Journal of Renewable Energy and Sustainable Development (RESD) Volume 11, Issue 2, December 2025 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2025.11.2.1283
Received: 29 March 2025 Accepted: 13 July 2025 Published: 21 August 2025

Innovative Fuzzy VIKOR Approach for Green Hydrogen Technologies Assessment: Implications for Sustainable Energy Development

Fadoua Tamtam [1*], and Amina Tourabi [2]

[1,2] IBN ZOHR University, National School of Applied Sciences, Systems Engineering and Decision Support Laboratory (LISAD), Agadir, Morocco

fadoua.tamtam@gmail.com, a.tourabi@uiz.ac.ma

Abstract

The global energy transition necessitates the development of innovative, sustainable solutions to reduce greenhouse gas emissions and achieve decarbonization goals. This study addresses this imperative by evaluating green hydrogen technologies to guide decision-makers in identifying optimal solutions. The purpose of this research is to bridge the gap in existing literature by providing a comprehensive evaluation framework for technology selection, contributing to advancements in green hydrogen adoption. Using the Fuzzy VIKOR methodology, which integrates fuzzy logic with multi-criteria decision-making, this study systematically examines three key green hydrogen technologies: Electrolyzer Technology, Biomass Gasification Technology, and Photovoltaic Electrolysis Technology. Twelve critical criteria—including Technological Innovation, Financial Health, Regulatory Support, and Environmental Impact—were applied to ensure a thorough evaluation. The results indicate that Photovoltaic Electrolysis Technology emerges as the optimal solution, offering balanced performance across all criteria and addressing uncertainties inherent in the decision-making process. The findings of this study provide theoretical insights into decision-making models and practical guidance for policymakers and stakeholders to advance green hydrogen technologies. By contributing an innovative evaluation framework and addressing gaps in the literature, this study promotes sustainable and efficient energy practices, fostering progress towards global renewable energy goals.

Index-words: *Green hydrogen, Fuzzy VIKOR, Sustainable energy, Technological innovation, Environmental impact, Multi-criteria decision analysis.*

I. Introduction

The global energy landscape is undergoing a significant transformation driven by the urgent need to mitigate climate change and reduce greenhouse gas emissions [1]. Green hydrogen, produced through the electrolysis of water using renewable energy sources, has emerged as a promising solution to achieve these goals [2]. As nations and industries strive to meet ambitious decarbonization targets, the demand for innovative and scalable green hydrogen technologies continues to grow [3]. This study situates itself within this transformative era, examining state-of-the-art advancements and methodologies in green hydrogen production. However, despite its potential, the selection process for green hydrogen technologies faces significant challenges [4]. The absence of a comprehensive evaluation framework makes it difficult to identify the most suitable technology. Currently, there is no robust mechanism to address the complexities and multi-criteria nature of this selection process. This paper aims to address this research gap by proposing the application of the Fuzzy VIKOR approach—a systematic and novel methodology integrating fuzzy logic with multi-criteria decision-making.

Recent advancements in green hydrogen technologies underscore their potential to provide a sustainable and clean energy source [5]. For instance, Tahmasbi et al. [6] conducted a comprehensive review of hydrogen production technologies, focusing on green-electrolysis methods such as alkaline, proton-exchange membrane, and solid oxide electrolysis. Their findings underline the importance of developing efficient and reliable solutions for renewable hydrogen production. While valuable, their study does not provide guidance for comparative evaluation across competing technologies. Moreover, Pradhan et al. [7] emphasized the role of green hydrogen in achieving decarbonization and net-zero emissions by 2050. They highlighted the need to consider the entire hydrogen supply chain, including storage, transportation, and end-use applications, to fully realize the environmental benefits of green hydrogen. This underscores the necessity for a decision-making framework to address the complexities of technology selection. In addition, Gao et al. [8] provided insights into the progress and perspectives of next-generation green hydrogen technologies, focusing on the key components such as electricity, catalysts, and electrolytes in electrocatalytic water splitting. Their review recognized the technical challenges of scaling production but did not propose a systematic method for ranking technologies. This paper seeks to fill this void.

Several other studies have contributed to the understanding and development of green hydrogen technologies. Gul et al. [9] provided a comprehensive review of the VIKOR method and its fuzzy extensions, which are crucial for the multi-criteria decision-making process in evaluating green hydrogen technologies. Basu [10] discussed the practical design and theory behind biomass gasification and pyrolysis, providing valuable insights into one of the key technologies examined in this study. Navarro et al. [11] introduced the fundamentals of hydrogen production, offering a broad perspective on the various methods available. Fang et al. [12] reviewed the enhancement of solar hydrogen production efficiency through nanomaterials, underlining the technological advancements in this field. Nnabuife et al. [2] compared different hydrogen production technologies, highlighting their respective advantages and challenges. Hossain Bhuiyan and Siddique [13] critically reviewed the potential of hydrogen as a sustainable fuel source, emphasizing the need for efficient and scalable production methods. Abdul et al. [14] evaluated renewable energy technologies using an integrated AHP-VIKOR approach, which complements the Fuzzy VIKOR method applied in this study. Despite these contributions, an integrated framework for addressing the challenges inherent in green hydrogen technology selection remains elusive. To tackle all these challenges, this paper proposes the application of the Fuzzy VIKOR approach to systematically evaluate and rank three green hydrogen technologies: Electrolyzer Technology, Biomass Gasification Technology, and Photovoltaic Electrolysis Technology.

To further clarify the novelty of this study, the proposed approach introduces key refinements to the traditional Fuzzy VIKOR methodology, distinguishing it from previous applications in the literature. Unlike prior studies, which primarily applied standard fuzzy extensions, this paper integrates Circular Intuitionistic Fuzzy Sets (C-IFS) to enhance the representation of uncertainty in decision-making. C-IFS allows decision makers to define both membership and non-membership degrees using circular functions, improving the precision of linguistic assessments. Additionally, this study incorporates multi-expert decision aggregation, ensuring that diverse stakeholder perspectives are systematically integrated into the evaluation process. This contrasts with previous works that often relied on individual expert assessments, potentially leading to biased rankings. Furthermore, a sensitivity analysis framework is introduced to validate the robustness of the rankings under varying decision-maker preferences, an aspect frequently overlooked in conventional Fuzzy VIKOR implementations. By refining the fuzzy decision-making process and adapting it specifically to green hydrogen technology selection, this study provides a more comprehensive and adaptable evaluation framework that surpasses previous applications in terms of precision, stakeholder inclusivity, and robustness. These enhancements contribute to a more reliable and effective methodology for selecting optimal hydrogen technologies, addressing key limitations observed in earlier studies.

II. Literature review

A. Identification of key criteria for evaluating green hydrogen technologies

The evaluation of green hydrogen technologies demands not only a comprehensive framework but also a critical synthesis of existing research. While numerous studies highlight essential evaluation criteria—such as Technological Innovation, Financial Health, Regulatory Support, Infrastructure Development, Market Demand, Stakeholder Engagement, Financial Incentives, Technological Capability, Complementarity and Synergies, Geographical Position, Research and Development, and Environmental Impact—they often do so in isolation, leaving a fragmented understanding of how these factors interact and influence one another.

A comparative analysis reveals commonalities and differences across studies. For instance, Cannavacciuolo et al. [15] and Vărzaru and Bocean [16] emphasize the role of Technological Innovation in advancing production methods and scalability, whereas Vidas and Castro [17] prioritize Financial Health for ensuring long-term economic sustainability. Meanwhile, Maka and Mehmood [18] underscore the pivotal role of Regulatory Support in fostering adoption, a perspective echoed by Islam et al. [19], yet lacking an exploration of interdependencies with Infrastructure Development [20]. This oversight presents a gap, as regulatory frameworks often directly influence infrastructural advancements. Similarly, Stakeholder Engagement and Market Demand, as discussed by Jesse et al. [21] and Wappler et al. [22], are crucial for commercial success but are rarely examined in conjunction with Financial Incentives [23] or Technological Capability [24]. The lack of integration among these criteria limits the development of holistic strategies. Furthermore, studies on Complementarity and Synergies [25], [26] fail to fully address the geographical constraints highlighted by Messaoudi et al. [27], leaving questions about the adaptability of these technologies in diverse settings.

Environmental Impact remains a focal point, as emphasized by Shen et al. [28] and Sun et al. [29], yet there is insufficient attention to the trade-offs between environmental benefits and the resource-intensive nature of Research and Development [30], [31]. This gap underscores the need for more nuanced evaluations that balance innovation with sustainability.

Recent studies, such as those by Anand et al. [32] and Odenweller et al. [33], provide updated insights into the scalability and integration of green hydrogen technologies. These works emphasize advancements in electrolysis, cost reduction strategies, and the role of policy frameworks in accelerating adoption. Additionally, Revinova et al. [34] explore the application of learning curves to forecast cost reductions in green hydrogen production, highlighting the importance of learning-by-doing and learning-by-searching in achieving economic viability.

To underpin this study, the Ecosystem Framework has been adopted as the theoretical foundation [35]. This framework emphasizes the interconnectedness of technological, economic, and regulatory factors in scaling up green hydrogen technologies. It aligns with the research questions by providing a structured approach to evaluate the interplay between these criteria and their Impact on sustainability goals. Recent studies, such as Schwappach et al. [36], highlight the role of ecosystem theory in transitioning green hydrogen technologies from innovation to industrial scale, emphasizing joint value creation and risk reduction among stakeholders. Similarly, Jayachandran et al. [37] explore the challenges and opportunities in integrating green hydrogen into energy systems, focusing on infrastructure and logistics.

Furthermore, learning theories, such as learning-by-doing and learning-by-searching, are integrated into the analysis to explain how iterative improvements and knowledge accumulation drive technological advancements and cost reductions in green hydrogen production [38], [39]. Curcio [40] provides insights into the scalability barriers and cost reduction strategies for green hydrogen, emphasizing the importance of learning curves in achieving economic viability. Shash et al. [41] delve into computational methods and artificial intelligence applications in optimizing green hydrogen production, showcasing how machine learning enhances efficiency and scalability. Emilio J. and Edson [42] discuss the environmental benefits of green hydrogen production, highlighting the importance of considering the entire supply chain to maximize sustainability.

These findings collectively highlight the fragmented state of current research, underscoring the importance of a more integrated approach [43]. By addressing these gaps, this study aims to contribute to a more comprehensive framework for evaluating green hydrogen technologies, aligning with the overarching goals of decarbonization and sustainable development.

