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Evaluation of Wave Energy Location by Using an Integrated MCDM Approach

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Abstract: In recent years, sudden global energy demand has led to the gradual exhaustion of fossil fuel, the world's main energy resource. With the negative impact of fossil fuel on the environment, governments and organizations have increased R&D funding on renewable energy resources such as solar and wave energy. Vietnam has a great potential for developing wave energy projects owing to the presence of a long coastline and vast ocean. Choosing an optimal location for wave-based power plant projects is a multicriteria decision that requires understanding the quantitative and qualitative elements for assessing the balance of factors when trying to reach the most accurate result. This study proposes a multi-criteria decision-making (MCDM) model, fuzzy-analytic hierarchical process (FAHP), and weighted aggregated sum product assessment (WASPAS) in evaluating potential wave energy stations at the Vietnamese coastline. The authors identify all criteria and sub-criteria affecting the wave power plant location selection process through literature review and expert interview. Selection criteria include wave height, the distance between two waves, number of waves, wind speed, wind duration, ocean depth, turbulence, water quality, coastal erosion, shipping density, protection laws, labor resources, safety conditions, and other related factors. FAHP was used to determining the weights of the identified criteria in the first stage of this study. Finally, the WASPAS model was employed to rank all the alternatives involved in making an effective decision. This study aimed to develop a tool to enhance decision-making when solving fuzzy multi-criteria problems. We propose a real-world model for the effectiveness of the proposed model.

Keywords: renewable energy; wave energy; fuzzy theory; optimization analysis; multicriteria decision making model; fuzzy multicriteria decision making; FANP; WASPAS; sustainability

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1. Introduction

In recent decades, the negative impact of thermal power plants and climate change on the environment has been the focus of the attention of policymakers globally. Thermal power plants through their burning of fossil-based fuels (coal, heavy oil) have become the largest source of greenhouse gas emissions, provoking global climate change. While nuclear power technology was a plausible alternative, it posed radioactive hazards and nuclear accidents at Chernobyl in 1986 and Fukushima in 2011, which caused long-term damage to socio-economic stability and the global environment [1].

Sustainable development has given birth to cleaner energy production technologies, which reduce fossil fuel consumption. These technologies generate electricity from renewable energy sources; some of these technologies have been commercialized and produce energy on a large scale. Examples of large-scale sustainable energy production technologies are wind power stations (located inland on islands, or at sea), solar power stations, tidal power stations, and geothermal electric generators [1].

Vietnam is a powerful marine country with rich history, tradition, and culture. Vietnam has taken advantage of its near-the-sea location to build and defend its country. Vietnam has a coastline of more than 3200 km, and the country has a landmass of over one million-square kilometers; both the coast and the land itself are important to the country's current and future socioeconomic development. The blue sea economy is a subset of the national economy, which has become a global trend. The blue sea economic model is a way to achieve sustainable development and renewable energy development. With its blue sea location, Vietnam has a great potential to develop wave energy [2].

The outcome of the research carried out by the Research Institute of Sea and Islands in Vietnam shows that the total annual wave energy capacity is 212 TWh/year, accounting for nearly 1% of the global value. Ninety percent of the current electricity demand in Vietnam is 230 TWh/year. In addition, the coastal area in Quang Ngai—Ninh Thuan has the best potential to develop coastal wave energy. The coastal areas of Quang Binh—Quang Nam, Binh Thuan, and Bac Lieu offer better potential to develop wave energy [3].

The unpredictability of waves is the largest drawback of tidal energy, despite being an endless form of energy that produces no waste and has low maintenance. Thus, the quality of a predictive model depends on its ability to enhance natural change and phenomena. Vietnam has not paid much attention to R&D in wave energy. This is crucial because the wave energy generators of Vietnam's coastal island could become a potential and endless energy source that offers low competitive electricity prices [3].

In the past decades, multi-criteria decision-making models (MCDM) have been used to solve complex problems [4], such as logistics of service-supplier selection in various industries [5,6], project finance selection [7], and convertible bond evaluation [8]. In the last few years, many MCDM techniques have been introduced, with each method dedicated to solving a problem. In addition, many hybrid MCDM models have been introduced to limit the decision-making approach, especially in uncertain environments [9,10].

The rest of this paper is structured as follows. Section 2 describes relevant literature on MCDM methods and the applications of MCDM models for location selection problems. Section 3 discusses the research process and the proposed model. In Section 4, the proposed model is applied to a real-world case study to demonstrate its feasibility. Section 5 concludes the paper.

2. Literature Review

Among many MCDM techniques, weighted aggregated sum product assessment (WASPAS) and fuzzy-analytic hierarchichal process (FAHP) are often employed in decision making processes that involve uncertain decision-making environments. The extended version of WASPAS method of Zavadskas et al. [11] is proposed because it can be applied in an uncertain decision making environment. In the proposed weighted aggregated sum product assessment with interval-valued intuitionistic fuzzy numbers (WASPAS-IVIF) method, the uncertainty of decision makers in stating their evaluations with regard to criteria importance/alternatives performance on criteria is expressed by interval-valued intuitionistic fuzzy numbers. Zavadskas et al. [12] also used a novel method based on multiple attribute weighted aggregated sum product assessment with grey attributes scores.

