Article

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

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 hierarchical 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 trans-
shipment port location.

D. E. Ighravwe et al. [16] used a fuzzy-grey-weighted aggregate sum product assess-
ment 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 selec-
tion 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, VlsKriterijumska 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 prob-
lems, 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 
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 location 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.

![Research Graph](image)

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, \( \tilde{A} \) is a fuzzy set, with membership functions written as \( \mu(x|\tilde{A}) \). A triangular fuzzy number (TFN), \( \tilde{L} \), 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 \((\tilde{l})\) membership function graph is shown in Figure 2. If \( \tilde{L} \) 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.](image)

\[
\mu(x|\tilde{L}) = \begin{cases} 
0, & x < l_1 \\
\frac{x - l_1}{l_2 - l_1}, & l_1 \leq x \leq l_2 \\
\frac{l_3 - x}{l_3 - l_2}, & l_2 \leq x \leq l_3 \\
0, & x > l_3 
\end{cases} 
\]  

(1)

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

\[
\tilde{L} = L^{(l)} \cdot R^{(r)} = (l_1 - (l_2 - l_1)y, l_3 + (l_2 - l_3)y), y \in [0, 1] 
\]  

(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:

\[
L_1^{(l)}, L_2^{(l)}, \ldots, L_n^{(l)}, \quad i = 1, 2, \ldots, n 
\]  

(3)

where \( L_i^{(l)}(j = 1, 2, \ldots, m) \) are the TFNs.
Fuzzy synthetic extent value of the $i$th object is defined as:

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

(4)

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

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

(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:

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

(6)

and

$$(L_2 \geq L_1) = hgt(L_1 \triangleright L_2) = \mu_{L_1}(d)$$

(7)

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

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):

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

(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:

$$V(L \geq L_1, L_2, \ldots, L_k) = V[(L \geq L_1) \text{ and } (L \geq L_2)]$$

and $(L \geq L_k) = \min V(L \geq L_i), i = 1, 2, \ldots, k$

(9)

Under the assumption that:

$$d'(B_i) = \min V(S_i \geq S_k)$$

(10)

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

$$W' = (d'(B_1), d'(B_2), d'(B_n))^T,$$

(11)

where $B_i$ are $n$ elements.

The normalized weight vectors are shown as:

$$W = (d(B_1), d(B_2), \ldots, d(B_n))^T$$

(12)

with $W$ as a nonfuzzy number.

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

$$CR = \frac{CI}{RI} = \frac{3 - n}{(n - 1) \times RI} \leq 0.1$$

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 \( a \) options and \( b \) decision criteria. Then define \( z_b \) as the importance for the criteria and \( x_{ab} \) as the performance level for option \( a \) evaluated in criterion \( b \). Finally, the overall relative importance of alternative \( y \), denoted as \( P_y^{(1)} \), is defined \[30\]

\[
P_y^{(1)} = \sum_{b=1}^{n} x_{ab} z_b
\]

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

\[
x_{ab} = \frac{x_{ab}}{\max_a x_{ab}} \quad \text{if } \max_a x_{ab} \text{ value is preferable}
\]

or

\[
x_{ab} = \frac{\min_a x_{ab}}{x_{ab}} \quad \text{if } \min_a x_{ab} \text{ value is preferable}
\]

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

\[
P_y^{(2)} = \prod_{b=1}^{n} (x_{ab})^{z_b}
\]

In order to 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 \[9\]:

\[
P_y = 0.5 P_y^{(1)} + 0.5 P_y^{(2)}
\]

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.

\[
P_y = \lambda \sum_{b=1}^{n} x_{ab} z_b + (1 - \lambda) \prod_{j=1}^{n} (x_{ab})^{z_b}
\]

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 (TECFA)        | WAV01  |
| 2  | Proximity to the grid (TECFA)                                            | WAV02  |
| 3  | Wave activity from other sources and areas (TECFA)                        | WAV03  |
| 4  | Coastal erosion (TRAEN)                                                  | WAV04  |
| 5  | Shipping density (TRAEN)                                                 | WAV05  |
| 6  | Climate at which the wave energy converter will operate (TECFA)           | WAV06  |
| 7  | Ocean salinity levels (TECFA)                                            | WAV07  |
| 8  | Ocean floor configuration and anchorage facilities (TECFA)                | WAV08  |
| 9  | Ocean currents treadmill (TECFA)                                          | WAV09  |
| 10 | Mean wave energy flux (TECFA)                                            | WAV010 |
| 11 | Protection law (TECFA)                                                   | WAV011 |
| 12 | Labor resource (ESOCF)                                                   | WAV012 |
| 13 | Safety condition (ESOCF)                                                 | WAV013 |
| 14 | Migration zones (ESOCF)                                                  | WAV014 |
| 15 | Return on investment (ESOCF)                                             | 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 \( \alpha = 0.5 \) and \( \beta = 0.5 \) [31]. \( \alpha \) represents the uncertain environment; \( \beta \) represents the attitude of the evaluator.