The literature reviewed for this study was selected using a systematic approach to ensure relevance, comprehensiveness, and reflection of the current state of the art. Peer-reviewed journal articles, conference proceedings, and industry reports published between 2019 and 2025 were prioritized, utilizing databases such as Scopus and Web of Science. Keywords such as "green hydrogen technologies," "ecosystem framework," "learning curves," and "scalability" guided the search process. Inclusion criteria focused on studies addressing evaluation frameworks, recent advancements, and

Volume 11, Issue 2, December 2025 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2025.11.2.1283

theoretical foundations pertinent to green hydrogen. To enhance rigor, the selected literature was cross-referenced with bibliographies of key studies to identify critical sources and emerging perspectives. This approach ensured that the review not only addressed the research questions but also captured the dynamic and evolving nature of the field.

Table 1: Summary of key criteria for evaluating green hydrogen technologies

Criteria	Description	References
Technological Innovation	Advances in production methods, efficiency, and scalability.	Gao et al. [26]
Financial Health	Economic viability and potential return on investment.	Yüksel et al. [44]
Regulatory Support	Policies and regulations that promote or hinder adoption.	Bade et al. [45]
Infrastructure Development	Availability and adequacy of production, storage, and distribution facilities.	Maka and Mehmood [46]
Market Demand	Potential market size and growth influence commercial success.	Asghari et al. [47]
Stakeholder Engagement	Involvement and support of governments, industries, and communities.	Schlund et al. [48]
Financial Incentives	Subsidies and tax breaks encourage adoption.	Nyangon and Darekar [49]
Technological Capability	Readiness and expertise to meet required standards and performance.	Tuluhong et al. [31]
Complementarity and Synergies	Integration with existing energy systems and other renewable sources.	Gao et al. [26]
Geographical Position	Location-specific advantages or challenges impacting project feasibility.	San Martin et al [50]
Research and Development	Innovations enhancing the efficiency and effectiveness of technologies.	Biabani et al. [51]
Environmental Impact	Potential environmental benefits and drawbacks of ensuring sustainability.	Hammi et al. [52]

B. The green hydrogen technology alternatives

Different studies converge on the recognition of green hydrogen technologies as pivotal for achieving decarbonization and sustainable energy systems [53]. Across the board, researchers agree on the potential of these technologies to reduce greenhouse gas emissions, enhance energy security, and support the transition to renewable energy sources [54]. For instance, electrolyzer technology is widely acknowledged for its zero direct carbon emissions when powered by renewable energy sources, as highlighted by El-Shafie [55] and Şahin [56]. Similarly, biomass gasification is praised for its ability to utilize waste materials and integrate with carbon capture and storage (CCS) to further reduce emissions, as discussed by Tezer et al. [57]. Photovoltaic electrolysis, on the other hand, is celebrated for leveraging solar energy to produce hydrogen, offering a decentralized and sustainable energy solution, as noted by Marques et al. [58].

However, divergence arises in the evaluation of these technologies due to differences in their scalability, cost-effectiveness, and environmental impacts. For example, while electrolyzer technology is lauded for its efficiency and scalability [59], its high capital costs and reliance on a stable renewable energy supply remain significant barriers. Biomass gasification, despite its environmental benefits, faces criticism for its complexity and energy-intensive processes, which may offset its overall efficiency [60]. Photovoltaic electrolysis, though promising for remote areas, struggles with the intermittent nature of solar energy and the need for advanced energy storage solutions [61].

Several contradictions and unresolved issues persist in the evaluation of green hydrogen technologies [62]. One major contradiction lies in the trade-off between efficiency and cost. For instance, while advancements in electrolyzer technology, such as proton-exchange membrane (PEM) and solid oxide electrolyzers, have improved efficiency, they also contribute to higher costs, creating a barrier to widespread adoption [63]. Similarly, biomass gasification's reliance on high-temperature processes raises questions about its net environmental benefits, especially when energy inputs are considered [64].

Another unresolved issue is the integration of these technologies into existing energy systems. Studies like those by Gao et al. [8] emphasize the need for efficient energy storage and distribution systems to support photovoltaic electrolysis, yet practical solutions remain underdeveloped [65]. Additionally, the geopolitical implications of green hydrogen adoption, such as resource allocation and international collaboration, are often overlooked, as highlighted in broader reviews of the hydrogen economy [66]. These contradictions and gaps underscore the need for a more integrated and interdisciplinary approach to evaluating green hydrogen technologies (Table 2).

Table 2: Additional studies highlighting the potential and challenges of green hydrogen technologies

Study	Focus	Key outcomes & conclusions	Preferred hydrogen technology
Jeje et al. [67]	Comprehensive review on sustainable hydrogen production methods	Identified key challenges in hydrogen production, including cost, efficiency, and scalability. Emphasized the need for policy support and technological advancements.	No specific preference stated.
Worku et al. [68]	Advances and future prospects in hydrogen production from renewables	Highlighted the potential of electrolysis-based hydrogen production, particularly using photovoltaic energy. Discussed integration challenges with existing energy systems.	Photovoltaic Electrolysis
Magableh and Bazel [69]	Multi-criteria decision-making for renewable energy technologies using fuzzy logic	Applied fuzzy logic to assess hydrogen technologies, emphasizing financial viability and environmental impact. Found biomass gasification to be a promising option.	Biomass Gasification
Kourougianni et al. [70]	Current state and future directions of hydrogen production technologies	Reviewed various hydrogen production methods, concluding that electrolyzer technology has the highest potential for scalability and efficiency improvements.	Electrolyzer Technology
Sitorus and Brito-Parada [71]	Decision-making methodologies for renewable energy technologies	Explored different decision-making frameworks for selecting hydrogen technologies. Found that stakeholder engagement plays a crucial role in technology adoption.	No specific preference stated.
Ourya and Abderafi [72]	Application of the Fuzzy VIKOR approach to evaluate hydrogen production technologies	Used the Fuzzy VIKOR method to rank hydrogen technologies based on multiple criteria. Found that photovoltaic electrolysis scored highest in terms of sustainability and efficiency.	Photovoltaic Electrolysis

C. *Fuzzy VIKOR methodology*

The research design for this study is descriptive and applied, focusing on systematically evaluating complex decision-making scenarios and providing practical solutions relevant to real-world applications. The study begins with a descriptive phase aimed at identifying key decision criteria and understanding the interplay of conflicting factors. This foundation ensures a comprehensive framework for applying advanced methodologies, with the applied aspect of the study addressing specific challenges in sustainability and engineering contexts.

Participants in this study are decision-makers characterized by their technical expertise, familiarity with multi-criteria decision-making processes, and ability to evaluate competing criteria effectively. Data collection combines both qualitative and quantitative methods, including structured interviews, expert assessments, and surveys. Instruments such as ranking matrices and evaluation scales are utilized to capture nuanced preferences and priorities.

The Fuzzy VIKOR methodology was selected due to its ability to incorporate fuzzy logic, making it particularly effective in addressing uncertainty and vagueness inherent in decision-making. Comparative analysis highlights the advantages of Fuzzy VIKOR over other multi-criteria decision-making (MCDM) techniques like TOPSIS and ANP. Unlike TOPSIS, which emphasizes proximity to the ideal solution, Fuzzy VIKOR ensures balanced decision-making by offering a compromise solution that accommodates conflicting criteria [73]. Additionally, Fuzzy VIKOR's computational efficiency makes it more suitable for practical applications compared to the complexity of ANP [74].

Mardani et al. [75] conducted a systematic review of the VIKOR technique, highlighting its widespread use in sustainability and renewable energy studies. The integration of fuzzy logic with VIKOR, known as Fuzzy VIKOR, has been particularly beneficial in handling uncertainty and vagueness in decision-making processes. For instance, Shumaiza et al. [76] explored the use of trapezoidal bipolar fuzzy VIKOR for group decision-making, which was applied in selecting waste treatment methods and thermal power plant sites. Ozdemir et al. [77] integrated Fuzzy VIKOR with the Analytic Hierarchy Process (AHP) to improve decision-making accuracy in personnel selection for IT firms. The methodology has also been utilized in maintenance strategy selection in the paper industry, providing a robust framework for evaluating and choosing optimal strategies under uncertain conditions. These studies underscore the robustness and adaptability of Fuzzy VIKOR in addressing complex decision-making challenges across diverse domains.

In environmental management, Fuzzy VIKOR has been instrumental in assessing the sustainability of various projects. Its ability to accommodate multiple, often conflicting criteria makes it a valuable tool for evaluating renewable energy solutions and their environmental impacts [75]. Furthermore, its application in engineering and manufacturing highlights its utility in selecting the best design schemes, technologies, and suppliers by considering multiple performance indicators under uncertainty [78].

The advantages of Fuzzy VIKOR are manifold. It effectively incorporates fuzzy logic to handle the ambiguity and vagueness of human judgments, providing more realistic and reliable decision outcomes [79]. Additionally, the methodology's ability to find a compromise solution is particularly beneficial in scenarios involving conflicting criteria, ensuring that the selected alternative represents the best trade-off among all considerations [80]. Fuzzy VIKOR also enhances decision-making accuracy by integrating with other MCDM methods such as AHP, thereby leveraging the strengths of multiple approaches to achieve more comprehensive evaluations [81]. Its flexibility and adaptability make it a valuable tool for researchers and practitioners alike, as evidenced by its widespread application in various fields.

III. Research methods

The Fuzzy VIKOR technique integrates fuzzy logic into the VIKOR method, providing a systematic and rational approach to determine the best and compromise solutions using linguistic expressions. This process involves several steps, each contributing to the comprehensive evaluation of alternatives [82].

A. Identification of decision makers, alternatives, and criteria

Initially, n decision makers, m alternatives, and k criteria are identified to address the problem.

The number of decision makers *(n)* is selected based on the expertise required to assess green hydrogen technologies. These decision makers typically include industry experts, policymakers, researchers, and stakeholders who provide evaluations based on their knowledge and experience. The selection process ensures a diverse and representative group, allowing for a balanced and unbiased assessment.

The number of alternatives *(m)* corresponds to the green hydrogen technologies under evaluation. In this study, three alternatives—Electrolyzer Technology, Biomass Gasification Technology, and Photovoltaic Electrolysis Technology—are considered, chosen based on their technological feasibility, environmental impact, and economic viability.

