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Article

Water Electrolysis Technology Selection for Green Hydrogen Production in Coastal Isolated Area

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Abstract. The concept of utilizing excess electricity from Renewable Energy (RE), coupled with green hydrogen fuel cells, offers an alternative sustainable model for RE power plants in isolated regions. The selection of the appropriate electrolyzer is a crucial step toward establishing an efficient and sustainable system. This study was designed to assess which electrolyzer holds the most promise within the system's design. Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), and Anion Exchange Membrane (AEM) were considered as alternatives. The selection process was carried out using the Multi Criteria Decision Making method, incorporating four main criteria: technical, economic, social, health-safety-environmental aspects, alongside ten sub-criteria that encompass factors such as maturity, reliability, robustness, efficiency, investment cost, community acceptance, availability of electrolyzer companies, environmental impact, risk of harm, and land requirements. The criteria-subcriteria weighting process was conducted using the Analytical Hierarchy Process (AHP). Additionally, the ranking process employed three other methods: Technique for Order of Preference by Similarity to Ideal Solution, Simple Multi-Attribute Rating Technique, and Multi-Objective Optimization on the Basis of Ratio Analysis. In the final evaluation, considering the ranking based on both the baseline case and variations of weight in the range of 5-10%, it was consistently observed that PEM ranked highest.

Keywords: Green hydrogen, electrolysis, AWE, PEM, AEM, MCDM, AHP.

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1. Introduction

In pursuit of the Net Zero Emissions (NZE) target, many countries worldwide have embarked on significant initiatives in the decarbonization process [1]. Green hydrogen has gained global recognition as a critical component in the energy transition required to attain this goal [2]. The Indonesian government, too, has deliberated the adoption of green hydrogen to achieve NZE by 2060 [3]. Notably, the Indonesian government has highlighted the role of green hydrogen as a future energy source in the net-zero roadmap outlined by the Ministry of Energy and Mineral Resources (KESDM) [4]. Furthermore, within the electricity sector, the 2021-2030 Electricity Supply Business Plan (RUPTL) released by the State Electricity Company (PLN) includes the utilization of fuel cells (hydrogen) for energy storage in electricity systems, particularly in remote areas [5].

On the flip side, as part of its efforts to reach the NZE target, PLN has initiated a program aimed at transitioning Diesel Power Plants into Renewable Energy (RE)-based power facilities. This program, known as the 'de-dieselization program', primarily focuses on isolated areas, such as off-grid regions and coastal areas on small islands in Indonesia. Typically, the approach used to meet the electricity demands in isolated areas involves a combination of Photovoltaic (PV) power plants and Battery Energy Storage Systems (BESS) [6]. However, in various other countries, programs have emerged for utilizing surplus electricity by transforming RE generators into Hydrogen Energy Storage Systems (HESS) [9], [10].

In recent years, significant progress has been made in the development of HESS. The combination of diverse resources, production methods, and supporting subsystems has led to increasingly efficient outcomes. Among the various methods used for green hydrogen production in integrated RE and hydrogen generation systems, water electrolysis stands out as the most widely employed approach [9]. Water electrolysis technology can be categorized into two groups based on operating temperature parameters: low and high temperature [10]. The low-temperature category encompasses technologies like Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), and Anion Exchange Membrane (AEM). In contrast, the high-temperature category includes Solid Oxide Electrolysis Cell (SOEC) [11]. It is worth noting that, as of now, only the low-temperature type has reached the commercial stage, while SOEC remains in the research and development phase [12]. In the process of designing a system using the HESS scheme, the selection of the electrolyzer type is a crucial and thoughtful consideration. Choosing the appropriate electrolyzer, aligned with the objectives and system characteristics, can lead to an efficient and sustainable design [13]. One comprehensive method available for making this selection is Multicriteria Decision Making (MCDM).

Numerous studies have been conducted to assess hydrogen production methods as a whole. For example, [14] employed the MCDM-Fuzzy Analytical Hierarchy Process (AHP) approach, considering economic, environmental, social, technical, and availability parameters to evaluate various green hydrogen production methods. Likewise, [15], conducted an assessment process that included economic, environmental, and social evaluation parameters for four alternative hydrogen production routes: coal gasification, methane steam reforming, biomass gasification, and wind turbine electrolysis, using the MCDM-Decision-Making Trial and Evaluation Laboratory (DEMATEL) and Evaluation based on Distance from Average Solution (EDAS) methods. From the available research, it is evident that MCDM has been widely utilized to select hydrogen production methods. However, to date, there has been no specific research addressing the selection of electrolyzer technology within green hydrogen production systems for HESS applications in isolated coastal areas.

This research was undertaken with the objective of addressing the question: 'What is the optimal low-temperature water electrolysis technology for the production of green hydrogen in coastal isolated areas?' To tackle this query, the initial step involved gaining a comprehensive understanding of the specifications and attributes associated with each electrolysis technology. The decision-making process was executed through a series of steps, beginning with alternative ranking outcomes. This ranking procedure started with method selection, followed by the identification of alternatives, the establishment of criteria and sub-criteria, a multicriteria assessment, and a discussion of the assessment results. Ultimately, the study concluded with findings and recommendations. In this manner, this article aimed to furnish a comprehensive insight into the selection of electrolysis technology in the context of the HESS, particularly within the framework of harnessing excess electricity.

1.1. Coastal Isolated Area

Coastal isolated areas may refer to regions along the coast that are relatively remote or isolated from major urban centers and have limited access to transportation, infrastructure, and services [16], [17]. Indonesia, being an archipelagic country with an extensive coastline, has numerous coastal isolated areas, including remote islands and villages [18]. One example of a coastal isolated area in Indonesia is Sulamu Village, Kupang Regency, East Nusa Tenggara Province.

One common challenge often encountered in coastal isolated areas involves limited access to electricity and clean water [19]. In Indonesia, the energy supply scheme in these regions is usually addressed through diesel power plants. Nevertheless, the government has introduced alternative schemes, utilizing renewable energy-based power plants that align with the region's potential [20]. Regarding the provision of clean water, residents typically buy water supplied by private entities [21].

Renewable energy-based power plants tend to be fluctuated, necessitating the integration of an energy storage into the built system. BESS is one of the most widely used storage types for isolated areas. Another energy storage scheme, known as hybrid energy storage, has been developed to combine hydrogen and batteries for efficient storage system in isolated areas [22]. However, implementing the hybrid energy storage scheme for spesific coastal isolated areas also faces challenges, such as limited access to a clean water source for produce hydrogen. herefore, to apply a sustainable HESS scheme, the components of the equipment and supporting systems for green hydrogen production must be designed to align with the characteristics of coastal isolated areas.

