Site Selection for an Offshore Wind Power Station Under a Fuzzy Environment

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Abstract

The Malaysian government's support for offshore wind power production has led to an increase in a few proposals. An important factor in the overall efficiency of any offshore wind farm is the site selection process, which is a multi-criteria decision-making (MCDM) task. However, classical MCDM techniques often fail to choose a suitable site because of three main challenges. First, compensation is regarded as a problem in the processing of information. Second, data usage and data leakage are often ignored in the decision-making process. Third, interaction difficulty in fuzzy environments is easily ignored. This study provides a framework for making site selection decisions for offshore wind farms while addressing the constraints. Fuzzy VIKOR is used in the second stage of the AHP process to analyze the site's results with respect to evaluation criteria for offshore wind farms. A comprehensive index system, which incorporates the veto criteria and evaluation criteria for selecting offshore wind power station sites, is devised. Then, the system is used to transmit imprecise information to decision makers by using a triangular fuzzy set. Likelihood-based valued comparisons indicate that imprecise choice information can be correctly used, and issues of information loss can be logically avoided. A case study of Malaysia is used to demonstrate the validity and practicality of the site selection technique. This research offers a theoretical basis for accurate offshore wind power evaluation in Malaysia.

Keywords: AHP; VIKOR; fuzzy; offshore; uncertainty

1. Introduction

The location or site of an offshore wind power station (OWPS) must be determined. Wind energy, construction, ecology, marine placemaking, electric grid accessibility lines, business, and society are all factors in a multi-criteria decision-making (MCDM) problem [1], further suggesting that OWPS site selection entails a series of problems. More worrisome, information is often uncertain. Making accurate predictions about the relative importance of various factors throughout the decision-making process is a difficult task. Mistakes may arise throughout the assessment process due to the imprecise nature of language used by experts or specialists, especially if they are unable to convey accurate values. Consequently, an important consideration in selecting OWPS sites is knowing how data should be displayed and handled. Prioritizing certain OWPS facility site possibilities require an appropriate and successful MCDM technique, and results may be used as soon as they are improved and integrated into the decision making. MCDM problems and various extensions of fuzzified word sets need a range of techniques to be developed. VIeKrite–Rijumska Optimizacija techniques, such as TOPSIS, complex proportional assessment (COPRAS), and weighted aggregated sum product assessment (WASPAS), are only a few examples of many available approaches to resolve the supplier selection concerns. Shemshadi et al. [2] improved the VIKOR technique by using Shannon entropy to obtain and use the target value. Mousavi-Nasab and Sotoudeh-Anvari [3] developed a general practice design and a material problem that can be solved by TOPSIS and COPRAS. To address real-world issues, Garg and Kumar [4] considered the interval-valued intuitionistic fuzzy set, and TOPSIS was constructed based on new exponential distance measurements and set

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pairing analysis theory. The practical applications of WASPAS, a fairly new and fundamental MCDM approach, are plenty [5]–[8].

With the assistance of the Malaysian government in generating offshore wind power, the number of proposals has risen sharply. The selection of a suitable site for offshore wind farms is a multi-faceted decision-making process. While the three problems stated above may hinder the easy selection of a site, the classical methods of MCDM can hardly address these concerns. For instance, during information processing, compensation is an issue. Then, when making judgments, data are seldom used, and data leakage occurs. Third, in fuzzy settings, interaction difficulties are often overlooked. Aiming to address these limitations, a framework for site selection for offshore wind farms is proposed. Fuzzy VIKOR with two-stage AHP is employed to analyze the offshore wind plant site. In particular, a comprehensive index system, which includes the veto criteria and assessment criteria, is initially developed to identify OWPS sites. Then, a triangular fuzzy set is utilized to convey imprecise information to decision makers (DMs), and likelihood-based valued comparisons are conducted to rationally address the difficulties of information loss while using the imprecise choice information. Finally, the validity and applicability of the site method are illustrated via an in-depth case study of Malaysia. A theoretical framework for the development of offshore wind power generation in Malaysia is provided by this study.

The MCDM outline for OWPS site selection presented in this research can provide managers with insightful information for analyzing and selecting ideal sites during OWPS decision making. MCDM techniques offer an efficient framework, as well as numerous competing criteria, for selecting renewable energy plants. However, the existing OWPS site selection decision-making procedure has several issues, which renders the current choices ill-suited to the actual circumstances. The challenges can be described as follows.

a. The selection of OWPS sites is generally a hazy process. OWPS site selection is extremely complicated; in fact, the evaluation results before OWPS development cannot be accurately calculated or quantified by simply using assessment data. DMs tend to make inaccurate practical assessments, and neither satisfaction nor dissatisfaction indices can be accurately measured. As a result, the decision for selecting a certain site is composed of only a limited amount of information for disposal. In other words, OWPS site selection is difficult to determine by simply relying on expert judgment.
b. When using weighted synthesis (a common traditional MCDM approach), the compensation problem often emerges. In certain cases, strong performance in some areas may overcome the worse performance elsewhere. Regarding wind energy and construction conditions and similar indices, certain site options may score exceptionally low on specific criteria set (e.g., environmental effects) and hence dropped as an option, whereas other factors may also score high with respect to pay concerns.
c. The OWPS site selection decision-making process may fail due to poor utilization of choice information and data loss. Furthermore, a practical means to discern between various levels of choices is often lacking when comparing optimal plan decisions for each pair of possibilities. The choice degrees of actual figures may be constructed using existing outranking algorithms, such as VIKOR, but they must be enhanced to deal with ambiguous data in real-world applications. Preference judgments must also be handled rationally to maintain their quality in an incomplete knowledge environment.