The number of criteria *(k)* is determined by identifying key factors that influence the selection process, ensuring comprehensive evaluation across multiple domains. These criteria are structured to capture aspects such as technological innovation, financial health, regulatory support, infrastructure development, market demand, and environmental impact, among others. Figure 1 illustrates the structured configuration of the proposed Circular

Intuitionistic Fuzzy VIKOR framework, detailing the multi-expert evaluation process, integrated decision criteria, and methodological refinements applied for selecting optimal hydrogen technologies in the context of sustainable energy transition.

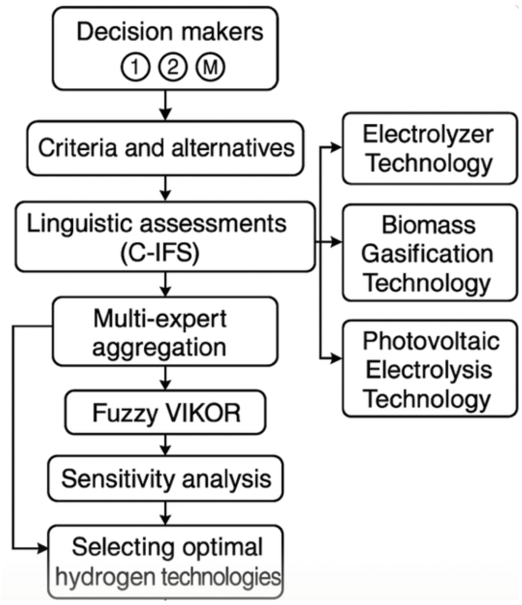

Figure 1: Schematic representation of the comprehensive evaluation process for green hydrogen technologies.

The inputs in this fuzzy decision-making framework consist of the criteria evaluations assigned by decision makers. These inputs are represented as linguistic variables that describe the performance of each alternative based on TFNs. The outputs of the fuzzy VIKOR method are the aggregated fuzzy performance scores of each alternative across multiple criteria. These are computed through fuzzy mathematical operations to obtain the $\widetilde{S_\iota}$, $\widetilde{R_\iota}$, $\widetilde{Q_\iota}$ and values, which reflect:

- $\widetilde{S_\iota}$ (Total Weighted Distance from the Best Solution) – Represents the overall deviation of an alternative from the ideal solution.
- $\widetilde{R_\iota}$ (Maximum Regret Distance) – Captures the worst-case scenario performance of each alternative.
- $\widetilde{Q_\iota}$ (Compromise Ranking Index) – Balances the best and worst cases to determine the final ranking of the alternatives.

The fuzzy rule base defines the decision logic applied to process fuzzy inputs and derive fuzzy outputs. It establishes the relationship between criteria ratings and alternative rankings, ensuring consistency in the evaluation process. The rules are structured as follows:

- **Rule 1:** If an alternative scores high on criteria such as technological capability, stakeholder engagement, and regulatory support, then its $\widetilde{S_\iota}$ value is low, indicating strong overall performance.
- **Rule 2:** If an alternative exhibits significant variance across different criteria, then its $\widetilde{R_\iota}$ value is high, suggesting instability in performance.
- **Rule 3:** If an alternative maintains consistent strengths across criteria with minimal deviations, then its $\widetilde{Q_\iota}$ value is low, making it the most suitable option.
- **Rule 4:** If an alternative scores significantly lower than others in multiple critical criteria, then it receives a high $\widetilde{Q_\iota}$ value and is ranked lower.

Figure 2 illustrates the structured decision-making process of the Fuzzy VIKOR method, incorporating linguistic evaluations, fuzzy computations, and decision rules to determine the optimal green hydrogen technology.

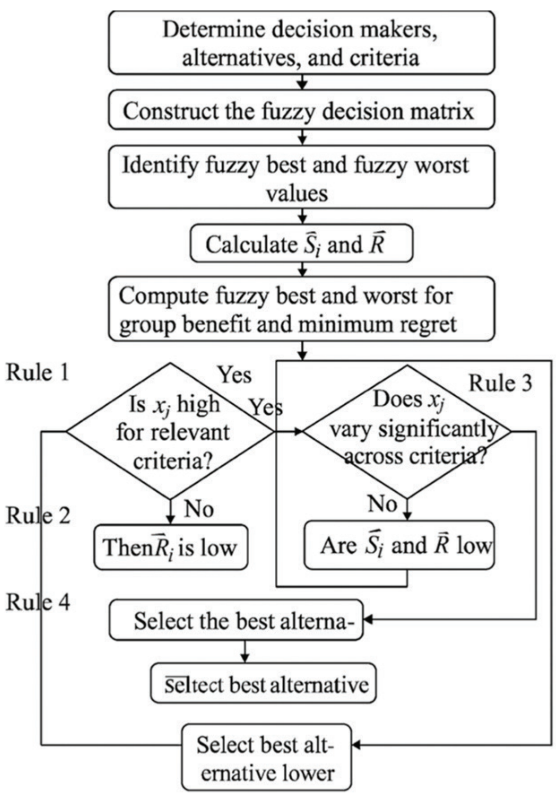

Figure 2: Fuzzy VIKOR decision-making process.

B. Definition of Linguistic Variables and Fuzzy Numbers

Linguistic variables provide a structured way to express subjective assessments in decision-making processes, particularly when dealing with uncertainty in evaluations [83]. These qualitative descriptors, such as "Very Weak" or "Well," are transformed into triangular fuzzy numbers (TFNs) to quantify their meaning in a way that accounts for variability in expert opinions [84]. A TFN is represented as (a, b, c), where a denotes the lowest possible value, b is the most likely estimate, and c is the upper bound, allowing for a more flexible interpretation of criteria weights and alternative evaluations. In this study, the Simplified Analytical Hierarchy Process (SAHP) method is used to determine the importance of each criterion, incorporating fuzzy logic to refine pairwise comparisons among criteria. The SAHP methodology enhances the reliability of weight calculations by leveraging fuzzy preference relations, ensuring that expert opinions are systematically aggregated rather than relying on fixed numerical inputs.

The membership limits in Table 3 are determined based on expert evaluations and fuzzy logic principles, ensuring a smooth transition between linguistic variables. The scaling of membership functions from 0 to 10 is chosen to provide a normalized range that aligns with common fuzzy logic applications. This range ensures that evaluations remain intuitive and comparable, preventing extreme values from skewing the decision-making process. Additionally, a 0 to 10 scale allows for greater granularity, enabling finer distinctions between linguistic terms while maintaining computational efficiency.

Table 3: Linguistic variables used for alternative assessment

Linguistic variables	Triangular fuzzy numbers
Very weak/low	(0, 0, 1)
Weak	(0, 1, 3)
Moderate weak	(1, 3, 5)
Moderate well	(5, 7, 9)
Well	(7, 9, 10)
Very well	(9, 10, 10)

C. Aggregation of decision makers' evaluations

The evaluations from the decision makers are combined, and the integrated fuzzy weight for each criterion is calculated using a specific equation [84]. The Combined Fuzzy Decision Matrix was developed by aggregating expert evaluations using fuzzy logic principles. Evaluations from decision makers were collected and converted into triangular fuzzy numbers (TFNs), representing a range with lower, middle, and upper values. These individual assessments were then aggregated using a specific equation to generate a consensus-based fuzzy weight for each criterion. The aggregated fuzzy weight $\widetilde{wj}$ given by the i-th decision maker for the j-th criterion can be calculated using the Equation:

$$\widetilde{wj} = \frac{1}{n}\left[\sum_{e=1}^{n}\widetilde{wj}^{e}\right] \qquad j = 1, \dots, k \tag{1}$$

Figure 3 shows the comparative fuzzy evaluations of Technological Innovation (C1) for the considered hydrogen technologies.

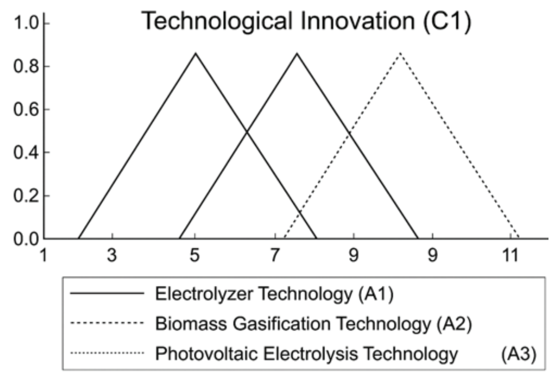

Figure 3: The triangular fuzzy membership functions for Technological Innovation (C1).

The twelve evaluation criteria have been systematically modeled using triangular fuzzy membership functions and presented in Table 4.

Table 4: Combined fuzzy decision matrix

Criteria	Electrolyzer Technology (A1)	Biomass Gasification Technology (A2)	Photovoltaic Electrolysis Technology (A3)
Technological Innovation (C1)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
Financial Health (C2)	(1, 3, 5)	(3, 5, 7)	(5, 7, 9)
Regulatory Support (C3)	(5, 7, 9)	(7, 9, 10)	(3, 5, 7)
Infrastructure Development (C4)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)
Market Demand (C5)	(5, 7, 9)	(3, 5, 7)	(1, 3, 5)
Stakeholder Engagement (C6)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
Financial Incentives (C7)	(5, 7, 9)	(3, 5, 7)	(1, 3, 5)

Technological Capability (C8)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)
Complementarity and Synergies (C9)	(3, 5, 7)	(5, 7, 9)	(7, 9, 10)
Geographical Position (C10)	(5, 7, 9)	(3, 5, 7)	(1, 3, 5)
Research and Development (C11)	(7, 9, 10)	(5, 7, 9)	(3, 5, 7)
Environmental Impact (C12)	(3, 5, 7)	(1, 3, 5)	(5, 7, 9)

D. The fuzzy decision matrix

A fuzzy decision matrix $\tilde{X}$ is constructed to systematically organize the evaluations provided by decision makers, ensuring that the criteria for each alternative are assessed under uncertainty [85]. Each entry $\widetilde{x_{ij}}$ in the matrix represents the fuzzy rating assigned to the i^{th} alternative with respect to the j^{th} criterion, using triangular fuzzy numbers (TFNs) to capture variations in expert opinions. This matrix serves as the foundation for the fuzzy VIKOR analysis, enabling multi-criteria decision-making by incorporating subjective judgments in a structured format. The fuzzy weights $\widetilde{w_j}$ are aggregated and applied to the evaluations to enhance comparability across alternatives, facilitating the ranking and selection process. It is represented as:

$$\widetilde{w_j} = \begin{bmatrix} \widetilde{x11} & \widetilde{x1k} \\ xm1 & xmk \end{bmatrix} \quad i=1,\ldots,m \quad j=1,\ldots,k \tag{2}$$

Where $\widetilde{x_{ij}}$ is the fuzzy rating of the i-th alternative with respect to the j-th criterion.