In addition, the lack of desalination infrastructure presents another hurdle, as different electrolysis technologies vary in their tolerance to water impurities. PEM technology is highly sensitive and requires deionized water, whereas AWE and AEM are more robust but still need pre-treatment in areas without desalination infrastructure.

Therefore, to apply a sustainable HESS scheme, the components of the equipment and supporting systems for green hydrogen production must be designed to align with the characteristics of coastal isolated areas.

2. Multi Criteria Decision Making (MCDM) Method

2.1. Weighting Method

The MCDM method has found extensive application in the realm of renewable energy, including hydrogen production systems. MCDM is employed for tasks ranging from site selection and strategic planning to the evaluation of diverse hydrogen production techniques [23], [24]. Figure 1 illustrates the procedural steps undertaken in this study.

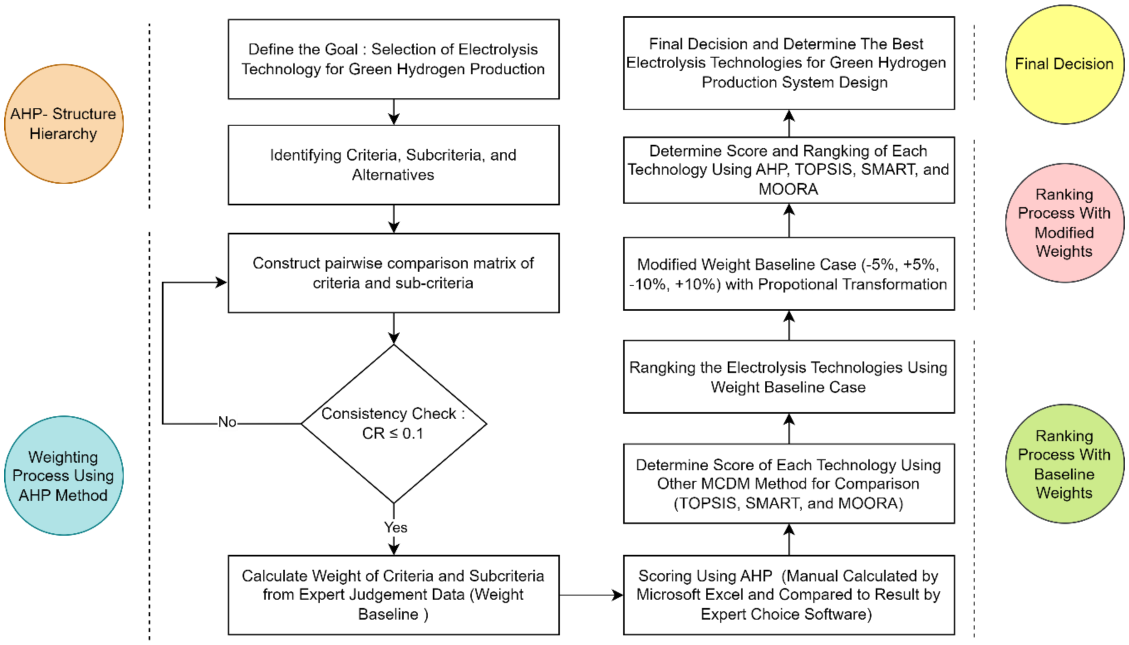

Fig. 2. Structure of proposed methodology.

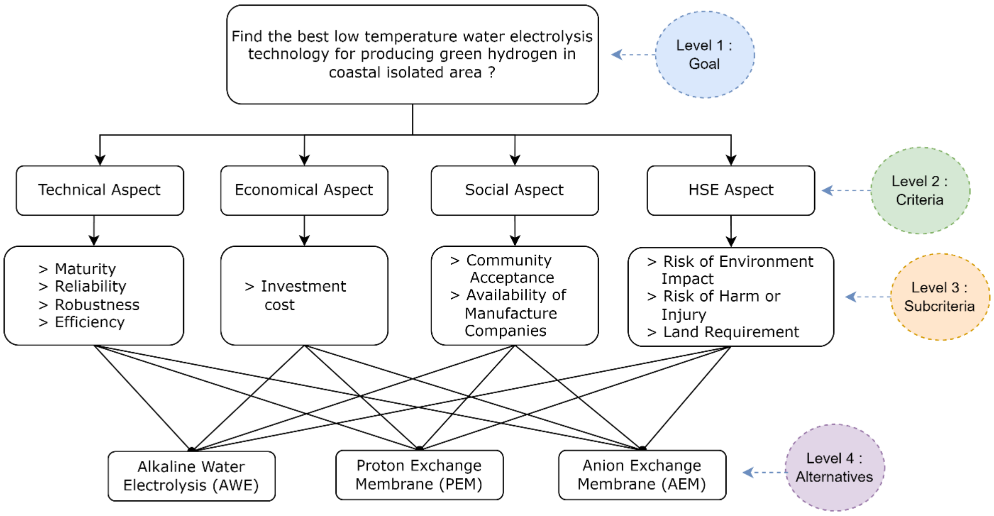

Fig. 1. MCDM-AHP structure for selection low temperature water electrolysis technology.

According to Fig. 1, the initial step involves establishing a problem model structure. AHP is fundamental component of MCDM, it provides a comprehensive and rational framework for structuring a decision problem model. The preparation of the MCDM-AHP model in a hierarchical format should align with the specific objectives [25], [26]. In this study, the objective was to identify the most suitable low-temperature electrolyzer technology for integration into a green hydrogen production system, which would be coupled with a seawater desalination unit. This hydrogen would subsequently serve as an energy storage solution at an off-grid solar power facility located in Sulamu Village, Kupang Regency, Nusa Tenggara Timur Province, Indonesia.

Figure 2 illustrates the hierarchical model structure using MCDM-AHP and reveals that the hierarchical model structure comprises four levels. Level 2 encompasses four criteria, level 3 includes ten sub-criteria, and level 4 involves three alternatives. Once the AHP hierarchical model structure is established, the subsequent step is to develop a pairwise comparison matrix. The result of this stage is the assignment of weight values to each criterion and subcriterion, which will be utilized in the alternative ranking calculation process [27].

