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Fuzzy TOPSIS for Ranking Wave Energy Converters

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ABSTRACT
Wave energy is one of the most promising clean and renewable sources of energy, particularly in coastal countries. Both of governmental and researchers interests in this field have resulted in developing several designs for wave energy converters (WECs). Generally, a WEC is a device that converts the kinetic and potential energy associated with wave motion into a beneficial mechanical or electrical energy. Typically, those developed WECs have different working principles, cost of installation, maintenance requirements as well as different impacts on environment. Considering the selection of a particular converter to be implemented in a definite scenario, it is critical to have a model to support the decision making process. In this paper, a multi-criteria decision making model is developed for this purpose. The provided model is capable of ranking the most popular WECs such as Point Absorber Converters, Attenuator Converters, Terminator Converters, Multi-Degrees of Freedom (MDF) Converters, Floating Oscillating Water Column (OWC) Converters, Fixed OWC Converters, Floating Overtopping Converters, and Fixed Overtopping Converters. In this context, the uncertainties associated with vague data and reliance on linguistic assessment in rating alternatives with respect to different criteria, it is essential to consider using the fuzzy approach in model development. Accordingly, this research relies on employing fuzzy Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The developed fuzzy TOPSIS decision making model accounts for different assessment criteria and evaluates different design alternatives against each criterion and accordingly provides the decision maker with an overall ranking for the different considered WECs.

Keywords: *Multi-criteria decision making, TOPSIS, Renewable energy, Wave energy, Triangular fuzzy numbers.*

1. Introduction

Exploiting energy from renewable sources is increasingly gaining more attention from governments as well as researchers not only to avoid the threats associated with the excessive depletion rates of conventional energy sources, but also to cope with the environmental concerns. Among the renewable and clean alternatives for energy generation, the wave energy is considered to be one of the most unexploited promising sources. Typically, in the course of wave power extraction, no wastes or pollutants such as carbon dioxide are resulted. Besides, the availability of wave energy through all the year times gives it a merit over some other renewable sources lacking this advantage [1]. Currently, despite the variety of technologies available for harnessing wave energy, there is only a very small portion out of the tremendous energy stored in waves that is are being commercially used in electricity generation. Actually, it has been reported that wave energy has not reached the economic feasibility to compete with other alternative sources of energy [2-5].

Accordingly, researchers have focused on highlighting the issues that hinder the commercial utilization of wave energy. Among these issues is the survivability of the devices along with the challenges in operational and maintenance activities in extreme weather conditions. Another factor is related to the difficulties associated with integrating power into the electricity grids and sometimes the lack of grid facilities in the locations of wave resources [5]. In addition to technical constraints, social as well as ecological constrains have been also investigated [6]. The continuing research and innovation in the field of wave energy has resulted in wide range of technologies for wave energy conversion. Several review articles have focused on the various working principles of Wave Energy Converters (WECs) as well as the status and challenges of the implementation of such devices [2, 7-11].

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Basically, there are three principal technologies for harnessing wave energy. Several developed devices can be categorized under these main working ideas. The first one relies on oscillating bodies; in which the rise and fall or oscillatory motion of floating objects can be used to generate electricity. While, the second one is known as oscillating water column that exploits the rise and fall of water level within an enclosed chamber to compress the air above the water level to drive a turbine. However, the third one is classified as overtopping systems; in which water from waves is captured in a reservoir above the sea level, and then released it back to the sea through turbines.

Besides, wave energy converters have been classified not only based on the working principles but also based on their location with respect to the coastline and with respect to water level as well [9]. For instance, onshore devices are the ones that can be placed on the coastline. Nevertheless, the near shore devices are deployed in approximately 10-20 meters of water depth, hundreds of meters or up to some kilometers away from shore. On the other hand, the offshore devices are floating or submerged devices in deep waters and moored to the sea bed [12]. In the literature, wave energy converters are also classified according to their horizontal size and orientation. To clarify, point absorbers are categorically small relative to a typical wavelength. Nevertheless, the line absorbers are horizontally extended floating devices such that their length approach to or larger than one typical wavelength. They are further classified as a terminator and attenuator [13]. A Line absorber acts as a terminator when it is aligned along the direction of the wave crests, though it acts as an attenuator if aligned normal to the wave crests [9].

