

RESEARCH ARTICLE

# An integrated multi-criteria decision-making model for site selection of wave energy converters: a case study

Ayan Pierre Abdi<sup>1</sup>, Emel Sadikoglu<sup>2</sup>, Harun Turkoglu<sup>1</sup>, Atilla Damci<sup>1\*</sup>, Sevilay Demirkesen<sup>2</sup>, David Arditi<sup>3</sup>, V. S. Ozgur Kirca<sup>1</sup>

<sup>1</sup> Istanbul Technical University, Faculty of Civil Engineering, Civil Engineering Department, İstanbul, Türkiye

<sup>2</sup> Gebze Technical University, Faculty of Engineering, Department of Civil Engineering, Kocaeli, Türkiye

<sup>3</sup> Illinois Institute of Technology, Department of Civil, Architectural, and Environmental Engineering, Chicago, Illinois

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## Abstract

The renewable energy generation has grown significantly in recent years, primarily due to the numerous advantages it offers over traditional fossil fuel sources. In coastal areas, wave energy stands out as an important renewable energy source. However, the selection of the optimal location for wave energy converters (WECs) is a challenging task as it requires the consideration of multiple contradictory criteria. To address this challenge, this study proposes an integrated multi-criteria decision-making (MCDM) model to determine the optimal location for the installation of WECs to maximize energy generation from waves. The proposed model considers four main criteria: (1) locational aspects, (2) efficiency of the wave energy converter, (3) cost, and (4) environmental aspects. These criteria are also divided into 17 sub-criteria. The model integrates the criteria importance through intercriteria correlation (CRITIC) method to calculate the criteria weights and the complex proportional assessment (COPRAS) method to rank the alternatives. The performance of the model is demonstrated through a case study involving two locations in the Black Sea region. Utilizing this decision-making model, decision-makers can optimize their energy generation by strategically placing WECs at the most advantageous and productive locations.

## 1. Introduction

Energy plays a vital role in facilitating development and fostering economic growth. However, the process of development inevitably leads to population growth, which in turn significantly augments the energy demand. This escalating demand for energy has drawn substantial attention from international organizations, prompting them to set their objectives accordingly. For example, one of the Sustainable Development Goals of the

United Nations is to ensure global access to affordable and clean energy by 2030 [1]. The exploration and adoption of new clean energy sources is primarily motivated by the detrimental environmental effects of global warming resulting from the use of fossil fuels [2,3]. Consequently, this impels the pursuit of renewable energy sources. Renewable energy sources, which are characterized by their regenerative nature and non-depletion, not only increase energy security but also decrease

Correspondence Atilla Damci

 [damcia@itu.edu.tr](mailto:damcia@itu.edu.tr)

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greenhouse gas emissions [2]. In response to rising environmental concerns, different countries have begun to replace conventional energy sources with renewable alternatives [3,4]. Notably, the utilization of renewable energy sources has experienced a significant increase in popularity, especially over the past two decades [4].

Renewable energy sources, such as solar, wind, wave, hydropower, bioenergy, and geothermal, have gained considerable attention in recent years. Among these renewable energy sources, wave energy is a promising alternative because of its low environmental impact, high energy intensity, and predictability [5,6]. It is estimated that wave energy could potentially meet 10% of global energy demand [7]. However, the use of wave energy is limited by the availability of appropriate locations as wave energy converters (WECs) need to be located in areas with strong wave energy potential [8]. Therefore, the selection of the optimal location for WECs is one of the most critical decisions to ensure the maximum utilization of wave power potential [5,9,10].

Several factors influence the potential and utilization of wave energy, including the unpredictability of wave duration and intensity, the initial investment costs, and the impact on the ecosystem and marine life [10]. Therefore, the selection of a suitable location for WECs is a complex task that requires the consideration of multiple contradictory criteria. This necessitates careful consideration of the site selection for WECs, which can be expressed in the form of a multi-criteria decision-making (MCDM) problem [11]. Using MCDM methods for WEC site selection can help to improve the decision-making process by providing a structured approach for considering multiple criteria and determining the optimal location for a WEC. Nevertheless, it is essential to note that MCDM methods have certain deficiencies, and each method has its advantages and disadvantages. Consequently, the proper use of MCDM methods in the selection of WEC locations enables decision-makers to obtain a more comprehensive view of the available options and make a more informed decision. In previous

studies, researchers have most often utilized the Analytical Network Process (ANP), Analytical Hierarchy Process (AHP), and Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods for WEC site selection [12,13]. Although the current literature reveals that decision-making models have been developed to solve the site selection problem for WECs, further research must be conducted to better reflect the effectiveness of MCDM methods in the site selection for WECs. The objective of this study is to develop a decision-making model that can be used to determine the optimal location for WEC installation. The proposed model uses the Criteria Importance Through Intercriteria Correlation (CRITIC) and Complex Proportional Assessment (COPRAS) methods. CRITIC is used to calculate the weights of the criteria, while COPRAS is used to rank the alternatives. To demonstrate the applicability of the model to a real-life case, a case study involving two site locations in the Black Sea is carried out. The results demonstrated that the proposed model can be useful in the selection of the most appropriate location for the installation of WECs.

