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Assessment of water electrolysis projects for green hydrogen production with a novel hybrid Q-learning algorithm and molecular fuzzy-based modelling

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ABSTRACT

Determining the most important criteria for increasing the efficiency of water electrolysis investments provides businesses with a competitive advantage. Although there are many studies in the literature on this importance, there are very few studies determining the most important of these performance indicators. To satisfy this gap, the purpose of this study is to make assessment of water electrolysis projects for green hydrogen production via a novel model. First, the balanced expert evaluation matrices are obtained by q-learning algorithm. Secondly, the criteria for water electrolysis investments are prioritized using molecular fuzzy Bayesian network (BANEW). Thirdly, green hydrogen strategies for water electrolysis investments are ranked with molecular fuzzy multi-objective particle swarm optimization (MOPSO). The most important contribution of this study to the literature is the determination of the criteria that should be applied primarily for the performance increase of water electrolysis investments by creating a new model. The use of molecular fuzzy numbers is a very important contribution of the model to the literature. In this process, the use of three-dimensional geometric figures allows the reduction of uncertainties in decision-making processes. The findings indicate that lifespan of electrolysers and production capacity are the most essential criteria. Additionally, proton exchange membrane electrolysers and alkaline water electrolysis are found as the most critical green hydrogen strategies. Extending the life of electrolysers is crucial to increase sustainability in hydrogen production and reduce long-term costs. In this context, research incentives should be provided for the development of materials and technologies to increase the durability of electrolysers. Similarly, establishing quality standards to extend the life of electrolysers also contributes to achieving this goal.

1. Introduction

Water electrolysis investments refer to projects that aim to separate water into hydrogen and oxygen using electrical energy. In this process, electric current is given to the water. As a result of this issue, water is divided into hydrogen and oxygen gases. These investments have critical importance in many respects. Water electrolysis produces hydrogen using electricity obtained from renewable energy sources. Hydrogen is a type of energy that can be an alternative to fossil fuels. Therefore, environmental pollution from energy production sources will decrease with the development of electrolysis projects [1]. This situation allows a more successful fight against a major problem that concerns the whole world, such as carbon emissions. Another benefit of water electrolysis investments is that they increase the energy security of countries. With the hydrogen obtained in this process, countries can produce the energy they need themselves. In this way, countries' external dependence on energy is reduced. On the other hand, hydrogen obtained by electrolysis of water can also be stored [2]. It is possible to reduce the problem of interruptions in energy production by using this energy when needed. This issue plays a very critical role in ensuring customer satisfaction.

To increase the performance of water electrolysis investments, improvements should be made to some variables. First, it is very essential to increase the efficiency of these projects. To achieve this goal, technological improvements should be made. It is possible to reduce losses in

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operational processes with the development of new generation electrolysers. Moreover, ensuring cost efficiency is another factor affecting the performance of these projects. In this context, financial support can be provided by the states to reduce the costs of electrolysis projects. These projects are provided with significant cost efficiency with opportunities such as tax reductions and low-interest loans [3]. In this way, it can be easier to increase the financial performance of the investments. Furthermore, providing a qualified workforce is also important for these projects to be more successful. Training programs can be organized on electrolysis technology. This can increase the performance of the projects by increasing the qualified workforce [4]. Similarly, this process can be contributed to by cooperating with universities and research institutions. This situation allows the development of new research projects. As a result of this condition, the performance of water electrolysis investments can be improved.

Determining the most important performance indicators is extremely critical for increasing the performance, effectiveness and efficiency of water electrolysis investments. This is important primarily for ensuring the efficiency of the projects. If these factors are not determined, it becomes very difficult to increase the efficiency and effectiveness of a complex investment such as water electrolysis. This situation causes energy, time and financial resources to be used in the wrong areas [5]. This level of waste of resources also negatively affects the performance of the projects. Critical performance indicators are needed to make the right decisions in the investment process. To increase the performance of the projects, the right strategies must be implemented at the right time. Otherwise, it becomes difficult to decide in which areas more investment should be made. This situation also causes the operational efficiency of the projects to decrease. In addition to them, if the most important performance indicators are not determined, businesses lose a significant competitive advantage. On the other hand, the complexity of water electrolysis projects makes it difficult to implement the right strategies at the right time. In summary, if the most important performance indicators are not determined, the financial resources of investments can be spent in inefficient areas. This negatively affects the efficiency and effectiveness of the projects. Due to these conditions, an evaluation should be conducted to define the most essential determinants of these investments. However, while most studies focus on the importance of indicators, there are very few studies that identify the most significant factors. This condition is identified as a significant deficiency in the literature on water electrolysis investments. Therefore, the main reason for the need for a new study is the limited studies on determining the most critical factors, which is defined as a significant deficiency in the literature on water electrolysis investments. In this context, determining the critical criteria and defining the priority strategies will increase the effectiveness of water electrolysis investments and contribute to green hydrogen production.

Accordingly, the purpose of this study is to make assessment of water electrolysis projects for green hydrogen production. To achieve this objective, a novel decision-making model has been generated. In the first section, the balanced expert evaluation matrices are obtained via q-learning algorithm. Within this regard, average scores and information values are calculated. Additionally, reward and penalty factors are determined. The second stage consists of prioritization of criteria for water electrolysis investments using molecular fuzzy BANEW. In this scope, fuzzy vectors, angels and entropy values are computed. The final stage is related to the ranking of green hydrogen strategies for water electrolysis investments using molecular fuzzy MOPSO. Within this context, weighted decision matrix, angels and initial velocity are identified. By considering these items, the following research questions can be identified.

(1) Which criteria plays the most critical role for effective water electrolysis investments?
(2) Which green hydrogen strategies should be priorly implemented for water electrolysis investments?

The main motivation of this study is to determine the green hydrogen strategies that should be implemented as a priority for water electrolysis investments. Although the factors affecting the performance of these projects are frequently emphasised, there is no consensus in the literature on which strategies are the most important. This situation significantly increases the need for new studies. By determining these priority factors, it is more possible to increase the efficiency and effectiveness of the projects. Another motivation of the study is to determine the most critical performance indicators for water electrolysis investments. Determining these criteria allows for a clearer understanding of the most accurate strategies. These issues can pave the way for the investors for to make appropriate strategic decisions. Multi-criteria decision-making models can be used to determine the most important criteria and the most priority strategies. In this process, there are some factors that need to be taken into consideration for this model to be developed correctly. Determining the performance indicators that have the most impact on water electrolysis investments is a very complex process. Therefore, for the most important indicators to be determined correctly, the uncertainty in the process must be reduced. On the other hand, these criteria can have a very significant effect on each other. In this context, it is important that the technique to be preferred in the weighting process of the criteria also considers the causal relationship between these factors.

The most important contribution of this study to the literature is the determination of the criteria that should be applied primarily for the performance increase of water electrolysis investments by creating a new model. Therefore, it is possible to mention both the theoretical and methodological contributions of this study. The most critical theoretical contribution of this study is the determination of the most important criteria for water electrolysis investments by evaluating the selected variables comprehensively. As a result of this issue, these findings are guiding for future research. There is an uncertainty in the literature regarding the importance weights of the factors affecting the performance of water electrolysis investments. This study offers a new perspective on which criteria are more critical. Determination of priority strategies for green hydrogen investments is another important theoretical contribution in this process. These findings guide both energy policy makers and sustainable energy investors. In this way, the operational efficiency of enterprises can be increased by implementing the most effective strategies on time. The increase in the profitability of the projects allows more investors to focus on this area. Because of this condition, it is possible to increase green hydrogen investments. On the other side, with respect to the methodological contribution, the main superiorities of the proposed model can be demonstrated as follows.