The WASPAS-G method has been used for selecting the right contractor in the construction industry. Selecting the right contractor is an important problem for an organization to solve during times when the competition in global markets increases. Ru-Xin Nie et al. [13] introduced a newly extended weighted aggregated sum product assessment (WASPAS) technique for solving a solar–wind power station location problem. These analyses effectively reveal that the extended WASPAS technique can well match the reality of decision-making challenges and appropriately handle a renewable energy station location selection problem. Pratibha Rani et al. [14] developed a new assessment framework for a fuel technology selection problem by using the multi-criteria weighted aggregated sum product assessment framework with q-rung orthopair fuzzy sets. Ding and Chou [15] introduced a fuzzy MCDM model based on triangular fuzzy number (TFN), linguistics values and a graded mean integration representation (GMIR) to evaluate and select an optimal transshipment port location.

D. E. Ighravwe et al. [16] used a fuzzy-grey-weighted aggregate sum product assessment methodical approach for multi-criteria analysis of maintenance performance systems. The results of model testing confirmed that the presented scheme was feasible in industrial settings, efficient and capable of revealing the best company's performance according to a certain set of six input criteria. Majid [17] employed the FAHP and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) methods to create a strategic model for selecting a solar wood drying location in Iran. Mesran et al. [18] conducted a study using a combination of analytic hierarchical process (AHP) and WASPAS methods that are expected to improve the results of decisions on teacher performance ranking. Seker and Aydin [19] introduced an entropy-based TOPSIS model to select an optimal location for a hydrogen energy plant in northern Turkey. In this paper, entropy-based TOPSIS was employed in an interval valued Pythagorean fuzzy (IVPF) environment to deal with the uncertain nature of the decision-making environment. Rao et al. [20] proposed a new two-tuple hybrid ordered weighted averaging (THOWA) model to assist in location selection for a city logistics center. Tan [21] developed a hybrid MCDM model utilizing factor analysis, AHP, and fuzzy TOPSIS to solve a wind power project location selection problem in Pakistan. Kizielewicz et al. [22] identified a set of criteria for solving a windfarm location selection problem. Riaz et al. [23] introduced a decision support system for sustainable energy planning decision management based on q-rung orthopair fuzzy set (q-ROFS). The proposed approach was applied to a sustainable energy planning problem in Pakistan in order to demonstrate the plan's feasibility and validity. [24–26].

Mardani et al. [24] reviewed an application of multiple criteria decision-making techniques and approaches. Kaya et al. [25] indicated that fuzzy analytic hierarchical process (AHP), as an individual tool or by integrating it with another MCDM method, is the most applied MCDM method, and type-1 fuzzy sets are the most preferred type of fuzzy sets. Siksnelyte et al. [26] presented an application of decision-making methods for dealing with sustainable energy development issues. In this study, 105 published papers related to energy sustainability issues and MCDM methods and published from 2004 to 2017 in the Web of Science Core Collection (WSCC) database were selected and reviewed. Salabun et al. [27] performed a comparative study of four MCDA methods, including TOPSIS, VlseKriterijumska Optimizacija I Kompromisno Resenje in Serbian (VIKOR), complex proportional assessment (COPRAS), and the Preference Ranking Organization Method for Enrichment of Evaluations II (PROMETHEE II) methods. The results show the influences of different parameter values on the results of these methods as well as the similarity of the rankings produced between the methods.

According to a review of the literature, many multi-criteria decision-making models have been developed and applied to many fields of science and engineering. Among these fields, MCDM techniques have been extensively applied in solving location selection problems, where the decision makers must evaluate both qualitative and quantitative criteria. There have been several applications of MCDM techniques in wave energy plant location selection, but very few works have tried to take on this problem in a fuzzy environment.

Therefore, the authors describe an MCDM model for assessment of wave energy potential in locations along the Vietnamese coast based on a fuzzy-analytic hierarchical process (FAHP) and weighted aggregated sum product assessment (WASPAS). Selection criteria include wave height, distance between two waves, number of waves, wind speed, wind duration, depth of the ocean, turbulence, water quality, coastal erosion, shipping density, protection laws, labor resources, safety conditions, and other related factors. The aim of the paper is to develop a tool to support decision makers in solving MCDM problems in fuzzy decision-making environments. In the first stage of this processes the authors applied an FAHP for determining the weight of all criteria affecting location selection and a WASPAS to rank all potential locations in the final stage [4].

3. Methodology

3.1. Research Development

This paper introduces a fuzzy multi-criteria decision-making (F-MCDM) model for deciding the optimal location for wave energy stations using the fuzzy-analytic hierarchical process (FAHP) and weighted aggregated sum product assessment (WASPAS) methods. As shown in Figure 1, this research had three main steps:

- Step 1: We identified all criteria and sub-criteria affecting the wave power plant lo-cation selection process through literature review and expert interview.
- Step 2: FAHP was used to determine the weights of the identified criteria.
- Step 3: WASPAS was employed to rank all the alternatives involved in making an effective decision.