This paper is the revised version of the paper that has been published in the 7th International Project and Construction Management Conference (IPCMC 2022) [14]. The introduction section has been revised to provide a better understanding of the justification and objective of this research. New references have been added to improve the literature review and to address the importance and contribution of this paper to the existing body of knowledge.

## 2. Literature Review

The review of literature is structured into two sub-headings: (1) site selection criteria and (2) multi-criteria decision-making approaches in renewable energy site selection.

### 2.1. Site selection criteria

Site selection criteria for renewable energy sources differ depending on the type of energy source. The identification of these criteria is typically based on a systematic literature review and expert opinions.

Two primary categories of criteria influence the suitability of a site for renewable energy production: (1) exclusion criteria and (2) evaluation criteria. Exclusion criteria are factors that make a site unsuitable for renewable energy production, while evaluation criteria are factors that are considered when evaluating the suitability of a site. According to the comprehensive review of Shao et al. [15], the exclusion criteria for the site selection of wave energy systems are water depth, wave power density, distance from shore, distance from ports, marine protected areas, and military exercise areas, while the evaluation criteria are water depth, wave power density, wave height, distance from shore, distance from ports and shipping density.

In renewable energy research, site selection is a challenging problem. In the past, researchers have treated it as a single-objective problem, aiming to identify alternatives with high potential resources or low costs. However, a number of researchers now acknowledge site selection as an MCDM problem involving economic, technical, environmental, social, and other factors [15]. In the field of renewable energy research, MCDM is considered as an effective and efficient approach since renewable energy problems include several factors that should be taken into consideration to come up with a solution [4]. MCDM provides a structured method for incorporating multiple criteria into decision-making, which can result in more comprehensive and well-informed decisions [15].

## 2.2. Multi-criteria decision-making approaches in renewable energy site selection

MCDM methods play an important role in analyzing complex real-life problems [2]. They are valuable in terms of selecting the most appropriate alternative among several alternatives while considering several criteria. In the field of renewable energy research, MCDM methods have been extensively used for various purposes, including assessing energy policies, selecting and evaluating renewable energy resources, and optimizing the selection of sites for renewable energy installations [4].

Using an MCDM method for selecting a suitable renewable energy site involves several steps. The decision-making process begins with the selection of relevant criteria. Subsequently, the collected data must be normalized to facilitate further analysis. In studies utilizing MCDM methods for renewable energy site selection, quantitative criteria values are normalized employing techniques such as standardization, extremum processing, linear scaling, and vector normalization. On the other hand, qualitative criteria are normalized via expert scoring. In cases involving both quantitative and qualitative criteria, reclassification, linguistic variables, and fuzzy theory are employed to normalize the data. After the data has been properly normalized, criteria weighting is employed to determine the relative importance of each criterion in influencing the decision-making outcomes. Equal weighting and rank-order weighting are the approaches that can be used to determine the weight of the criteria. Most of the researchers use a rank-order weighting approach by utilizing methods, namely, AHP, ANP, linguistic quantifiers, fuzzy measures, and rank correlation analysis. Finally, several approaches can be employed to validate the MCDM process's outcomes. These include comparing the results with existing locations, comparing them with results obtained using other MCDM methods, and conducting sensitivity analysis to assess the robustness of the outcomes [15].

Wave energy site selection research has predominantly used MCDM methods, including DEMATEL, AHP, and ANP over the recent years [2, 5]. AHP is an important MCDM method that relies on the establishment of relative priorities among criteria to achieve the desired objective. This method entails decomposing the problem into smaller and consistent elements by constructing hierarchies of criteria. ANP, as the generalized form of AHP, is better suited for addressing complex decision-making problems. It includes a control hierarchy of criteria and sub-criteria, along with networks of influence. On the other hand, DEMATEL is a method that develops and evaluates structural models by considering cause-and-effect

relationships [5]. The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method aims to identify the alternative that is closest to the positive ideal solution, which has the best attribute values, and farthest from the negative ideal solution involving the worst attribute values [4].

Several researchers have incorporated various MCDM methods into their models for wave energy site selection. For example, Chakraborty [5] developed a framework to evaluate the wave energy potential of different site locations, employing MCDM methods, namely, AHP, ANP, fuzzy decision making, and DEMATEL to determine criteria weighting. Optimization methods were also employed to forecast optimal values for the criteria and criteria weighting. Ghosh et al. [10] combined MCDM methods with ANN for the site selection of wave energy projects. Wang et al. [8] proposed a fuzzy MCDM framework that integrated fuzzy ANP and TOPSIS to evaluate the selection of wave energy plant locations. In another study, Wang et al. [16] introduced an MCDM model incorporating fuzzy AHP and weighted aggregated sum product assessment (WASPAS) to evaluate potential wave energy stations. In addition, Wang et al. [17] presented a novel and comprehensive framework that incorporated Data Envelopment Analysis (DEA), Fuzzy Best-Worst Method (Fuzzy BWM), and Simulation-based Fuzzy Multi-Criteria Interactive Decision-Making method (Fuzzy TODIM) for selecting optimal wave energy project locations.