Definitely, the wide range of technologies available for wave energy converters with varied pros and cons for each provide flexibility in employing those devices. Nevertheless, the selection of the most appropriate device to be considered represents a challenge for the decision maker. Several researchers have focused only on the site selection. Multi criteria decision making models have been extensively employed in literature for site selection problems in particular countries such as in [14-20]. Others have focused on wave energy converter and location pairing. For instance, identifying the best converter-location pairs for wave energy harvesting is presented in [21] based on a set of guide lines for screening and narrowing down the converters suitable for particular locations. Further, a systematic approach employing three stages for determining wave energy farm locations and using techno-economic performance indicators for ranking and identifying the best device for a definite location is introduced in [22]. Numerical modeling has been employed in [23] to compare some wave energy converters with different working principles; in which the comparison was made only in terms of the estimated mean absorbed energy relative to some characteristics of the device. A study devoted to identify the best option for employing wave energy converter in Caspian Sea using benchmark tables is presented in [24]. Besides, the performance of some wave energy converters has been assessed in the Indian shelf sea based on multi criteria evaluation [25]. Additionally, a multi-index model based on the analytic hierarchy process has been developed to account for several assessment criteria to evaluate different WECs [26].

Definitely, with the diversity of WECs as well as the variability in their operating principles and operating conditions, several criteria are affecting the selection of the most appropriate technology to be employed. Particularly, this multi criteria decision making problem is associated with significant uncertainties. Typically, research attempting to model the uncertainties in decision analysis can be basically done through either probability theory or fuzzy set theory. The probability theory can model the stochastic nature in decision analysis, while the fuzzy set theory can successfully capture the subjectivity in human judgment. Further, it can handle scenarios associated with fuzziness and imprecision resulting from various sources such as unquantifiable information, incomplete information and non-obtainable or costly obtained information [27]. This represents a typical decision making scenario in ranking different wave energy converters alternatives with respect to different criteria.

One of the most widely employed multi criteria decision making approaches is the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). The popularity of the TOPSIS methodology can be attributed to its simplicity and computational efficiency. Further, the extension of the classical TOPSIS methodology to incorporate fuzzy logic modeling, i.e. fuzzy TOPSIS, has been also effectively adopted in several decision modeling applications [28]. The successful implementation of fuzzy TOPSIS in energy field has been reported by several researches [29-33].

In this paper, the fuzzy TOPSIS methodology has been employed to rank a set of wave energy converters with respect to a set of assessment criteria. The remainder of this paper is structured as follows: In the next section, a framework of the adopted research methodology and the background related to decision making using TOPSIS in fuzzy environment are presented. Section 3 is devoted for the model development. In Section 4, the detailed results of fuzzy TOPSIS implementation are demonstrated. Further, the conclusions are highlighted in Section 5.

2. Research Methodology

The proposed framework for employing fuzzy TOPSIS for ranking the wave energy converters is illustrated in Figure 1. In this paper, the extended TOPSIS, developed in [34], has been adopted as a methodology for modeling multi-criteria group decision making problems in a fuzzy environment using triangular fuzzy numbers (TFNs). Basically, standard TOPSIS targets to select best alternatives which simultaneously characterized by the shortest distance from the positive ideal solution and the farthest distance from the negative ideal solution. Where, the positive ideal solution is the one that maximizes the benefit criteria and minimizes the cost criteria. However, the negative ideal solution is the one that maximizes the cost criteria and minimizes the benefit criteria. To handle the vagueness in decision data and to incorporate subjective human judgments into the model, decision makers rely on interval judgment through the use of linguistic terms. Then these linguistic terms are interpreted in various forms of fuzzy numbers such as the triangular ones [34].

The employed methodology starts with surveying the literature to identify the different WECs alternatives as well as their different assessment criteria. Further, the procedure entails selecting the linguistic scale for establishing the importance weights of the WECs assessment criteria as well as the linguistic scale for rating each WEC with respect to each assessment criteria. Five point scales of linguistic variables and their corresponding TFNs are selected for this purpose as presented in Table 1. Assume the decision problem entails m alternatives A_1, A_2, …., A_m which should be assessed with respect to n *criteria* C_1,C_2, … ,C_n. The decision group involved in the decision making process that consist of K decision-makers D_1, D_2,…, D_K are asked to use these linguistic variables to individually assign weights for the criteria as well as rate each alternative with respect to each criteria. The fuzzy rating of the k^{th} decision maker for alternative A_i with respect to criterion C_j as;

$$\tilde{x}_{ij}^{k} = \left(a_{ij}^{k}, b_{ij}^{k}, c_{ij}^{k}\right), \tag{1}$$

and the weight of criterion C_j as;

$$\widetilde{w}_{j}^{k} = \left(w_{j1}^{k}, w_{j2}^{k}, w_{j3}^{k}\right). \tag{2}$$