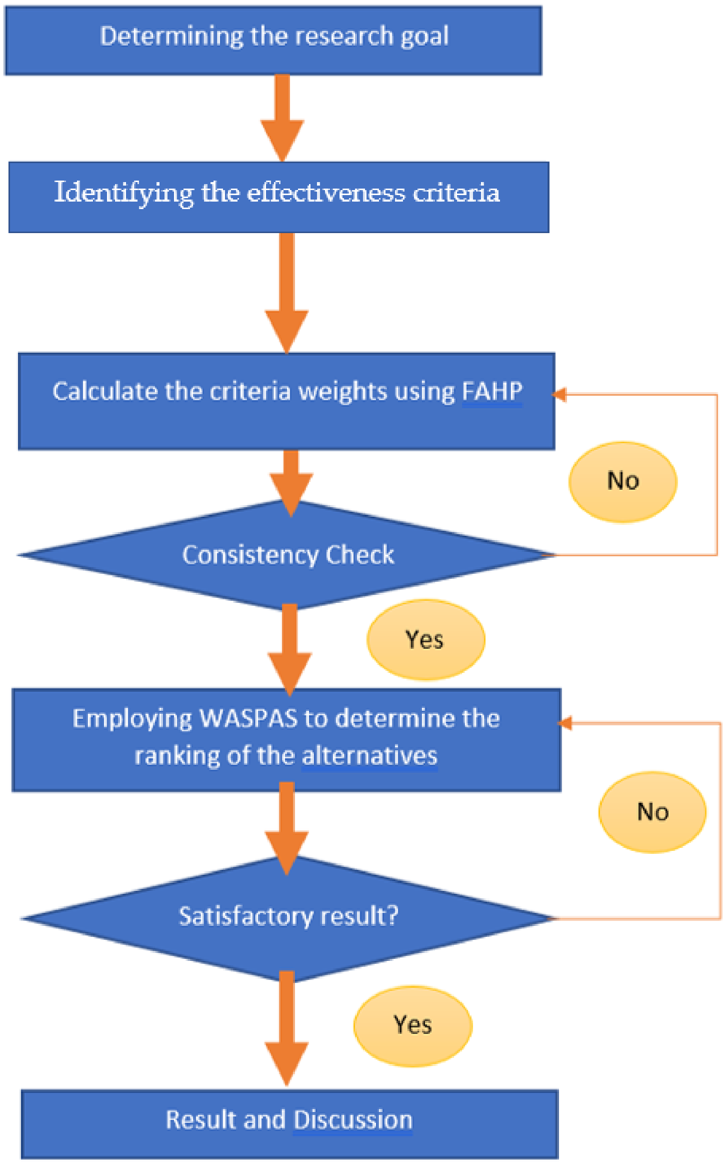

Figure 1. Research graph. FAHP, fuzzy-analytic hierarchical process; WASPAS, weighted aggregated sum product assessment.

3.2. Fuzzy Sets Theory

Zadeh [28] introduced the fuzzy set theory in 1965 to process the vagueness and uncertainty of human thinking. Since then, many studies have used fuzzy set theory to represent ambiguous data and apply mathematical operators to the fuzzy domain. A fuzzy set is defined as a set of objects with a membership function, which assigns each object to a membership grade ranging from 0 to 1. A fuzzy set is denoted by placing a tilde above a symbol.

For example, $\widetilde{A}$ is a fuzzy set, with membership functions written as $\mu\left(x\middle|\widetilde{A}\right)$. A triangular fuzzy number (TFN), $\widetilde{L}$, consists of a triplet $(l_1/l_2/l_3)$, where l_1 is the smallest likely value, l_2 is the most probable value, and l_3 is the largest possible value. A triangular fuzzy number ($\widetilde{l}$) membership function graph is shown in Figure 2. If $\widetilde{L}$ is a TFN, each value of the membership function is between [0, 1] and can be explained, as shown in Equation (1):

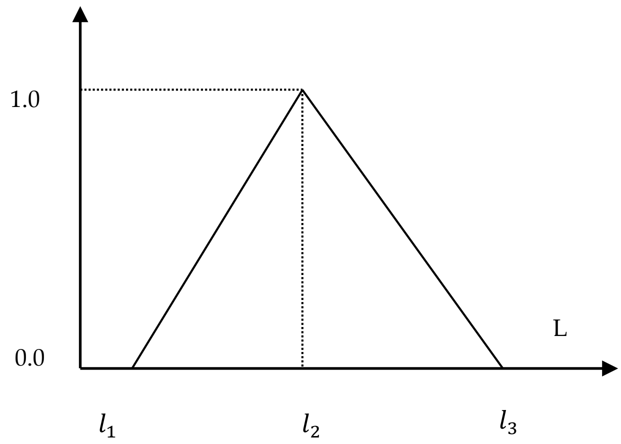

Figure 2. A triangular fuzzy number.