Several studies in the renewable energy site selection literature have integrated MCDM methods with Geographic Information Systems (GIS). Le et al. [18] developed a framework that combines GIS and MCDM to evaluate marine use and locate WECs. Vasileiou et al. [19] presented a combined form of GIS and AHP in a framework to identify suitable marine areas for offshore wind and energy systems. In the framework, unsuitable areas were determined using GIS data based on exclusion criteria and suitable areas were evaluated using AHP based on evaluation criteria including economic, technical and socio-political aspects.

In addition to integrated models, researchers have developed new approaches for wave energy site selection. Bolturk and Kahraman [20] presented a novel MCDM method referred to as Interval-Valued Intuitionistic Fuzzy Combinative Distance-based Assessment (IVIF-CODAS) for the selection of wave energy facility locations. Another approach that selects the appropriate site for WECs via a different point of view is proposed by Kamranzad and Hadadpour [3]. The authors developed an evaluation index based on a multi-criteria approach that considered various criteria for identifying appropriate WEC locations.

While MCDM methods have been widely utilized in renewable energy site location studies, the number of studies focusing specifically on WEC site locations is limited [8]. Therefore, there is still a need for developing models to use in selecting the optimal location for WECs. Furthermore, the literature review reveals that existing studies in this field have mostly utilized AHP, ANP, and DEMATEL methods. This finding is supported by the findings of the studies conducted by Kaya et al. [21] and Khanlari and Nazari [22]. Since different methods have their strengths and weaknesses, there is a need to develop site selection models that utilize recently developed MCDM methods, which may in turn allow researchers to evaluate the positive and negative impacts of using different MCDM methods. Therefore, the objective of this study is to propose a model for selecting WEC site locations by employing less frequently utilized MCDM methods, namely CRITIC and COPRAS.

### 3. Research Methodology

This study intends to develop a model in which an engineer can select the optimal location for WECs efficiently. The tasks that were performed to achieve this objective can be summarized as follows: (1) reviewing the literature on site selection of WECs to establish a justification for the research showing that the use of recently developed MCDM methods is mostly ignored; (2) determining the criteria based on the information obtained in the literature review; (3) calculating the weights of criteria by CRITIC method; (4) ranking the

alternatives by COPRAS method to determine the most appropriate location for WECs.

The proposed model is constructed utilizing two MCDM methods, namely CRITIC and COPRAS. In the proposed model, the CRITIC method, which was developed by Diakoulaki et al. [23] in 1995, is preferred to calculate the weights of the criteria, because the CRITIC method uses statistical measurements (i.e., standard deviation and correlation) to objectively determine the relative importance of the criteria [24]. According to Pan et al. [25], the CRITIC method outperforms the entropy method and the standard deviation method in the objective calculation of weights due to its comprehensive evaluation of not only the numerical values in the decision matrix but also their variability and correlation. In addition, the CRITIC method does not rely on subjective judgments as in the AHP and it is easier and quicker to apply than the AHP for decision-making problems involving a large number of criteria because of the exponential rise in the number of pairwise comparisons [26]. On the other hand, in the proposed model, the COPRAS method, which was developed by Zavadskas et al. [27] in 1994, is used to rank the alternatives based on their relative weights, as the COPRAS method necessitates much less computation and can demonstrate the utility degree, compared to other methods such as AHP and TOPSIS [28, 29, 30].

#### 4. The Development of the Proposed Multi-Criteria Decision-Making Model

The first step of the development of the proposed model is to determine the WEC site selection criteria. After an in-depth literature review, interviews were conducted with experts to finalize the site selection criteria for WECs. The proposed model considers four main criteria: (1) locational aspects factors ( $LF$ ), (2) efficiency of the wave energy converter factors ( $EF$ ), (3) cost factors ( $CF$ ), and (4) environmental aspects factors ( $EA$ ). For the first main criterion, locational aspects factors, there are nine sub-criteria: incident wave power ( $LF_1$ ), incident significant wave height ( $LF_2$ ), incident

wave period ( $LF_3$ ), water depth ( $LF_4$ ), maritime transportation density ( $LF_5$ ), extreme wave height ( $LF_6$ ), time variation of incident wave power ( $LF_7$ ), shape parameter of incident wave spectrum ( $LF_8$ ), and currents ( $LF_9$ ). The second main criterion, efficiency of the wave energy converter factors, has no sub-criteria. The third main criterion, cost factors, comprises of four sub-criteria: material cost ( $CF_1$ ), installation cost ( $CF_2$ ), operation and maintenance costs ( $CF_3$ ), and accessibility ( $CF_4$ ). Finally, the fourth main criterion, environmental aspects factors, consists of three sub-criteria: water quality ( $EA_1$ ), endemic species ( $EA_2$ ), and migration routes ( $EA_3$ ). A comprehensive overview of the main criteria and their corresponding sub-criteria, along with their relevant references, are presented in Table 1.

After identifying the criteria, the evaluation matrix is constructed. Using the CRITIC method, the following step involves calculating the weights of the main and sub-criteria. CRITIC method calculation steps are presented below [35]:

*Step 1:* Constructing the decision matrix  $X$  with  $n$  number of alternatives and  $m$  number of criteria.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{bmatrix} \quad (1)$$

where  $x_{ij}$  indicates the element of the decision matrix for  $i^{th}$  alternative ( $i=1,2,\dots,m$ ) in  $j^{th}$  criterion ( $j=1,2,\dots,n$ ).