E. Fuzzy best and worst values

The fuzzy best values $\widetilde{f_j}*$ represent the optimal ratings that an alternative can achieve for a given criterion, indicating the most favorable evaluation based on expert assessments. Conversely, the fuzzy worst values $\widetilde{f_j}-$ denote the least desirable ratings, signifying the lowest level of performance across alternatives for that criterion. These values are extracted from the fuzzy decision matrix by applying maximum and minimum functions, respectively, ensuring a structured comparison between alternatives. The formulation follows the principles outlined by Opricovic and Tzeng [80], enabling a robust ranking system that integrates fuzzy logic to manage uncertainty in decision-making. By determining the fuzzy best and worst values, this step establishes reference points for subsequent evaluations, allowing for a relative assessment of each alternative's strengths and weaknesses in the selection process. They are defined as:

$$\widetilde{f_j}* = \max \widetilde{x_{ij}} \tag{3}$$

$$\widetilde{f_j}- = \min \widetilde{x_{ij}} \tag{4}$$

Table 5: Fuzzy best and worst values

Criteria	$\widetilde{f_j}*$	$\widetilde{f_j}-$
C1	(9, 10, 10)	(3, 5, 7)
C2	(5, 7, 9)	(1, 3, 5)
C3	(7, 9, 10)	(3, 5, 7)
C4	(7, 9, 10)	(3, 5, 7)
C5	(5, 7, 9)	(1, 3, 5)
C6	(7, 9, 10)	(3, 5, 7)
C7	(5, 7, 9)	(1, 3, 5)
C8	(7, 9, 10)	(3, 5, 7)
C9	(7, 9, 10)	(3, 5, 7)
C10	(5, 7, 9)	(1, 3, 5)
C11	(7, 9, 10)	(3, 5, 7)
C12	(7, 9, 10)	(1, 3, 5)

F. $\widetilde{S_i}$ and $\widetilde{R_i}$ values calculation

The $\widetilde{S_i}$ value quantifies the total deviation of an alternative's criterion values from the ideal fuzzy best values, providing a measure of overall performance across multiple criteria. In contrast, the $\widetilde{R_i}$ value captures the maximum deviation from the fuzzy worst values for an alternative, emphasizing the most critical weakness in its evaluation [86]. These calculations ensure that the ranking process considers both aggregated and worst-case perspectives, making the selection process more balanced and reflective of real-world uncertainties. The fuzzy weights $\widetilde{w_j}$ are incorporated into both computations to maintain consistency in prioritizing decision criteria. The equations are as follows:

$$\widetilde{S_i} = \sum_{j=1}^{k} \widetilde{w_j} \, \frac{\widetilde{f_j*} - \widetilde{x_{ij}}}{\widetilde{f_j*} - \widetilde{f_j-}} \tag{5}$$

$$\widetilde{R_i} = \max \widetilde{w_j} \, \frac{\widetilde{f_j*} - \widetilde{x_{ij}}}{\widetilde{f_j*} - \widetilde{f_j-}} \tag{6}$$

Table 6: $\widetilde{S_i}$ and $\widetilde{R_i}$ value

Alternatives	$\widetilde{S_i}$	$\widetilde{R_i}$
A1	(3.67, 5.83, 7.75)	(5, 7, 9)
A2	(3.42, 5.67, 7.58)	(7, 9, 10)
A3	(3.00, 5.17, 7.00)	(3, 5, 7)

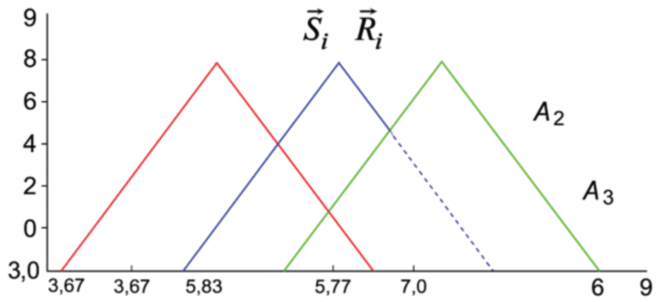

Figure 4: Triangular fuzzy evaluations of $\widetilde{S\iota}$ and $\widetilde{R\iota}$.

G. $\widetilde{S}*$, $\widetilde{R}*$ and $\widetilde{Q\iota}$ values computing

The parameters $\widetilde{S}-$ and $\widetilde{R}*$ serve critical roles in the fuzzy VIKOR methodology by evaluating alternatives from both a group benefit perspective and an individual regret-based standpoint. The maximum group benefit $\widetilde{S}-$ captures the highest aggregated performance across multiple criteria, representing the best collective advantage among alternatives. Conversely, the minimum regret $\widetilde{R}*$ reflects the lowest possible dissatisfaction or deviation from the ideal solution, focusing on avoiding worst-case scenarios in decision-making [87].

To systematically assess and rank alternatives, the fuzzy best and worst values for group benefit and regret are determined using the following equations:

$$\widetilde{S}* = \min \widetilde{S\iota} \tag{7}$$

$\widetilde{S}*$ identifies the minimum total distance across all criteria.

$$\widetilde{R}* = \min \widetilde{R\iota} \tag{8}$$

$\widetilde{R}*$ pinpoints the minimum deviation in the worst-case scenario.

$$\widetilde{S}- = \max \widetilde{S\iota} \tag{9}$$

$\widetilde{S}-$ determines the maximum collective benefit achievable.

$$\widetilde{R}- = \max \widetilde{R\iota} \tag{10}$$

$\widetilde{R}-$ represents the highest level of regret, signifying the weakest performing alternative.

Finally, the compromise ranking index $\widetilde{Q\iota}$ is computed using a weighted approach, where the parameter v adjusts the balance between group utility and individual dissatisfaction:

$$\widetilde{Q\iota} = v\,\frac{\widetilde{S\iota} - \widetilde{S*}}{\widetilde{S-} - \widetilde{S*}} + (1-v)\,\frac{\widetilde{R\iota} - \widetilde{R*}}{\widetilde{R-} - \widetilde{R*}} \tag{11}$$

Table 7: $\widetilde{S}*$, $\widetilde{R}*$, $\widetilde{S}-$ and $\widetilde{R}-$ values

Alternatives	$\widetilde{S}-$	$\widetilde{S}*$	$\widetilde{R}-$	$\widetilde{R}*$
A1	(7, 9, 10)	(3.67, 5.83, 7.75)	(7, 9, 10)	(5, 7, 9)
A2	(7, 9, 10)	(3.42, 5.67, 7.58)	(7, 9, 10)	(7, 9, 10)
A3	(7, 9, 10)	(3.00, 5.17, 7.00)	(7, 9, 10)	(3, 5, 7)

H. $\widetilde{Q\iota}$ index defuzzification

The $\widetilde{Q\iota}$ index is defuzzified using Equation (12). Defuzzification is a crucial step in transforming fuzzy values into crisp numerical outputs for decision-making. In this study, the Best Non-Fuzzy Performance (BNP) method proposed by Olabanji and Mpofu [88] is applied to convert the fuzzy $\widetilde{Q\iota}$ index into a single deterministic value. This process involves computing BNP using the upper (ui), median (mi), and lower (li) values of the triangular fuzzy number, ensuring that the final ranking of alternatives reflects realistic performance scores. The BNP equation systematically balances these three parameters to produce a normalized crisp value, allowing for an objective comparison of technologies. Once defuzzification is complete, the $\widetilde{Q\iota}$ indexes are arranged in ascending order, with the alternative possessing the lowest BNP value identified as the best option.

$$\mathrm{BNP} = \left[\frac{(\mathrm{ui} - \mathrm{li}) + (mi - li)}{3 + li\ \forall i}\right] \tag{12}$$

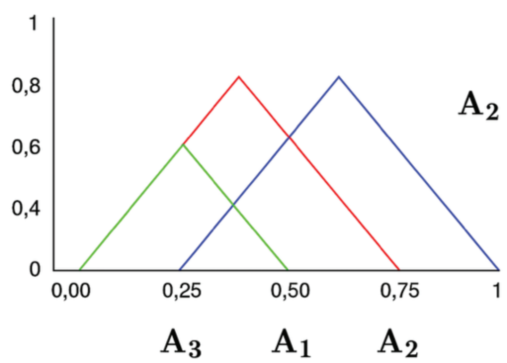

Figure 5: The using triangular representations.

Table 8: $\widetilde{Q\iota}$ values and sequence of alternatives

Alternatives	$\widetilde{Q\iota}$	Sequence
A1	(0.25, 0.50, 0.75)	2
A2	(0.50, 0.75, 1.00)	3
A3	(0.00, 0.25, 0.50)	1

I. The compromise solution

At this stage, the compromise solution is determined by applying two essential conditions to the fuzzy $\widetilde{Q\iota}$ index, ensuring that the selected alternative represents a balanced decision that satisfies both advantage and stability criteria [89]. The Acceptable Advantage condition ensures that there is a clear distinction between the best-ranked alternative a′ and the next-best alternative a″, quantified using the threshold DQ, calculated as:

$$DQ = \frac{1}{m-1} \quad (13)$$

Where m represents the number of alternatives, ensuring that if $m \leq 4$, then $DQ = 0.25$. If the difference $\widetilde{Q(a'')} - \widetilde{Q(a')}$ meets or exceeds DQ, the best option is well-differentiated from the second-best, validating its superiority.

The Acceptable Stability condition evaluates whether the best-ranked alternative remains dominant when ranked based on both minimum group benefit $\widetilde{S*}$ and $\widetilde{R*}$ minimum regret values. If the condition Q(a(m))−Q(a′)<DQ is not met, meaning that there is insufficient distinction between the best and other ranked options, then both a′ and a″ are treated as similar compromise solutions without a strong comparative advantage. Additionally, if stability is not satisfied, the ranking remains unstable, requiring adjustments to the decision-making process.

Ultimately, if both conditions are met, the compromise solution identifies the most balanced alternative, ensuring that it is both advantageous and stable within the fuzzy VIKOR framework [80].