(1) The use of molecular fuzzy numbers, which are quite recently developed in the analysis process of the study, is a very important contribution of the model to the literature. Molecular fuzzy numbers are a structure obtained by integrating molecular geometry and fuzzy numbers. The main purpose here is to provide a more precise geometric modelling that traditional fuzzy numbers cannot provide. In this process, the use of three-dimensional geometric figures allows the reduction of uncertainties in decision-making processes. Type-1 fuzzy numbers work on a specific membership function. Molecular fuzzy numbers are more suitable for more complex systems. In this process, uncertainty is calculated not only at a point, but also on an angle and a vector. Interval type-2 fuzzy numbers allow the uncertainty to be modelled in a wider range. However, these ranges increase complexity and may be insufficient in certain calculations. Molecular fuzzy numbers handle these wide-range uncertainties with a three-dimensional modelling. In this way, it is possible to obtain more precise analysis results.
(2) The Bayesian network approach also provides superiority over the model by calculating the importance weights of the criteria. There are many different criteria that affect the performance of water electrolysis investments. These criteria can also affect each

other. In this context, this complex structure needs to be addressed in detail to determine the most important criteria. Analytic hierarchy process (AHP) offers a hierarchical structure used to determine the importance of criteria in multi-criteria decision-making processes. In this process, definite decisions and definite data are considered. In addition, AHP does not model causal relationships when making comparisons between criteria. Similarly, CRITIC considers the correlations between criteria. On the other hand, it does not consider the concept of causality in the analysis process. Bayesian networks can define causal relationships between criteria. On the other hand, DEMATEL is also used to determine the interactions between criteria and to establish a causal relationship. However, these relationships are completely based on expert opinions and do not directly address uncertainty. However, Bayesian networks can model causal relationships in a deeper way. In addition to this issue, uncertainty in the process can also be managed more successfully with probabilities.

(3) Obtaining balanced expert evaluation matrices with the q-learning algorithm provides significant contributions to the literature. This situation primarily offers the possibility of integrating machine learning into decision-making models. Traditional fuzzy decision-making models are usually based on expert opinions in a static manner. Using the q-learning approach in this model offers a dynamic and adaptable approach that enables learning from expert evaluations. In this process, it is learned which experts provide the most reliable inputs. Balanced evaluation matrices are created using this data. This situation significantly reduces the bias in the process. Thus, more reliable analysis results can be obtained. Ensuring expert accuracy with a feedback mechanism also increases the effectiveness of the process. Q-learning evaluates the accuracy of expert judgments with reward and punishment systems. Uncertainty can be managed much more effectively with this iterative learning process. A large number of experts can take part in decision-making processes. In this case, the evaluations of experts may be inconsistent. The q-learning algorithm allows for the integration of different expert opinions in a balanced manner. Owing to this condition, it is possible to increase the consistency of the model.

The organization of this manuscript is shown as follows. Literature examination is conducted in the second part. In this part, the main missing part in the literature can be underlined. The third part gives information about the steps of the proposed model. This new model is mainly generated to satisfy the missing part in the literature. In the fourth part, the analysis results are shared. The discussion of these results is taken place in the fifth section. In the sixth section, the main conclusions and limitations are stated. To fill these limitations in the future studies, some recommendations are also presented.

2. Literature review

Expectation lifespan on electrolysers is one of the important criteria for increasing the efficiency of the methods used in the electrolysis of water for hydrogen production. Electrolysis of water is one of the technologies used to produce hydrogen among various technologies [6]. It is also one of the leading methods to be used for green hydrogen production [7,8]. Hydrogen production by electrolysis is obtained by separating water into hydrogen and oxygen atoms with the help of electricity [9]. The performance of the electrolysers that perform this process is important for the long-term use of the system [10]. As a matter of fact, Bin et al. [11] emphasised that the variety of electrolysers used for the electrolysis of water affects hydrogen production costs. For example, alkaline electrolysers (AWE) are one of the preferred methods for large-scale hydrogen production due to high efficiency and low cost [12]. In addition; Wang et al. [13,14], stated that the optimum timing of electrolysers increases hydrogen production and makes it more efficient. This reduces hydrogen production costs. Finally, Esfandiari et al. [15] reported that the type of material used in hydrogen production is one of the criteria affecting the functionality and production cost of the system.

One of the important criteria for increasing the efficiency of the methods used in the electrolysis of water is the production capacity. The production capacity of electrolysers affects energy efficiency [16]. In addition, using the right electrolyser to produce hydrogen will also help increase production capacity and efficiency [17,18]. Nnabuife et al. [19] stated in their study that optimising electrolyser designs and operating principles will reduce hydrogen production costs [20,21]. Similarly, Sawmy et al. [22] emphasised that selecting the electrolyser capacity in accordance with the amount of energy to be produced will increase energy efficiency. Finally, Elaouzy et al. [23] mentioned that hydrogen produced by electrolysis of water is environmentally friendly. At the same time, it is argued that the improvement of hydrogen production, storage, transport and utilisation methods increases energy efficiency.

Hydrogen production costs are another important criterion in increasing the efficiency of the methods used in water electrolysis. The increase in production costs reduces the effectiveness, sustainability and efficiency of hydrogen production [24,25]. For this reason, applications to reduce production costs will carry hydrogen production to an important place in renewable energy production [26]. Kim et al. [27] argued that technological innovations and research investments will reduce hydrogen production costs. Laimon and Yusaf [28] emphasised that new system dynamics should be developed for the sustainability of hydrogen production. In addition, Ham et al. [29] pointed out that different electrolysis techniques are used for hydrogen production in their study. They also suggested that production techniques should be developed to reduce unit costs. Veenstra and Mulder [30] concluded that the profitability of hydrogen production through electrolysis is not only related to costs but also to hydrogen and energy markets. Finally, Du et al. [14,20], indicated that meeting the energy required for hydrogen production from renewable energy sources increases environmental sustainability. This will increase the demand for renewable energy in countries and reduce external dependence on energy.

Ensuring the efficiency of water use is one of the criteria affecting the electrolysis performance of water. Using water efficiently in the electrolysis method where water is used as raw material helps to produce more energy [31]. In addition, the use of production systems suitable for water resources is also important in terms of efficient use of water [32,33]. As a matter of fact, Requena-Leal et al. [34] stated that the use of methods developed in accordance with the quality and content of water in the electrolysis method will increase hydrogen production. In addition, Cuesta-Mota et al. [35] conducted a study on obtaining hydrogen from wastewater generated during textile dyeing. At the end of the study, the reusability of wastewater increases the performance of electrolysis projects. In addition, Zhang et al. [36] suggested that the development of hydrolysis technologies that can produce hydrogen from seawater will increase hydrogen production capacity. In addition, this method has helped to increase hydrogen production in countries with insufficient freshwater resources.

Hydrogen production by electrolysis enables green hydrogen production. Hydrogen energy has been used more and more recently. Although the usage rate is low today, it is among the renewable energy types that are important for the future. A literature review on the subject has been carried out and some important issues have been reached. In line with these issues, green hydrogen production remains in the background among renewable energy types due to reasons such as high technology and the structure of the water to be used for raw materials. In addition, considering that the technology required to use the electrolysis method requires high costs, it is less preferred. This paper provides an opportunity to overcome these disadvantages. To overcome these disadvantages, water electrolysis technology, which is a new technology, gains importance. Interest in this field should be increased. However, each investment in this field will cause an increase in cost. For example, new technical applications need to be developed to reduce hydrogen production costs. However, it will not be financially feasible to make too many improvements. Therefore, the most important criterion affecting the electrolysis performance of water is determined. There is no study focusing on this issue in the literature. This is considered as a gap in the literature on hydrogen production by electrolysis. In this context, it is necessary to determine the most important criteria for the development of strategies. New strategies need to be developed to overcome this gap. To overcome this gap, a new decision-making model and a priority analysis are included in the study.