*Step 2:* Determining the normalized decision matrix.

$$r_{ij} = \frac{x_{ij} - x_j^{min}}{x_j^{max} - x_j^{min}} \quad (2)$$

where  $r_{ij}$  represents a normalized value of the decision matrix for  $i^{th}$  alternative in  $j^{th}$  criterion,  $x_j^{min} = \min(x_1, x_2, \dots, x_m)$  and  $x_j^{max} = \max(x_1, x_2, \dots, x_m)$ .

*Step 3:* Computing the standard deviation ( $\sigma_j$ ) for each criterion  $j$ .

$$\sigma_j = \sqrt{\frac{x_{ij} - \bar{x}_{ij}}{n - 1}} \quad (3)$$

where  $\bar{x}_{ij}$  indicates the mean of  $j^{th}$  criterion.

Table 1. The main and sub-criteria of the wave energy site selection problem

| Main Criteria                      | Sub-criteria                                                 | References |     |     |     |      |      |      |      |      |      |      |      |      |
|------------------------------------|--------------------------------------------------------------|------------|-----|-----|-----|------|------|------|------|------|------|------|------|------|
|                                    |                                                              | [2]        | [3] | [5] | [8] | [10] | [15] | [16] | [17] | [19] | [31] | [32] | [33] | [34] |
| Locational aspects factors (LF)    | Incident wave power (LF <sub>1</sub> )                       |            | *   |     |     |      | *    |      |      |      |      |      | *    | *    |
|                                    | Incident significant wave height (LF <sub>2</sub> )          | *          | *   | *   | *   | *    | *    |      | *    |      |      | *    | *    | *    |
|                                    | Incident wave period (LF <sub>3</sub> )                      | *          |     |     |     | *    |      |      |      |      |      | *    |      | *    |
|                                    | Water depth (LF <sub>4</sub> )                               | *          |     |     | *   | *    | *    |      |      | *    |      |      | *    | *    |
|                                    | Maritime transportation density (LF <sub>5</sub> )           |            |     |     | *   | *    | *    | *    |      | *    |      |      |      |      |
|                                    | Extreme wave height (LF <sub>6</sub> )                       |            | *   |     |     |      |      |      |      |      |      |      |      | *    |
|                                    | Time variation of incident wave power (LF <sub>7</sub> )     |            | *   |     |     |      |      |      |      |      |      |      |      | *    |
|                                    | Shape parameter of incident wave spectrum (LF <sub>8</sub> ) |            | *   |     |     | *    |      |      |      |      |      |      |      | *    |
|                                    | Currents (LF <sub>9</sub> )                                  |            |     |     |     |      |      |      |      |      | *    |      |      |      |
| Efficiency of the WEC factors (EF) |                                                              | -          | *   |     |     |      |      |      |      |      |      |      |      |      |
| Cost factors (CF)                  | Material cost (CF <sub>1</sub> )                             |            |     |     |     |      |      |      | *    |      | *    |      |      |      |
|                                    | Installation cost (CF <sub>2</sub> )                         |            |     |     |     |      |      |      | *    |      | *    |      |      |      |
|                                    | Operation and maintenance costs (CF <sub>3</sub> )           |            |     |     |     |      |      |      | *    |      | *    |      |      |      |
|                                    | Accessibility (CF <sub>4</sub> )                             |            | *   |     |     |      |      |      |      | *    | *    | *    | *    | *    |
| Environmental aspects factors (EA) | Water quality (EA <sub>1</sub> )                             |            |     |     | *   | *    |      |      |      |      | *    |      |      | *    |
|                                    | Endemic species (EA <sub>2</sub> )                           |            |     |     |     |      |      |      |      |      |      |      |      | *    |
|                                    | Migration routes (EA <sub>3</sub> )                          |            |     |     |     |      |      | *    |      |      |      |      |      | *    |

Step 4: Constructing the symmetric matrix.

Step 5: Calculating the value that represents the measure of conflict ( $r_{jk}$ ).

$$r_{jk} = \frac{\sum (x_{ij} - \bar{x}_{ij})(x_{ik} - \bar{x}_{ik})}{\sqrt{(\sum (x_{ij} - \bar{x}_{ij})^2 - (\sum (x_{ik} - \bar{x}_{ik})^2)}} \quad (4)$$

where  $x_{ik}$  displays the element of the decision matrix for  $i^{th}$  alternative in  $k^{th}$  criterion and  $\bar{x}_{ik}$  indicates the mean of  $k^{th}$  criterion.

*Step 6:* Using the multiplicative aggregation formula to compute the amount of information ( $C_j$ ).

$$C_j = \sigma_j \sum_{i=1}^m (1 - r_{ij}) \quad (5)$$

*Step 7:* Determining the weights of the criteria ( $w_j$ ).

$$w_j = \frac{C_j}{\sum_{j=1}^m C_j} \quad (6)$$

The proposed model employs the calculation steps of the COPRAS method to determine the ranking of alternative WEC sites. Initially, an initial decision matrix is constructed. Then, the elements of the initial decision matrix are normalized to obtain a weighted normalized decision matrix. The sums of the weighted normalized values are then calculated for both beneficial and non-beneficial criteria. Next, the relative importance of the alternatives is determined and then the quantified utility is calculated for each alternative. Finally, the alternatives are ranked based on their quantitative utility values. COPRAS method calculation steps are presented below [28]:

*Step 1:* Constructing the initial decision matrix  $X$  with  $n$  number of alternatives and  $m$  number of criteria.