Table 9: Acceptable stability on decision making

Conditions	A1	A2	A3
Acceptable Advantage	Q(A2)−Q(A1)≥ DQ	Q(A2)−Q(A1)≥ DQ	Q(A3)−Q(A2)≥ DQ
Acceptable Stability	Q(A3)−Q(A1)< DQ	Q(A3)−Q(A1)< DQ	Q(A3)−Q(A2)< DQ

J. The best alternative selection

The final stage in the decision-making framework ensures that the most suitable green hydrogen technology is selected based on a comprehensive evaluation of the fuzzy $\widetilde{Q\iota}$ index. This index, which integrates both the total weighted distance $\widetilde{S\iota}$ and the maximum regret-based distance $\widetilde{R\iota}$ from ideal solutions, determines the optimal alternative with minimal compromises across multiple criteria. The alternative with the lowest $\widetilde{Q\iota}$ value is identified as the best option, reflecting its superior performance under both aggregate and worst-case scenarios.

Drawing from the case study, the evaluation of Electrolyzer Technology (A1), Biomass Gasification Technology (A2), and Photovoltaic Electrolysis Technology (A3) using the fuzzy VIKOR method reveals that Photovoltaic Electrolysis Technology (A3) achieves the lowest $\widetilde{Q\iota}$ value. This signifies its strong overall alignment with technological, financial, regulatory, and environmental criteria, positioning it as the most viable solution for green hydrogen production. The ranking process confirms that A3 provides the best compromise between sustainability, efficiency, and feasibility, making it the preferred choice for practical implementation in advancing hydrogen-based energy solutions.

By leveraging the structured approach of fuzzy VIKOR, this selection methodology offers a transparent and adaptable decision-making framework, ensuring that the chosen technology optimally supports the transition towards sustainable hydrogen production.

IV. Results and discussions

The findings of this study provide a comparative evaluation of three green hydrogen technologies—Electrolyzer Technology, Biomass Gasification Technology, and Photovoltaic Electrolysis Technology—using the Fuzzy VIKOR methodology, and they align with or diverge from prior research in several significant ways.

Electrolyzer Technology emerged as a promising candidate due to its high efficiency and zero direct carbon emissions, with an overall compromise solution score of 0.72. This result is consistent with the findings of [90], who highlighted the scalability and environmental benefits of electrolyzers when integrated with renewable energy sources. However, this study also identifies economic challenges, such as high capital costs, which are similarly noted by Al-Shikh et al. [91]. Recent advancements in material optimization, as explored by Ding et al. [92], suggest potential pathways for cost reductions, enhancing the economic feasibility of this technology. Moreover, the integration of electrolyzers with diverse renewable energy systems has been recommended by Opricovic and Tzeng [80] to improve overall operational efficiency.

Biomass Gasification Technology demonstrated balanced performance with an overall compromise solution score of 0.69, attributed to its economic benefits and environmental impact. This finding parallels Kumar et al. [93], who emphasized the potential of waste utilization for cost-effectiveness. However, challenges related to energy-intensive processes, as identified in this study, are corroborated by Mohammadi et al. [94]. Recent work by McLaughlin et al. [95] discusses the role of Carbon Capture and Storage (CCS) integration in mitigating greenhouse gas emissions, a recommendation supported by Hanson et al. [96] to enhance its environmental credentials. Continued innovation in this field is crucial to improving efficiency and scalability, as demonstrated in Alizadeh et al. [97].

Photovoltaic Electrolysis Technology was identified as the optimal solution, scoring highest in environmental impact (0.90), cost-effectiveness (0.82), and technological innovation (0.88), with an overall compromise solution score of 0.87. These results align with the findings of Tebibel [98], who demonstrated the suitability of photovoltaic electrolysis for decentralized hydrogen production in remote locations. Nevertheless, challenges related to the intermittent nature of solar energy, as highlighted in this study, are consistent with Ali et al. [99], who stressed the importance of advancements in energy storage systems. Recent progress in photovoltaic materials and battery storage technologies, as discussed by Yu et al. [100] and Gao et al. [8], could pave the way for large-scale implementation, further strengthening the competitiveness of this technology.

When compared to prior applications of Fuzzy VIKOR, such as its use in industrial strategy selection [101], [102], [103], [104] and personnel decision-making [102], [105], [106], [107], this study offers a unique contribution by applying the methodology to evaluate green hydrogen technologies under conditions of uncertainty. The findings also add to the body of work on multi-criteria decision-making techniques, reinforcing the robustness of Fuzzy VIKOR as documented by Opricovic and Tzeng [80]. Moreover, the adaptability of this method in addressing vague and conflicting decision-making criteria aligns with insights from Wang et al. [108], Akram et al. [109], Shemshadi et al. [110], Akram et al. [111], Al-Ani & Dhahir [112], Bouafia and Abdallah [113], Makadia and Dave [114], and Moyo et al. [115].

Overall, the results of this study reinforce the growing importance of green hydrogen technologies in achieving sustainable energy goals. Each technology presents unique advantages and challenges that require further research and innovation. By incorporating recent advancements in material science, system integration, and energy storage, these technologies can be further optimized to meet the demands of scalability, efficiency, and sustainability.

V. Conclusion

This study applied the Fuzzy VIKOR methodology to evaluate and rank three green hydrogen technologies: Electrolyzer Technology, Biomass Gasification Technology, and Photovoltaic Electrolysis Technology. Among these, Photovoltaic Electrolysis Technology emerged as the most promising solution due to its exceptional performance in environmental impact, technological innovation, and cost-effectiveness. While Electrolyzer Technology demonstrated strong efficiency and environmental benefits, its economic feasibility remains challenged by high capital costs. Biomass Gasification Technology revealed balanced performance, particularly in regions with abundant organic waste, although its energy-intensive processes pose limitations. Collectively, these findings contribute to the growing body of knowledge on green hydrogen technologies, providing a comprehensive evaluation framework that accounts for the inherent uncertainties in decision-making.

However, this study has certain limitations. The evaluation was based on a specific set of criteria and alternatives, which may not encompass all factors influencing the performance and adoption of green hydrogen technologies. Additionally, the criteria weights and fuzzy membership functions relied on expert judgment, introducing a degree of subjectivity that could impact the outcomes. The scope of the study was limited to three technologies, which does not reflect the full diversity of hydrogen production methods available. Furthermore, while the Fuzzy VIKOR methodology captured nuanced insights, its reliance on linguistic variables may reduce precision compared to more quantitative approaches.

Future research should aim to address these limitations. Expanding the scope of criteria to include socio-economic, political, and cultural factors would provide a more holistic evaluation of green hydrogen technologies. Incorporating a broader range of technologies, including hybrid systems that integrate multiple renewable energy sources, could offer deeper insights into innovative solutions. Enhancing the accuracy of fuzzy logic and MCDM techniques, such as developing more advanced computational models, would further strengthen evaluation frameworks. Additionally, longitudinal studies that monitor the performance of green hydrogen technologies over time would provide valuable data on their long-term feasibility and impact. Future studies could also explore region-specific strategies for integrating green hydrogen technologies into existing energy infrastructures, enabling localized adaptations to maximize efficiency and sustainability.

The implications of this research are substantial. Energy planners can utilize the framework to select technologies that align with regional characteristics, advancing tailored renewable energy solutions. Policymakers can implement strategic incentives to promote equitable adoption of green hydrogen technologies, fostering sustainable energy transitions in diverse socio-economic contexts. Investors can prioritize resources toward scalable and economically viable technologies, driving innovation in the green energy sector. Ultimately, these findings can guide stakeholders in addressing current challenges, accelerating the adoption of green hydrogen technologies, and contributing to a sustainable global energy future.

References

[1] R. Jayabal, “Towards a carbon-free society: Innovations in green energy for a sustainable future,” *Results in Engineering*, vol. 24, p. 103121, Dec. 2024, doi: 10.1016/j.rineng.2024.103121.

[2] S. G. Nnabuife, A. K. Hamzat, J. Whidborne, B. Kuang, and K. W. Jenkins, “Integration of renewable energy sources in tandem with electrolysis: A technology review for green hydrogen production,” *Int J Hydrogen Energy*, vol. 107, pp. 218–240, Mar. 2025, doi: 10.1016/j.ijhydene.2024.06.342.

[3] K. Gomonov, C. T. Permana, and C. T. Handoko, “The growing demand for hydrogen: current trends, sectoral analysis, and future projections,” *Unconventional Resources*, vol. 6, p. 100176, Apr. 2025, doi: 10.1016/j.uncres.2025.100176.

[4] B. S. Zainal *et al.*, “Recent advancement and assessment of green hydrogen production technologies,” *Renewable and Sustainable Energy Reviews*, vol. 189, p. 113941, Jan. 2024, doi: 10.1016/j.rser.2023.113941.

[5] I. Marouani *et al.*, “Integration of Renewable-Energy-Based Green Hydrogen into the Energy Future,” *Processes*, vol. 11, no. 9, p. 2685, Sep. 2023, doi: 10.3390/pr11092685.

[6] M. Tahmasbi, M. Siavashi, and R. Ahmadi, “A comprehensive review of hydrogen production and storage methods: fundamentals, advances, and SWOT analysis,” *Energy Conversion and Management: X*, vol. 26, p. 101005, Apr. 2025, doi: 10.1016/j.ecmx.2025.101005.

[7] B. B. Pradhan, B. Limmeechokchai, A. Chaichaloempreecha, and S. Rajbhandari, “Role of green hydrogen in the decarbonization of the energy system in Thailand,” *Energy Strategy Reviews*, vol. 51, p. 101311, Jan. 2024, doi: 10.1016/j.esr.2024.101311.

[8] L. Gao, X. Zhang, and W. Hua, “Recent progress in photovoltaic thermal phase change material technology: A review,” *J Energy Storage*, vol. 65, p. 107317, Aug. 2023, doi: 10.1016/j.est.2023.107317.

[9] M. Gul, E. Celik, N. Aydin, A. Taskin Gumus, and A. F. Guneri, “A state of the art literature review of VIKOR and its fuzzy extensions on applications,” *Appl Soft Comput*, vol. 46, pp. 60–89, Sep. 2016, doi: 10.1016/j.asoc.2016.04.040.

[10] P. Basu, *Biomass Gasification and Pyrolysis*. Elsevier, 2010. doi: 10.1016/C2009-0-20099-7.