3. Methodology

In this paper, the water electrolysis projects for green hydrogen production are evaluated using BANEW and MOPSO methods. The criteria determined for water electrolysis investments are prioritized with the help of BANEW, and the green hydrogen strategies are ranked by MOPSO. In this process, balanced expert evaluation matrices are constructed with the Q-learning algorithm. In addition, Molecular fuzzy sets are integrated into the proposed methodology so that linguistic uncertainty can be analysed, and results can be compared according to different molecular geometry shapes. The models included in the proposed methodology are introduced below.

3.1. Preliminary

A molecular fuzzy set with degrees of membership (M), non-membership (N) and hesitancy (H) satisfies the condition in Eq. (1) [37].

$$M_X(x) + N_X(x) + H_X(x) = 1 \tag{1}$$

Normalization of any molecular fuzzy number is carried out according to the "Valence Shell Electron Pair Repulsion" theory. Accordingly, the membership degree is explained as the normalized angles from the molecular geometry analysis by Eq. (2).

$$M_X(x) = f(\measuredangle_x) = 1 - \frac{\measuredangle_x}{\measuredangle_{max}} \tag{2}$$

The non-membership degree is defined with the help of Eq. (3).

$$N_X(x) = \frac{\measuredangle_x}{\measuredangle_{max}} \tag{3}$$

In this case, the degree of hesitancy is determined as in Eq. (4) according to the condition in Eq. (1).

$$H_X(x) = 1 - M_X(x) - N_X(x) \tag{4}$$

The normalization of the angles (Γ) is obtained using the maximum value of the angle matrix or the different molecular geometry shapes. This process is formulated by Eq. (5).

$$\Gamma_{sh}\left(\measuredangle_{x_i,x_j}\right) = \begin{cases} \frac{\measuredangle_{x_i,x_j}}{\measuredangle_{max}};\ sh = general \\ \frac{\measuredangle_{x_i,x_j}}{\pi};\ sh = linear \\ \frac{\measuredangle_{x_i,x_j}}{\frac{2\pi}{3}};\ sh = trigonal\ planar \\ \frac{\measuredangle_{x_i,x_j}}{\frac{\pi}{2}};\ sh = tetrahedral \\ \frac{\measuredangle_{x_i,x_j}}{\frac{2\pi}{5}};\ sh = trigonal\ bipyramidal \\ \frac{\measuredangle_{x_i,x_j}}{\frac{\pi}{3}};\ sh = octahedral \end{cases} \tag{5}$$

3.2. Fusion learning in imperfect expert environment based on Q-learning algorithm

In decision problems analysed with evaluations collected from different experts, the experiences of the experts play an important role. Therefore, the evaluations of other experts should be balanced according to the most experienced expert. Q-learning algorithm is one of the most successful algorithms that balances evaluations iteratively with reward, penalty and learning rate parameters [38]. After calculating the reward and penalty degrees between the most experienced expert and the others, the evaluations are updated according to different learning rates. This update is iterative, and the iterations continue until the absolute difference of the evaluations between the experts remains below the specified threshold value. When the condition is met, the stable evaluations of others are obtained.

3.3. Molecular fuzzy Bayesian networks-based weighting (MF-BANEW)

The BANEW method is an innovative model that integrates computational factors such as entropy, conditional probability and information gain used in data science into the multi-criteria decision-making problem. Thus, criteria priorities are computed more accurately and closer to reality. In addition, objective results are achieved [13,21]. By integrating molecular fuzzy numbers and normalization according to geometry shapes, comparison of criteria priorities becomes possible. The steps of the method can be itemized as follows.

- After the linguistic evaluations collected from experts are transformed into molecular fuzzy numbers, these numbers are averaged and averaged relation values are constructed.
- Molecular fuzzy vectors with n-1 elements are constructed, excluding diagonal values.
- Molecular fuzzy vectors are multiplied using dot products using Eq. (6).

$$(x_i.x_j) = \sum_{t=1}^{n-1} \left(M_{i,t} \cdot M_{j,t} + N_{i,t} \cdot N_{j,t} + H_{i,t} \cdot H_{j,t}\right) \tag{6}$$

- To calculate the angles between vectors, the dot products are divided by the magnitude of the molecular fuzzy vectors and the inverse cosine function is applied to the division result. Eq. (7) shows this process.

$$\measuredangle_{x_i,x_j} = cos^{-1}\left(\frac{(x_i.x_j)}{\left(\sum_{t=1}^{n-1}\left(M_{i,t}^2 + N_{i,t}^2 + H_{i,t}^2\right)\right).\left(\sum_{t=1}^{n-1}\left(M_{j,t}^2 + N_{j,t}^2 + H_{j,t}^2\right)\right)}\right) \tag{7}$$

- The angles are normalized according to different molecular geometric shapes with the help of Eq. (5).
- The reciprocal values of the normalized angle values are used to construct the normalization of the relation matrix. The reciprocal values are divided by the sum of the reciprocal values, and normalization of the relation matrix is created.
- The entropy values of the criteria are calculated.
- Information gain is estimated by the difference between the entropy values by Eq. (8).

$$Inf\_Gain(C_i) = Entropy(C_i) - Entropy\left(C_i \middle| C_j\right) \tag{8}$$

- Finally, the priority values of the criteria are obtained by dividing the information gain values of the criteria by the sum of information gain with Eq. (9).