In this study, the criteria and sub-criteria weighting process was conducted using the AHP method developed by Thomas L. Saaty, employing Saaty's nine-point rating system to determine the weighting of importance [28]. The weighting procedure commences with the creation of pairwise comparison matrices and the assessment of matrix consistency. If the obtained Consistency Ratio (CR) value is $\leq$ 0.1, the comparison matrix is affirmed as consistent. Conversely, if the CR value exceeds 0.1, the comparison matrix is deemed inconsistent and requires further review [29], [30]. Following the confirmation of the consistency of all pairwise comparison matrices, the subsequent step involves the computation of eigenvector (w) values [31].

The value of the eigenvector variable (w) signifies the weight of the criteria-subcriteria. In determining weight values using the eigenvalue and eigenvector method (exact method), it is essential that the sum of all weight values equals 1 ($w_1 + w_2 + ... + w_n = 1$). For example, in a 4x4 matrix, the sum of $w_1+w_2+w_3+w_4$ should equate to 1. If the solution yields a sum of $w_1+w_2+w_3+w_4 \neq 1$, then the eigenvector value must be normalized [32]. Once the weight values for scoring each subcriterion are obtained, the subsequent step is the ranking process.

2.2. Ranking Methods

The ranking process using the MCDM method sometimes yields decisions that are highly dependent on the method employed. Therefore, diversifying the MCDM methods in the analysis is crucial for obtaining more reliable results [33]. In this study, four MCDM methods have been utilized, namely AHP, Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Simple Multi-Attribute Rating Technique (SMART), and Multi-Objective Optimization on the Basis of Ratio Analysis (MOORA).

The steps for the ranking process using the AHP method are generally akin to the weighting process using AHP. In the ranking process, the pairwise comparison matrix comprises the evaluation values of each alternative based on each sub-criterion. Consequently, there are ten pairwise comparison matrix with a size of 3x3 involved in the calculations. The outcomes of these calculations, representing the values of each alternative based on the ten matrices, are then multiplied by the weights assigned to each sub-criterion. The resulting values constitute the scores for each alternative. The subsequent step involves summing up the total scores for each alternative across all sub-criteria, with these results serving as the basis for ranking preferences.

While the AHP method relies entirely on expert opinions for the assessment process, the TOPSIS, SMART, and MOORA methods obtain values for each alternative from literature review references. The initial step in the ranking process using these three methods is to determine the value of each alternative for each sub-criterion, forming a decision matrix. For a 3-alternative, 10-subcriterion MCDM problem, the decision matrix is presented in Table 1, where X_{ij} (i= 1,2, 3; j= 1, 2, ..., 10) represents the performance value of the ith alternative against the j^{th} sub-criterion.

Table 1. Decision matrix table with 3 alternatives and 10 sub-criteria.

Alternative (A_i)	Subcriteria (SC_j)			
	SC_1	SC_2	…	SC_{10}
A_1	X_{11}	X_{12}	…	X_{110}
A_2	X_{21}	X_{22}	…	X_{210}
A_3	X_{31}	X_{32}	…	X_{310}

Once the decision matrix, as presented in Table 1, is established, the subsequent step involves performing the ranking calculations using each of the MCDM methods. Below, we provide a detailed explanation of the ranking steps:

(i) TOPSIS is a multi-criteria decision-making technique that hinges on selecting an alternative that is closest to the positive ideal solution while being farthest from the negative ideal solution [34]. The TOPSIS ranking process commences with the creation of a normalized decision matrix, achieved through the application of Eq. (1) [35]:

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{3} x^2{}_{ij}}}, i = 1,2,3; j = 1,2,\dots,10 \quad (1)$$

The subsequent step involves the creation of a y_{ij} matrix, achieved by multiplying the weights for each sub-criterion (w_j) with the value of each attribute (r_{ij}) using Eq. (2):

$$y_{ij} = r_{ij}\, w_j, i = 1,2,3; j = 1,2,\dots,10 \quad (2)$$

The next step involves determining the positive ideal solution matrix and the negative ideal solution matrix using Eq. (3) and (4), where $i = 1,2,3, j = 1,2,\dots,10)$:

$$\{y_1^+,\dots,y_{10}^+\} = \{(\max_i y_{ij} | j \in K), (\min_i y_{ij} | j \in K')\} \quad (3)$$

$$\{y_1^-,\dots,y_{10}^-\} = \{(\min_i y_{ij} | j \in K), (\max_i y_{ij} | j \in K')\} \quad (4)$$

Once the ideal solution matrix is determined, the subsequent step involves calculating the distance between the value of each alternative (A_i) and the positive ideal solution (D_i^+) and negative ideal solution (D_i^-) matrices using Eq. (5) and (6) [36]:

$$D_i^+ = \sqrt{\sum_{j=1}^{10} (y_{ij} - y_j^+)^2} \quad i = 1,2,3\,; j = 1,2,\dots,10 \quad (5)$$

$$D_i^- = \sqrt{\sum_{j=1}^{10} (y_{ij} - y_j^-)^2} \quad i = 1,2,3\,; j = 1,2,\dots,10 \quad (6)$$

The last step involves computing the preference value for each alternative. The calculation of the preference value for each alternative (V_i) can be done using Eq. (7) [37] :

$$V_i = \frac{D_i^+}{D_i^+ + D_i^+}\ , i = 1,2,3, \quad 0 \leq V_i \leq 1 \quad (7)$$

In the TOPSIS method, a higher Vi value signifies that the alternative Ai holds a superior ranking and is deemed the most suitable choice.

(ii) MOORA is a multi-criteria decision-making method where the calculation of alternative rankings is based on the nature of the sub-criteria, whether they are beneficial or non-beneficial. The ranking process in the MOORA method starts with establishing a normalized decision matrix using Eq. (1) [38], [39]. This is followed by the creation of a yij matrix using Eq. (2). To calculate the ranking of each alternative, the preference value for each alternative is determined using Eq. (8) [40]):

$$V_i = \sum_{j=1}^{g} w_j r_{ij} - \sum_{j=g+1}^{n-g} w_j r_{ij} \quad (8)$$

where w_j is the weight for each criterion j obtained from the calculation results using the AHP method, g is the number of sub-criteria that are beneficial, while n-g the number of sub-criteria that are non-beneficial. The highest V_i value in calculations using the MOORA method is defined as the best alternative ([41].