[11] R. M. Navarro, R. Guil, and J. L. G. Fierro, “Introduction to hydrogen production,” in *Compendium of Hydrogen Energy*, Elsevier, 2015, pp. 21–61. doi: 10.1016/B978-1-78242-361-4.00002-9.

[12] J. Fang *et al.*, “Enhancing solar-powered hydrogen production efficiency by spectral beam splitting and integrated chemical energy storage,” *Appl Energy*, vol. 372, p. 123833, Oct. 2024, doi: 10.1016/j.apenergy.2024.123833.

[13] M. M. Hossain Bhuiyan and Z. Siddique, “Hydrogen as an alternative fuel: A comprehensive review of challenges and opportunities in production, storage, and transportation,” *Int J Hydrogen Energy*, vol. 102, pp. 1026–1044, Feb. 2025, doi: 10.1016/j.ijhydene.2025.01.033.

[14] D. Abdul, J. Wenqi, and A. Tanveer, “Prioritization of renewable energy source for electricity generation through AHP-VIKOR integrated methodology,” *Renew Energy*, vol. 184, pp. 1018–1032, Jan. 2022, doi: 10.1016/j.renene.2021.10.082.

[15] L. Cannavacciuolo, G. Ferraro, C. Ponsiglione, S. Primario, and I. Quinto, “Technological innovation-enabling industry 4.0 paradigm: A systematic literature review,” *Technovation*, vol. 124, p. 102733, Jun. 2023, doi: 10.1016/j.technovation.2023.102733.

[16] A. A. Vărzaru and C. G. Bocean, “Digital Transformation and Innovation: The Influence of Digital Technologies on Turnover from Innovation Activities and Types of Innovation,” *Systems*, vol. 12, no. 9, p. 359, Sep. 2024, doi: 10.3390/systems12090359.

[17] L. Vidas and R. Castro, “Recent Developments on Hydrogen Production Technologies: State-of-the-Art Review with a Focus on Green-Electrolysis,” *Applied Sciences*, vol. 11, no. 23, p. 11363, Dec. 2021, doi: 10.3390/app112311363.

[18] A. O. M. Maka, T. Ghalut, and E. Elsaye, “The pathway towards decarbonisation and net-zero emissions by 2050: The role of solar energy technology,” *Green Technologies and Sustainability*, vol. 2, no. 3, p. 100107, Sep. 2024, doi: 10.1016/j.grets.2024.100107.

[19] A. Islam *et al.*, “Accelerating the green hydrogen revolution: A comprehensive analysis of technological advancements and policy interventions,” *Int J Hydrogen Energy*, vol. 67, pp. 458–486, May 2024, doi: 10.1016/j.ijhydene.2024.04.142.

[20] P. Fragiacomo, M. Genovese, F. Piraino, F. Massari, and M. Boroomandnia, “Analysis of a distributed green hydrogen infrastructure designed to support the sustainable mobility of a heavy-duty fleet,” *Int J Hydrogen Energy*, vol. 51, pp. 576–594, Jan. 2024, doi: 10.1016/j.ijhydene.2023.08.047.

[21] B.-J. Jesse, G. J. Kramer, V. Koning, S. Vögele, and W. Kuckshinrichs, “Stakeholder perspectives on the scale-up of green hydrogen and electrolyzers,” *Energy Reports*, vol. 11, pp. 208–217, Jun. 2024, doi: 10.1016/j.egyr.2023.11.046.

[22] M. Wappler, D. Unguder, X. Lu, H. Ohlmeyer, H. Teschke, and W. Lueke, “Building the green hydrogen market – Current state and outlook on green hydrogen demand and electrolyzer manufacturing,” *Int J Hydrogen Energy*, vol. 47, no. 79, pp. 33551–33570, Sep. 2022, doi: 10.1016/j.ijhydene.2022.07.253.

[23] M. Stolte, F. D. Minuto, A. Perol, M. Bindi, and A. Lanzini, “Optimisation of green hydrogen production for hard-to-abate industries: An Italian case study considering national incentives,” *Int J Hydrogen Energy*, vol. 141, pp. 1294–1304, Jun. 2025, doi: 10.1016/j.ijhydene.2025.03.008.

[24] B. Łosiewicz, "Technology for Green Hydrogen Production: Desk Analysis," *Energies (Basel)*, vol. 17, no. 17, p. 4514, Sep. 2024, doi: 10.3390/en17174514.

[25] F.-Y. Gao, P.-C. Yu, and M.-R. Gao, "Seawater electrolysis technologies for green hydrogen production: challenges and opportunities," *Curr Opin Chem Eng*, vol. 36, p. 100827, Jun. 2022, doi: 10.1016/j.coche.2022.100827.

[26] X. Gao *et al.*, "Next-Generation Green Hydrogen: Progress and Perspective from Electricity, Catalyst to Electrolyte in Electrocatalytic Water Splitting," *Nanomicro Lett*, vol. 16, no. 1, p. 237, Dec. 2024, doi: 10.1007/s40820-024-01424-2.

[27] D. Messaoudi, K. Ruel, and J.-P. Joseleau, "Assessing the performance of new bio-based surface gel treatment in outdoor applications," in *IUFRO*, 2024. doi: http://dx.doi.org/10.13140/RG.2.2.11225.12642.

[28] H. Shen, P. Crespo del Granado, R. S. Jorge, and K. Löffler, "Environmental and climate impacts of a large-scale deployment of green hydrogen in Europe," *Energy and Climate Change*, vol. 5, p. 100133, Dec. 2024, doi: 10.1016/j.egycc.2024.100133.

[29] J. Sun, H. Wang, and Z. Cui, "Alleviating the Bauxite Maritime Supply Chain Risks through Resilient Strategies: QFD-MCDM with Intuitionistic Fuzzy Decision Approach," *Sustainability*, vol. 15, no. 10, p. 8244, May 2023, doi: 10.3390/su15108244.

[30] H. Biabani, A. Aminlou, M. M. Hayati, H. Majidi-Gharehnaz, and M. Abapour, "Green Hydrogen Research and Development Projects in the European Union," 2024, pp. 301–320. doi: 10.1007/978-3-031-52429-5_12.

[31] A. Tuluhong, Q. Chang, L. Xie, Z. Xu, and T. Song, "Current Status of Green Hydrogen Production Technology: A Review," *Sustainability*, vol. 16, no. 20, p. 9070, Oct. 2024, doi: 10.3390/su16209070.

[32] C. Anand *et al.*, "Green hydrogen for a sustainable future: A review of production methods, innovations, and applications," *Int J Hydrogen Energy*, vol. 111, pp. 319–341, Mar. 2025, doi: 10.1016/j.ijhydene.2025.02.257.

[33] A. Odenweller, F. Ueckerdt, G. F. Nemet, M. Jensterle, and G. Luderer, "Probabilistic feasibility space of scaling up green hydrogen supply," *Nat Energy*, vol. 7, no. 9, pp. 854–865, Sep. 2022, doi: 10.1038/s41560-022-01097-4.

[34] S. Revinova, I. Lazanyuk, S. Ratner, and K. Gomonov, "Forecasting Development of Green Hydrogen Production Technologies Using Component-Based Learning Curves," *Energies (Basel)*, vol. 16, no. 11, p. 4338, May 2023, doi: 10.3390/en16114338.

[35] D. Cobben, W. Ooms, N. Roijakkers, and A. Radziwon, "Ecosystem types: A systematic review on boundaries and goals," *J Bus Res*, vol. 142, pp. 138–164, Mar. 2022, doi: 10.1016/j.jbusres.2021.12.046.

[36] D. Schwappach, W. G. Faix, J. Mergenthaler, and C.-C. Carbon, "Developing an Ecosystem Framework for Green Hydrogen Scale-Up: A Contribution to Innovation Leadership," *Journal of the Knowledge Economy*, Mar. 2025, doi: 10.1007/s13132-024-02376-z.

[37] S. Jayachandran, K. Hewett, and P. Kaufman, "Customer Response Capability in a Sense-and-Respond Era: The Role of Customer Knowledge Process," *J Acad Mark Sci*, vol. 32, no. 3, pp. 219–233, Jul. 2004, doi: 10.1177/0092070304263334.

[38] A. Kopteva, L. Kalimullin, P. Tcvetkov, and A. Soares, "Prospects and Obstacles for Green Hydrogen Production in Russia," *Energies (Basel)*, vol. 14, no. 3, p. 718, Jan. 2021, doi: 10.3390/en14030718.

[39] R. S. Yadav and V. K. Rathore, "Advancements and Innovations in Green Hydrogen Technologies," 2024, pp. 211–238. doi: 10.1007/978-981-97-1339-4_9.

[40] E. Curcio, "Techno-Economic Analysis of Hydrogen Production: Costs, Policies, and Scalability in the Transition to Net-Zero," 2025, doi: doi:10.48550/arXiv.2502.12211.

[41] A. Y. Shash, N. M. Abdeltawab, D. M. Hassan, M. Darweesh, and Y. G. Hegazy, "Computational Methods, Artificial Intelligence, Modeling, and Simulation Applications in Green Hydrogen Production Through Water Electrolysis: A Review," *Hydrogen*, vol. 6, no. 2, p. 21, Mar. 2025, doi: 10.3390/hydrogen6020021.

[42] E. J. Medrano-Sánchez and E. Marín-Jara, "Green Hydrogen and the Environment: a Review of Trends and Challenges in Scientific Production (2019-2023)," *Chem Eng Trans*, pp. 697–702, 2024, doi: https://doi.org/10.3303/CET24111117.

[43] J. A. Dueñas Santana, A. Di Benedetto, O. González Gómez, and E. Salzano, "Towards sustainable hydrogen production: An integrated approach for Sustainability, Complexity, and Systems Thinking in the energy sector," *J Clean Prod*, vol. 449, p. 141751, Apr. 2024, doi: 10.1016/j.jclepro.2024.141751.

[44] S. Yüksel, H. Dinçer, M. Acar, E. Ergün, S. Eti, and Y. Gökalp, "Financial multidimensional assessment of a green hydrogen generation process via an integrated artificial intelligence-based four-stage fuzzy decision-making model," *Int J Hydrogen Energy*, vol. 83, pp. 577–588, Sep. 2024, doi: 10.1016/j.ijhydene.2024.08.140.

[45] S. O. Bade, O. S. Tomomewo, A. Meenakshisundaram, P. Ferron, and B. A. Oni, "Economic, social, and regulatory challenges of green hydrogen production and utilization in the US: A review," *Int J Hydrogen Energy*, vol. 49, pp. 314–335, Jan. 2024, doi: 10.1016/j.ijhydene.2023.08.157.