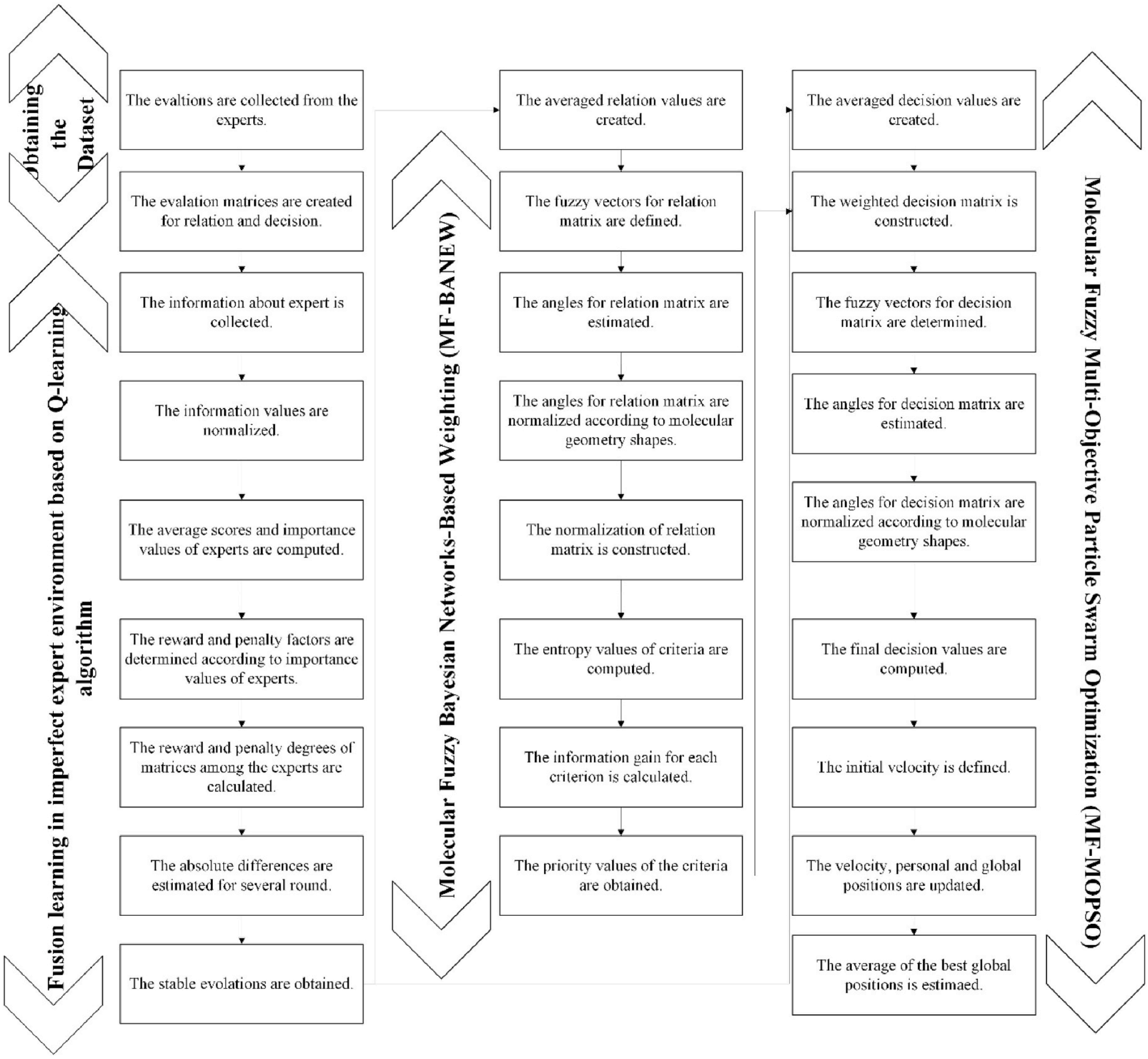

Fig. 1. The flowchart.

Table 1
Green hydrogen strategies.

Strategy	Short Version
Proton exchange membrane electrolysers	PREME
Alkaline water electrolysis	ALKWE
Solid oxide electrolysis	SOXE
Anion exchange membrane electrolysis	ANEXCME
Photoelectrochemical water splitting	PHWS

$$prority(C_i) = \frac{Inf\_Gain(C_i)}{\sum_{k=1}^{n} Inf\_Gain(C_k)} \quad bb \tag{9}$$

3.4. *Molecular fuzzy multi-objective particle swarm optimization (MF-MOPSO)*

This method is a combination of multi-objective particle swarm optimization and molecular fuzzy decision-making model. Since the method includes a molecular fuzzy set, it is possible to compare the ranking results and to analyse the interaction between the alternatives. At the same time, since the method is an optimization algorithm, it examines the Pareto-optimal solutions iteratively and presents the most suitable solution [37]. Thus, MF-MOPSO provides that a balanced result

Table 2
The linguistic scales for relation matrix.

Expert 1	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF		S	M	H
PCAP	M		H	H
CSTHP	S	S		S
WUSEFF	M	S	H	
Expert 2	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF		H	S	S
PCAP	S		H	H
CSTHP	S	H		S
WUSEFF	S	S	S	
Expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF		S	S	S
PCAP	M		M	H
CSTHP	M	M		S
WUSEFF	M	M	S	

Table 3
The linguistic scales for decision matrix.

Expert 1	EXPLF	PCAP	CSTHP	WUSEFF
PREME	S	S	H	M
ALKWE	H	S	H	H
SOXE	H	H	S	S
ANEXCME	H	H	S	H
PHWS	H	H	M	S
Expert 2	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
PREME	S	S	H	M
ALKWE	H	S	H	H
SOXE	S	S	S	S
ANEXCME	S	S	S	S
PHWS	H	H	M	S
Expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
PREME	H	H	H	M
ALKWE	H	S	H	H
SOXE	H	H	M	M
ANEXCME	H	H	M	M
PHWS	H	H	M	M

Table 4
The variables for selecting the most experienced expert.

Variable	Expert 1	Expert 2	Expert 3
Age	54	49	48
Total experience	28	24	22
Education	PhD	PhD	PhD
Profession	Professor	Chief of executive officer	Board member
Amount of article	180	5	7
Global experience	10	6	5
Number of license and certification	8	4	6
Teaching experience	24	2	4
Amount of conference	80	11	3
Amount of patents	14	4	9

Table 5
The normalized values, average scores and the importance values of the experts.

Variable	Expert 1	Expert 2	Expert 3
Age	1.00	0.91	0.89
Total experience	1.00	0.86	0.79
Education	1.00	1.00	1.00
Profession	1.00	0.80	0.90
Amount of article	1.00	0.03	0.04
Global experience	1.00	0.60	0.50
Number of license and certification	1.00	0.50	0.75
Teaching experience	1.00	0.08	0.17
Amount of conference	1.00	0.14	0.04
Amount of patents	1.00	0.29	0.64
Average scores	1.00	0.52	0.57
Importance values	0.478	0.249	0.273

is produced in solving the problem. The steps of the MF-MOPSO can be itemized as follows.

- After the linguistic evaluations collected from experts are transformed into molecular fuzzy numbers, these numbers are averaged and averaged decision values are created.
- Weighted decision values are obtained by using the priority values of the criteria.
- Molecular fuzzy vectors with n-elements are constructed.
- Molecular fuzzy vectors are multiplied using dot products using Eq. (10).

Table 6
The reward degrees of the relation matrix among the experts.

Expert 1-Expert 2	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF	(0.00, 0.00, 0.00)	(0.04, −0.02, −0.01)	(0.05, −0.04, −0.01)	(-0.04, 0.02, 0.01)
PCAP	(0.05, −0.04, −0.01)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)
CSTHP	(0.00, 0.00, 0.00)	(0.04, −0.02, −0.01)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)
WUSEFF	(0.05, −0.04, −0.01)	(0.00, 0.00, 0.00)	(-0.04, 0.02, 0.01)	(0.00, 0.00, 0.00)
Expert 1-expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)	(0.05, −0.04, −0.01)	(-0.04, 0.03, 0.01)
PCAP	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)	(-0.10, 0.07, 0.03)	(0.00, 0.00, 0.00)
CSTHP	(-0.05, 0.04, 0.01)	(-0.05, 0.04, 0.01)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)
WUSEFF	(0.00, 0.00, 0.00)	(-0.05, 0.04, 0.01)	(-0.04, 0.03, 0.01)	(0.00, 0.00, 0.00)

Table 7
The penalty degrees of the relation matrix among the experts.

Expert 1-Expert 2	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF	(0.00, 0.00, 0.00)	(-0.07, 0.05, 0.02)	(-0.10, 0.07, 0.02)	(0.07, −0.05, −0.02)
PCAP	(-0.10, 0.07, 0.02)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)
CSTHP	(0.00, 0.00, 0.00)	(-0.07, 0.05, 0.02)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)
WUSEFF	(-0.10, 0.07, 0.02)	(0.00, 0.00, 0.00)	(0.07, −0.05, −0.02)	(0.00, 0.00, 0.00)
Expert 1-expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)	(-0.10, 0.07, 0.02)	(0.07, −0.05, −0.02)
PCAP	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)	(0.17, −0.12, −0.05)	(0.00, 0.00, 0.00)
CSTHP	(0.10, −0.07, −0.02)	(0.10, −0.07, −0.02)	(0.00, 0.00, 0.00)	(0.00, 0.00, 0.00)
WUSEFF	(0.00, 0.00, 0.00)	(0.10, −0.07, −0.02)	(0.07, −0.05, −0.02)	(0.00, 0.00, 0.00)

Table 8
The updated values of the relation matrix.