Fuzzy sets are often employed when dealing with real-world inaccuracies. While the traditional fuzzy set conveys only membership and non-membership information, Atanassov’s intuitive complex numbers provide extra information for scenario description [9]. IFS is effective in dealing with intrinsically erroneous or unreliable judgments, which may hinder DMs to convey their confirmation, rejection, and reluctance of decision-making activities [10],[11]. IFS has been widely used in MCDM scenarios in recent years, further indicating their capacity to cope with incomplete data [12]–[16].

Case studies can be used to develop and validate model frameworks. AHP and VIKOR can help to evaluate OWPS sites based on sustainability criteria. However, as quantitative assessments are also lacking, fuzzy set theory is used to handle uncertainties. In the following sections, the approach and its applications are described in depth.

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The remainder of this paper is organized as follows. Section 2 discusses the relevant literature and research gaps in OWPS site selection. Section 3 presents the suggested technique based on fuzzy AHP and fuzzy VIKOR. Section 4 presents the case study. Sections 5 and 6 discuss the managerial implications and conclusions.

2. Review of literature on OWPS site selection and assessment

Important studies on OWPS site selection have been few in the last decade, but the results of those that used MCDM methodologies have been outstanding in several cases around the world. The most commonly used methods are the AHP, ANP, preference ranking method for enrichment evaluations based on similarity to the ideal solution (TOPSIS), reality-expressing eradication and selection (ELECTRE), decision-making trial, and evaluation lab [17] used in OWPS assessment (PROMETHEE). The fuzzy set concept and the gray concept are often used in conjunction with MCDM approaches to deal with unclear and incomplete information or preferences. Chaouachi et al. [17] employed AHP to consider economic investment, security concerns, operational expenditure, and capacity performance while selecting offshore wind farms in the Baltic States. To assist in the site selection of Iranian offshore wind farms, Fetanat and Khorasaninejad [18] utilized fuzzy ANP and fuzzy DEMATEL as part of a unique hybrid MCDM technique. Six factors (depth and height, environment, distance from facilities, economic factors, wind resources, and culture) with related sub-criteria were identified. Wu et al. [19] proposed a decision framework incorporating triangular intuitionistic fuzzy numbers, ANP, and PROMETHEE to select the best OWPS site in a Chinese case study, taking into account six criteria: wind resources (surroundings), economics (construction), society, and risks. Lo et al. [20] established a gray DEMATEL-based ANP model for the website designing of OWPS sites in Taiwan and considered wind and marine variables and shore support conditions, as well as economic ramifications, environmental effects, and societal consequences.

Before establishing costly OWPS sites, appropriate areas must be classified in an orderly manner to aid in maximizing production, decreasing socioeconomic costs, limiting environmental impacts, maximizing social benefits, and fostering the affected regions' sustainability. Identifying resources, circumstances, financial and ecological elements, social repercussions, and political considerations is a preliminary and essential step in the development of new onshore wind farms. When developing a framework for the site selection of onshore wind farms, only a few scholars have considered sustainability concerns. In this study, the sustainability-based decision criteria are adopted from the works and authenticated by subject matter authorities.

AHP, TOPSIS, and ELECTRE (all of them are MCDM approaches) are often used by DMs from the energy sector, but related studies are few. Lee et al. [21] used AHP to evaluate the relative efficiency of various power technologies. Kaya and Kahraman [22] utilized TOPSIS to analyze an energy-related decision-making challenge. Grujic et al. [23] developed a selection process amongst many different heat demand options by using ELECTRE. The decision-making support system for energy analysis has been enhanced by the studies, further verifying the usefulness of MCDM techniques.

Compensation challenges partly exist in the main decisions [24]. These challenges can be addressed using ELECTRE [25],[26]. With the capability to decrease the binary relationship (outranking relation), ELECTRE as an outranking mechanism (OM) may minimize index compensation and provide reliable results over a wide range of application domains [27]. Values of good agreement and the non-concordance index are calculated using preference and aversion criteria [28], and fuzzy logic is used. Among the recent approaches, ELECTRE-III is a valuable pairwise strategy for providing more information compared with ELECTRE-I and ELECTRE-II [29].

The fuzzy set concept has lately been used in MCDM by scholars utilizing Zadeh's fuzzy set concept. According to Perera et al. [30], fuzzy TOPSIS and layer charts may be used to help develop hybrid power systems. A hybrid MCDM model was created by linking FAHP and TOPSIS as a means of finding the best biofuel supply and mixture [31]. Kaya and Kahraman [22] proposed the improved TOPSIS method for selecting the best energy technology alternative. According to the works, fuzzy techniques can effectively resolve MCDM issues.

Furthermore, according to Zadeh, the sum of participation u and non-membership v is 1 in fuzzy set theory. However, in practice, a person's membership and non-membership ratings are

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frequently not equal to 1 [29]. Atanassov's intuitionistic fuzzy set was designed to solve the problem as an extension of Zadeh's fuzzy set. In light of IFS theory, DMs can convey ambiguous information in decision making, and this applies to both members of and non-members of the group [32]. IFS has become popular in recent years and is now being used extensively in decision-making situations [29],[33]–[37].

Regarding OWPS site selection, particularly in the Malaysian setting, the literature is dearth. For the first time, this study attempts to identify the most ideal sites for OWPS development by using triangular fuzzy sets, AHP, and VIKOR. AHP is a tried-and-tested method for solving MCDM issues. Meanwhile, the triangular fuzzy and VIKOR methods outperform other traditional MCDM approaches for site selection in OWPS. Both methods are cutting-edge methodologies presenting numerous advantages. In particular, the innovative VIKOR method is used to generate a highly robust and accurate ranking of alternatives in MCDM, and it can process uncertainties defined as fuzzy climates while consolidating data from human judgments. Indeed, this work is the first one to use AHP/WASPAS for OWPS sites in Malaysia, thus helping fill the void in the existing literature on sustainable energy site selection.