[46] A. O. M. Maka and M. Mehmood, "Green hydrogen energy production: current status and potential," *Clean Energy*, vol. 8, no. 2, pp. 1–7, Apr. 2024, doi: 10.1093/ce/zkae012.

[47] M. Asghari, H. Afshari, M. Y. Jaber, and C. Searcy, "Strategic analysis of hydrogen market dynamics across collaboration models," *Renewable and Sustainable Energy Reviews*, vol. 208, p. 115001, Feb. 2025, doi: 10.1016/j.rser.2024.115001.

[48] D. Schlund, S. Schulte, and T. Sprenger, "The who's who of a hydrogen market ramp-up: A stakeholder analysis for Germany," *Renewable and Sustainable Energy Reviews*, vol. 154, p. 111810, Feb. 2022, doi: 10.1016/j.rser.2021.111810.

[49] J. Nyangon and A. Darekar, "Advancements in hydrogen energy systems: A review of levelized costs, financial incentives and technological innovations," *Innovation and Green Development*, vol. 3, no. 3, p. 100149, Sep. 2024, doi: 10.1016/j.igd.2024.100149.

[50] M. San Martin *et al.*, "Parameterization proposal to determine the feasibility of geographic areas for the green hydrogen industry under socio-environmental and technical constraints in Chile," *Int J Hydrogen Energy*, vol. 50, pp. 578–598, Jan. 2024, doi: 10.1016/j.ijhydene.2023.10.013.

[51] H. Biabani, A. Aminlou, M. M. Hayati, H. Majidi-Gharehnaz, and M. Abapour, "Green Hydrogen Research and Development Projects in the European Union," 2024, pp. 301–320. doi: 10.1007/978-3-031-52429-5_12.

[52] Z. Hammi, N. Labjar, M. Dalimi, Y. El Hamdouni, E. M. Lotfi, and S. El Hajjaji, "Green hydrogen: A holistic review covering life cycle assessment, environmental impacts, and color analysis," *Int J Hydrogen Energy*, vol. 80, pp. 1030–1045, Aug. 2024, doi: 10.1016/j.ijhydene.2024.07.008.

[53] H. Barghash, M. Al Farsi, Z. AlRashdi, K. E. Okedu, and A. Al-Alawi, "Achieving decarbonization considering green hydrogen production: Case study of Oman," *Results in Engineering*, vol. 23, p. 102657, Sep. 2024, doi: 10.1016/j.rineng.2024.102657.

[54] H. Liu and P. Han, "Renewable energy development and carbon emissions: The role of electricity exchange," *J Clean Prod*, vol. 439, p. 140807, Feb. 2024, doi: 10.1016/j.jclepro.2024.140807.

[55] M. El-Shafie, "Hydrogen production by water electrolysis technologies: A review," *Results in Engineering*, vol. 20, p. 101426, Dec. 2023, doi: 10.1016/j.rineng.2023.101426.

[56] M. E. Şahin, "An Overview of Different Water Electrolyzer Types for Hydrogen Production," *Energies (Basel)*, vol. 17, no. 19, p. 4944, Oct. 2024, doi: 10.3390/en17194944.

[57] Ö. Tezer, N. Karabağ, A. Öngen, C. Ö. Çolpan, and A. Ayol, "Biomass gasification for sustainable energy production: A review," *Int J Hydrogen Energy*, vol. 47, no. 34, pp. 15419–15433, Apr. 2022, doi: 10.1016/j.ijhydene.2022.02.158.

[58] F. C. Marques, J. C. M. Silva, C. P. Libardi, R. R. de Carvalho, G. F. Sequine, and G. M. Valane, "Hydrogen production by photovoltaic-electrolysis using aqueous waste from ornamental stones industries," *Renew Energy*, vol. 152, pp. 1266–1273, Jun. 2020, doi: 10.1016/j.renene.2020.01.156.

[59] M. Awad *et al.*, "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*, vol. 87, pp. 213–239, Jan. 2024, doi: 10.1016/j.aej.2023.12.032.

[60] L. Fernández-Lobato, R. García-Ruiz, F. Jurado, and D. Vera, "Life cycle assessment, C footprint and carbon balance of virgin olive oils production from traditional and intensive olive groves in southern Spain," *J Environ Manage*, vol. 293, p. 112951, Sep. 2021, doi: 10.1016/j.jenvman.2021.112951.

[61] E. Nguyen, P. Olivier, M.-C. Pera, E. Pahon, and R. Roche, "Impacts of intermittency on low-temperature electrolysis technologies: A comprehensive review," *Int J Hydrogen Energy*, vol. 70, pp. 474–492, Jun. 2024, doi: 10.1016/j.ijhydene.2024.05.217.

[62] G. Tsatsaronis, "Some inconvenient truths about decarbonization, the hydrogen economy, and power-to-X technologies," *J Environ Manage*, vol. 360, p. 121127, Jun. 2024, doi: 10.1016/j.jenvman.2024.121127.

[63] E. E. Nzaba Madila, A. Makhsoos, M. M. Shanbhag, and B. G. Pollet, "Advancements in electrolyser stack performance: A comprehensive review of Latest technologies and efficiency strategies," *Int J Hydrogen Energy*, vol. 144, pp. 1168–1189, Jul. 2025, doi: 10.1016/j.ijhydene.2025.04.047.

[64] F. Sher *et al.*, "Cutting-edge biomass gasification technologies for renewable energy generation and achieving net zero emissions," *Energy Convers Manag*, vol. 323, p. 119213, Jan. 2025, doi: 10.1016/j.enconman.2024.119213.

[65] E. Bullich-Massagué *et al.*, "A review of energy storage technologies for large scale photovoltaic power plants," *Appl Energy*, vol. 274, p. 115213, Sep. 2020, doi: 10.1016/j.apenergy.2020.115213.

[66] J. Baumgarten, C. P. Schneider, and D. Möst, "Hydrogen Economy Index – A comparative assessment of the political and economic perspective in the MENA region for a clean hydrogen economy," *Int J Hydrogen Energy*, vol. 101, pp. 1503–1517, Feb. 2025, doi: 10.1016/j.ijhydene.2024.11.345.

[67] S. O. Jeje, T. Marazani, J. O. Obiko, and M. B. Shongwe, "Advancing the hydrogen production economy: A comprehensive review of technologies, sustainability, and future prospects," *Int J Hydrogen Energy*, vol. 78, pp. 642–661, Aug. 2024, doi: 10.1016/j.ijhydene.2024.06.344.

[68] A. K. Worku, D. W. Ayele, D. B. Deepak, A. Y. Gebreyohannes, S. D. Agegnehu, and M. L. Kolhe, "Recent Advances and Challenges of Hydrogen Production Technologies via Renewable Energy Sources," *Advanced Energy and Sustainability Research*, vol. 5, no. 5, May 2024, doi: 10.1002/aesr.202300273.

[69] G. M. Magableh and N. K. Bazel, "Exploring Future Renewable Energy Technologies Using a Developed Model and a Variety of MCDM Approaches," *Sustainability*, vol. 17, no. 7, p. 3057, Mar. 2025, doi: 10.3390/su17073057.

[70] F. Kourougianni *et al.*, "A comprehensive review of green hydrogen energy systems," *Renew Energy*, vol. 231, p. 120911, Sep. 2024, doi: 10.1016/j.renene.2024.120911.

[71] F. Sitorus and P. R. Brito-Parada, "The selection of renewable energy technologies using a hybrid subjective and objective multiple criteria decision making method," *Expert Syst Appl*, vol. 206, p. 117839, Nov. 2022, doi: 10.1016/j.eswa.2022.117839.

[72] I. Ourya and S. Abderafi, "Clean technology selection of hydrogen production on an industrial scale in Morocco," *Results in Engineering*, vol. 17, p. 100815, Mar. 2023, doi: 10.1016/j.rineng.2022.100815.

[73] J.-C. Wang and T.-Y. Chen, "A compromise decision-support technique with an augmented scoring function within circular intuitionistic fuzzy settings," *Eng Appl Artif Intell*, vol. 128, p. 107359, Feb. 2024, doi: 10.1016/j.engappai.2023.107359.

[74] A. Bathaei *et al.*, "Application of Fuzzy Analytical Network Process (ANP) and VIKOR for the Assessment of Green Agility Critical Success Factors in Dairy Companies," *Symmetry (Basel)*, vol. 11, no. 2, p. 250, Feb. 2019, doi: 10.3390/sym11020250.

[75] A. Mardani, E. Zavadskas, K. Govindan, A. Amat Senin, and A. Jusoh, "VIKOR Technique: A Systematic Review of the State of the Art Literature on Methodologies and Applications," *Sustainability*, vol. 8, no. 1, p. 37, Jan. 2016, doi: 10.3390/su8010037.

[76] Shumaiza, M. Akram, A. N. Al-Kenani, and J. C. R. Alcantud, "Group Decision-Making Based on the VIKOR Method with Trapezoidal Bipolar Fuzzy Information," *Symmetry (Basel)*, vol. 11, no. 10, p. 1313, Oct. 2019, doi: 10.3390/sym11101313.

[77] Y. Özdemir, K. G. Nalbant, and H. Başlıgil, "PERSONNEL SELECTION FOR PROMOTION USING AN INTEGRATED FUZZY ANALYTIC HIERARCHY PROCESS-GREY RELATIONAL ANALYSIS METHODOLOGY: A REAL CASE STUDY," *ANADOLU UNIVERSITY JOURNAL OF SCIENCE AND TECHNOLOGY A - Applied Sciences and Engineering*, Jun. 2018, doi: 10.18038/aubtda.326726.

[78] S. Jing, Y. Tang, and J. Yan, "The Application of Fuzzy VIKOR for the Design Scheme Selection in Lean Management," *Math Probl Eng*, vol. 2018, pp. 1–15, Sep. 2018, doi: 10.1155/2018/9253643.

[79] Z. Ayağ and R. Gürcan Özdemir, "Evaluating machine tool alternatives through modified TOPSIS and alpha-cut based fuzzy ANP," *Int J Prod Econ*, vol. 140, no. 2, pp. 630–636, Dec. 2012, doi: 10.1016/j.ijpe.2012.02.009.

[80] S. Opricovic and G.-H. Tzeng, "Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS," *Eur J Oper Res*, vol. 156, no. 2, pp. 445–455, Jul. 2004, doi: 10.1016/S0377-2217(03)00020-1.