The membership function of $\widetilde{L}$ is defined as:

$$\mu(x|\widetilde{L}) = \begin{cases} 0, & x < l_1 \\ \frac{x-l_1}{l_2-l_1}, & l_1 \le x \le l_2 \\ \frac{l_3-x}{l_3-l_2}, & l_2 \le x \le l_3 \\ 0, & x > l_3 \end{cases} \tag{1}$$

A fuzzy number can be defined by its corresponding left- and right-side representation:

$$\widetilde{L} = L^{l(y)},\ L^{r(y)} = \ (l_1 - (l_2 - l_1)y, l_3 + (l_2 - l_3)y).y \in [0, 1] \tag{2}$$

where $l(y)$ and $r(y)$ denote the left-side representation and the right-side representation of a fuzzy number, respectively.

3.3. Fuzzy Analytical Hierarchy Process (FAHP) Model

Fuzzy analytical hierarchical process (FAHP) is the fuzzy extension of AHP to handle its limitation in working with uncertain decision-making environments. Let $X = \ \{x_1,\ x_2, \ldots .x_n\}$ be the set of objects and $K = \ \{k_1,\ k_2, \ldots .k_n\}$ be the goal set. According to Chang's [29] extent analysis method, each object is taken, and an extent analysis of its goals is performed. Therefore, the l extent analysis values for each object can be obtained. These values are denoted as:

$$L^1_{k_i}, L^2_{k_i}, \ldots, L^m_{k_i}, \quad i = 1, 2, \ldots, n \tag{3}$$

where $L^j_k (j = 1, 2, \ldots, m)$ are the TFNs.

Fuzzy synthetic extent value of the *i*th object is defined as:

$$S_i = \sum_{j=1}^{m} L_{k_i}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} L_{k_i}^{j} \right]^{-1} \tag{4}$$

The possibility that $L_1 \geq L_2$ is defined as:

$$V(L_1 \geq L_2) = sup_{y \geq x} \left[min\left(\mu_{L_1}(x),\right), \left(\mu_{L_2}(y)\right) \right] \tag{5}$$

where the pair (x, y) exists with $x \geq y$ and $\mu_{L_1}(x) = \mu_{L_2}(y)$, then $V(L_1 \geq L_2) = 1$.

Since L_1 and L_2 are convex fuzzy numbers:

$$V(L_1 \geq L_2) = 1,\ if\ l_1 \geq l_2 \tag{6}$$

and

$$(L_2 \geq L_1) = hgt(L_1 \frown L_2) = \mu_{L_1}(d) \tag{7}$$

where d is the ordinate of the highest intersection point D between μ_{L_1} and μ_{L_2}.

With $L_1 = (o_1, p_1, q_1)$ and $L_2 = (o_2, p_2, q_2)$, the ordinate of point D is calculated by (8):

$$V(L_2 \geq L_1) = hgt(L_1 \frown L_2) = \frac{l_1 - q_2}{(p_2 - q_2) - (p_1 - o_1)} \tag{8}$$

In order to compare L_1 and L_2, we need to calculate the values of $V(L_1 \geq L_2)$ and $V(L_2 \geq L_1)$.

The possibility for a convex fuzzy number to be greater than k convex fuzzy numbers $L_i(i = 1, 2, \ldots k)$ is calculated as:

$$\begin{gathered} V(L \geq L_1, L_2, \ldots, L_k) = V[(L \geq L_1)\ and\ (L \geq L_2)\ ] \\ \text{and } (L \geq L_k) = \text{min V (L} \geq L_i),\ i = 1, 2, \ldots,\ k \end{gathered} \tag{9}$$

Under the assumption that:

$$d'(B_i) = minV(S_i \geq S_k) \tag{10}$$

for $k = 1, 2, \ldots n$ and $k\#i$, the weight vector is determined as:

$$W' = \left(d'(B_1), d'(B_2), \ldots d'(B_n)\right)^T, \tag{11}$$

where B_i are n elements.

The normalized weight vectors are shown as:

$$W = (d(B_1), d(B_2), \ldots., d(B_n))^T \tag{12}$$

with W as a nonfuzzy number.

An evaluation of a Saaty's matrix is used to test for its consistency.

$$CR = \frac{CI}{RI} = \frac{\overline{\lambda} - n}{(n-1) \times RI} \leq 0.1$$

where:

- Consistency Ratio (*CR*);
- Consistency Index (*CI*);
- Random Index (*RI*).

3.4. Weighted Aggregated Sum Product Assessment (WASPAS)

One of the most utilized and efficient multi-criteria decision making models for assessing multiple options in numerous criteria is the weighted sum model (WSM). Firstly, there are $\boldsymbol{a}$ options and $\boldsymbol{b}$ decision criteria. Then define $\boldsymbol{z_b}$ as the importance for the criteria and $\boldsymbol{x_{ab}}$ as the performance level for option $\boldsymbol{a}$ evaluated in criterion $\boldsymbol{b}$. Finally, the overall relative importance of alternative $\boldsymbol{y}$, denoted as $\boldsymbol{P_y^{(1)}}$, is defined [30]

$$\boldsymbol{P_y^{(1)}} = \sum_{b=1}^{n} \boldsymbol{\bar{x}_{ab} z_b} \tag{13}$$

where the linear normalization for each initial criterion value is calculated as follows,

$$\boldsymbol{\bar{x}_{ab}} = \frac{\boldsymbol{x_{ab}}}{\boldsymbol{max_a x_{ab}}} \text{ if } \boldsymbol{max_a x_{ab}} \text{ value is preferable} \tag{14}$$

or

$$\boldsymbol{\bar{x}_{ab}} = \frac{\boldsymbol{min_a x_{abb}}}{\boldsymbol{x_{ab}}} \text{ if } \boldsymbol{min_{ab} x_{ab}} \text{ value is preferable} \tag{15}$$