Expert 1-Expert 2	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF	(0.00, 0.00, 0.00)	(0.81, 0.14, 0.05)	(0.61, 0.29, 0.10)	(0.94, 0.06, 0.00)
PCAP	(0.61, 0.29, 0.10)	(0.00, 0.00, 0.00)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
CSTHP	(0.80, 0.15, 0.05)	(0.81, 0.14, 0.05)	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)
WUSEFF	(0.61, 0.29, 0.10)	(0.80, 0.15, 0.05)	(0.94, 0.06, 0.00)	(0.00, 0.00, 0.00)
Expert 1-expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)	(0.62, 0.29, 0.10)	(0.94, 0.06, 0.00)
PCAP	(0.60, 0.30, 0.10)	(0.00, 0.00, 0.00)	(0.92, 0.07, 0.01)	(0.95, 0.05, 0.00)
CSTHP	(0.78, 0.16, 0.05)	(0.78, 0.16, 0.05)	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)
WUSEFF	(0.60, 0.30, 0.10)	(0.78, 0.16, 0.05)	(0.94, 0.06, 0.00)	(0.00, 0.00, 0.00)

Table 9
The absolute differences for relation matrix (round 1).

Expert 1-Expert 2	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF	(0.000,0.000,0.000)	(0.011,0.007,0.004)	(0.015,0.011,0.004)	(0.011,0.007,0.004)
PCAP	(0.015,0.011,0.004)	(0.000,0.000,0.000)	(0.000,0.000,0.000)	(0.000,0.000,0.000)
CSTHP	(0.000,0.000,0.000)	(0.011,0.007,0.004)	(0.000,0.000,0.000)	(0.000,0.000,0.000)
WUSEFF	(0.015,0.011,0.004)	(0.000,0.000,0.000)	(0.011,0.007,0.004)	(0.000,0.000,0.000)
Expert 1-expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF	(0.000,0.000,0.000)	(0.000,0.000,0.000)	(0.015,0.011,0.004)	(0.011,0.008,0.004)
PCAP	(0.000,0.000,0.000)	(0.000,0.000,0.000)	(0.026,0.019,0.008)	(0.000,0.000,0.000)
CSTHP	(0.015,0.011,0.004)	(0.015,0.011,0.004)	(0.000,0.000,0.000)	(0.000,0.000,0.000)
WUSEFF	(0.000,0.000,0.000)	(0.015,0.011,0.004)	(0.011,0.008,0.004)	(0.000,0.000,0.000)

Table 10
The stable molecular fuzzy values for relation matrix.

Expert 1	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)	(0.60, 0.30, 0.10)	(0.95, 0.05, 0.00)
PCAP	(0.60, 0.30, 0.10)	(0.00, 0.00, 0.00)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
CSTHP	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)
WUSEFF	(0.60, 0.30, 0.10)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.00, 0.00, 0.00)
Expert 2	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF	(0.00, 0.00, 0.00)	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)
PCAP	(0.80, 0.15, 0.05)	(0.00, 0.00, 0.00)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
CSTHP	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)
WUSEFF	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.00, 0.00, 0.00)
Expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
EXPLF	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)	(0.66, 0.25, 0.08)	(0.90, 0.08, 0.02)
PCAP	(.60, 0.30, 0.10)	(0.00, 0.00, 0.00)	(0.84, 0.13, 0.03)	(0.95, 0.05, 0.00)
CSTHP	(0.74, 0.20, 0.07)	(0.74, 0.20, 0.07)	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)
WUSEFF	(0.60, 0.30, 0.10)	(0.74, 0.20, 0.07)	(0.90, 0.08, 0.02)	(0.00, 0.00, 0.00)

$$(x_i.x_j) = \sum_{t=1}^{m} \left(M_{i,t} \cdot M_{j,t} + N_{i,t} \cdot N_{j,t} + H_{i,t} \cdot H_{j,t}\right) \tag{10}$$

- To calculate the angles between vectors, the dot products are divided by the magnitude of the molecular fuzzy vectors and the inverse cosine function is applied to the division result. Eq. (11) shows this process.

$$\measuredangle_{x_i,x_j} = cos^{-1}\left(\frac{(x_i.x_j)}{\left(\sum_{t=1}^{m}\left(M_{i,t}^2 + N_{i,t}^2 + H_{i,t}^2\right)\right).\left(\sum_{t=1}^{m}\left(M_{j,t}^2 + N_{j,t}^2 + H_{j,t}^2\right)\right)}\right) \tag{11}$$

- The angles are normalized according to different molecular geometric shapes.
- The reciprocal values of the normalized angle values are used to construct the final decision matrix. The reciprocal values are divided by the sum of the reciprocal values, and the final decision values are computed.
- Initial velocity is determined by Eq. (12) with r between −1 and 1.

Table 11
The stable molecular fuzzy values for decision matrix.

Expert 1	EXPLF	PCAP	CSTHP	WUSEFF
PREME	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)
ALKWE	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
SOXE	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)
ANEXCME	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)
PHWS	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)	(0.80, 0.15, 0.05)
Expert 2	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
PREME	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)
ALKWE	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
SOXE	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)
ANEXCME	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)	(0.80, 0.15, 0.05)
PHWS	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)	(0.80, 0.15, 0.05)
Expert 3	**EXPLF**	**PCAP**	**CSTHP**	**WUSEFF**
PREME	(0.85, 0.12, 0.03)	(0.85, 0.12, 0.03)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)
ALKWE	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
SOXE	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.74, 0.20, 0.07)	(0.74, 0.20, 0.07)
ANEXCME	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.74, 0.20, 0.07)	(0.84, 0.13, 0.03)
PHWS	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)	(0.74, 0.20, 0.07)

Table 12
The averaged relation values.

	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF	(0.00, 0.00, 0.00)	(0.85, 0.12, 0.03)	(0.69, 0.23, 0.08)	(0.88, 0.09, 0.02)
PCAP	(0.67, 0.25, 0.08)	(0.00, 0.00, 0.00)	(0.91, 0.08, 0.01)	(0.95, 0.05, 0.00)
CSTHP	(0.78, 0.17, 0.06)	(0.83, 0.13, 0.04)	(0.00, 0.00, 0.00)	(0.80, 0.15, 0.05)
WUSEFF	(0.67, 0.25, 0.08)	(0.78, 0.17, 0.06)	(0.88, 0.09, 0.02)	(0.00, 0.00, 0.00)

Table 13
The angels between any two vectors for relation matrix.

	$\measuredangle_{\alpha_1}$	$\measuredangle_{\alpha_2}$	$\measuredangle_{\alpha_3}$	$\measuredangle_{\alpha_4}$
$\measuredangle_{\alpha_1}$		0.251	0.157	0.181
$\measuredangle_{\alpha_2}$	0.251		0.167	0.104
$\measuredangle_{\alpha_3}$	0.157	0.167		0.132
$\measuredangle_{\alpha_4}$	0.181	0.104	0.132	

Table 14
The Normalized Relation Matrix for linear shape.

	EXPLF	PCAP	CSTHP	WUSEFF
EXPLF		0.102	0.163	0.142
PCAP	0.102		0.154	0.246
CSTHP	0.163	0.154		0.194
WUSEFF	0.142	0.246	0.194	