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{i1} & \cdots & x_{ij} \end{bmatrix} \quad (7)$$

where  $x_{ij}$  indicates the element of the decision matrix for  $i^{th}$  alternative ( $i=1,2,\dots,m$ ) in  $j^{th}$  criterion ( $j=1,2,\dots,n$ ).

*Step 2:* Normalization of the initial decision matrix.

$$\bar{x}_{ij} = \frac{x_{ij}}{\sum_{j=1}^n x_{ij}} \quad (8)$$

where  $\bar{x}_{ij}$  represents a normalized value of the decision matrix for  $i^{th}$  alternative in  $j^{th}$  criterion.

*Step 3:* Constructing the weighted normalized decision matrix ( $\hat{x}_{ij}$ ).

$$\hat{x}_{ij} = \bar{x}_{ij} \cdot w_j \quad (9)$$

*Step 4:* Computing the sums of weighted normalized values for beneficial ( $P_i$ ) and non-beneficial ( $R_i$ ) criteria for each alternative  $i$ .

$$P_i = \sum_{j=1}^k \hat{x}_{ij} \quad (10)$$

where  $P_i$  represents the sum of the normalized weighted values for the criteria to be maximized and  $k$  is the number of criteria required to be maximized.

$$R_i = \sum_{j=k+1}^m \hat{x}_{ij} \quad (11)$$

where  $R_i$  represents the sum of the normalized weighted values for the criteria to be minimized and  $(m-k)$  is the number of criteria required to be minimized.

*Step 5:* Calculating the relative significances of each alternative  $i$  ( $Q_i$ ).

$$Q_i = P_i + \frac{\sum_{i=1}^m R_i}{R_i (\sum_{i=1}^m \frac{1}{R_i})} \quad (12)$$

*Step 6:* Calculating the quantitative utility for each alternative  $i$  ( $U_i$ ).

$$U_i = \frac{Q_i}{Q_{max}} \times 100 \quad (13)$$

where  $Q_{max}$  represents the maximum relative significance value.

*Step 7:* Ranking the alternatives in descending order based on the quantitative utility values ( $U_i$ ).

## 5. Implementation of the Proposed Model for Wave Energy Site Selection: A Case Study

The value of the proposed model can be best demonstrated by a real-life problem. The case involves two distinct locations, namely Kefken ( $A_1$ ) at coordinates 41.25° N, 30.20° E and Karaburun ( $A_2$ ) at coordinates 41.50° N, 28.70° E, both situated in the Black Sea. The selection of two different locations in the Black Sea is justified by its substantial wave energy potential, as recognized in previous research [36]. The decision hierarchy for this case is presented in Fig. 1.

