggregated. Fossil-Stream Reforming follows closely with a weight of 0.093, reflecting its strong performance, likely driven by cost efficiency. Other renewable-based technologies, such as RW-Biomass Dark Fermentation (0.089), RW-Biomass Thermochemical Pyrolysis (0.079), and Water Splitting via Electrolysis (0.076), also received relatively high scores, demonstrating the increasing viability of renewable and water-based hydrogen production pathways.

Conversely, methods such as Fossil-Hydrocarbon Pyrolysis (0.038) and RW-Biomass Liquefaction (0.056) received the lowest preference scores, indicating comparatively lower performance against the evaluation criteria.

The overall inconsistency ratio of the pairwise comparisons is reported as 0.07, which is within the acceptable threshold (<0.10), confirming the logical consistency of the decision-makers' judgments.

The sensitivity analysis, as illustrated in Fig 4, shows the performance variation of green hydrogen production alternatives in response to changing weights of the evaluation criteria: Cost, Energy Efficiency, Technological Advancement, and Sustainability. This analysis is essential for evaluating the robustness of the AHP model and

understanding the sensitivity of final rankings to shifts in decision-maker priorities.
The results indicate that the Cost criterion exerts the most significant influence on the overall performance of the alternatives. Alternatives such as Fossil-Steam Reforming (blue line) and RW-Biomass Bio (goldenrod line) display high sensitivity to cost fluctuations, with their performance scores peaking under cost-dominant scenarios. This implies that initial investment and operational expenses remain crucial determinants in the selection process, especially for cost-intensive or fossil-based technologies.
In contrast, under the Energy Efficiency and Technological Improvement criteria, the performance scores of the alternatives show minimal divergence. Most alternatives remain within a narrow performance band, suggesting that these criteria do not substantially disrupt the overall rankings. This indicates a relative equilibrium in technological maturity and energy conversion efficiency among the compared options. A notable observation is the convergence of performance scores across alternatives when Sustainability is emphasized. The graph shows less variation under this criterion, implying that while sustainability is an essential evaluation factor, it is less discriminating among alternatives. This could be attributed to the fact that most green hydrogen pathways inherently align with environmental sustainability principles. Alternatives such as RW-Biomass Bio, RW-Biomass Dark, and RW-Water consistently perform well across all criteria and maintain relatively high scores even when the weights shift. Their robustness under different conditions highlights their suitability for long-term deployment. Conversely, fossil-fuel-based options such as Fossil-Partial Oxidation and Fossil-Hydrocarbon Reforming (red and brown lines) exhibit consistently lower performance and less adaptability, emphasizing their comparative disadvantages in sustainable energy planning.
Overall, the sensitivity analysis validates the stability and resilience of the AHP model. The top-ranked alternatives maintain their superiority across a wide range of weight configurations, affirming that the final decision is not overly sensitive to minor judgmental variations. These findings support previous MCDM studies, which emphasize the importance of cost criteria while also acknowledging the moderating role of technological and environmental factors (Govindan and Jepsen, 2016).

To further assess the stability of the model and examine the influence of individual criteria on the final prioritization of hydrogen production alternatives, a dynamic sensitivity analysis was conducted.

As shown in Fig 5, this analysis provides a visual representation of how each alternative's ranking responds to variations in the relative weights of the four main criteria: Cost (50.2%), Energy Efficiency (22.5%), Technological Improvements (17.8%), and Sustainability (9.4%).
The left panel of the figure illustrates the default weights assigned to each criterion, which were derived from expert judgments using the AHP pairwise comparison method. The results indicate that Cost is the most dominant factor, accounting for over half of the total decision weight. This aligns with current literature in energy planning, where initial investment and operating expenditures significantly shape the viability of hydrogen technologies (Dincer and Acar, 2015).