The aggregate fuzzy rating;

$$\tilde{x}_{ij} = \left(a_{ij}, b_{ij}, c_{ij}\right) \tag{3}$$

of i^{th} alternative with respect to j^{th} criterion can be obtained, as in [35], as follows:

$$a_{ij} = \min_k\{a_{ij}^{k}\}, \tag{4}$$

$$b_{ij} = \frac{1}{K}\sum_{k=1}^{K} b_{ij}^{k}, \ \ and \tag{5}$$

$$c_{ij} = \max_k\{c_{ij}^{k}\} \ . \tag{6}$$

Similarly, the aggregate fuzzy weight;

$$\widetilde{w}_{j} = \left(w_{j1}, w_{j2}, w_{j3}\right) \tag{7}$$

for the j^{th} criterion can be obtained, as in [35], as follows:

$$w_{j1} = \min_k\{w_{j1}^{k}\}, \tag{8}$$

$$w_{j2} = \frac{1}{K}\sum_{k=1}^{K} w_{j2}^{k}, \ \ and \tag{9}$$

$$w_{j3} = \max_k\{w_{j3}^{k}\} \cdot \tag{10}$$

After calculating the aggregated weights and ratings, the combined fuzzy decision matrix can be represented as;

$$\tilde{X} = \left[\tilde{x}_{ij}\right]_{m\times n} \tag{11}$$

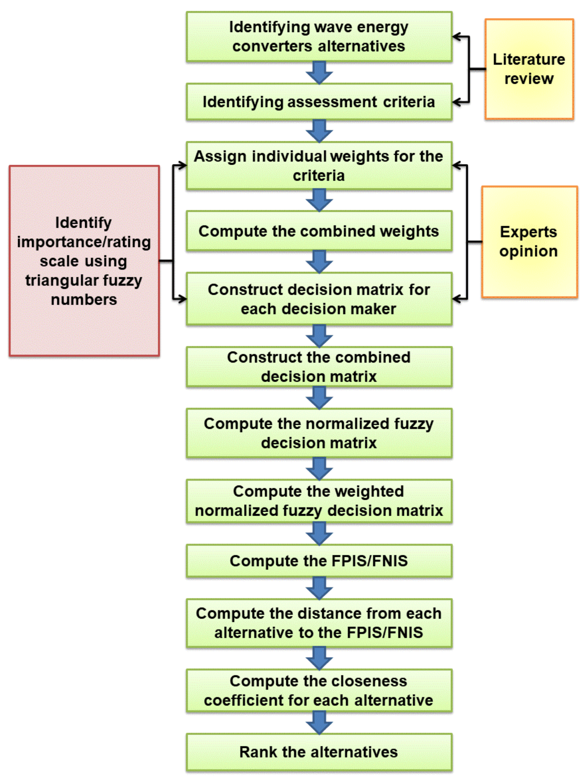

Figure 1- Framework for employing fuzzy TOPSIS

Table 1. Linguistic variables for criteria importance weights/alternative ratings

For importance weights	For rating	Fuzzy set
Extremely unimportant	Very Low	(1,1,3)
unimportant	Low	(1,3,5)
important	Average	(3,5,7)
Very important	High	(5,7,9)
Extremely important	Very High	(7,9,9)

Then, the normalized decision matrix can be computed as in [35];

$$\widetilde{R} = \left[\tilde{r}_{ij}\right]_{m\times n} \tag{12}$$

Where, for benefit criteria:

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right), and\ \ c_j^* = \max_i\{c_{ij}\} \tag{13}$$

However, for cost criteria

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{a_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{c_{ij}}\right), and\ \ a_j^- = \min_i\{a_{ij}\} \tag{14}$$

Then, the weighted normalized fuzzy decision matrix can be calculated as follows [35].

$$\widetilde{V} = \left[\tilde{v}_{ij}\right]_{m\times n} \quad , \tag{15}$$

Where $\tilde{v}_{ij} = \tilde{r}_{ij} \otimes \widetilde{w}_j$. (16)