Another method that is commonly used when assessing multiple options using the total relative importance of option $\boldsymbol{y}$ denoted as $\boldsymbol{P_y^{(2)}}$ is the weight product model (WPM). It is defined as follows [30]:

$$\boldsymbol{P_y^{(2)}} = \prod_{b=1}^{n} (\boldsymbol{\bar{x}_{ab}})^{z_b} \tag{16}$$

In order in incorporate both methods to evaluate further the importance of options, the weights of total relative importance are then equally divided between the WSM and WPM results for a total score [9]:

$$\boldsymbol{P_y} = 0.5\boldsymbol{P_y^{(1)}} + 0.5\boldsymbol{P_y^{(2)}} \tag{17}$$

For better accuracy and making effective decisions, the coefficients that defined WSM and WPM are changed to achieve better suitability depending on the problem. This change in coefficients is called the weighted aggregated sum product assessment method, which was used to rank options in this study.

$$\boldsymbol{P_y} = \lambda \sum_{b=1}^{n} \boldsymbol{\bar{x}_{ab} z_b} + (1-\lambda) \prod_{j=1}^{n} (\boldsymbol{\bar{x}_{ab}})^{z_b} \tag{18}$$

4. A Numerical Example

In Vietnam, Decision No. 1208/QD-TTg approved the master plan for National Power Development in 2011–2020 with a vision to implement the plan to 2030. The plan aimed to meet domestic electricity demand and increase annual electricity production. In 2015, electricity import was approximately 194–210 TWh, and by 2020, it was projected to reach 330–362 TWh and approximately 695–834 TWh in 2030. With wave power, especially when wave technology is more advanced, electromagnetic wave generators will play an important role in green energy and product diversification. Multiple energy sources contribute to national energy security and socioeconomic development [3].

Ocean wave energy, an infinite form of energy, creates no waste and requires low maintenance. However, tides may be unpredictable. Thus, the model that depends on nature is substantial. In addition, it is unsuitable to build this type of energy plant. In Vietnam, stakeholders have not paid much attention to the research on wave energy or its application.

This study describes an MCDM approach for the assessment of wave energy potential locations at the Vietnamese coast based on an FAHP and the WASPAS method. For evaluation, the model will be used to select an optimal location from 10 potential suppliers (Table 1).

Table 1. Ten potential locations for building a wave power energy station.

No	Provinces/City	Symbol
1	Quang Ngai	W001
2	Khanh Hoa	W002
3	Ninh Thuan	W003
4	Quang Binh	W004
5	Quang Nam	W005
6	Binh Thuan	W006
7	Bac Lieu	W007
8	Vung Tau	W008
9	Da Nang	W009
10	Phu Yen	W010

A total of 15 criteria were considered to evaluate and choose the best location, based on literature review and experts' selection (Table 2).

Table 2. All sub-criteria affecting the decision processes.

No	Criterion		Symbol
1	Consistency of the wave energy resource on an annual basis	Technological Factors (TECFA)	WAV01
2	Proximity to the grid		WAV02
3	Wave activity from other sources and areas		WAV03
4	Coastal erosion	Transport and Environment (TRAEN)	WAV04
5	Shipping density		WAV05
6	Climate at which the wave energy converter will operate		WAV06
7	Ocean salinity levels	Efficiency Potential (EFFPO)	WAV07
8	Ocean floor configuration and anchorage facilities		WAV08
9	Ocean currents treadmill		WAV09
10	Mean wave energy flux		WAV010
11	Protection law	Economic and Social Factor (ESOCF)	WAV011
12	Labor resource		WAV012
13	Safety condition		WAV013
14	Migration zones		WAV014
15	Return on investment		WAV015

All input data were determined by 12 experts in renewable energy project management and the field of wave energy. Table 3 shows a fuzzy comparison matrix for all criteria from FAHP model:

Table 3. Fuzzy comparison matrices for criteria.