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

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

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

\[
g_{0.5,0.5}([U_{MAIN2,TRAEN}]) = 1/4
\]

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:

\[
YZ_1 = (1 \times 4 \times 2 \times 1/3)^{1/4} = 1.28
\]

\[
YZ_2 = (1/4 \times 1 \times 1 \times 1/3)^{1/4} = 0.54
\]

\[
YZ_3 = (1/2 \times 1 \times 1 \times 1/4)^{1/4} = 0.6
\]

\[
YZ_4 = (3 \times 3 \times 4 \times 1)^{1/4} = 2.45
\]

\[
\sum YZ = QA_1 + QA_2 + QA_3 + QA_4 = 4.87
\]

\[
\omega_1 = \frac{1.28}{4.87} = 0.26
\]

\[
\omega_2 = \frac{0.54}{4.87} = 0.11
\]

\[
\omega_3 = \frac{0.6}{4.87} = 0.12
\]

\[
\omega_4 = \frac{2.45}{4.87} = 0.5
\]

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

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

With the number of criteria as 4, get \( n = 4 \), then \( \lambda_{\text{max}} \) and \( CI \) are calculated as follows:

\[
\lambda_{\text{max}} = \frac{4.23 + 4.18 + 3.8 + 4.18}{4} = 4.0976
\]

\[
CI = \frac{\lambda_{\text{max}} - n}{n - 1} = \frac{4.0976 - 4}{4 - 1} = 0.0325
\]
For CR, with \( n = 4 \), get \( RI = 0.9 \)

\[
CR = \frac{CI}{RI} = \frac{0.0325}{0.9} = 0.036
\]

CR = 0.036 ≤ 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                                  | WAV10  | 0.0239 |
| 11 | Protection law                                         | WAV11  | 0.0317 |
| 12 | Labor resource                                         | WAV12  | 0.2023 |
| 13 | Safety condition                                       | WAV13  | 0.1657 |
| 14 | Migration zones                                        | WAV15  | 0.0837 |
| 15 | Return on investment                                   | WAV14  | 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.