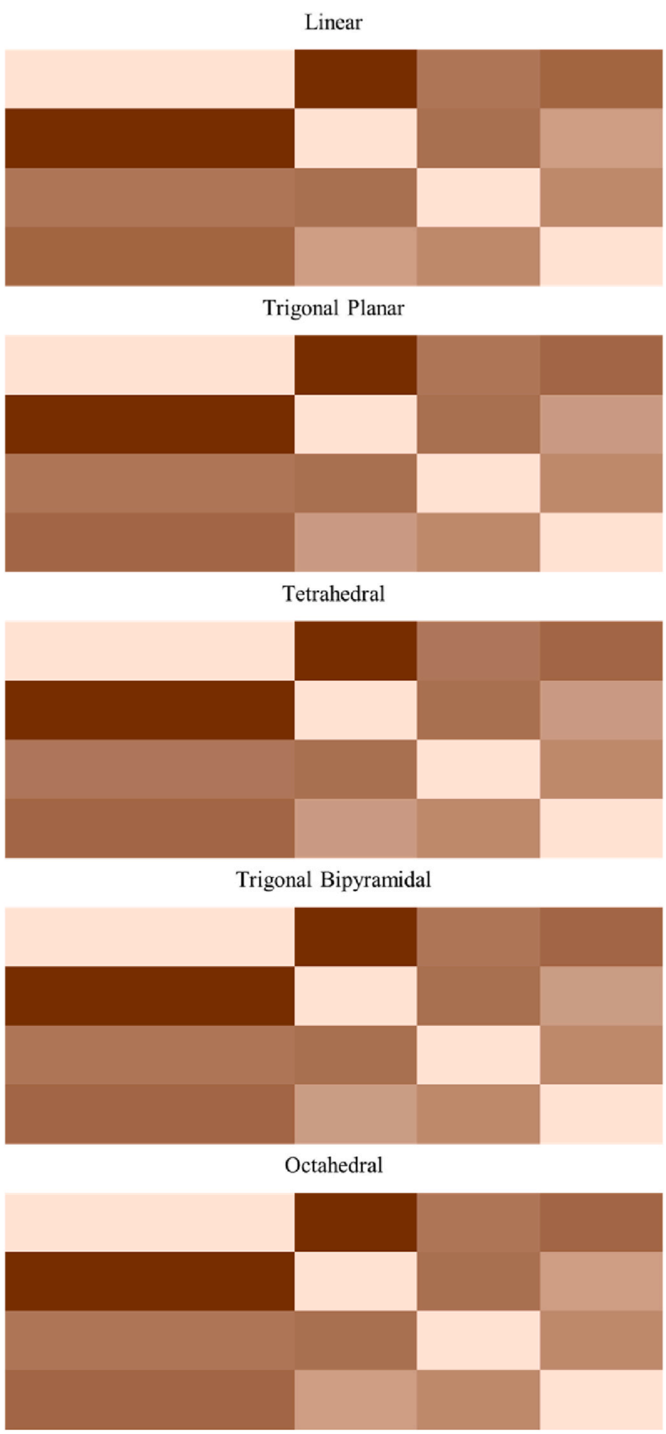

Fig. 2. The heat map according to five shapes.

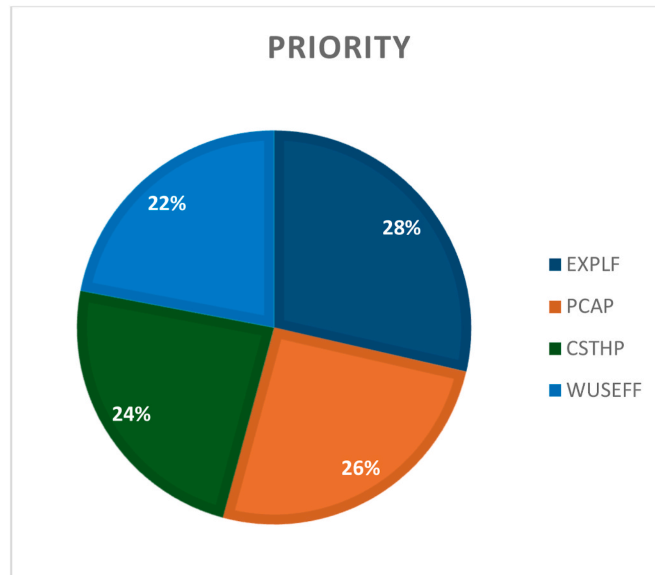

Fig. 3. The priorities of criteria for linear shape.

$$Velocity_{ij}(1) = 0.1 \bullet \left(Position_{max_i} - Position_{min_i}\right) \bullet r \tag{12}$$

- The velocity, personal and global positions are updated until the difference between two consecutive updated best global positions remains below the threshold value
- When the stopping condition of the iteration is met, the average of the best global positions is calculated using Eq. (13), and the alternatives are ranked according to these average values.

$$\frac{1}{m}\sum_{i=1}^{m} P_{ij} \tag{13}$$

The flowchart of the proposed methodology can be summarized as in Fig. 1.

4. Analysis results

In this paper, which is prepared to determine the most suitable green hydrogen strategies for water electrolysis investments, the determined criteria are expected lifespan of electrolysers (EXPLF), production capacity (PCAP), cost of hydrogen production (CSTHP), water usage efficiency (WUSEFF). This set of criteria is determined by literature and field research. Green hydrogen strategies evaluated according to these criteria are summarized in Table 1.

In accordance with the proposed methodology, after the criteria determined for water electrolysis investments are evaluated against each other, green hydrogen alternatives are evaluated according to these criteria by the experts. The linguistic scale that experts use for evaluation are negligible (N), low (L), moderate (M), significant (S) and high (H). Accordingly, the evaluations collected from the experts for the relation matrix are given in Table 2.

Evaluations about the alternatives are then collected from these three experts. Using the same linguistic scale, the evaluations of green

Table 15
The criteria priority orders for all shapes and learning rates.

Learning rate:0.1	Linear	Trigonal Planar	Tetrahedral	Trigonal Bipyramidal	Octahedral
EXPLF	1	1	1	1	1
PCAP	2	2	2	2	2
CSTHP	3	3	3	3	3
WUSEFF	4	4	4	4	4
Learning rate:0.5	**Linear**	**Trigonal planar**	**Tetrahedral**	**Trigonal bipyramidal**	**Octahedral**
EXPLF	1	1	1	1	1
PCAP	2	2	2	2	2
CSTHP	3	3	3	3	3
WUSEFF	4	4	4	4	4
Learning rate:1	**Linear**	**Trigonal planar**	**Tetrahedral**	**Trigonal bipyramidal**	**Octahedral**
EXPLF	1	1	1	1	1
PCAP	2	2	2	2	2
CSTHP	3	3	3	3	3
WUSEFF	4	4	4	4	4

Table 16
The averaged decision values.

	EXPLF	PCAP	CSTHP	WUSEFF
PREME	(0.82, 0.14, 0.04)	(0.82, 0.14, 0.04)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)
ALKWE	(0.95, 0.05, 0.00)	(0.80, 0.15, 0.05)	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)
SOXE	(0.90, 0.08, 0.02)	(0.90, 0.08, 0.02)	(0.78, 0.17, 0.06)	(0.78, 0.17, 0.06)
ANEXCME	(0.90, 0.08, 0.02)	(0.90, 0.08, 0.02)	(0.78, 0.17, 0.06)	(0.86, 0.11, 0.03)
PHWS	(0.95, 0.05, 0.00)	(0.95, 0.05, 0.00)	(0.60, 0.30, 0.10)	(0.78, 0.17, 0.06)

Table 17
The angels between any two vectors for decision matrix.

	$\measuredangle_{\alpha_1}$	$\measuredangle_{\alpha_2}$	$\measuredangle_{\alpha_3}$	$\measuredangle_{\alpha_4}$	$\measuredangle_{\alpha_5}$
$\measuredangle_{\alpha_1}$		0.227	0.190	0.223	0.310
$\measuredangle_{\alpha_2}$	0.227		0.164	0.142	0.274
$\measuredangle_{\alpha_3}$	0.190	0.164		0.050	0.136
$\measuredangle_{\alpha_4}$	0.223	0.142	0.050		0.145
$\measuredangle_{\alpha_5}$	0.310	0.274	0.136	0.145	

hydrogen strategies collected for the decision matrix are shown in Table 3.

After obtaining expert evaluations with linguistic scale for relation and decision matrices, analysis is performed with the proposed model. First, other expert evaluations are balanced according to best expert. Then, criteria priorities determined for water electrolysis investments are calculated and finally green hydrogen strategies are ranked. The results of the stages of this proposed model are presented under separate headings.