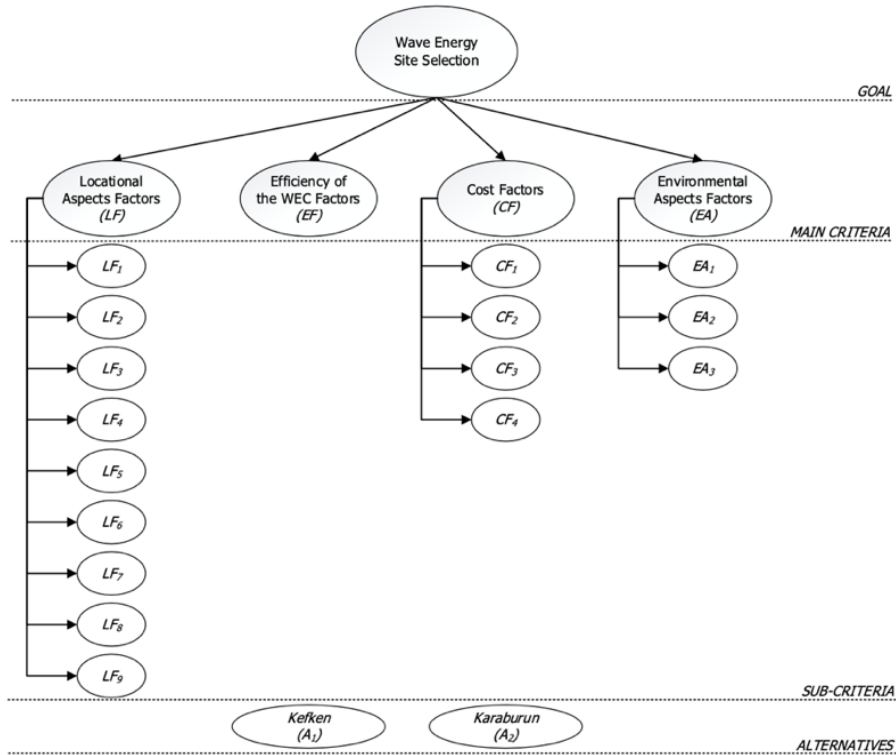


Fig. 1. The decision hierarchy of the wave energy site selection problem

After the development of the decision hierarchy of the wave energy site selection problem, the next step involves constructing the initial decision matrix to apply the CRITIC and COPRAS methods. Table 2 presents the initial decision matrix and the data utilized for evaluating the performance of the alternatives. The water quality ( $EA_1$ ) and migration routes ( $EA_3$ ) criteria are qualitative. The water quality ( $EA_1$ ) criterion is assessed on a scale ranging from 1 to 5, with 1 indicating “very bad” and 5 indicating “very good”. Similarly, the migration routes ( $EA_3$ ) criterion is evaluated on a scale from 0 to 1.5, with 0 representing “not on the migration route”, 0.5 representing “only on the migration route of birds of prey”, 1 representing “only on the migration route of marine animals”, and 1.5 representing “on the migration route of both”. In contrast, the remaining criteria are quantitative. Moreover,  $LF_5$ ,  $LF_6$ ,  $LF_7$ ,  $LF_9$ ,  $CF_1$ ,  $CF_2$ ,  $CF_3$ ,  $CF_4$ ,  $EA_1$ ,  $EA_2$ , and  $EA_3$  are non-beneficial criteria where lower values are considered favorable, while the other criteria are beneficial and aim to be

maximized. In other words, the aim is to minimize  $LF_5$ ,  $LF_6$ ,  $LF_7$ ,  $LF_9$ ,  $CF_1$ ,  $CF_2$ ,  $CF_3$ ,  $CF_4$ ,  $EA_1$ ,  $EA_2$ , and  $EA_3$  criteria, whereas maximizing the remaining criteria.

In this study, the metocean model developed by Ozhan and Abdalla [37] is employed to gather the data for the  $LF_2$ ,  $LF_3$ ,  $LF_4$ ,  $LF_6$ ,  $LF_7$ , and  $LF_8$  criteria. The  $LF_5$  criterion value is determined using Eq. 13, while Eq. 14 is utilized to assess the  $EA_3$  criterion. Furthermore, the  $LF_1$  criterion value is computed using Eq. 15 as proposed by Chakraborty [5].

$$P_{LF_5} = \sum_{i=1}^N \frac{1}{d_i} \quad (13)$$

where  $d_i$  represents the distance from any maritime facility that could potentially interfere with the installation location of the WEC, while  $N$  denotes the total number of facilities (i.e.,  $i = 1, 2, \dots, N$ ) located within a 10 km radius of the specified point.

$$P_{EA_3} = (a + b) \times 0.2 + c \times 1 + d \times 0.6 \quad (14)$$

**Table 2.** Initial decision matrix of two alternative sites for the wave energy converter

| Criterion | Measurement Unit | $A_1$ (Kefken) | $A_2$ (Karaburun) |
|-----------|------------------|----------------|-------------------|
| $LF_1$    | kW               | 3,198.69       | 4,140.54          |
| $LF_2$    | m                | 3.05           | 3.42              |
| $LF_3$    | s                | 7              | 7.2               |
| $LF_4$    | m                | 20             | 20                |
| $LF_5$    | point            | 1              | 0.17              |
| $LF_6$    | m                | 9.2            | 6.4               |
| $LF_7$    | m                | 0.84           | 1.01              |
| $LF_8$    | s                | 0.28           | 0.33              |
| $LF_9$    | cm/s             | 10             | 10                |
| $EF$      | %                | 70             | 70                |
| $CF_1$    | \$               | 3,882,403      | 4,696,916         |
| $CF_2$    | \$               | 685,130        | 828,867           |
| $CF_3$    | \$/year          | 280,204.91     | 362,711.51        |
| $CF_4$    | km               | 1.4            | 0.6               |
| $EA_1$    | 1-5 scale        | 4              | 3                 |
| $EA_2$    | point            | 30             | 15                |
| $EA_3$    | 0-0.5 scale      | 1              | 1.5               |

where  $a$ ,  $b$ ,  $c$ , and  $d$  represent the counts of plant species, animal species, marine species, and amphibians that are specific to the region under investigation, respectively.

$$P_w = \left( \frac{\rho \times g^2}{64\pi} \right) \times T_p \times H_s^2 \quad (15)$$

where  $P_w$  is the average wave power,  $H_s$  is the incident significant wave height,  $T_p$  is the peak period,  $\rho$  is the density of water, and  $g$  is the gravitational acceleration.

The weights of the criteria are determined using the CRITIC method. To compute the correlation coefficient of the criteria, the initial decision matrix is normalized as can be seen in Table 3.

The weights of the criteria are then obtained and presented in Table 4. The weight of the  $j^{th}$  criterion is denoted as  $w_j$ , while  $C_j$  represents the quantity of information contained in the  $j^{th}$  criterion.