| WAV01 | WAV02 | WAV03 | WAV04 | WAV05 | WAV06 | WAV07 | WAV08 | WAV09 | WAV10 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 0.8000| 0.9000| 0.9000| 0.7000| 0.8000| 0.7000| 0.8000| 0.9000| 1.0000| 0.8000|
| 0.8000| 0.9000| 0.9000| 0.9000| 0.8000| 0.7000| 0.8000| 0.9000| 1.0000| 0.8000|
| 0.8889| 1.0000| 0.8889| 0.6667| 0.7778| 1.0000| 0.8889| 0.8889| 1.0000| 0.8889|
| 0.8889| 0.8000| 0.8000| 0.9000| 0.9000| 0.7000| 1.0000| 0.8000| 0.7000| 0.9000|
| 0.8889| 0.8889| 1.0000| 0.8889| 0.8889| 0.8889| 0.7778| 0.8889| 1.0000| 1.0000|
| 0.9000| 0.9000| 0.9000| 0.9000| 0.8000| 0.9000| 1.0000| 0.9000| 0.9000| 0.8000|
| 1.0000| 0.7778| 0.7778| 0.7778| 0.8889| 0.8889| 1.0000| 1.0000| 0.8889| 1.0000|
| 1.0000| 1.0000| 0.8889| 1.0000| 0.8889| 1.0000| 0.8889| 1.0000| 1.0000| 0.8889|
| 1.0000| 0.9000| 0.9000| 0.9000| 0.9000| 0.8000| 0.7000| 0.9000| 0.8000| 1.0000|
| 1.0000| 0.9000| 0.9000| 0.9000| 0.8000| 0.8000| 0.7000| 0.9000| 0.8000| 0.9000|
| 0.9000| 0.9000| 0.9000| 0.8000| 0.8000| 0.6000| 0.8000| 0.9000| 1.0000| 0.9000|
| 1.0000| 0.8889| 0.5556| 0.8889| 0.8889| 1.0000| 0.8889| 1.0000| 0.8889| 0.7778|
| 0.8000| 0.8000| 0.8000| 0.8000| 1.0000| 1.0000| 0.9000| 0.8000| 0.8000| 0.8000|
| 0.7778| 1.0000| 1.0000| 1.0000| 1.0000| 1.0000| 0.8889| 0.8889| 0.8889| 1.0000|
| 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 | 0.0638 | 0.0729 | 0.0638 | 0.0729 | 0.0820 | 0.0911 | 0.0729 |
| WAV02 | 0.0677 | 0.0761 | 0.0761 | 0.0592 | 0.0677 | 0.0638 | 0.0729 | 0.0846 | 0.0677 |
| WAV03 | 0.0738 | 0.0830 | 0.0738 | 0.0553 | 0.0646 | 0.0729 | 0.0830 | 0.0738 | 0.0830 |
| WAV04 | 0.0645 | 0.0645 | 0.0725 | 0.0725 | 0.0654 | 0.0830 | 0.0830 | 0.0645 | 0.0645 |
| WAV05 | 0.0229 | 0.0229 | 0.0258 | 0.0229 | 0.0229 | 0.0229 | 0.0229 | 0.0229 | 0.0229 |
| WAV06 | 0.0233 | 0.0233 | 0.0233 | 0.0233 | 0.0233 | 0.0233 | 0.0233 | 0.0233 | 0.0233 |
| WAV07 | 0.0214 | 0.0166 | 0.0166 | 0.0166 | 0.0166 | 0.0170 | 0.0214 | 0.0190 | 0.0214 |
| WAV08 | 0.0305 | 0.0305 | 0.0271 | 0.0305 | 0.0271 | 0.0305 | 0.0271 | 0.0305 | 0.0271 |
| WAV09 | 0.0239 | 0.0215 | 0.0215 | 0.0215 | 0.0191 | 0.0215 | 0.0215 | 0.0191 | 0.0215 |
| WAV10 | 0.0260 | 0.0234 | 0.0234 | 0.0234 | 0.0208 | 0.0234 | 0.0234 | 0.0208 | 0.0234 |
| WAV11 | 0.0215 | 0.0215 | 0.0191 | 0.0215 | 0.0191 | 0.0215 | 0.0215 | 0.0191 | 0.0215 |
| WAV12 | 0.0317 | 0.0282 | 0.0176 | 0.0282 | 0.0176 | 0.0282 | 0.0282 | 0.0176 | 0.0282 |
| WAV13 | 0.0178 | 0.0178 | 0.0178 | 0.0178 | 0.0223 | 0.0223 | 0.0223 | 0.0223 | 0.0223 |
| WAV14 | 0.1289 | 0.1657 | 0.1657 | 0.1657 | 0.1657 | 0.1473 | 0.1473 | 0.1473 | 0.1473 |
| WAV15 | 0.0178 | 0.0178 | 0.0178 | 0.0178 | 0.0178 | 0.0178 | 0.0178 | 0.0178 | 0.0178 |

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 | 0.9813 | 0.9813 | 0.9813 | 0.9813 | 0.9904 | 1.0000 | 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 | 0.9915 | 0.9915 | 0.9915 | 0.9915 | 0.9915 | 0.9915 | 1.0000 | 0.9915 |
| WAV05 | 0.9970 | 0.9970 | 1.0000 | 0.9970 | 0.9970 | 0.9970 | 0.9970 | 0.9970 | 1.0000 | 0.9970 |
| WAV06 | 0.9973 | 0.9973 | 0.9973 | 0.9973 | 0.9942 | 0.9973 | 0.9973 | 0.9973 | 1.0000 | 0.9973 |
| WAV07 | 1.0000 | 0.9946 | 0.9946 | 0.9946 | 0.9946 | 0.9946 | 0.9946 | 0.9946 | 1.0000 | 0.9946 |
| 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 | 0.9975 | 0.9975 | 0.9975 | 0.9975 | 1.0000 | 0.9975 |
| WAV10 | 1.0000 | 0.9973 | 0.9973 | 0.9942 | 0.9942 | 0.9942 | 0.9942 | 0.9942 | 1.0000 | 0.9942 |
| WAV11 | 0.9975 | 0.9975 | 0.9975 | 0.9947 | 0.9947 | 0.9947 | 0.9947 | 0.9947 | 1.0000 | 0.9947 |
| WAV12 | 1.0000 | 0.9963 | 0.9815 | 0.9963 | 0.9963 | 0.9963 | 0.9963 | 0.9963 | 1.0000 | 0.9963 |
| WAV13 | 0.9950 | 0.9950 | 0.9950 | 0.9950 | 0.9950 | 0.9950 | 0.9950 | 0.9950 | 1.0000 | 0.9950 |
| WAV14 | 0.9592 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 1.0000 | 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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References