(iii) SMART is a multi-criteria decision-making method that computes alternative rankings based on utility values [42]. The ranking process starts by calculating the utility value for each alternative. The utility value for beneficial sub-criteria can be calculated using Eq. (9):

$$u_j(a_i) = \frac{c_{out} - c_{min}}{c_{max} - c_{min}} \text{ x } 100\% \quad (9)$$

Meanwhile, the calculation of the utility value of non-beneficial sub-criteria can be calculated using Eq. (10) [43] :

$$u_j(a_i) = \frac{c_{max} - c_{out}}{c_{max} - c_{min}} \text{ x } 100\% \quad (10)$$

The $u_j(a_i)$ value represents the utility value of the jth subcriterion for the ith alternative, c_{max} stands for the maximum subcriterion value for subcriterion j, c_{min} represents the minimum subcriterion value for subcriterion j, and c_{out} is the value of the i^{th} alternative subcriterion for subcriterion j.

Determining the final value of each alternative is calculated by multiplying the utility value of the sub-criteria ($u_j(a_i)$) obtained from Eq. (9)-(10) with the normalized weight value of each sub-criteria from the AHP calculation. Calculation of the final value of each alternative using the SMART method can be done using Eq. (11) [44] :

$$V(a_i) = \sum_1^j w_j\, u_j(a_i)\ , \ i = 1,2,3\,; j = 1,2,\dots,10 \quad (11)$$

where $V(a_i)$ is the total value for the ith alternative, wj is the weight for each criterion j obtained from the calculation results using the AHP method, and u_j (a_i is the utility value of the j^{th} criterion for the i^{th} alternative. The highest $V(a_i)$ value in calculations using the SMART method is defined as the best alternative.

2.3. Identification of Alternatives

This study focused exclusively on low-temperature electrolysis technology. This choice was driven by considerations of technology readiness level (TRL) parameters, as low-temperature electrolysis has advanced to the commercial stage, while SOEC remains in the research and development phase [12]. Figure 3 presents a simplified block diagram that outlines the electrolysis technology selection process employed in designing a green hydrogen production system for coastal isolated areas with limited access to fresh water resources.

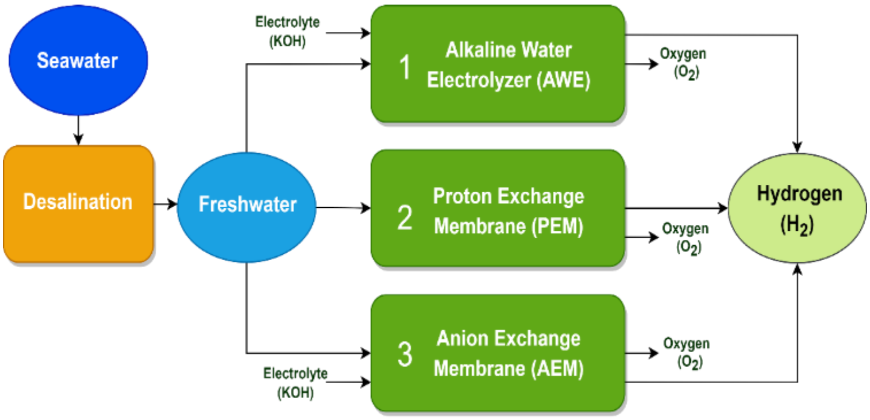

Fig. 3. Block diagram of different electrolysis technologies applied to coastal isolated area.

As depicted in the simplified block diagram presented in Fig. 3, there are three electrolysis technologies designated as alternatives. This selection aligns with recommendations made by IRENA, and the three technologies in question are AWE, PEM, and AEM [45]. Each electrolysis technology comes with its unique set of advantages and disadvantages. Consequently, a trade-off process is essential to arrive at a decision regarding the most suitable technology. The characteristics of each technology are detailed in the following subsection

2.3.1. Alkaline water electrolysis (AWE)

AWE is a well-established water splitting method and boasts the highest level of technological maturity compared to other water splitting techniques. Its operational parameters encompass a temperature range of 60-80°C, alkaline concentration (5M KOH/NaOH), a current density of 0.2-0.4 A/cm2, and an efficiency level hovering around 63-71% of the Lower Heating Value (LHV) of hydrogen [46]. The single cell voltage in AWE varies between 1.23-2.25 V [47], and the technology can achieve a lifespan of nearly 100,000 hours[48]. A noteworthy aspect is AWE's response to sudden changes in power, which may not be as swift as in PEM technology. AWE's response time can be measured in minutes. Consequently, in some system designs, it is equipped with capacitors to serve as an energy buffer [33], [49]. AWE technology entails investment costs ranging from 500-1000 USD per kilowatt (kW), with estimated operation and maintenance (O&M) costs spanning between 2-6% per annum [33][50]. The chemical reaction process in AWE is depicted in Eq. (12)–(14) [51] :

$$\text{Cathode: } 2H_2O(l) + 2e^- \longrightarrow 2OH^-(aq) + H_2(g) \quad (12)$$
$$\text{Anode : } 2OH^-(aq) \rightarrow H_2O(l) + \tfrac{1}{2} O_2(g) + 2e^- \quad (13)$$
$$\text{Total reaction: } 2H_2O(l) \rightarrow 2 H_2(g) + O_2(g) \quad (14)$$

2.3.2. Proton exchange membrane water electrolysis (PEMWE)

The PEM water electrolyzer is currently one of the most widely used water splitting technologies for producing green hydrogen. In PEM, deionized water is used as the feedwater without the need for additional electrolytic additives. PEM water electrolyzers offer several advantages, including a high current density, greater energy efficiency, low gas permeability, and relatively straightforward handling and maintenance [52]. The current density of PEM typically reaches around 1 A/cm2, and it operates within the temperature range of 60-80°C. The single cell voltage in PEM technology ranges from 1.23 to 3 V [47]. Thanks to the utilization of Membrane Electrode Assembly (MEA), PEM has a long lifespan that can extend from 50,000 to 100,000 hours without the need for maintenance. Regarding costs, PEM technology investments generally range from 700 to 1400 USD per kilowatt (kW), with estimated operation and maintenance (O&M) costs varying between 3-5% per annum [33], [50]. The chemical reactions that occur in the PEM water electrolysis process are elucidated in Eq. (15) – (17) [53] :

$$\text{Cathode: } 2H^+ (aq) + 2e^- \longrightarrow H_2 (g) \quad (15)$$
$$\text{Anode : } 2H_2O (l) \longrightarrow 4H^+ (aq) + 4 e^- + O_2 (g) \quad (16)$$
$$\text{Total reaction: } 2H_2O (l) \longrightarrow 2 H_2 (g) + O_2 (g) \quad (17)$$