4.1. *Constructing the balanced expert evaluation matrices using Q-learning algorithm*

In the first step of this phase of the proposed model, demographic information of the experts is analysed to select the most experienced expert. The variables to be analysed and their values are shared in Table 4.

For analysis, values are normalized. For variables other than education and profession variables, values are divided by the largest value. For the education variable, since all three experts are at the same level, it is analysed as 1. For other qualitative variable, the first expert is coded as 1, the second expert as 0.8 and the last expert as 0.9 due to the importance of the professions. Then, the average of the normalized values is computed to obtain the average score variable. Finally, the average scores are divided by the sum of the average scores to calculate the importance values of the experts. The normalized values, average scores and the importance values of the experts are presented in Table 5.

When the importance values of the experts are examined, it is determined that the most experienced expert is the first expert. The importance value of the first expert, 0.478, is used as the penalty factor for Q-learning. The reward factor is the importance values of the other experts. Immediately after the linguistic scales collected for the relation matrix are transformed into molecular fuzzy numbers, the reward degrees of the relation matrix among the experts are calculated. The reward degrees of the relation matrix are displayed in Table 6.

Similarly, the penalty degrees of relation matrix among experts are computed. The penalty degrees of relation matrix are illustrated in Table 7.

After obtaining the reward and penalty degrees for the relation matrix, the molecular fuzzy evaluation values are updated according to different learning rates. The updated values of the relation matrix for the case where the learning rate is 0.1 are shared in Table 8.

Afterwards, the absolute differences between the Q values of the experts for the relation matrix are calculated. This difference is the condition for the algorithm to continue. In other words, it is the condition that shows whether the expert evaluations are balanced or not. The absolute differences calculated at the end of the first round are displayed in Table 9.

Since some of the values at the end of the first round are above the threshold value of 0.02, the condition is not met. Therefore, iterations are applied until the maximum of the absolute differences are below the threshold value. With the fourth iteration, the maximum of the absolute differences between the first and third experts meets the condition. Since the maximum of the absolute differences between the first and second experts already meets the condition, the first round is sufficient. Thus, stable evaluations are obtained. The stable molecular fuzzy values of experts for relation matrix are shared in Table 10.

The algorithm for the relation matrix is similarly performed for the decision matrix. The stable molecular fuzzy values of experts for decision matrix are shared in Table 11.

4.2. *Prioritization of criteria for water electrolysis investments using molecular fuzzy BANEW*

The values in Table 10 are averaged and the averaged relation matrix is constructed. The averaged relation values are summarized in Table 12.

Then, 3-element molecular fuzzy vectors are created by excluding the diagonal values for each criterion. Next, these four vectors are multiplied with each other in pairs using the dot product operator. These

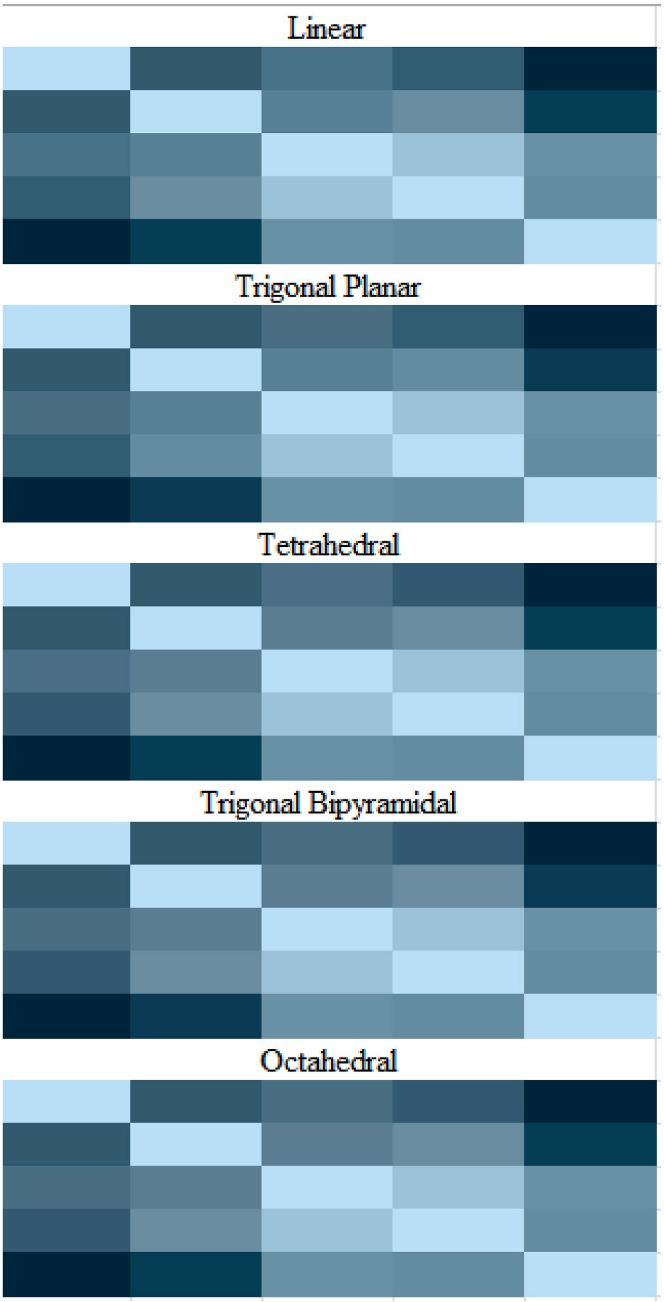

Fig. 4. The heat map according to five shapes for decision matrix.

Table 18
The final decision matrix according to linear shape.

	PREME	ALKWE	SOXE	ANEXCME	PHWS
PREME		0.065	0.077	0.066	0.047
ALKWE	0.065		0.089	0.103	0.054
SOXE	0.077	0.089		0.290	0.107
ANEXCME	0.066	0.103	0.290		0.101
PHWS	0.047	0.054	0.107	0.101	

dot products are divided by the molecular fuzzy vector to obtain the cosine of the angle between the vectors. The inverse cosine function is used for the value of the angle. The angles in radians between any two vectors for relation matrix are tabulated in Table 13.

In the next step, these angles are normalized according to the molecular geometry shapes. The heat map of the normalization result according to five shapes is visualized in Fig. 2.

After the normalization process, the reciprocal values are estimated, and the normalized relation matrix is constructed with reciprocal values. The normalized relation matrix for linear shape is shown in Table 14.

According to the Bayesian network process, entropy, conditional probability and information gains for the criteria are computed respectively. Finally, the information gain value of the criteria is divided by the sum of information gains to determine the priorities of the criteria. The criteria priorities for linear shape thus obtained are visualized in Fig. 3.

The criteria priority order for all molecular geometry shapes and different learning rates is presented in Table 15.

Since the order of priority of the criteria does not change in all possible cases, it is both consistent and valid. Thus, the order of the criteria for water electrolysis investments is lifespan of electrolysers (EXPLF), production capacity (PCAP), cost of hydrogen production (CSTHP), water usage efficiency (WUSEFF). In other words, the most effective criterion in water electrolysis investments is the lifespan of electrolysers, while the least effective criterion is water usage efficiency.

4.3. Ranking of green hydrogen strategies for water electrolysis investments using molecular fuzzy MOPSO

The molecular fuzzy numbers in Table 11 are averaged and the averaged decision matrix is created. The averaged decision values are summarized in Table 16.

Afterwards, the values of the averaged decision matrix are multiplied with priority of criteria, and the weighted decision matrix is constructed. Then, 4-element molecular fuzzy vectors are created from the weighted decision matrix. Next, these five vectors are multiplied with each other in pairs using the dot product operator. These dot products are divided by the molecular fuzzy vector to obtain the cosine of the angle between the vectors. The inverse cosine function is used for the value of the angle. The angles in radians between any two vectors for decision matrix are tabulated in Table 17.