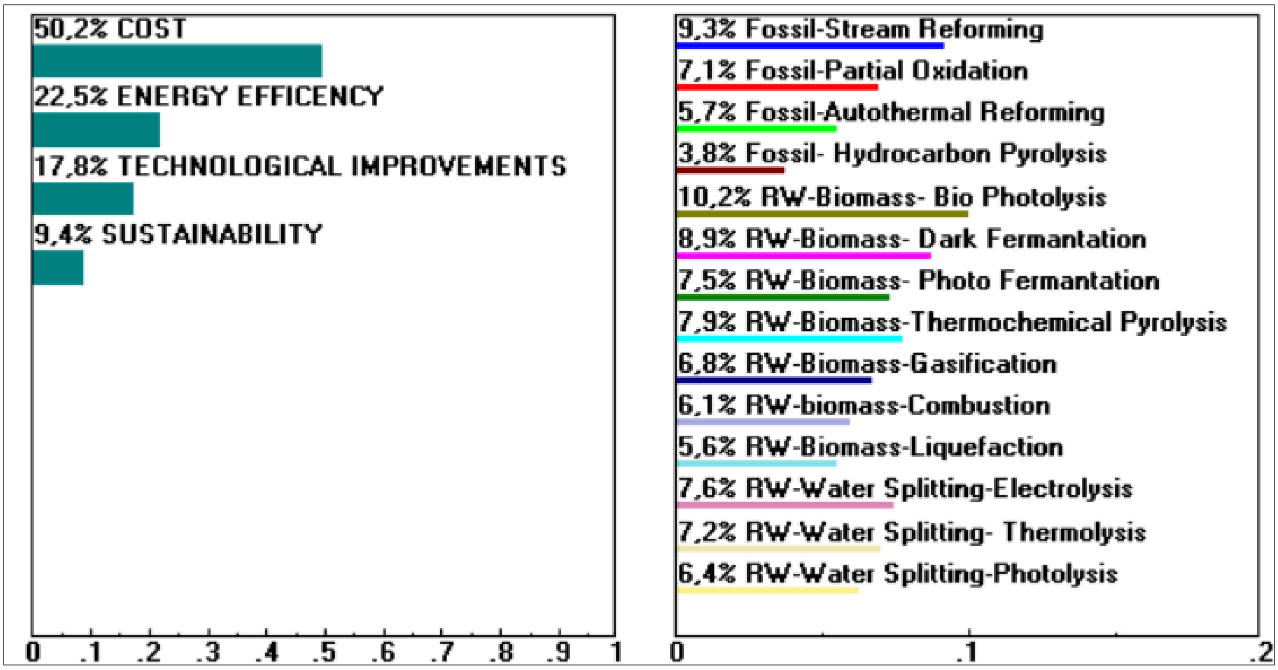

Fig. 5. Dynamic sensitivity analysis of the AHP model

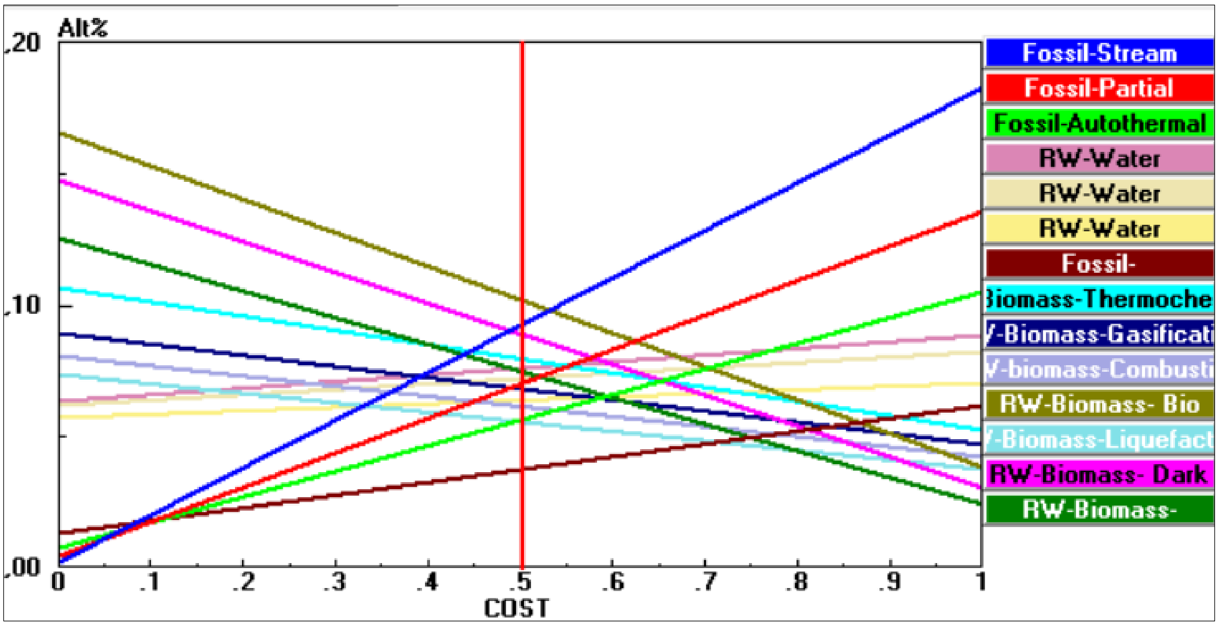

Fig. 6. Gradient Sensitivity Analysis for Cost Criterion in AHP Model

The right panel of the figure depicts the overall priority percentages of the 14 evaluated green hydrogen production alternatives. RW-Biomass Bio Photolysis (10.2%), RW-Biomass Dark Fermentation (8.9%), and RW-Biomass Thermochemical Pyrolysis (7.9%) emerge as the top-performing alternatives under the given weighting scheme. These biomass-based methods demonstrate strong performance across cost-effectiveness and technological feasibility, reflecting their increasing prominence in renewable hydrogen pathways (IEA, 2022).

Conversely, fossil-based alternatives such as Fossil-Hydrocarbon Pyrolysis (3.8%) and Fossil-Autothermal Reforming (5.7%) rank lower in the prioritization due to their higher environmental impacts and lower sustainability scores. These findings confirm that the model appropriately penalizes alternatives that are misaligned with long-term decarbonization goals.

The dynamic sensitivity analysis reveals that minor shifts in criterion weights, especially in cost and technological advancement, have a significant impact on the relative rankings of alternatives. This underscores the importance of understanding decision-maker preferences and conducting robust justification of weights, especially in policy-driven environments. Additionally, the relatively low sensitivity of rankings to the sustainability criterion indicates that while environmental impact is essential, its lower weight diminishes its discriminatory power in the current model structure.

Such dynamic visual tools are particularly useful for stakeholders to simulate real-world trade-offs and conduct “what-if” analyses under different strategic priorities, as recommended in multi-criteria energy system planning literature (Pohekar and Ramachandran, 2004).

To complement the static and dynamic analyses, a gradient sensitivity analysis was conducted to assess how variations in a single dominant criterion is Cost, impact the global rankings of hydrogen production alternatives. As depicted in Fig 6, this technique examines the trajectory (i.e., gradient) of each alternative’s overall score as the weight of the cost criterion increases from 0% to 100%, while maintaining proportional adjustments in the weights of the remaining criteria.