2.3.3. Anion exchange membrane water electrolysis (AEMWE)

AEM water electrolysis is a relatively recent electrochemical method for water splitting. An AEM electrolyzer can be described as a combination of AWE and PEM electrolyzers, offering the advantages of AWE electrolyzers while mitigating the weaknesses of PEM electrolyzers [54]. Fundamentally, the working principle of AEM water electrolysis technology aligns with AWE. Its operational parameters include operating within a temperature range of 50-60°C, employing an alkaline concentration (1M KOH/NaOH), achieving a current density of 0.2-1 A/cm2, with the single cell voltage in AEM ranging from 1.23-2.2 V. The lifespan of AEM technology typically extends to around 30,000 hours [55], [56]. Regarding costs, AEM technology investments typically fall within the range of 750-1,100 USD per kilowatt (kW), with estimated operation and maintenance (O&M) costs ranging from 3-5% per annum [57], [58]. The chemical reactions that occur in the AEM water electrolysis process are detailed in Eq. (18) – 20 [59] :

$$\text{Cathode: } 2H_2O(l) + 2e^- \rightarrow 2OH^- (aq) + H_2(g) \quad (18)$$

$$\text{Anode: } 2OH^-(aq) \rightarrow H_2O(l) + \tfrac{1}{2} O_2(g) + 2e^- \quad (19)$$

$$\text{Total reaction: } 2H_2O(l) \rightarrow 2\, H_2(g) + O_2(g) \quad (20)$$

2.4. Definition of Subcriteria

When making decisions about designing a sustainable hydrogen production system, to consider various criteria within the evaluation process is imperative. These criteria encompass technical, economic, social, and health, safety, and environment (HSE) aspects [33], [60]. Such criteria are integral components of the evaluation framework employed by policymakers to assess and determine the composition of a production system. In this study, these criteria will be applied with a specific focus on selecting electrolyzer technology. More detailed descriptions of these criteria are presented in the form of sub-criteria. An explanation of the sub-criteria is provided as follows:

- Maturity: The technical specification related to maturity value is technology readiness level (TRL).
- Reliability: The technical specification related to the reliability value of electrolysis technology is lifetime (hour).
- Robustness: Specifications related to robustness values are resilience (resistance to feed water impurities) and dynamics (ability to perform well in power fluctuation situations).
- Efficiency: The technical specification related to the efficiency value of electrolysis technology is voltage efficiency.
- Investment cost: It refers to the initial costs (investment) required to adopt and implement a particular electrolysis technology.
- Community acceptance: It refers to the level of acceptance of the people affected by the technology in question, including local people, stakeholders, and the surrounding community. Technology that is not well received can potentially trigger conflict.
- Availability of manufacture companies: It refers to the availability of electrolyzer technology on the market produced by manufacturer companies.
- Risk of environtmental impact: It refers to the negative impact of technology on the surrounding natural environment, including land, water, air, and biodiversity.
- Risk of harm or injury: It refers to the potential risks to the health and safety of humans involved in operating, maintaining, or interacting with the technology.
- Land requirement: It refers to the area of land required for electrolysis technology to operate. Technologies that require large areas of land have the potential to change land use patterns and can have a significant impact on the environment.

In Table 2, information is presented regarding the pairwise comparison matrix for each criterion and sub-criteria obtained from the results of expert participation through questionnaires. This matrix is used to calculate the weight values of the criteria-sub-criteria using the AHP.

Table 2. Criteria-subcriteria pairwise comparison.

Criteria	T	E	S	HSE
Technical (T)	1	5	1	1/3
Economy (E)	1/5	1	1/3	1/3
Social (S)	1	3	1	1
HSE	3	3	1	1

Technical criteria	M	R	Rs	Ef
Maturity (M)	1	1	1	1/3
Reliability (R)	1	1	1	1
Robustness(Rs)	1	1	1	1
Efficiency (Ef)	3	1	1	1

Social criteria	Availability of manufacture companies
Community acceptance	3

HSE criteria	Rei	RoHI	Lr
Risk of environmental impact (Rei)	1	1	1
Risk of harm or injury (RoHI)	1	1	1
Land requirement (Lr)	1	1	1

The initial step before proceeding with the weight calculation process using the exact (eigenvector) method is to assess the consistency of the matrix by computing the CR value. The calculated CR value for the criteria matrix is 0.098, for the technical criteria is 0.057, and for the criterion HSE is 0. These results indicate an "acceptable consistent" condition for all criteria. The subsequent step involves calculating the weights for each criterion and sub-criteria. The eigenvector values, used as weight values for each criterion-sub-criterion, must undergo normalization, ensuring that the sum of all weights ($w_1 + w_2 + ...+ w_n$) equals 1. Table 3 presents the outcomes of the weight calculations for each criterion and sub-criteria.

According to the information provided in Table 3, the criterion HSE carries the highest weight at the criteria level, signifying that, in the eyes of experts, the most crucial aspect in designing a hydrogen production system is health, safety, and environmental considerations. This weight is consistently distributed among each of the sub-criteria. The criterion 'social aspects' is assigned the second highest weight, with the community acceptance sub-criterion exerting the most dominant influence compared to other sub-criteria. The criterion 'technical aspects' comes in third in terms of weight, with the efficiency sub-criterion being the most influential. Finally, the criterion 'economic aspects' exhibits the lowest weight values. The weight values of the sub-criteria resulting from the AHP method's calculation process cannot be used directly. These values must be further computed by multiplying them with the criteria's weight values (from the level above). The outcomes of the calculation of weights for scoring (weight baseline case) in the evaluation process are also depicted in Fig. 4.

The results of the weighting calculations for scoring each sub-criterion in Fig. 4 are not only used by the AHP ranking method, but also by other ranking methods (TOPSIS, MOORA, SMART).

Table 3. Summary of criteria-subcriteria weight calculation.