Followed, the Fuzzy Positive Ideal Solution (FPIS) A^* and Fuzzy Negative Ideal Solution (FNIS) A^- can be calculated as:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots\ldots, \tilde{v}_n^*)\ where\ \ \tilde{v}_j^*\ \max_i\{\tilde{v}_{ij3}\}; \tag{17}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots\ldots, \tilde{v}_n^-)\ where\ \tilde{v}_j^- = \min_i\{\tilde{v}_{ij1}\}. \tag{18}$$

Further, the extended TOPSIS with TFNs that uses the vertex method to calculate the distance between two TFNs [34] will be employed. Consider the two TFNs; $\tilde{x} = (a_1, b_1, c_1)$, $\tilde{y} = (a_2, b_2, c_2)$. Then, the distance between the two TFNs as in Eq. (19);

$$d(\tilde{x}, \tilde{y}) = \sqrt{\tfrac{1}{3}\left[(a_1 - a_2)^2 + (b_1 - b_2)^2 + (c_1 - c_2)^2\right]}. \tag{19}$$

Accordingly, the distance from each alternative to the FPIS and to the FNIS will be denoted as d_i^* and d_i^-; respectively. And these are calculated as follows:

$$d_i^* = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^*), \text{ and} \tag{20}$$

$$d_i^- = \sum_{j=1}^n d(\tilde{v}_{ij}, \tilde{v}_j^-), \tag{21}$$

Then, the closeness coefficient CC_i for each alternative can be calculated as follows:

$$CC_i = \frac{d_i^-}{d_i^- + d_i^*}. \tag{22}$$

Finally, the alternatives can be ranked such that the higher the closeness coefficient, the better the alternative.

3. Model Development

The developed fuzzy TOPSIS model considers eight wave energy converters. These are: Point Absorber Converters, Attenuator Converters, Terminator Converters, Multi-Degrees of Freedom (MDF) Converters, Floating Oscillating Water Column (OWC) Converters, Fixed OWC Converters, Floating Overtopping Converters, and Fixed Overtopping Converters. In this section, a brief about each of these WECs will be introduced.

Generally, point absorbers are oscillating body converters characterized by small dimensions relative to incident wave lengths. A one body point absorber basically consists of a floating buoy of a cylindrical, spherical or a hollow cylinder. In which, the buoy oscillates due to the large wave forces exerted on it against a fixed reference normally in the sea bottom. The wave energy is extracted with a Power Take-Off (PTO) system from the relative motion between the buoy and the fixed reference. Mainly, the oscillating kinetic energy resulted from the heave, which is the dominating oscillation of the floater, is converted into electrical power. In a two-body point absorber, a submerged oscillating body is added under the buoy. Commonly, the PTO is engaged between the buoy and the submerged body so that the long PTO connections can be avoided [36].

Attenuators are basically floating oscillating body devices that are placed parallel to the predominant wave direction and it can flexibly move to ride the waves. The Pelamis device is a typical example of the attenuator wave energy converters type. It is sea snake-like offshore device that is mainly consists of a number of semi-submerged cylinders linked by hinged joints. The oscillation induced by the wave motion on separate sections of tube is harnessed by hydraulic rams at the joints which in turn drive electrical generators located inside the device [37]. However, in terminator converters the size of the buoy of is larger, and the converter is placed perpendicular to the predominant wave direction such that it can physically intercept the waves. A typical example is the ‘BioWAVE’ terminator. It is mainly installed on a fixed platform on the seabed and with the pendulum body capable of swinging back and forth with waves to generate electricity [38].

Researchers introduced the multi-degree of freedom wave energy converters to enhance the converters' capability in capturing wave energy as opposed to devices that are capable of capturing energy in only one or two directions. According to the structural characteristics of the device, some of the devices mainly rely on multi-axis series structure. In these devices, the energy can be absorbed in multiple directions, for instance, through connecting a number of floating bodies in a cross-like configuration. Others rely on parallel structure through using parallel mechanisms or parallel robot-like structure [26].