Many other studies have been conducted to compensate for the knowledge gap. Oftentimes, expert consensus is used to validate the most important parameters affecting OWPS site selection. Then, F-AHP and WASPAS have been used to find the best sites. A common example of the indicator system includes wind resources, environmental impact, building and maintenance requirements, social impact, onshore circumstances, and impact on the economy and other subsequent effects.

3. Triangular fuzzy AHP and VIKOR

Here, a framework is proposed for selecting the best site for OWPS. This framework includes two stages. First, the triangular fuzzy AHP is used to compute the weights of the criteria. Then, the triangular fuzzy VIKOR is used to rank and select the best site for the OWPS. Figure 1 shows the framework of this study.

A. Fuzzy AHP

The first phase of fuzzy AHP requires breaking the issue into a hierarchical structure consisting of the objective, criteria, sub-criteria, and alternatives to develop the model. Then, the items are compared in pairwise manner based on their relative significance to the objective, the criteria, and the sub-criterion. The relative significance values are created using triangular fuzzy numbers (TFNs) on a scale between 1 and 9 to account for the imprecision of qualitative human judgments. In this analysis, we use the TFNs $\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$, where $\tilde{1}$ represents "equal relative significance" and $\tilde{9}$ represents "excessive relative importance." Table 1 provides detailed information on the TFNs, their accompanying membership functions, and the linguistic variables connected with them. A reciprocal value is given to the inverse comparison, i.e., $x_{ab} = 1/x_{ab}$, where x_{ab} represents the relative significance of the $ath\ element\ to\ the\ bth\ element.$

$$\tilde{X} = \begin{bmatrix} 1 & \cdots & \tilde{x}_{1c} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{c1} & \cdots & 1 \end{bmatrix} \tag{1}$$

In the third stage, once all pairwise comparisons have been completed on an individual basis, group preference vectors are constructed by combining the individual evaluations. The two possible approaches are aggregating individual judgments (AIJ) and combining individual priorities (AIP). AIJ is suited for group members behaving as a unit, whereas AIP is acceptable for distinct people. Here, the average aggregation method is used.

The score function is computed by

$$w_b = \frac{y1+4*y2+y3}{6}, \tag{2}$$

where $y1, y2,$ and $y3$ are the triangular fuzzy numbers.

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After obtaining the composite evaluation matrix of all comparisons, the reliability is assessed by calculating the consistency index (CI) using the maximum eigenvalue max, and n is the matrix length.

$$CI = \frac{(\lambda_{max} - c)}{(c - 1)} \tag{3}$$

The consistency of the judgment may be determined by calculating the consistency ratio (CR) af

$$CR = \frac{CI}{RI} \tag{4}$$

where RI is the random CI. If CR is less than 0.1, then the evaluation matrix is acceptable; otherwise, it is inconsistent. Judgments must be examined and refined to create a consistent matrix. Subsequently, the normalization matrix is computed by dividing each value in the aggregated matrix by the sum of each column. Then, the weights of the criteria are computed by summing up each row then dividing the result by the number of criteria. At this stage, the weights of the criteria can be obtained.

B. Fuzzy VIKOR

Consider a collection of d options designated as $WTA = WTA_1, WTA_2, \ldots . WTA_d$ to be assessed based on n criteria, i.e., $WTC = WTC_1, WTC_2, \ldots . WTC_c$. The weights of the criterion are given by $w_b (b = 1,2, \ldots, c)$.

Step 1: Construct the fuzzy decision matrix for the options (M) and the criterion (W) as follows:

$$\tilde{M} = \begin{array}{c c} & \begin{array}{ccc} WTC_1 & WTC_2 & WTC_c \end{array} \\ \begin{array}{c} WTA_1 \\ WTA_2 \\ WTA_d \end{array} & \begin{bmatrix} \tilde{m}_{11} & \cdots & \tilde{x}_{1c} \\ \vdots & \ddots & \vdots \\ \tilde{m}_{d1} & \cdots & \tilde{m}_{cd} \end{bmatrix} \end{array} \tag{5}$$

$a = 1,2,3 \ldots \ldots c; b = 1,2,3, \ldots \ldots d.$

Step 2: Defuzzify the components of the fuzzy decision matrix for the criterion weights and alternatives by converting them into definite values.

$$x = \frac{y1 + 4*y2 + y3}{6} \tag{6}$$

Step 3: Compute the beneficial and non-beneficial values for the s_b^*, s_b^- of all criteria.

$$s_b^* = \min_a \tilde{m}_{ab}$$
(7)

$$s_b^- = \max_a \tilde{m}_{ab}$$
(8)

Step 4: Compute the values of e_a, f_a.

$$e_a = \sum_{b=1}^{c} w_b \frac{s_b^* - \tilde{m}_{ab}}{s_b^* - s_b^-} \tag{9}$$

$$f_a = \max_b w_b \frac{s_b^* - \tilde{m}_{ab}}{s_b^* - s_b^-}$$
(10)

Step 5: Compute the value of R_a.

$$R_a = \lambda \frac{e_a - \max_a e_a}{\min_a e_a - \max_a e_a} + (1 - \lambda) \frac{e_a - \max_a f_a}{\min_a f_a - \max_a f_a},$$
(11)

where λ is the weight for the method with the greatest group utility, and $1 - \lambda$ is the weight of the individual's regret.