Weight Calculation		**Alias**
Criteria	**Subcriteria**	
Technical (0.251)	Maturity (0.188)	TRL Level
	Reliability (0.241)	Lifetime
	Robustness (0.241)	Resilience and Dynamics
	Efficiency (0.331)	Voltage efficiency
Economy (0.083)	Investment Cost (1)	Capital cost
Social (0.274)	Community acceptance (0.75)	Public acceptance
	Availability of Manufacture Companies (0.25)	Number of electrolyzer manufacture companies
HSE (0.392)	Risk of Environmental impact (0.333)	Environment
	Risk of harm or injury (0.333)	Hazard
	Land requirement (0.333)	Electrolyzer footprint

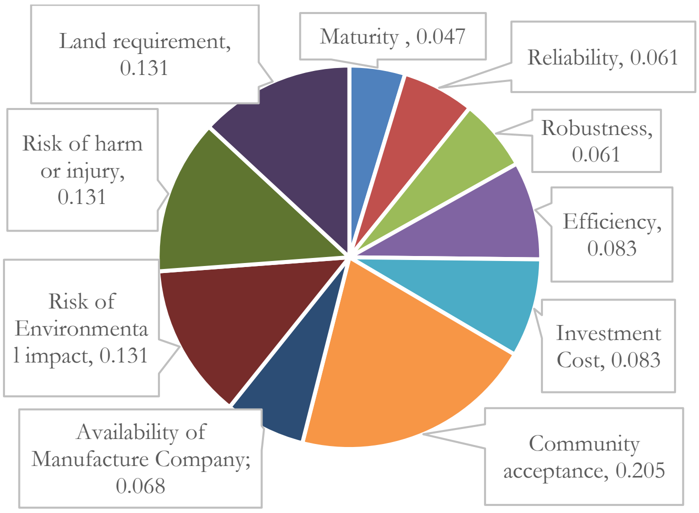

Fig. 4. Distribution of scoring weight subcriteria for the assessment.

3. Result and Discussion

3.1. Multicriteria Assessment Result

Once the weight values for scoring for each sub-criterion are determined, the subsequent step is to initiate the scoring evaluation process for each alternative. The primary aim of this evaluation process is to ascertain the ranking of a range of available alternatives. Table 4 provides information about the pairwise comparison matrix of each alternative for each sub-criterion. Each evaluation of alternatives for sub-criteria is a comparison matrix with dimensions 3x3.

The calculated CR values for the alternative matrices of each sub-criterion indicate "acceptable consistent" results. To provide further detail, the CR value for the sub-criteria reliability, robustness, community acceptance, availability of manufacturing company, risk of environmental impact, risk of harm or injury, and land requirements is 0. The CR value for the sub-criteria efficiency and investment cost is 0.025, while the CR value for maturity is 0.033. Following the verification of the alternative pairwise comparison matrix's consistency for each sub-criterion, the subsequent step involves computing the score for each alternative. The eigenvector value obtained serves as the score for each alternative, but this value must undergo normalization. Subsequently, the obtained score value is multiplied by the weight for scoring values depicted in Fig. 4. The results of calculating the final score for each alternative using the AHP method are presented in Table 5.

The results of the final score calculations with the AHP method, conducted manually using Excel software through the exact method, are presented in Table 5.

These results indicate that the top-ranking technology is PEM, followed by AEM in second place, and AWE in third place. AWE technology secures the third position and excels in the sub-criteria maturity and investment cost. In contrast, PEM demonstrates a singular advantage exclusively in the sub-criterion efficiency, while AEM does not exhibit specific superiority in any sub-criterion. PEM and AEM outperform AWE in the criterion HSE, represented by the sub-criteria risk of environmental impact, risk of harm or injury, and land requirement, which carry the highest scoring weights in the evaluation process. Additionally, a final score calculation is conducted using Expert Choice software for comparison purposes, and the results are presented in Fig. 5.

Table 4. Alternatives pairwise comparison for each sub-criterion.

	AWE	PEM	AEM
AWE	(1,1,1,1,1,1,1,1,1,1)	(3,1,3,1/3,5,1,1,1/3,1/3,1/3)	(5,3,1,1,3,1,3,1/3,1/3,1/3)
PEM	(1/3,1,1/3,3,1/5,1,1,3,3,3)	(1,1,1,1,1,1,1,1,1,1)	(3,3,1/3,5,1,1,3,1,1,1)
AEM	(1/5,1/3,1,1,1/3,1,1/3,3,3,3)	(1/3,1/3,3,1/5,1,1,1/3,1,1,1)	(1,1,1,1,1,1,1,1,1,1)

Table 5. Ranking of alternatives for hydrogen production using AHP.

Subcriteria	Alternatives score using AHP			Score x Weight		
	AWE	PEM	AEM	AWE	PEM	AEM
Maturity	0.637	0.258	0.105	0.030	0.012	0.005
Reliability	0.429	0.429	0.143	0.026	0.026	0.009
Robustness	0.429	0.143	0.429	0.026	0.009	0.026
Efficiency	0.185	0.659	0.156	0.015	0.055	0.013
Investment Cost	0.659	0.156	0.185	0.055	0.013	0.015
Community acceptance	0.333	0.333	0.333	0.068	0.068	0.068
Availability of Manufacture Company	0.429	0.429	0.143	0.029	0.029	0.010
Risk of Environmental impact	0.143	0.429	0.429	0.019	0.056	0.056
Risk of harm or injury	0.143	0.429	0.429	0.019	0.056	0.056
Land requirement	0.143	0.429	0.429	0.019	0.056	0.056
Total score				0.306	0.380	0.314
Rank				3	1	2

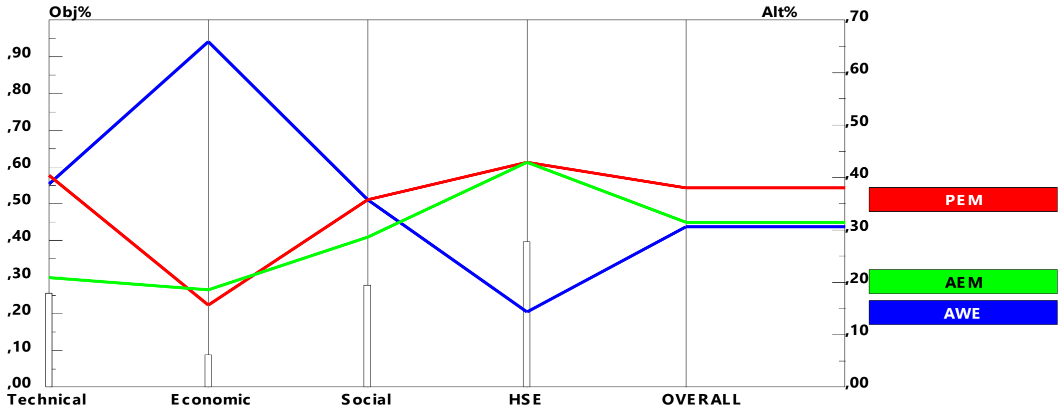

Fig. 5. Alternatives scoring by expert choice software.