Oscillating Water Column (AWC) Converters are mainly composed of hollow chamber that is partly submerged in water. The structure might be floating or fixed such as the shore-mounted ones. The chamber has an opening under the water surface such that the waves are forced into the chamber resulting in pushing the trapped air above the water column to be compressed to rotate a turbine [39]. On the other hand, the overtopping wave energy converters consist of an inclined structure which can be either floating or fixed to the shore. This structure works as a water collector as the wave propagates. After capturing the water from waves, it is held into an above sea level reservoir. The collected water can be then released back to the sea through conventional low-head hydro turbines installed at the bottom of the reservoir [40].

In the developed model, the considered alternatives have been assessed against seven criteria as shown in Figure 2. These assessment criteria include efficiency, establishing cost, operational cost, failure rate, mean time to repair, ease of maintenance, and adverse environmental impact. In developing the fuzzy TOPSIS model, both of the efficiency and ease of maintenance are considered as benefit criteria while the remaining criteria are considered as cost criteria.

The framework presented in the previous section has been employed to develop the model. The linguistic scale and the corresponding TFNs represented in Table 1 are used to assign relative weights for the seven considered criteria as well as rating the considered eight WECs with respect to those criteria. The criteria relative importance weights and the alternative ratings are based on the assessment of three experts involved in the decision making process. A decision matrix for each expert has been individually constructed and then linguistic terms in each have been substituted by their associated FTNs. The aggregated decision matrix and the detailed results are presented in the next section.

4. Results and Discussions

According to the framework presented in Figure 1, the aggregated fuzzy importance of the criteria and the aggregated fuzzy decision matrix have been calculated and presented in Table 2. In the same table, the c_j^* values for the benefit criteria have been determined as well as the a_j^- values for the cost criteria. Then, the normalized fuzzy decision matrix has been computed as presented in Table 3. Next, the weighted normalized fuzzy decision matrix has been calculated as shown in Table 4. From this matrix, the Fuzzy Positive Ideal Solution (FPIS) A^* and Fuzzy Negative Ideal Solution (FNIS) A^- can be identified as highlighted in the last two rows in Table 4.