Table 1: Triangular fuzzy scale

Magnitude of significance	Fuzzy number	Linguistic term	Membership function
1	$\tilde{1}$	Equally significant/favored	(1,1,3)
3	$\tilde{3}$	Weakly essential/preferred	(1,3,5)
5	$\tilde{5}$	Notably more essential/favored	(3,5,7)
7	$\tilde{7}$	Extremely essential/preferred	(5,7,9)
9	$\tilde{9}$	Extremely more	(7,9,9)

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		essential/favored	

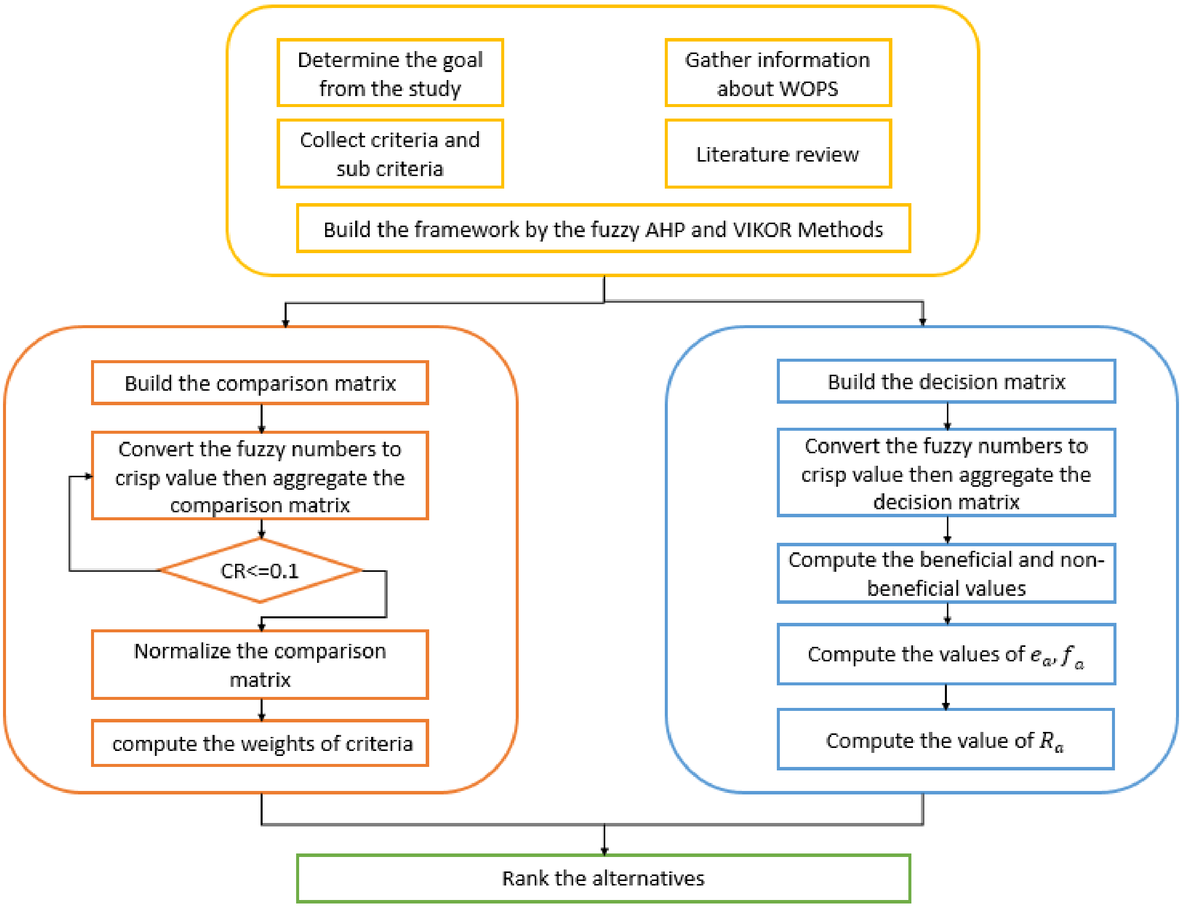

Figure 1: Framework of this study.

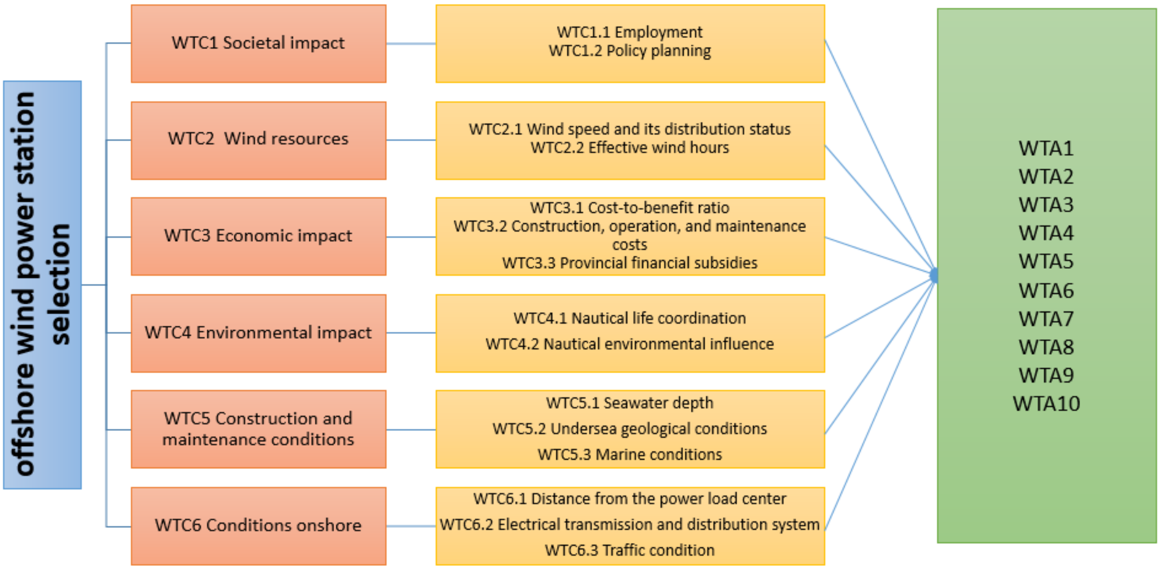

Figure 2: Criteria and alternatives used in this study.