The simulations conducted using Expert Choice software in Fig. 5 yield identical results to the manual calculations. The ranking results obtained through the AHP method exclusively rely on expert opinions, without considering other input sources [61]. To validate the experts' opinions, it is essential to perform rankings using other MCDM methods that not only incorporate expert opinions but also utilize values obtained from literature reviews.

In theory, employing the MCDM method in the evaluation process offers several advantages, including the ability to integrate quantitative and qualitative sub-criteria within a unified analytical framework. Nonetheless, in practice, the sub-criteria used must first be converted into quantitative data [62], [63]. Therefore, prior to commencing the ranking process using the TOPSIS, SMART, and MOORA methods, the values of sub-criteria that tend to be qualitative, such as robustness, community acceptance, risk of environmental impact, and risk of hazard, must be converted using the linguistic conversion guidelines outlined in Table 6.

Table 6. Linguistic equivalence to crisp values.

Robustness	Community acceptance	Risk of environmental	Risk of Hazard	Value
Very Bad	Strongly disagree	Very Low	Very Low	1
Bad	Disagree	Low	Low	3
Acceptable	Moderately Agree	Medium	Medium	5
Good	Agree	High	High	7
Very Good	Strongly Agree	Very High	Very High	9

Utilizing the guidelines for linguistic conversions, the values of each sub-criterion that tend to be qualitative can be converted into quantitative data. Thus, Table 7 provides a summary of the data employed in the evaluation process using the TOPSIS, SMART, and MOORA methods. The weight values for each sub-criterion still rely on the AHP calculation outcomes as presented in Table 7.

Table 7 provides the definitions for the codes (+) and (-). The code (+) signifies that the sub-criterion is beneficial, implying that a higher value is preferable. Conversely, the code (-) designates the sub-criterion as non-beneficial (cost), indicating that a lower value is preferable [64]. The final evaluation, as detailed in the TOPSIS method using Eq. (1) - (7), yields alternative preference values (Vi) for PEM (0.724), AEM (0.639), and AWE (0.370). In the MOORA method, using Eq. (8), the Vi values for PEM (0.063), AEM (0.033), and AWE (-0.083) are obtained. For the SMART method, the calculation results using Eq. (9) – (11) produce alternative preference values for PEM (0.776), AEM (0.649), and AWE (0.375). A comparison of the final evaluation results for alternative rankings among the four different MCDM methods using the weight baseline case is presented in Fig. 6.

Table 7. Decision matrix for scoring with TOPSIS, SMART, and MOORA methods.

Subcriteria	Types	Value			Ref.
		AWE	PEM	AEM	
Maturity (TRL level)	+	9	8	6	EJ, [47], [65]
Reliability (lifetime hours)	+	100,000	90,000	30,000	EJ, [66], [67]
Robustness (resilience and dynamics)	+	7	9	7	EJ, [68], [69])
Efficiency (%)	+	70	75	60	EJ, [12], [70])
Investment cost (USD/kW)	-	716	1,227	1,100	EJ, [57], [71]
Community acceptance	+	5	7	7	EJ
Availability of manufacture company	+	17	13	3	EJ, [57]
Risk of environmental impact	-	5	3	3	EJ, [33]
Risk of harm or injury	-	5	1	3	EJ, [33]

EJ=Expert judgement

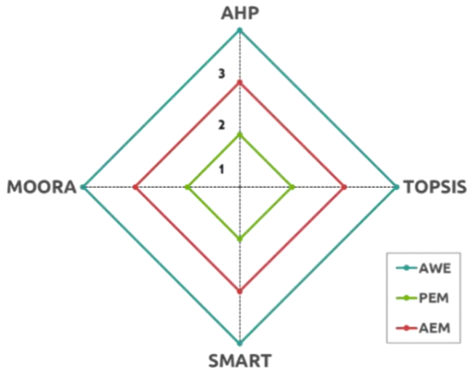

Fig. 6. Ranking of electrolysis technology as a function of the MCDM using weight baseline case.

The results of the calculations using the AHP, TOPSIS, SMART, and MOORA methods consistently rank the alternative electrolyzer technologies in the same rank order: PEM (1) - AEM (2) - AWE (3). This consistency in ranking results demonstrates the robustness of the rankings across various MCDM methods.

3.2. Discussion

Various MCDM methods were utilized in the analysis to determine the choice of electrolyzer technology for designing a green hydrogen production system. Figure 4 illustrates the weight distribution data (weight baseline case), where the four sub-criteria with the highest scores are community acceptance, risk of environmental impact, risk of harm or injury, and land requirements. These sub-criteria belong to the criteria social aspects and HSE, signifying their significant influence according to the expert opinions collected through the questionnaire. To assess the consistency of the evaluation results, simulations were conducted to investigate the effects of changes in the baseline weight values of the four sub-criteria, with variations in the range of 5-10% across four scenarios. The weight changes were proportionally adjusted, ensuring that when the scores for these four sub-criteria were reduced, the weights for the remaining six sub-criteria increased, and vice versa, while maintaining a total weight of 1 [33]. Table 8 provides information on the changes in scoring weight values for the four scenarios.

Changes in weights for scoring 4 sub-criteria in 4 scenarios as presented in Table 8 follow the following conditions:

- Sub-criteria from Social and environmental aspects namely community acceptance, risk of environmental impact, risk of harm or injury, and land requirement are decreased by a 5%, whereas the rest of criteria are adjusted correspondingly to maintain the total weights at 100%.
- Sub-criteria from Social and environmental aspects namely community acceptance, risk of environmental impact, risk of harm or injury, and land requirement are increased by a 5%, whereas the rest of criteria are adjusted correspondingly to maintain the total weights at 100%.
- Sub-criteria from Social and environmental aspects namely community acceptance, risk of environmental impact, risk of harm or injury, and land requirement are decreased by a 10%, whereas the rest of criteria are adjusted correspondingly to maintain the total weights at 100%.

The ranking results using the provisions of the 4 scenarios are presented in Fig. 7. The ranking methods used to see the effect of changes in scoring weights are AHP, TOPSIS, SMART, and MOORA.

Table 8. Variation of weights related to social and environmental factors from the baseline case.