1. Toan, D.V. Năng lượng tái tạo trên biển và định hướng phát triển tại Việt Nam. Vietnam Institute of Seas and Islands. 2015. Available online: http://www.vasi.gov.vn/uploaded/8/655_NANG_LUONG_TAI_TREN_BIEN_VA_DINH_HUONG_PHAT_TRIEN_TAI_VIET_NAM.pdf (accessed on 11 November 2020).
2. Ha, T.H. Phát triển năng lượng biển tại Việt Nam là phù hợp với xu thế của toàn cầu. 2018. Available online: https://baotaininguyenmoitruong.vn/phat-trien-nang-luong-bien-o-viet-nam-la-phu-hop-voi-xu-the-cua-toan-cau-223934.html (accessed on 11 November 2020).
3. Vietnam Administration of Seas and Islands. Năng lượng biển là tiềm năng không lồ của biển đảo Việt Nam. 2019. Available online: http://www.vasi.gov.vn/712/nang-luong-song-tiem-nang-khong-lo-cua-bien-dao-viet-nam/t708/c223/11575 (accessed on 11 November 2020).
4. Hwang, C.L.; Yoon, K. Multiple Attribute Decision Making: Methods and Applications; Springer: New York, NY, USA, 1981.
5. Liao, H.; Wu, D.; Huang, Y.; Ren, P.; Xu, Z.; Verma, M. Green logistic provider selection with a hesitant fuzzy linguistic thermodynamic method integrating cumulative prospect theory and PROMETHEE. Sustainability 2018, 10, 1291. [CrossRef]
6. Safari, H.; Fagheyi, M.S.; Ahangari, S.S.; Fathi, M.R. Applying PROMETHEE method based on entropyweight for supplier selection. Bus. Manag. Strategy 2012, 3, 97–106.
7. Garcia-Bernabeu, A.; Mayor-Vitoria, F.; Mas-Verdu, F. A Mcdm Approach for Project Finance Selection: An application in the Renewable Energy Sector. Rev. Electrónica Comun. 2015, 16, 13–26.
8. Lee, W.S.; Yang, Y.T. Valuation and choice of convertible bonds based on MCDM. Appl. Financ. Econ. 2013, 23, 861–868. [CrossRef]
9. Wang, C.-N.; Viet, V.T.H.; Ho, T.P.; Nguyen, V.T.; Nguyen, V.T. Multi-Criteria Decision Model for the Selection of Suppliers in the Textile Industry. Symmetry 2020, 12, 979. [CrossRef]
10. Chien, F.; Wang, C.-N.; Nguyen, V.T.; Nguyen, V.T.; Chau, K.Y. An Evaluation Model of Quantitative and Qualitative Fuzzy Multi-Criteria Decision-Making Approach for Hydroelectric Plant Location Selection. Energies 2020, 13, 2783. [CrossRef]
11. Zavadskas, E.K.; Antucheviciene, J.; Hajiajha, S.H.R.; Hashemi, S.S. Extension of weighted aggregated sum product assessment with interval-valued intuitionistic fuzzy numbers (WASPAS-IVIF). Appl. Soft Comput. 2014, 24, 1013–1021. [CrossRef]
12. Zavadskas, E.K.; Turskis, Z.; Antucheviciene, J. Selecting a contractor by using a novel method for multiple attribute analysis: Weighted Aggregated Sum Product Assessment with grey values (WASPAS-G). Stud. Inform. Control 2015, 24, 141–150. [CrossRef]
13. Nie, R.-X.; Wang, J.-Q.; Zhang, H.-Y. Solving Solar-Wind Power Station Location Problem Using an Extended Weighted Aggregated Sum Product Assessment (WASPAS) Technique with Interval Neutrosophic Sets. Symmetry 2017, 9, 106. [CrossRef]
14. Rani, P.; Mishra, A.R. Multi-criteria weighted aggregated sum product assessment framework for fuel technology selection using q-rung orthopair fuzzy sets. Sustain. Prod. Consum. 2020, 24, 90–104. [CrossRef]
15. Ighravwe, D.E.; Oke, S.A. A fuzzy-grey-weighted aggregate sum product assessment methodical approach for multi-criteria analysis of maintenance performance systems. Int. J. Syst. Assur. Eng. Manag. 2017, 8, 961–973. [CrossRef]
16. Hanine, M.; Bouthkhoum, O.; Maknissi, A.; Tikiouine, E.; Agouti, A. Decision making under uncertainty using PEES–fuzzy AHP–fuzzy TOPSIS methodology for landfill location selection. Environ. Syst. Decis. 2016, 36, 351–367. [CrossRef]
17. Azizi, M. Strategic model for location selection of solar wood drying by applying TOPSIS. Econ. Manag. Sustain. 2017, 2, 15–23. [CrossRef]
18. Mesran, M.; Suginam, S.; Utomo, D.P. Implementation of AHP and WASPAS (Weighted Aggregated Sum Product Assessment) Methods in Ranking Teacher Performance. IJISTECH 2020, 3, 173–182.
19. Seker, S.; Aydin, N. Hydrogen production facility location selection for Black Sea using entropy based TOPSIS under IVPF environment. Int. J. Hydrogen Energy 2020, 45, 15855–15868. [CrossRef]
20. Rao, C.; Goh, M.; Zhao, Y.; Zheng, J. Location selection of city logistics centers under sustainability. Transp. Res. Part D Transp. Environ. 2015, 36, 29–44. [CrossRef]
21. Tan, Q. The Selection of Wind Power Project Location in the Southeastern Corridor of Pakistan: A Factor Analysis, AHP, and Fuzzy-TOPSIS Application. *Energies* 2018, 11, 1940.