4. Case study

The best sites for OWPS in Malaysia were identified using the proposed aggregated framework. A panel of three experts, each of them with at least ten years of experience in the energy-related sector,

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was requested to choose the potential alternatives and essential evaluation criteria to ensure that the conclusions would be objective. Only some of them are experts in wind power, but all of them are knowledgeable in constructing and evaluating actual turbines. Aside from power electronics, hydrology, science, architecture, and the environment, the others are experts in subjects related to OWPS site selection. In the research, we relied on a set of 6 primary criteria and 15 secondary criteria. Figure 2 illustrates the link between parameters, sub-criteria, and alternative options.

The steps can be described as follows. First, let experts evaluate the criteria and compute the comparison matrix according to Eq. (1). Second, compute the crisp value for all criteria according to Eq. (2). Third, aggregate the comparison matrix into a single matrix, as shown in Table 2. Fourth, compute the consistency ratio according to Eqs. (3) and (4). If the consistency ratio is less than 0.1, then the opinions of experts are reliable. Fifth, normalize the aggregate matrix. Sixth, compute the weights of criteria. Seventh, repeat the previous steps to compute the weights of the sub-criteria. Finally, compute the global weights of all criteria. Figures 3 and 4 shows the weights of the criteria sub-criteria, respectively.

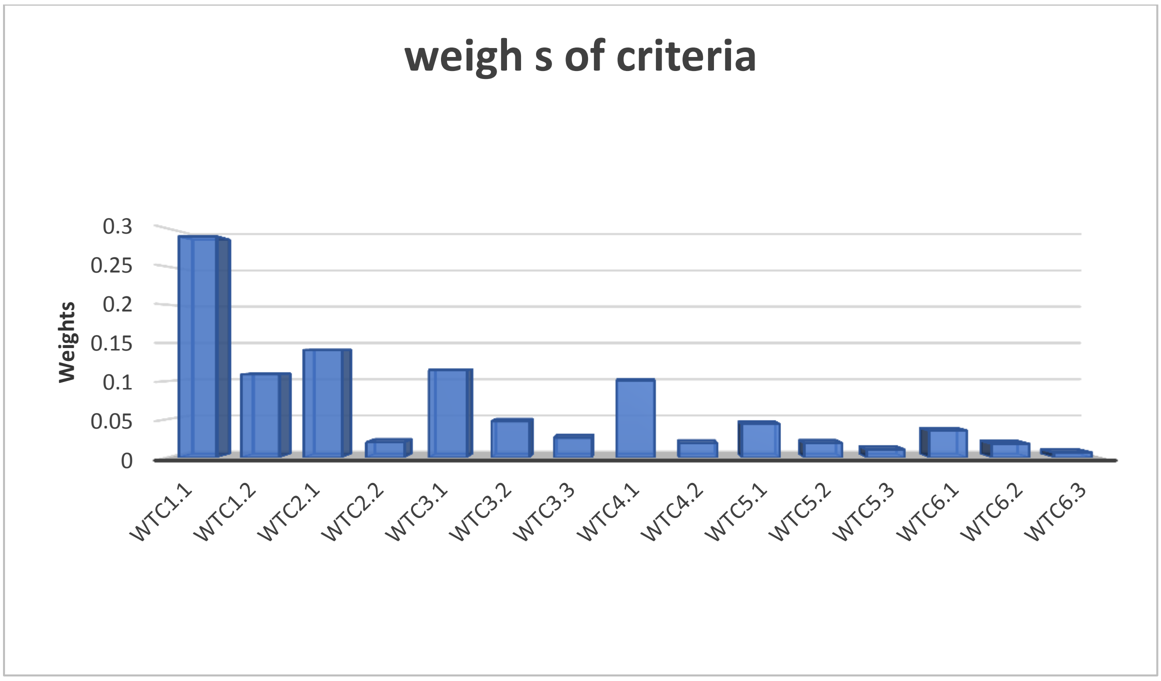
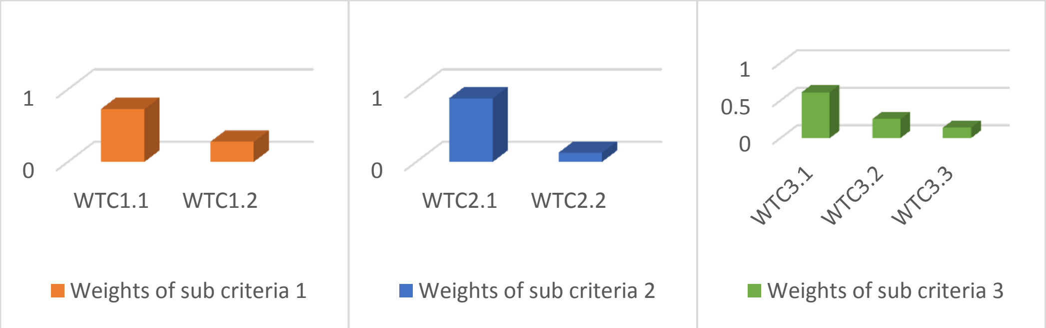


Figure 3: Criteria weights.