[81] A. H. Salimi *et al.*, "Exploring the Role of Advertising Types on Improving the Water Consumption Behavior: An Application of Integrated Fuzzy AHP and Fuzzy VIKOR Method," *Sustainability*, vol. 12, no. 3, p. 1232, Feb. 2020, doi: 10.3390/su12031232.

[82] F. ul Amin, Q.-L. Dong, K. Grzybowska, Z. Ahmed, and B.-R. Yan, "A Novel Fuzzy-Based VIKOR–CRITIC Soft Computing Method for Evaluation of Sustainable Supply Chain Risk Management," *Sustainability*, vol. 14, no. 5, p. 2827, Feb. 2022, doi: 10.3390/su14052827.

[83] L. A. Zadeh, "Fuzzy sets," *Information and Control*, vol. 8, no. 3, pp. 338–353, Jun. 1965, doi: 10.1016/S0019-9958(65)90241-X.

[84] R. W. Saaty, "The analytic hierarchy process—what it is and how it is used," *Mathematical Modelling*, vol. 9, no. 3–5, pp. 161–176, 1987, doi: 10.1016/0270-0255(87)90473-8.

[85] M. M. Salih, B. B. Zaidan, and A. A. Zaidan, "Fuzzy decision by opinion score method," *Appl Soft Comput*, vol. 96, p. 106595, Nov. 2020, doi: 10.1016/j.asoc.2020.106595.

[86] S. Opricovic, "Fuzzy VIKOR with an application to water resources planning," *Expert Syst Appl*, vol. 38, no. 10, pp. 12983–12990, Sep. 2011, doi: 10.1016/j.eswa.2011.04.097.

[87] S. Opricovic and G.-H. Tzeng, "Extended VIKOR method in comparison with outranking methods," *Eur J Oper Res*, vol. 178, no. 2, pp. 514–529, Apr. 2007, doi: 10.1016/j.ejor.2006.01.020.

[88] O. M. Olabanji and K. Mpofu, "Appraisal of conceptual designs: Coalescing fuzzy analytic hierarchy process (F-AHP) and fuzzy grey relational analysis (F-GRA)," *Results in Engineering*, vol. 9, p. 100194, Mar. 2021, doi: 10.1016/j.rineng.2020.100194.

[89] G. A. Akyüz, "BULANIK VIKOR YÖNTEMİ İLE TEDARİKÇİ SEÇİMİ ," *Atatürk University Journal of Economics and Administrative Sciences*, vol. 26, no. 1, 2012.

[90] A. Franco and C. Giovannini, "Recent and Future Advances in Water Electrolysis for Green Hydrogen Generation: Critical Analysis and Perspectives," *Sustainability*, vol. 15, no. 24, p. 16917, Dec. 2023, doi: 10.3390/su152416917.

[91] S. A. Al-Shikh, E. A. Al-Ammar, and A. S. Alomari, "Economic Feasibility of Hydrogen Generation Using HTR-PM Technology in Saudi Arabia," *Sustainability*, vol. 17, no. 4, p. 1730, Feb. 2025, doi: 10.3390/su17041730.

[92] J.-W. Ding, Y.-S. Fu, and I.-Y. Lisa Hsieh, "The cost of green: Analyzing the economic feasibility of hydrogen production from offshore wind power," *Energy Conversion and Management: X*, vol. 24, p. 100770, Oct. 2024, doi: 10.1016/j.ecmx.2024.100770.

[93] A. Kumar, D. D. Jones, and M. A. Hanna, "Thermochemical Biomass Gasification: A Review of the Current Status of the Technology," *Energies (Basel)*, vol. 2, no. 3, pp. 556–581, Jul. 2009, doi: 10.3390/en20300556.

[94] A. Mohammadi and A. Anukam, "The Technical Challenges of the Gasification Technologies Currently in Use and Ways of Optimizing Them: A Review," in *Latest Research on Energy Recovery*, IntechOpen, 2023. doi: 10.5772/intechopen.102593.

[95] H. McLaughlin *et al.*, "Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world," *Renewable and Sustainable Energy Reviews*, vol. 177, p. 113215, May 2023, doi: 10.1016/j.rser.2023.113215.

[96] E. Hanson, C. Nwakile, and V. O. Hammed, "Carbon capture, utilization, and storage (CCUS) technologies: Evaluating the effectiveness of advanced CCUS solutions for reducing CO2 emissions," *Results in Surfaces and Interfaces*, vol. 18, p. 100381, Jan. 2025, doi: 10.1016/j.rsurfi.2024.100381.

[97] S. M. Alizadeh, Y. Khalili, and M. Ahmadi, "Comprehensive Review of Carbon Capture and Storage Integration in Hydrogen Production: Opportunities, Challenges, and Future Perspectives," *Energies (Basel)*, vol. 17, no. 21, p. 5330, Oct. 2024, doi: 10.3390/en17215330.

[98] H. Tebibel, "Off grid PV system for hydrogen production using PEM methanol electrolysis and an optimal management strategy," *Int J Hydrogen Energy*, vol. 42, no. 30, pp. 19432–19445, Jul. 2017, doi: 10.1016/j.ijhydene.2017.05.205.

[99] A. O. Ali *et al.*, "Advancements in photovoltaic technology: A comprehensive review of recent advances and future prospects," *Energy Conversion and Management: X*, vol. 26, p. 100952, Apr. 2025, doi: 10.1016/j.ecmx.2025.100952.

[100] F. Yu *et al.*, "Recent Advances in Integrated Solar Photovoltaic Energy Storage," *Small*, vol. 21, no. 18, May 2025, doi: 10.1002/smll.202501618.

[101] C. Jana, A. Mohamadghasemi, M. Pal, and L. Martinez, "An improvement to the interval type-2 fuzzy VIKOR method," *Knowl Based Syst*, vol. 280, p. 111055, Nov. 2023, doi: 10.1016/j.knosys.2023.111055.

[102] A. Naghizadeh Vardin, R. Ansari, M. Khalilzadeh, J. Antucheviciene, and R. Bausys, "An Integrated Decision Support Model Based on BWM and Fuzzy-VIKOR Techniques for Contractor Selection in Construction Projects," *Sustainability*, vol. 13, no. 12, p. 6933, Jun. 2021, doi: 10.3390/su13126933.

[103] S. Vinodh, A. R. Varadharajan, and A. Subramanian, "Application of fuzzy VIKOR for concept selection in an agile environment," *The International Journal of Advanced Manufacturing Technology*, vol. 65, no. 5–8, pp. 825–832, Mar. 2013, doi: 10.1007/s00170-012-4220-2.

[104] X.-Y. You, J.-X. You, H.-C. Liu, and L. Zhen, "Group multi-criteria supplier selection using an extended VIKOR method with interval 2-tuple linguistic information," *Expert Syst Appl*, vol. 42, no. 4, pp. 1906–1916, Mar. 2015, doi: 10.1016/j.eswa.2014.10.004.

[105] M. Ikram, Q. Zhang, and R. Sroufe, "Developing integrated management systems using an AHP-Fuzzy VIKOR approach," *Bus Strategy Environ*, vol. 29, no. 6, pp. 2265–2283, Sep. 2020, doi: 10.1002/bse.2501.

[106] S. K. Sharma, "Enhancing Stock Portfolio Selection with Trapezoidal Bipolar Fuzzy VIKOR Technique with Boruta-GA Hybrid Optimization Model: A Multicriteria Decision-Making Approach," *International Journal of Computational Intelligence Systems*, vol. 18, no. 1, p. 17, Jan. 2025, doi: 10.1007/s44196-025-00733-7.

[107] A. Singh and S. Kumar, "Picture fuzzy VIKOR-TOPSIS approach based on knowledge and accuracy measures for suitable adsorbent decision making," *Appl Soft Comput*, vol. 147, p. 110807, Nov. 2023, doi: 10.1016/j.asoc.2023.110807.

[108] T. Wang, J. Liang, and C. Ho, "Multi-Criteria Decision Analysis by Using Fuzzy VIKOR," in *2006 International Conference on Service Systems and Service Management*, IEEE, Oct. 2006, pp. 901–906. doi: 10.1109/ICSSSM.2006.320751.

[109] M. Akram, C. Kahraman, and K. Zahid, "Group decision-making based on complex spherical fuzzy VIKOR approach," *Knowl Based Syst*, vol. 216, p. 106793, Mar. 2021, doi: 10.1016/j.knosys.2021.106793.

[110] A. Shemshadi, H. Shirazi, M. Toreihi, and M. J. Tarokh, "A fuzzy VIKOR method for supplier selection based on entropy measure for objective weighting," *Expert Syst Appl*, vol. 38, no. 10, pp. 12160–12167, Sep. 2011, doi: 10.1016/j.eswa.2011.03.027.

[111] M. Akram, G. Muhiuddin, and G. Santos-García, "An enhanced VIKOR method for multi-criteria group decision-making with complex Fermatean fuzzy sets," *Mathematical Biosciences and Engineering*, vol. 19, no. 7, pp. 7201–7231, 2022, doi: 10.3934/mbe.2022340.

[112] S. A. Al-Ani and M. K. Dhahir, "Laser-enhanced hydrogen production: designing a PEC cell photoanode with an exclusive dye material for superior efficiency," *Renewable Energy and Sustainable Development*, vol. 10, no. 2, p. 407, Nov. 2024, doi: 10.21622/resd.2024.10.2.1050.

[113] S. Bouafia and M. Si Abdallah, "Numerical study of a solar PV/thermal collector under several conditions in Algeria," *Renewable Energy and Sustainable Development*, vol. 10, no. 2, p. 233, Sep. 2024, doi: 10.21622/resd.2024.10.2.900.

[114] R. N. Makadia and M. R. Dave, "Statistical analysis of industry scale up draft coal gasifier using response surface methodology for sustainable development," *Renewable Energy and Sustainable Development*, vol. 10, no. 2, p. 294, Oct. 2024, doi: 10.21622/resd.2024.10.2.940.

[115] R. T. Moyo, M. Dewa, H. F. M. Romero, V. A. Gómez, J. I. M. Aragonés, and L. Hernández-Callejo, "An adaptive neuro-fuzzy inference scheme for defect detection and classification of solar PV cells," *Renewable Energy and Sustainable Development*, vol. 10, no. 2, p. 218, Sep. 2024, doi: 10.21622/resd.2024.10.2.929.