	TECFA	TEAEN	EFFPO	ESOCF
TECFA	(1,1,1)	(3,4,5)	(1,2,3)	(1/2,1/3,1/4)
TRAEN	(1/5,1/4,1/3)	(1,1,1)	(1,1,1)	(1/2,1/3,1/4)
EFFPO	(1/3,1/2,1)	(1,1,1)	(1,1,1)	(1/3,1/4,1/5)
ESOCF	(4,3,2)	(4,3,2)	(5,4,3)	(1,1,1)

For defuzzification, obtain the coefficients α = 0.5 and β = 0.5 [31]. α represents the uncertain environment; β represents the attitude of the evaluator.

$$g_{0.5,0.5}(\overline{a_{TECFA,TRAEN}}) = [(0.5 \times 3.5) + (1 - 0.5) \times 4.5] = 4$$

$$f_{0.5}(L_{TECFA,TRAEN}) = (4 - 3) \times 0.5 + 3 = 3.5$$

$$f_{0.5}(U_{TECFA,TRAEN}) = 5 - (5 - 4) \times 0.5 = 4.5$$

$$g_{0.5,0.5}(\overline{a_{MAIN2,TRAEN}}) = 1/4$$

The remaining calculation and the fuzzy number priority point are similar to the above calculation. Table 4 presents the real number priority when comparing the main criteria pairs.

Table 4. Real number priority.

	TECFA	MAIN2	EFFPO	ESOCF
TECFA	1	4	2	1/3
TRAEN	1/4	1	1	1/3
EFFPO	1/2	1	1	1/4
ESOCF	3	3	4	1

To calculate the maximum individual value:

$$YZ1 = (1 \times 4 \times 2 \times 1/3)^{1/4} = 1.28$$

$$YZ2 = (1/4 \times 1 \times 1 \times 1/3)^{1/4} = 0.54$$

$$YZ3 = (1/2 \times 1 \times 1 \times 1/4)^{1/4} = 0.6$$

$$YZ4 = (3 \times 3 \times 4 \times 1)^{1/4} = 2.45$$

$$\sum YZ = QA1 + QA2 + QA3 + QA4 = 4.87$$

$$\omega_1 = \frac{1.28}{4.87} = 0.26$$

$$\omega_2 = \frac{0.54}{4.87} = 0.11$$

$$\omega_3 = \frac{0.6}{4.87} = 0.12$$

$$\omega_4 = \frac{2.45}{4.87} = 0.5$$

$$\begin{bmatrix} 1 & 4 & 2 & 1/3 \\ 1/4 & 1 & 1 & 1/3 \\ 1/2 & 1 & 1 & 1/4 \\ 3 & 3 & 4 & 1 \end{bmatrix} \times \begin{bmatrix} 0.26 \\ 0.11 \\ 0.12 \\ 0.50 \end{bmatrix} = \begin{bmatrix} 1.1 \\ 0.46 \\ 0.46 \\ 2.09 \end{bmatrix}$$

$$\begin{bmatrix} 1.1 \\ 0.46 \\ 0.46 \\ 2.09 \end{bmatrix} / \begin{bmatrix} 0.26 \\ 0.11 \\ 0.12 \\ 0.50 \end{bmatrix} = \begin{bmatrix} 4.23 \\ 4.18 \\ 3.8 \\ 4.18 \end{bmatrix}$$

With the number of criteria as 4, get $n = 4$, then λ_{max} and CI are calculated as follows:

$$\lambda_{max} = \frac{4.23 + 4.18 + 3.8 + 4.18}{4} = 4.0976$$

$$CI = \frac{\lambda_{max} - n}{n - 1} = \frac{4.0976 - 4}{4 - 1} = 0.0325$$

For CR, with n = 4, get RI = 0.9

$$CR = \frac{CI}{RI} = \frac{0.0325}{0.9} = 0.036$$

$CR = 0.036 \leq 0.1$, so the pairwise comparison data are consistent and do not need to be re-evaluated. The calculated weight of each sub criteria using FAHP is shown in Table 5.

Table 5. Weight of all sub-criteria.

No	Sub-Criteria	Symbol	Weight
1	Consistency of the wave energy resource on an annual basis	WAV01	0.0911
2	Proximity to the grid.	WAV02	0.0846
3	Wave activity from other sources and areas	WAV03	0.0830
4	Coastal erosion	WAV04	0.0258
5	Shipping density	WAV05	0.0259
6	Climate at which the wave energy converter will operate	WAV06	0.0214
7	Ocean salinity levels	WAV07	0.0305
8	Ocean floor configuration and anchorage facilities	WAV08	0.0239
9	Ocean currents treadmill	WAV09	0.0260
10	Mean wave energy flux	WAV010	0.0239
11	Protection law	WAV011	0.0317
12	Labor resource	WAV012	0.2023
13	Safety condition	WAV013	0.1657
14	Migration zones	WAV015	0.0837
15	Return on investment	WAV014	0.0806

The WASPAS model was applied for ranking all potential locations in the final stage. The normalized matrix and normalized weighted matrix are shown in Tables 6 and 7.

Table 6. Normalized matrix.