Criteria	Subcriteria	(a) - 5%	(b) +5%	(c) - 10%	(d) +10%
Technical	Maturity	0.051	0.044	0.054	0.040
	Reliability	0.065	0.056	0.069	0.052
	Robustness	0.065	0.056	0.069	0.052
	Efficiency	0.089	0.077	0.096	0.071
Economy	Investment Cost	0.090	0.077	0.096	0.071
Social	Community acceptance	0.195	0.215	0.185	0.226
	Availability of Manufacture Company	0.073	0.063	0.079	0.058
HSE (Health, Safety and Envronment)	Risk of Environmental impact	0.124	0.137	0.117	0.144
	Risk of harm or injury	0.124	0.137	0.117	0.144
	Land requirement	0.124	0.137	0.117	0.144
Total		1	1	1	1

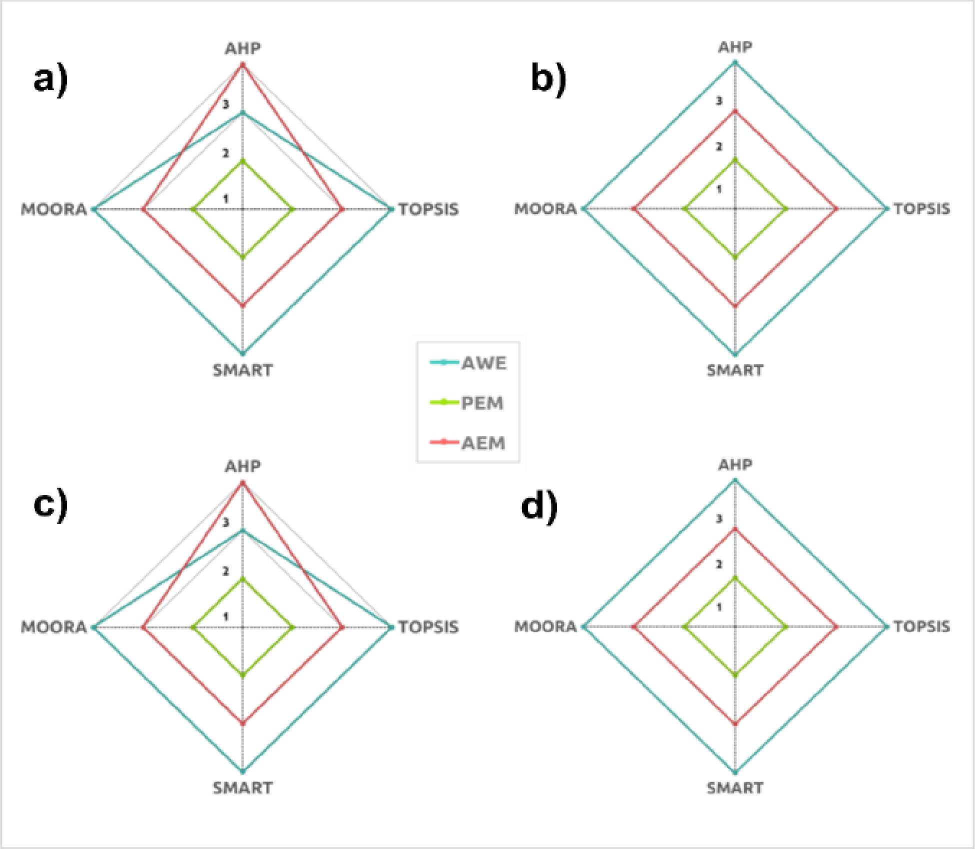

Fig. 7. Sensitivity of the ranking under the variation of the weights corresponding to social and HSE for the cases in Table 8.

The ranking results in Fig. 7 indicate that, in general, changes in scoring weights within the 5-10% range, whether in scenarios of weight increase or decrease, do not lead to a change in the first rank for each MCDM method used. The calculations consistently show that PEM technology maintains the highest score. However, in scenarios where weights (a) and (c) are reduced, the results show that there has been a change in ranking for the second and third places in the calculation results using the AHP method, with the result that the second place is AEM, and the third place is AWE. This change in rankings does not significantly affect the decision-making process, as the MCDM analysis's objective, as depicted in the AHP hierarchy in Fig. 2, is to select only the electrolyzer technology ranked first.

The comparison of hydrogen production technologies (PEM, AWE, AEM) between coastal isolated areas and urban or industrial settings remains limited in the literature. Several important differences can be identified when applying hydrogen production technologies in coastal isolated areas. While the recommendation to use PEM technology is consistent in both settings due to its high efficiency and fast response to power fluctuations, coastal areas present unique challenges that are less prominent in urban or industrial environments. For instance, coastal regions often lack sufficient desalination infrastructure, which means technologies like PEM, which require deionized water, must undergo additional pre-treatment steps. In contrast, technologies such as AWE and AEM, which are more tolerant of water impurities, still face significant operational challenges due to the fluctuating and unstable nature of renewable energy in these areas. Urban and industrial settings typically have more stable energy inputs and infrastructure, reducing the stress on the electrolyzer systems. These key differences highlight that while PEM remains a strong candidate for green hydrogen production, the environmental and technical constraints in coastal areas necessitate additional considerations for robustness and system design, which are critical for successful implementation in isolated regions.

4. Conclusion

The analysis, based on Multi-Criteria Decision-Making (MCDM), has been employed to select a low-temperature electrolysis technology for designing a green hydrogen production system in isolated coastal areas, which includes a Hydrogen Energy Storage System (HESS) integrated with a seawater desalination unit. The study considered three alternative electrolysis technologies: AWE, PEM, and AEM. Criteria and sub-criteria were weighted using the AHP method through exact calculations, and four different MCDM methods (AHP, TOPSIS, SMART, and

MOORA) were used for the alternative ranking process. The evaluation process encompassed technical, economic, social, and HSE aspects, each with several sub-criteria. The technical aspects consisted of the sub-criteria maturity, reliability, robustness, efficiency. The economical aspects consisted of the sub-criterion investment cost. The social aspects consisted of two sub-criteria community acceptance and the availability of technology manufacturing companies. The criterion HSE consisted of the sub-criteria risk of environmental impact, risk of harm or injury, and land requirements.

The results of the AHP analysis demonstrated that AWE excelled in the sub-criteria maturity and investment cost, PEM was superior in terms of efficiency, and AEM did not show specific dominance in any sub-criterion. The final evaluation results using the weight baseline case across the four MCDM methods consistently ranked the technologies as PEM (1) - AEM (2) - AWE (3). Even when implementing proportional changes in the scores for the top four sub-criteria within the 5-10% range, the rankings remained unchanged, with PEM consistently occupying the first position. Therefore, based on the study's findings, PEM technology is recommended as the most suitable option for designing green hydrogen production systems in isolated coastal areas with excess electricity utilization through HESS.

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