This form of analysis is particularly useful in evaluating the marginal impact of a criterion on the decision outcome and detecting any ranking reversals or crossing points among alternatives (Peniwati, 2007). The vertical red line in the graph marks the baseline cost weight at 50.2%, as determined from expert judgments.

Key Observations:

- Fossil-Steam Reforming (blue line) and Fossil-Partial Oxidation (red line) show sharply increasing slopes, indicating that their ranking significantly improves as cost becomes a more dominant criterion. This suggests their relative strength in economic feasibility compared to environmental or technological considerations.
- Conversely, RW-Biomass Bio Photolysis, RW-Biomass Dark Fermentation, and RW-Biomass Thermochemical Pyrolysis exhibit negative gradients, meaning their prioritization declines as the cost criterion weight increases. This behaviour reflects the higher upfront investment associated with biomass-based green hydrogen technologies, despite their advantages in sustainability and innovation.
- Several alternatives—such as RW-Water Electrolysis, Gasification, and Autothermal Reforming—show relatively flat gradients, implying that their rankings remain fairly stable across varying cost emphases. These pathways may represent more balanced trade-offs between economic and non-economic factors.

The presence of multiple intersection points among lines indicates potential ranking reversals depending on how much importance is assigned to cost. This insight is crucial for decision-makers operating under uncertain financial constraints or dynamic policy environments. It reinforces the notion that criteria prioritization should align with long-term sustainability goals, not just short-term cost considerations (Macharis et al. 2004). In summary, the gradient sensitivity analysis confirms that cost is a highly influential and volatile criterion, and alternative rankings are sensitive to its assigned weight. Therefore, any AHP-based decision support system should carefully justify the weight distribution to reflect stakeholder priorities accurately and transparently.