	W001	W002	W003	W004	W005	W006	W007	W008	W009	W010
WAV01	0.8000	0.9000	0.9000	0.7000	0.8000	0.7000	0.8000	0.9000	1.0000	0.8000
WAV02	0.8000	0.9000	0.9000	0.9000	0.8000	0.7000	0.8000	1.0000	0.8000	0.8000
WAV03	0.8889	1.0000	0.8889	0.6667	0.7778	1.0000	0.8889	0.8889	1.0000	1.0000
WAV04	0.8000	0.8000	0.8000	0.9000	0.9000	0.7000	1.0000	0.8000	0.7000	0.9000
WAV05	0.8889	0.8889	1.0000	0.8889	0.8889	0.8889	0.7778	0.8889	1.0000	1.0000
WAV06	0.9000	0.9000	0.9000	0.9000	0.8000	0.9000	0.9000	1.0000	0.9000	0.8000
WAV07	1.0000	0.7778	0.7778	0.7778	0.8889	0.8889	1.0000	1.0000	0.8889	1.0000
WAV08	1.0000	1.0000	0.8889	1.0000	0.8889	1.0000	0.8889	1.0000	1.0000	0.8889
WAV09	1.0000	0.9000	0.9000	0.9000	0.8000	0.7000	0.9000	0.8000	1.0000	0.9000
WAV010	1.0000	0.9000	0.9000	0.8000	0.8000	0.7000	0.9000	0.8000	0.9000	0.9000
WAV011	0.9000	0.9000	0.9000	0.8000	0.8000	0.6000	0.8000	0.9000	1.0000	0.9000
WAV012	1.0000	0.8889	0.5556	0.8889	0.8889	1.0000	0.8889	1.0000	0.8889	0.7778
WAV013	0.8000	0.8000	0.8000	0.8000	1.0000	1.0000	0.9000	0.9000	0.8000	0.8000
WAV014	0.7778	1.0000	1.0000	1.0000	1.0000	0.8889	0.8889	0.8889	1.0000	1.0000
WAV015	0.7000	0.8000	1.0000	0.6000	1.0000	0.9000	0.8000	0.9000	0.8000	0.9000

Table 7. Normalized weighted matrix.

	W001	W002	W003	W004	W005	W006	W007	W008	W009	W010
WAV01	0.0729	0.0820	0.0820	0.0638	0.0729	0.0638	0.0729	0.0820	0.0911	0.0729
WAV02	0.0677	0.0761	0.0761	0.0761	0.0677	0.0592	0.0677	0.0846	0.0677	0.0677
WAV03	0.0738	0.0830	0.0738	0.0553	0.0646	0.0830	0.0738	0.0738	0.0830	0.0830
WAV04	0.0645	0.0645	0.0645	0.0725	0.0725	0.0564	0.0806	0.0645	0.0564	0.0725
WAV05	0.0229	0.0229	0.0258	0.0229	0.0229	0.0229	0.0201	0.0229	0.0258	0.0258
WAV06	0.0233	0.0233	0.0233	0.0233	0.0207	0.0233	0.0233	0.0259	0.0233	0.0207
WAV07	0.0214	0.0166	0.0166	0.0166	0.0190	0.0190	0.0214	0.0214	0.0190	0.0214
WAV08	0.0305	0.0305	0.0271	0.0305	0.0271	0.0305	0.0271	0.0305	0.0305	0.0271
WAV09	0.0239	0.0215	0.0215	0.0215	0.0191	0.0167	0.0215	0.0191	0.0239	0.0215
WAV10	0.0260	0.0234	0.0234	0.0208	0.0208	0.0182	0.0234	0.0208	0.0234	0.0234
WAV11	0.0215	0.0215	0.0215	0.0191	0.0191	0.0143	0.0191	0.0215	0.0239	0.0215
WAV12	0.0317	0.0282	0.0176	0.0282	0.0282	0.0317	0.0282	0.0317	0.0282	0.0247
WAV13	0.0178	0.0178	0.0178	0.0178	0.0223	0.0223	0.0201	0.0201	0.0178	0.0178
WAV14	0.1289	0.1657	0.1657	0.1657	0.1657	0.1473	0.1473	0.1473	0.1657	0.1657
WAV15	0.0586	0.0670	0.0837	0.0502	0.0837	0.0753	0.0670	0.0753	0.0670	0.0753

The exponentially weighted matrix is shown in Table 8.

Table 8. Exponentially weighted matrix.

	W001	W002	W003	W004	W005	W006	W007	W008	W009	W010
WAV01	0.9799	0.9904	0.9904	0.9680	0.9799	0.9680	0.9799	0.9904	1.0000	0.9799
WAV02	0.9813	0.9911	0.9911	0.9911	0.9813	0.9703	0.9813	1.0000	0.9813	0.9813
WAV03	0.9903	1.0000	0.9903	0.9669	0.9794	1.0000	0.9903	0.9903	1.0000	1.0000
WAV04	0.9822	0.9822	0.9822	0.9915	0.9915	0.9717	1.0000	0.9822	0.9717	0.9915
WAV05	0.9970	0.9970	1.0000	0.9970	0.9970	0.9970	0.9935	0.9970	1.0000	1.0000
WAV06	0.9973	0.9973	0.9973	0.9973	0.9942	0.9973	0.9973	1.0000	0.9973	0.9942
WAV07	1.0000	0.9946	0.9946	0.9946	0.9975	0.9975	1.0000	1.0000	0.9975	1.0000
WAV08	1.0000	1.0000	0.9964	1.0000	0.9964	1.0000	0.9964	1.0000	1.0000	0.9964
WAV09	1.0000	0.9975	0.9975	0.9975	0.9947	0.9915	0.9975	0.9947	1.0000	0.9975
WAV10	1.0000	0.9973	0.9973	0.9942	0.9942	0.9908	0.9973	0.9942	0.9973	0.9973
WAV11	0.9975	0.9975	0.9975	0.9947	0.9947	0.9879	0.9947	0.9975	1.0000	0.9975
WAV12	1.0000	0.9963	0.9815	0.9963	0.9963	1.0000	0.9963	1.0000	0.9963	0.9921
WAV13	0.9950	0.9950	0.9950	0.9950	1.0000	1.0000	0.9977	0.9977	0.9950	0.9950
WAV14	0.9592	1.0000	1.0000	1.0000	1.0000	0.9807	0.9807	0.9807	1.0000	1.0000
WAV15	0.9706	0.9815	1.0000	0.9581	1.0000	0.9912	0.9815	0.9912	0.9815	0.9912