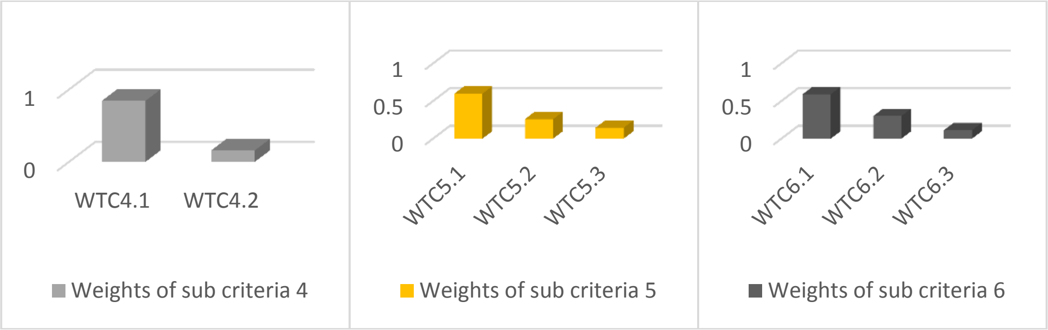


Figure 4: Sub-criteria weights.

Table 2: Comparative matrix of the main criteria.

	WTC$_1$	**WTC$_2$**	**WTC$_3$**	**WTC$_4$**	**WTC$_5$**	**WTC$_6$**
WTC$_1$	1	4.33	3.11	5.67	6.33	3.78
WTC$_2$	0.07	1	1.88	1.88	6.33	2.44
WTC$_3$	0.43	0.62	1	3.1	5.67	5
WTC$_4$	0.18	0.62	0.43	1	4.43	5.1
WTC$_5$	0.16	0.16	0.18	0.37	1	5.67

We apply the steps of fuzzy VIKOR to rank the alternatives. The experts' evaluation of the criteria and alternatives and the resultant decision matrix are shown in Tables 3.1 to 3.3. The values are aggregated into a single matrix (Table 3). Then, the beneficial and non-beneficial values are computed according to Eqs. (7) and (8), and the values of e_a, f_a are computed according to Eqs. (9) and (10) (Tables 4 and 5), respectively. Finally, the value of R_a is computed (Table 5), and the alternatives are ranked (Figure 5). The results show that the best site is WTA$_5$, whereas the worst alternative is WTA$_1$.

Table 3: Decision matrix of the first expert.

	WTC$_{1.1}$	**WTC$_{1.2}$**	**WTC$_{2.1}$**	**WTC$_{2.2}$**	**WTC$_{3.1}$**	**WTC$_{3.2}$**	**WTC$_{3.3}$**	**WTC$_{4.1}$**	**WTC$_{4.2}$**	**WTC$_{5.1}$**	**WTC$_{5.2}$**	**WTC$_{5.3}$**	**WTC$_{6.1}$**	**WTC$_{6.2}$**	**WTC$_{6.3}$**
WTA$_1$	7	3	5	7	5	7	7	3	3	5	1.3	1.3	1.3	3	5
WTA$_2$	1.3	7	7	5	7	5	5	1.3	1.3	5	5	5	1.3	1.3	5
WTA$_3$	5	3	3	5	5	5	5	7	7	1.3	1.3	1.3	5	5	3
WTA$_4$	5	5	1.3	3	3	1.3	7	7	5	5	7	5	1.3	1.3	1.3
WTA$_5$	5	7	7	3	7	5	7	5	3	5	5	5	3	7	7
WTA$_6$	5	7	7	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA$_6$	5	7	5	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA$_7$	1.3	1.3	3	3	1.3	7	1.3	3	3	5	7	3	7	5	5
WTA$_8$	1.3	5	3	7	7	1.3	1.3	1.3	7	7	7	5	7	5	5
WTA$_9$	1.3	3	3	7	7	7	5	5	3	3	3	5	7	7	5
WTA$_{10}$	7	3	5	7	5	7	7	3	3	5	1.3	1.3	1.3	3	5

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Table 4: Decision matrix of the second expert.

	$WTC_{1.1}$	**$WTC_{1.2}$**	**$WTC_{2.1}$**	**$WTC_{2.2}$**	**$WTC_{3.1}$**	**$WTC_{3.2}$**	**$WTC_{3.3}$**	**$WTC_{4.1}$**	**$WTC_{4.2}$**	**$WTC_{5.1}$**	**$WTC_{5.2}$**	**$WTC_{5.3}$**	**$WTC_{6.1}$**	**$WTC_{6.2}$**	**$WTC_{6.3}$**
WTA_1	5	3	7	3	7	5	7	5	3	5	5	5	3	7	7
WTA_2	1	7	7	5	7	5	5	1.3	1.3	5	5	5	1.3	1.3	5
WTA_3	1	3	3	7	7	7	5	5	3	3	3	5	7	7	5
WTA_4	5	5	1.3	3	3	1.3	7	7	5	5	7	5	1.3	1.3	1.3
WTA_5	5	3	7	3	7	5	7	5	3	5	5	5	3	7	7
WTA_6	1	3	3	3	1.3	7	1.3	3	3	5	7	3	7	5	5
WTA_6	5	7	5	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA_7	1	5	3	3	1.3	7	1.3	3	3	5	7	3	7	5	5
WTA_8	5	7	5	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA_9	5	5	1.3	3	3	1.3	7	7	5	5	7	5	1.3	1.3	1.3
WTA_{10}	5	3	7	3	7	5	7	5	3	5	5	5	3	7	7

Table 5: Decision matrix of the third expert.