22. Kizielewicz, B.; Wałróbski, J.; Salabun, W. Identification of Relevant Criteria Set in the MCDA Process—Wind Farm Location Case Study. *Energies* 2020, 13, 6548. [CrossRef]

23. Riaz, M.; Salabun, W.; Farid, H.M.A.; Ali, N.; Wałróbski, J. A Robust q-Rung Orthopair Fuzzy Information Aggregation Using Einstein Operations with Application to Sustainable Energy Planning Decision Management. *Energies* 2020, 13, 2155.

24. Mardani, A.; Jusoh, A.; Zavadskas, E.K.; Cavallaro, F.; Khalifah, Z. Sustainable and Renewable Energy: An Overview of the Application of Multiple Criteria Decision Making Techniques and Approaches. *Sustainability* 2015, 7, 13947–13984. [CrossRef]

25. Kaya, I.; Çolak, M.; Terzi, F. A comprehensive review of fuzzy multi criteria decision making methodologies for energy policy making. *Energy Strat. Rev.* 2019, 24, 207–228. [CrossRef]

26. Siksnelyte, I.; Zavadskas, E.K.; Streimikiene, D.; Sharma, D. An Overview of Multi-Criteria Decision-Making Methods in Dealing with Sustainable Energy Development Issues. *Energies* 2018, 11, 2754. [CrossRef]

27. Salabun, W.; Wałróbski, J.; Shekhovtsov, A. Are MCDA Methods Benchmarkable? A Comparative Study of TOPSIS, VIKOR, COPRAS, and PROMETHEE II Methods. *Symmetry* 2020, 12, 1549. [CrossRef]

28. Zadeh, L. Fuzzy sets. *Inf. Control* 1965, 8, 338–353. [CrossRef]

29. Chang, D.-Y. Extent analysis and synthetic decision. *Optim. Tech. Appl.* 1992, 1, 352.

30. Triantaphyllou, E.; Mann, S.H. An examination of the effectiveness of multi-dimensional decision-making methods: A decision-making paradox. *Decis. Support Syst.* 1989, 5, 303–312. [CrossRef]

31. Tang, Y.-C.; Beynon, M.J. Application and Development of a Fuzzy Analytic Hierarchy Process within a Capital Investment Study. *J. Econ. Manag.* 2005, 1, 207–230.