In the next step, these angles are normalized according to the molecular geometry shapes. The heat map of the normalization result according to five shapes is visualized in Fig. 4.

After the normalization process, the reciprocal values are computed, and the final decision matrix is constructed with reciprocal values. The final decision matrix for linear shape is shown in Table 18.

Finally, velocity, personal and global positions are calculated within the optimization steps. The rounds are repeated iteratively until the best global positions are obtained. When the condition is met, the best global positions are averaged and the ranking values of green hydrogen alternatives for water electrolysis investments are obtained. The ranking values of green hydrogen alternatives for water electrolysis investments for linear shape are shown in Fig. 5.

The ranking of alternatives order for all molecular geometry shapes and different learning rates is exhibited in Table 19.

Since the ranking of green hydrogen alternatives for water electrolyze investments does not change in all possible cases, it is both consistent and valid. Thus, the ranking of the green hydrogen alternatives for water electrolysis investments is PREME, ALKWE, PHWS, SOXE and ANEXCME, respectively. In other words, the most suitable alternative of green hydrogen alternatives is the proton exchange membrane electrolysers, while the least suitable alternative is anion exchange membrane electrolysis.

5. Discussion

One of the methods used for green hydrogen production is the electrolysis of water. This method aims to produce clean and sustainable energy to reduce carbon emissions [39]. To increase the efficiency of hydrogen production projects by electrolysis method, it is necessary to strengthen and diversify electrolysers, develop methods to increase

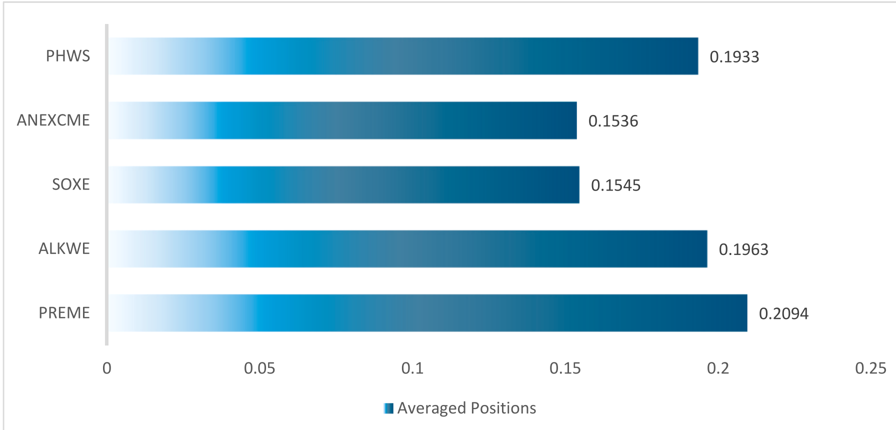

Fig. 5. The averaged positions of green hydrogen alternatives according to linear shape. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 19
The ranking of green hydrogen alternatives for all shapes and learning rates.

Learning rate: 0.1	Linear	Trigonal Planar	Tetrahedral	Trigonal Bipyramidal	Octahedral
PREME	1	1	1	1	1
ALKWE	2	2	2	2	2
SOXE	4	4	4	4	4
ANEXCME	5	5	5	5	5
PHWS	3	3	3	3	3
Learning rate: 0.5	**Linear**	**Trigonal planar**	**Tetrahedral**	**Trigonal bipyramidal**	**Octahedral**
PREME	1	1	1	1	1
ALKWE	2	2	2	2	2
SOXE	4	4	4	4	4
ANEXCME	5	5	5	5	5
PHWS	3	3	3	3	3
Learning rate: 1	**Linear**	**Trigonal planar**	**Tetrahedral**	**Trigonal bipyramidal**	**Octahedral**
PREME	1	1	1	1	1
ALKWE	2	2	2	2	2
SOXE	4	4	4	4	4
ANEXCME	5	5	5	5	5
PHWS	3	3	3	3	3

production capacity, reduce the cost of hydrogen production, and use water, which is the raw material in hydrogen production, efficiently and effectively [40]. Expectation lifespan on electrolysers is one of the important criteria in increasing the efficiency of hydrogen production in water electrolysis. Ajeeb et al. [41] examined the effect of electrolysis techniques on environmental sustainability. They also stated that different electrolysis methods and the lifetime of electrolyser materials increase energy consumption and efficiency. Similarly, Norman et al. [42] analysed two different electrolyser alternatives. In the findings obtained, it was emphasised that materials should be selected in accordance with the size and energy use of the enterprises for hydrogen production. In addition, Mio et al. [43] stated that there is different production techniques for hydrogen produced in accordance with energy needs. He also emphasised that hydrogen produced using different materials involves different costs. He stated that enterprises should make their investments by analysing these costs. Finally, Pashchenko [44] proposes a system in which the hydrogen produced will be compressed and stored as well as hydrogen production. He also emphasised that the use of this stored energy in the enterprise will increase energy efficiency in the enterprise.

Production capacity is one of the important criteria for improving hydrogen production performance by electrolysis. Correct determination of hydrogen production capacity provides energy efficiency and cost advantage [45]. Choosing the right production capacity affects the success of the project as well as ensuring energy efficiency. Hassan et al. [46] states that the development of hydrogen storage methods will benefit the increase of production capacity. Similarly, Singla et al. [47] suggested that the use of more environmentally friendly hydrogen production methods will increase the use of carbon-free energy. In addition; Mandrela et al. [48] emphasise that the efficiency of hydrogen production techniques affects the production capacity. For example, electrolysis of water by alkaline method focuses on large-scale systems and industrial applications. This means longer system life and higher hydrogen production capacity [49]. In addition, Tostado-Véliz et al. [50] highlight that selecting the appropriate electrolyser for hydrogen production is important in terms of ensuring the energy requirements of the enterprises. Thus, the enterprise will be able to produce the energy it needs.

6. Conclusion

This study evaluates the water electrolysis projects for green hydrogen production with a novel model. In the first stage, the balanced expert evaluation matrices are obtained by q-learning algorithm. Moreover, the criteria for water electrolysis investments are prioritized using molecular fuzzy BANEW. Finally, green hydrogen strategies for water electrolysis investments are ranked via molecular fuzzy MOPSO. It is identified that lifespan of electrolysers and production capacity are the most essential criteria. Additionally, proton exchange membrane electrolysers and alkaline water electrolysis are found as the most critical green hydrogen strategies.

The most important contribution of this study to the literature is the determination of the criteria that should be applied primarily for the performance increase of water electrolysis investments by creating a new model. The proposed model has also some superiorities. The use of molecular fuzzy numbers is a very important contribution of the model to the literature. Owing to this condition, the use of three-dimensional geometric figures allows the reduction of uncertainties in decision-making processes. The biggest limitation of this study is the small number of experts. A sufficient amount of data and expert opinions are required for the successful application of the Q-learning algorithm. However, only the opinions of 3 experts can be considered in this study. The main reason for this is that it is very difficult to reach many experts who have sufficient knowledge about the details of water electrolysis projects. To eliminate this limitation, experts can be created with artificial intelligence in future studies. In this way, it is possible to increase the number of experts. Considering all these issues, some future study topics can be suggested for water electrolysis investments and green hydrogen production. Future research can focus on developing more durable materials and new technologies to extend the life of electrolysers. The issues obtained from these studies can contribute to extending the life of electrolysers. On the other hand, in future studies, the performance and economic feasibility of new technologies can be evaluated with comparative analyses. In addition to them, in the next studies, the effects of different quality standards on electrolysis systems can be examined.

CRediT authorship contribution statement

Hasan Dinçer: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Serkan Eti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Merve Acar:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Serhat Yüksel:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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