	$WTC_{1.1}$	**$WTC_{1.2}$**	**$WTC_{2.1}$**	**$WTC_{2.2}$**	**$WTC_{3.1}$**	**$WTC_{3.2}$**	**$WTC_{3.3}$**	**$WTC_{4.1}$**	**$WTC_{4.2}$**	**$WTC_{5.1}$**	**$WTC_{5.2}$**	**$WTC_{5.3}$**	**$WTC_{6.1}$**	**$WTC_{6.2}$**	**$WTC_{6.3}$**
WTA_1	5	7	5	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA_2	1.3	7	7	5	7	5	5	1.3	1.3	5	5	5	1.3	1.3	5
WTA_3	5	3	3	5	5	5	5	7	7	1.3	1.3	1.3	5	5	3
WTA_4	1.3	3	3	3	1.3	7	1.3	3	3	5	7	3	7	5	5
WTA_5	5	7	7	3	7	5	7	5	3	5	5	5	3	7	7
WTA_6	5	7	7	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA_6	1.3	3	3	7	7	7	5	5	3	3	3	5	7	7	5
WTA_7	1.3	3	3	3	1.3	7	1.3	3	3	5	7	3	7	5	5
WTA_8	5	7	7	3	7	5	7	5	3	5	5	5	3	7	7
WTA_9	5	7	7	3	7	5	3	3	3	5	7	3	3	3	1.3
WTA_{10}	5	7	5	3	7	5	3	3	3	5	7	3	3	3	1.3

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Table 6: Aggregated decision matrix.

	WTC$_{1.1}$	**WTC$_{1.2}$**	**WTC$_{2.1}$**	**WTC$_{2.2}$**	**WTC$_{3.1}$**	**WTC$_{3.2}$**	**WTC$_{3.3}$**	**WTC$_{4.1}$**	**WTC$_{4.2}$**	**WTC$_{5.1}$**	**WTC$_{5.2}$**	**WTC$_{5.3}$**	**WTC$_{6.1}$**	**WTC$_{6.2}$**	**WTC$_{6.3}$**
WTA$_1$	5.7	4.3	5.7	4.3	6.3	5.7	5.7	3.7	3.0	5.0	4.4	3.1	2.4	4.3	4.4
WTA$_2$	1.3	7.0	7.0	5.0	7.0	5.0	5.0	1.3	1.3	5.0	5.0	5.0	1.3	1.3	5.0
WTA$_3$	3.8	3.0	3.0	5.7	5.7	5.7	5.0	6.3	5.7	1.9	1.9	2.5	5.7	5.7	3.7
WTA$_4$	3.8	4.3	1.9	3.0	2.4	3.2	5.1	5.7	4.3	5.0	7.0	4.3	3.2	2.5	2.5
WTA$_5$	5.0	5.7	7.0	3.0	7.0	5.0	7.0	5.0	3.0	5.0	5.0	5.0	3.0	7.0	7.0
WTA$_6$	3.8	5.7	5.7	3.0	5.1	5.7	2.4	3.0	3.0	5.0	7.0	3.0	4.3	3.7	2.5
WTA$_6$	3.8	5.7	4.3	4.3	7.0	5.7	3.7	3.7	3.0	4.3	5.7	3.7	4.3	4.3	2.5
WTA$_7$	1.3	3.1	3.0	3.0	1.3	7.0	1.3	3.0	3.0	5.0	7.0	3.0	7.0	5.0	5.0
WTA$_8$	3.8	6.3	5.0	4.3	7.0	3.8	3.8	3.1	4.3	5.7	6.3	4.3	4.3	5.0	4.4
WTA$_9$	3.8	5.0	3.8	4.3	5.7	4.4	5.0	5.0	3.7	4.3	5.7	4.3	3.8	3.8	2.5
WTA$_{10}$	5.7	4.3	5.7	4.3	6.3	5.7	5.7	3.7	3.0	5.0	4.4	3.1	2.4	4.3	4.4

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Table 7: Beneficial and non-beneficial values.

	$WTC_{1.1}$	$WTC_{1.2}$	$WTC_{2.1}$	$WTC_{2.2}$	$WTC_{3.1}$	$WTC_{3.2}$	$WTC_{3.3}$	$WTC_{4.1}$	$WTC_{4.2}$	$WTC_{5.1}$	$WTC_{5.2}$	$WTC_{5.3}$	$WTC_{6.1}$	$WTC_{6.2}$	$WTC_{6.3}$
WTA_1	0.00	0.07	0.04	0.01	0.01	0.02	0.01	0.05	0.01	0.01	0.01	0.01	0.03	0.01	0.00
WTA_2	0.29	0.00	0.00	0.01	0.00	0.02	0.01	0.10	0.02	0.01	0.01	0.00	0.04	0.02	0.00
WTA_3	0.13	0.11	0.11	0.00	0.03	0.02	0.01	0.00	0.00	0.04	0.02	0.01	0.01	0.00	0.00
WTA_4	0.13	0.07	0.14	0.02	0.09	0.05	0.01	0.01	0.01	0.01	0.00	0.00	0.02	0.01	0.01
WTA_5	0.04	0.04	0.00	0.02	0.00	0.02	0.00	0.03	0.01	0.01	0.01	0.00	0.02	0.00	0.00
WTA_6	0.13	0.04	0.04	0.02	0.04	0.02	0.02	0.07	0.01	0.01	0.00	0.01	0.02	0.01	0.01
WTA_6	0.13	0.04	0.07	0.01	0.00	0.02	0.02	0.05	0.01	0.02	0.00	0.01	0.02	0.01	0.01
WTA_7	0.29	0.11	0.11	0.02	0.11	0.00	0.03	0.07	0.01	0.01	0.00	0.01	0.00	0.01	0.00
WTA_8	0.13	0.02	0.05	0.01	0.00	0.04	0.01	0.06	0.01	0.00	0.00	0.00	0.02	0.01	0.00
WTA_9	0.13	0.05	0.09	0.01	0.03	0.03	0.01	0.03	0.01	0.02	0.00	0.00	0.02	0.01	0.01
WTA_{10}	0.00	0.07	0.04	0.01	0.01	0.02	0.01	0.05	0.01	0.01	0.01	0.01	0.03	0.01	0.00