In a renewable energy project, deciding the location required MCDM. The decision-maker must consider both quantitative and qualitative factors. Although some studies have reviewed applications of MCDM approaches for wave energy plant location selection, few have focused on the problem of a fuzzy environment. This study attempted to fill the gap by discussing an MCDM model for the assessment of wave energy potential locations on the Vietnamese coast based on a FAHP and the WASPAS method. Table 9 and Figure 3 shown the ranking order as follows: W009, W002, W008, W010, W003, W005, W007, W001, W004, and W006. Da Nang (W009) appears to be the optimal location for building a wave power energy station.

Table 9. Results from WASPAS model.

Alternatives	*Q*	Ranking
W001	0.6854	8
W002	0.7441	2
W003	0.7405	5
W004	0.6845	9
W005	0.7264	6
W006	0.6841	10
W007	0.7134	7
W008	0.7414	3
W009	0.7467	1
W010	0.7411	4

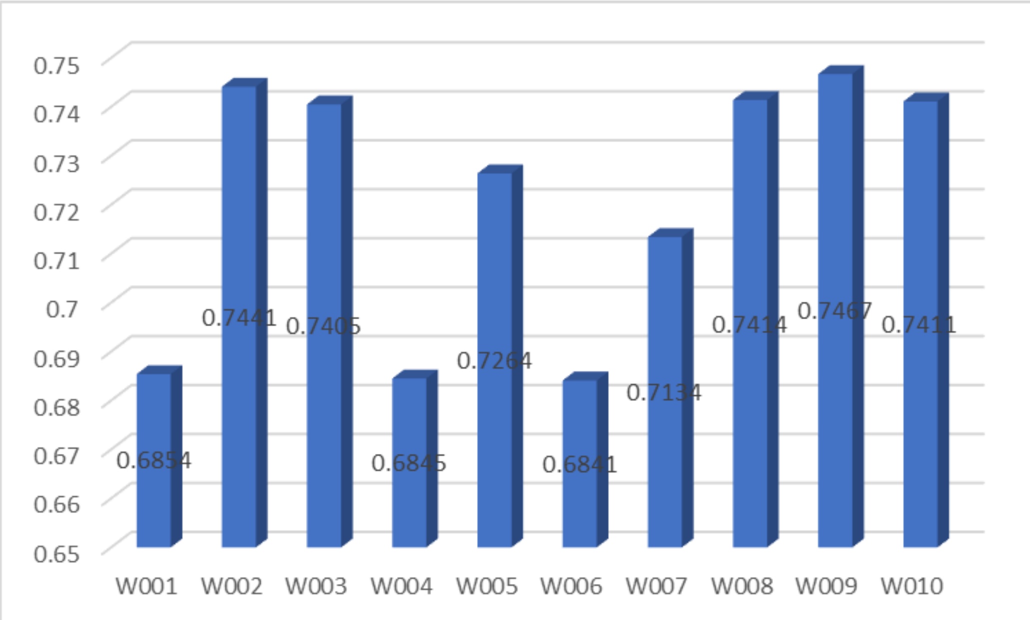

Figure 3. Final ranking from WASPAS.

5. Conclusions

Identifying the location at which to build a wave power energy project is one of the most challenging problems. This study describes an MCDM model for the assessment of wave energy potential locations on the Vietnamese coast based on FAHP and the WASPAS method. We used the F-MCDM approach for wave energy station site selection in Vietnam. The results of model evaluation confirmed that the presented scheme was feasible for any renewable energy project and capable of identifying the best location based on 15 input criteria. The novel model is unique, and the combined frameworks offer the highest accuracy in estimating the location assessment in a multi-criteria framework. This research offers a flexible and practical approach for the decision-maker and provides useful guidelines for wave energy station site selection globally.

The outcome of this research can be applied by academicians and managers for practical purposes. It can also help practitioners make appropriate decisions using MCDM techniques in renewable energy.

The study can be expanded to other MCDM approaches such as TOPSIS, DEA, and ELECTRE II. Future research can investigate different methods of handling uncertain location selection processes, such as carrying out a comparative analysis of different models for identifying the optimal support tool for the location selection problems of renewable energy projects.

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