5 Conclusion

This study presents a comprehensive decision-making framework for evaluating green hydrogen production alternatives using the AHP model. In an era where sustainable energy planning is increasingly complex, the proposed model offers a systematic method for integrating technical, economic, environmental, and social criteria into strategic decision-making. The results demonstrate that AHP is a robust and transparent tool capable of managing multidimensional assessments in emerging energy systems.

The analysis revealed that biomass-based hydrogen production pathways, particularly RW-Biomass Bio Photolysis and Dark Fermentation, consistently outperformed fossil-based options under the baseline criteria weights. These alternatives provide synergies between environmental sustainability and technological innovation, although they are often limited by higher initial investment costs.

The sensitivity analyses, including performance-based, dynamic, and gradient sensitivity techniques, confirmed the dominant influence of the cost criterion, which accounted for over 50% of the total decision weight. Alternatives such as Fossil-Steam Reforming and Partial Oxidation gained priority when cost was emphasized, reflecting their economic viability but highlighting trade-offs in sustainability and long-term decarbonization compatibility.

Conversely, the performance stability of several renewable-based methods across different weight configurations suggests their strategic value under policy frameworks prioritizing environmental impact, technological maturity, and energy security. The sensitivity results also underscore the importance of aligning decision models with evolving national and regional energy strategies, as even small shifts in stakeholder priorities may lead to ranking reversals.

From a practical perspective, this study offers energy planners and policymakers a decision-support tool that is adaptable, scalable, and grounded in expert knowledge. It provides a transparent mechanism for justifying investment decisions in green hydrogen technologies, decisions that must carefully balance economic feasibility with long-term environmental objectives.

For future work, the integration of Fuzzy AHP, hybrid MCDM approaches (e.g., AHP-TOPSIS), or life cycle-based indicators can further enhance the decision model's depth and realism. Additionally, the application of the framework to specific regional contexts or dynamic policy scenarios (e.g., carbon pricing, subsidies) would strengthen its relevance for real-world planning.

In conclusion, AHP proves to be a valuable methodological tool for navigating the multifaceted landscape of green hydrogen production planning, offering a structured path toward sustainable energy transition.

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Authors' contributions:

MT conceptualized the study, conducted the data analysis, literature review and drafted the manuscript. SUS contributed to the methodology design and manuscript revision. Both authors read and approved the final version of the manuscript.

Conflict of interest disclosure:

The author declares no conflict of interest.

References

Çetinkaya E, Dinçer I, Naterer GF (2012) Life cycle assessment of various hydrogen production methods. Int J Hydrogen Energy 37:2071–2080

Dinçer I, Acar C (2015) Review and evaluation of hydrogen production methods for better sustainability. Int J Hydrogen Energy 40:11094–11111

Govindan K, Jepsen MB (2016) ELECTRE: A comprehensive literature review on methodologies and applications. Eur J Oper Res 250:1–29

International Energy Agency (2022) Global Hydrogen Review 2022. https://www.iea.org/reports/global-hydrogen-review-2022

Li W, Ren X, Ding S, Dong L (2020) A multi-criterion decision-making for sustainability assessment of hydrogen production technologies based on objective grey relational analysis. Int J Hydrogen Energy 45:34385–34395

Macharis C, Springael J, De Brucker K, Verbeke A (2004) PROMETHEE and AHP: The design of operational synergies in multicriteria analysis. Eur J Oper Res 153:307–317

Pohekar SD, Ramachandran M (2004) Application of multi-criteria decision making to sustainable energy planning—A review. Renew Sustain Energy Rev 8:365–381

Peniwati K (2007) Criteria for evaluating group decision-making methods. Math Comput Model 46:935–947

Russo RFSM, Camanho R (2015) Criteria in AHP: A systematic review of literature. Procedia Comput Sci 55:1123–1132

Saaty TL (1980) The analytic hierarchy process (AHP). J Oper Res Soc 41:1073–1076

Valente A, Iribarren D, Dufour J (2016) Life cycle assessment of hydrogen energy systems: A review of methodological choices. Int J Life Cycle Assess 22:346–363

Yıldırım B, Kantürk Figen A, Karakılçık M (2024) Hidrojen üretim yöntemleri. Hidrojen Teknolojileri 19