The results obtained from the CRITIC method indicate that material cost ( $CF_1$ ), installation cost ( $CF_2$ ), operation and maintenance costs ( $CF_3$ ), time variation of incident wave power ( $LF_7$ ), and migration routes ( $EA_3$ ) hold the highest weight

among all the criteria. Material cost ( $CF_1$ ), installation cost ( $CF_2$ ), operation and maintenance costs ( $CF_3$ ), time variation of incident wave power ( $LF_7$ ), and migration routes ( $EA_3$ ) are significant criteria in selecting a site for a WEC due to their impact on the financial feasibility, operational efficiency, and environmental sustainability of the project. Material and installation costs affect the overall budget of a project, while operation and maintenance costs determine its long-term financial sustainability over time. Time variation of incident wave power assists in determining the consistency and reliability of wave energy resources, whereas migration routes guarantee minimal disruption of marine ecosystems and adherence to environmental regulations. Considering these criteria when selecting locations for WECs, it becomes possible to select a location that maximizes the financial feasibility, operational efficiency, and environmental sustainability of wave energy conversion. These findings align with the previous study conducted by Wang et al. [17], which also emphasized the significant influence of costs compared to other factors.

Table 3. Normalized decision matrix

| Criterion | $A_1$ (Kefken) | $A_2$ (Karaburun) | $\sigma_j$ |
|-----------|----------------|-------------------|------------|
| $LF_1$    | 0.000          | 1.000             | 0.707      |
| $LF_2$    | 0.000          | 1.000             | 0.707      |
| $LF_3$    | 0.000          | 1.000             | 0.707      |
| $LF_4$    | 0.000          | 0.000             | 0.000      |
| $LF_5$    | 0.000          | 1.000             | 0.707      |
| $LF_6$    | 0.000          | 1.000             | 0.707      |
| $LF_7$    | 1.000          | 0.000             | 0.707      |
| $LF_8$    | 0.000          | 1.000             | 0.707      |
| $LF_9$    | 0.000          | 0.000             | 0.000      |
| $EF$      | 0.000          | 0.000             | 0.000      |
| $CF_1$    | 1.000          | 0.000             | 0.707      |
| $CF_2$    | 1.000          | 0.000             | 0.707      |
| $CF_3$    | 1.000          | 0.000             | 0.707      |
| $CF_4$    | 0.000          | 1.000             | 0.707      |
| $EA_1$    | 0.000          | 1.000             | 0.707      |
| $EA_2$    | 0.000          | 1.000             | 0.707      |
| $EA_3$    | 1.000          | 0.000             | 0.707      |

Table 4. The weights of the criteria for the WEC site selection problem

| Criterion | Amount of information ( $C_j$ ) | Weight ( $w_j$ ) |
|-----------|---------------------------------|------------------|
| $LF_1$    | 9.192                           | 0.059            |
| $LF_2$    | 9.192                           | 0.059            |
| $LF_3$    | 9.192                           | 0.059            |
| $LF_4$    | 0.000                           | 0.000            |
| $LF_5$    | 9.192                           | 0.059            |
| $LF_6$    | 9.192                           | 0.059            |
| $LF_7$    | 14.849                          | 0.095            |
| $LF_8$    | 9.192                           | 0.059            |
| $LF_9$    | 0.000                           | 0.000            |
| $EF$      | 0.000                           | 0.000            |
| $CF_1$    | 14.849                          | 0.095            |
| $CF_2$    | 14.849                          | 0.095            |
| $CF_3$    | 14.849                          | 0.095            |
| $CF_4$    | 9.192                           | 0.059            |
| $EA_1$    | 9.192                           | 0.059            |
| $EA_2$    | 9.192                           | 0.059            |
| $EA_3$    | 14.849                          | 0.095            |

Similarly, the studies by Wang et al. [8] and Wang et al. [16] highlighted the importance of protection laws and migration routes as crucial criteria.

The criteria with the highest weights are followed by incident wave power ( $LF_1$ ), incident significant wave height ( $LF_2$ ), incident wave period

( $LF_3$ ), maritime transportation density ( $LF_5$ ), extreme wave height ( $LF_6$ ), time variation of incident wave power ( $LF_7$ ), shape parameter of incident wave spectrum ( $LF_8$ ), accessibility ( $CF_4$ ), water quality ( $EA_1$ ), and endemic species ( $EA_2$ ), which have the second-highest weights. After determining the weights of the criteria using the CRITIC method, the COPRAS method is employed to rank the potential locations for installing WECs. The initial decision matrix is constructed, as shown in Table 2, and then the elements of the initial decision matrix are normalized (Table 5) to create the weighted normalized decision matrix (Table 6).

Next, the weighted normalized values for both beneficial and non-beneficial criteria are summed to assess the relative significance of each alternative location. Subsequently, the quantitative utility for each alternative is calculated, leading to the ranking of the alternatives. The results obtained from the COPRAS method (Table 7) indicate that  $A_2$  (Karaburun) is the most appropriate alternative due to its higher utility value compared to  $A_1$  (Kefken).

The findings of this research are consistent with the results of the authors' previous study conducted

by Pierre Abdi et al. [14]. While both studies favor the same location, it is worth noting that other studies such as Polat et al. [38] have demonstrated that applying different MCDM methods for the same problem can result in different outcomes. Consequently, this study provides decision-makers the chance to employ the proposed model in different locations, enabling them to compare the results and ensure the selection of the most suitable location.

The proposed MCDM model for the site selection of WECs is advantageous for participants in the renewable energy industry. First, the proposed model allows energy companies and investors to select optimal locations which in turn can maximize energy generation and minimize costs. The model can also be used by governments and policymakers to identify appropriate sites for wave energy projects, thereby promoting sustainable energy development. Furthermore, the proposed model's criteria to minimize environmental impact ensure the selection of sites that preserve ecological balance and minimize disruption in coastal areas.