Table 8: Values of e_a, f_a, and R_a.

	e_a	f_a	R_a
WTA_1	0.286108	0.072576	0.130821
WTA_2	0.519441	0.289306	0.778977
WTA_3	0.487729	0.125881	0.417633
WTA_4	0.581285	0.140857	0.530814
WTA_5	0.203597	0.044169	0
WTA_6	0.422752	0.125881	0.36024
WTA_7	0.399734	0.125881	0.339909
WTA_8	0.769672	0.289306	1
WTA_9	0.366562	0.125881	0.31061

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WTA_{10}	0.442414	0.125881	0.377608

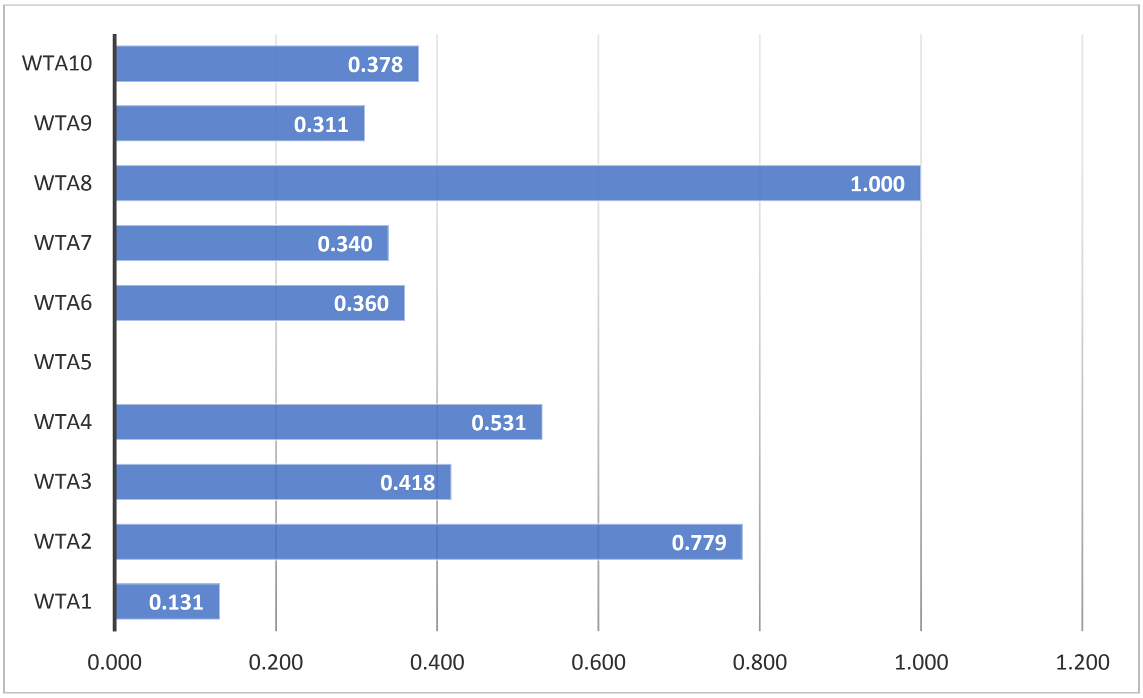

Figure 5: Site ratings of the fuzzy VIKOR method.

5. Managerial implications

The reduction of greenhouse gas emission relies mostly on emerging nations, such as Malaysia. Amidst its journey towards a low-carbon economy, Malaysia has also maximized its wind energy potential. However, offshore wind production is a relatively young field in Malaysia. The suggested assessment framework identified “policy planning” as the most influential criterion for developing onshore wind in the country. According to professionals and scholars, onshore wind may grow rapidly and competitively with other forms of energy in terms of cost if a clear legal framework and sufficient support mechanisms are put in place. A comprehensive legal framework and adequate methods of support for onshore wind power expansion have been emphasized in the discussions for achieving net-zero emissions by 2050. As part of Malaysia’s offshore wind program, support mechanisms, licensing procedures, and international standard power purchase orders must all be carefully considered.

6. Conclusion

The OWPS site problem was addressed in this study by performing a unique MCDM solution for integrating the AHP and VIKOR techniques. A case study on Malaysia was also demonstrated. Presenting the assessments in a fuzzy triangular environment allowed the experts to share their knowledge while resolving difficulties arising from their evaluation of ambiguous language words. The framework proposed in this work included sustainability considerations based on previous onshore wind power appraisal studies and expert knowledge. Wind resources, environmental impact, installation and renovation circumstances, impact on society, onshore conditions, and economic impact were also considered. First, the importance levels of the OWPS evaluation criteria were defined using AHP. Then, the OWPS sites were rated using VIKOR. Sensitivity analyses and comparisons with other methods were conducted to assess the robustness of the proposed model. Aimed at helping DMs to select the best site, the proposed model required the use of unique measurement tools. A 15-member committee was convened to gather a range of opinions. In the future, other multi-criteria evaluation techniques (ELECTRE, ANP, VIKOR, PROMETHEE, etc.) may be utilized, and their findings can be further examined. A new set of criteria may also be developed to alleviate the shortcomings of the proposed method.

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