**Table 5.** Normalized decision matrix

| Criterion | $A_1$ (Kefken) | $A_2$ (Karaburun) |
|-----------|----------------|-------------------|
| $LF_1$    | 0.436          | 0.564             |
| $LF_2$    | 0.471          | 0.529             |
| $LF_3$    | 0.493          | 0.507             |
| $LF_4$    | 0.500          | 0.500             |
| $LF_5$    | 0.855          | 0.145             |
| $LF_6$    | 0.590          | 0.410             |
| $LF_7$    | 0.454          | 0.546             |
| $LF_8$    | 0.459          | 0.541             |
| $LF_9$    | 0.500          | 0.500             |
| $EF$      | 0.500          | 0.500             |
| $CF_1$    | 0.453          | 0.547             |
| $CF_2$    | 0.453          | 0.547             |
| $CF_3$    | 0.436          | 0.564             |
| $CF_4$    | 0.700          | 0.300             |
| $EA_1$    | 0.571          | 0.429             |
| $EA_2$    | 0.667          | 0.333             |
| $EA_3$    | 0.400          | 0.600             |

Table 6. Weighted normalized decision matrix

| Criterion | A <sub>1</sub> (Kefken) | A <sub>2</sub> (Karaburun) |
|-----------|-------------------------|----------------------------|
| $LF_1$    | 0.026                   | 0.033                      |
| $LF_2$    | 0.028                   | 0.031                      |
| $LF_3$    | 0.029                   | 0.030                      |
| $LF_4$    | 0.000                   | 0.000                      |
| $LF_5$    | 0.050                   | 0.009                      |
| $LF_6$    | 0.035                   | 0.024                      |
| $LF_7$    | 0.043                   | 0.052                      |
| $LF_8$    | 0.027                   | 0.032                      |
| $LF_9$    | 0.000                   | 0.000                      |
| $EF$      | 0.000                   | 0.000                      |
| $CF_1$    | 0.043                   | 0.052                      |
| $CF_2$    | 0.043                   | 0.052                      |
| $CF_3$    | 0.041                   | 0.053                      |
| $CF_4$    | 0.041                   | 0.018                      |
| $EA_1$    | 0.033                   | 0.025                      |
| $EA_2$    | 0.039                   | 0.020                      |
| $EA_3$    | 0.038                   | 0.057                      |

Table 7. Results of COPRAS method

| Alternatives      | $P_i$ | $R_i$ | $Q_i$ | Utility values ( $U_i$ ) | Ranking |
|-------------------|-------|-------|-------|--------------------------|---------|
| $A_1$ (Kefken)    | 0.109 | 0.406 | 0.428 | 88.258                   | 2       |
| $A_2$ (Karaburun) | 0.125 | 0.360 | 0.485 | 100.000                  | 1       |

## 6. Conclusions

In recent years, there has been significant growth in the generation of renewable energy. Among the renewable energy resources available in coastal areas, wave energy holds a prominent position. Wave energy is recognized as a crucial renewable energy source due to its ability to generate high power density and utilization factor while causing minimal harm to the environment compared to other renewable energy sources. However, the conversion of wave energy is affected by the location. Therefore, the careful selection of optimal site locations becomes vital to fully exploit the potential of wave power.

This study presents a proposed MCDM model for determining the optimal location for installing WECs. The proposed MCDM model employs the CRITIC method for calculating the weights of the criteria and the COPRAS method for ranking the

alternatives. The findings of the CRITIC method indicate that material cost (CF1), installation cost (CF2), operation and maintenance costs (CF3), time variation of incident wave power (LF7), and migration routes (EA3) hold the highest weight among all the criteria. To demonstrate the value of the proposed model, a case study is carried out in the Black Sea, specifically focusing on two locations: Kefken and Karaburun. The findings demonstrate that Karaburun is the most appropriate alternative, as it exhibits the highest utility degree. The results of this study are consistent with the findings of our previous research [39]. However, it should be noted that different MCDM methods may yield different outcomes for the same decision-making problem. Nevertheless, discussions with decision-makers indicate that this method is reliable and applicable for selecting wave energy sites, offering reasonable and rational results.

In addition to offering a unique perspective by using less commonly used MCDM methods, this study acknowledges certain limitations. The proposed model considers a certain number of criteria that can be increased to improve the performance of the model. It should be also noted that the results obtained are specific to the selected

locations, reflecting the nature of the research problem. Therefore, future research endeavors could focus on investigating additional criteria and different geographical locations. Such research would provide further insights into the site selection of WECs.

## Declaration

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## Author Contributions

A. P. Abdi: Formal Analysis, Writing - Original Draft; E. Sadikoglu: Writing - Original Draft, Visualization; H. Turkoglu: Methodology, Writing - Original Draft; A. Damci: Conceptualization, Writing - Review and Editing; S. Demirkesen: Conceptualization, Writing - Review and Editing; D. Ardit: Supervision, Writing - Review and Editing; V. S. O. Kirca: Conceptualization, Writing - Review and Editing.

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## Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

## Ethics Committee Permission

Not applicable.

## Conflict of Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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