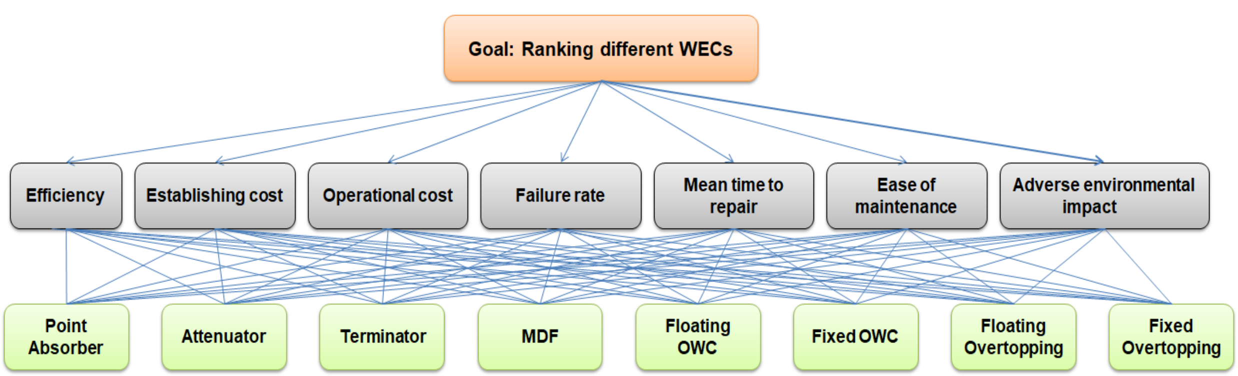

Figure 2 - The hierarchy of assessment criteria and WECs alternatives

Table 2. Aggregated fuzzy weights and aggregate fuzzy decision matrix

Weights	5.00	7.67	9.00	3.00	5.67	9.00	5.00	7.67	9.00	5.00	7.67	9.00	3.00	6.33	9.00	5.00	7.67	9.00	1.00	4.33	7.00
	Efficiency			Establishing Cost			Operational Cost			Failure Rate			Mean time to repair			Ease of maintenance			Environmental impact		
Point Absorber	3.00	5.67	9.00	3.00	5.67	9.00	3.00	5.67	9.00	3.00	7.00	9.00	3.00	5.67	9.00	3.00	5.00	7.00	5.00	7.67	9.00
Attenuator	5.00	7.00	9.00	3.00	5.00	7.00	3.00	5.00	7.00	5.00	7.67	9.00	7.00	9.00	9.00	1.00	3.00	7.00	5.00	8.33	9.00
Terminator	3.00	5.00	7.00	5.00	7.67	9.00	7.00	9.00	9.00	5.00	8.33	9.00	7.00	9.00	9.00	1.00	1.00	3.00	3.00	5.00	7.00
MDF	5.00	8.33	9.00	1.00	5.00	9.00	3.00	5.00	7.00	1.00	4.33	7.00	5.00	7.00	9.00	3.00	6.33	9.00	3.00	5.00	7.00
Floating OWC	3.00	5.00	7.00	3.00	5.00	7.00	3.00	6.33	9.00	5.00	7.67	9.00	7.00	9.00	9.00	1.00	3.00	5.00	5.00	7.00	9.00
Fixed OWC	1.00	3.00	5.00	1.00	1.67	5.00	1.00	1.00	3.00	1.00	1.00	3.00	1.00	1.00	3.00	7.00	9.00	9.00	1.00	3.67	7.00
Floating Overtopping	3.00	7.67	9.00	7.00	9.00	9.00	5.00	7.00	9.00	5.00	7.67	9.00	7.00	9.00	9.00	1.00	1.00	3.00	5.00	8.33	9.00
Fixed Overtopping	3.00	7.67	9.00	1.00	1.67	5.00	1.00	1.67	5.00	1.00	1.00	3.00	1.00	1.00	3.00	7.00	9.00	9.00	1.00	1.67	5.00
cj* for benefit criteria			9.00															9.00			
aj⁻ for cost criteria				1.00			1.00			1.00			1.00						1.00		

Table 3. Normalized fuzzy decision matrix

	Efficiency			Establishing Cost			Operational Cost			Failure Rate			Mean time to repair			Ease of maintenance			Environmental impact		
Point Absorber	0.33	0.63	1.00	0.11	0.18	0.33	0.11	0.18	0.33	0.11	0.14	0.33	0.11	0.18	0.33	0.33	0.56	0.78	0.11	0.13	0.20
Attenuator	0.56	0.78	1.00	0.14	0.20	0.33	0.14	0.20	0.33	0.11	0.13	0.20	0.11	0.11	0.14	0.11	0.33	0.78	0.11	0.12	0.20
Terminator	0.33	0.56	0.78	0.11	0.13	0.20	0.11	0.11	0.14	0.11	0.12	0.20	0.11	0.11	0.14	0.11	0.11	0.33	0.14	0.20	0.33
MDF	0.56	0.93	1.00	0.11	0.20	1.00	0.14	0.20	0.33	0.14	0.23	1.00	0.11	0.14	0.20	0.33	0.70	1.00	0.14	0.20	0.33
Floating OWC	0.33	0.56	0.78	0.14	0.20	0.33	0.11	0.16	0.33	0.11	0.13	0.20	0.11	0.11	0.14	0.11	0.33	0.56	0.11	0.14	0.20
Fixed OWC	0.11	0.33	0.56	0.20	0.60	1.00	0.33	1.00	1.00	0.33	1.00	1.00	0.33	1.00	1.00	0.78	1.00	1.00	0.14	0.27	1.00
Floating Overtopping	0.33	0.85	1.00	0.11	0.11	0.14	0.11	0.14	0.20	0.11	0.13	0.20	0.11	0.11	0.14	0.11	0.11	0.33	0.11	0.12	0.20
Fixed Overtopping	0.33	0.85	1.00	0.20	0.60	1.00	0.20	0.60	1.00	0.33	1.00	1.00	0.33	1.00	1.00	0.78	1.00	1.00	0.20	0.60	1.00

Table 4. Weighted normalized fuzzy decision matrix

	Efficiency			Establishing Cost			Operational Cost			Failure Rate			Mean time to repair			Ease of maintenance			Environmental impact		
Point Absorber	1.67	4.83	9.00	0.33	1.00	3.00	0.56	1.35	3.00	0.56	1.10	3.00	0.33	1.12	3.00	1.67	4.26	7.00	0.11	0.57	1.40
Attenuator	2.78	5.96	9.00	0.43	1.13	3.00	0.71	1.53	3.00	0.56	1.00	1.80	0.33	0.70	1.29	0.56	2.56	7.00	0.11	0.52	1.40
Terminator	1.67	4.26	7.00	0.33	0.74	1.80	0.56	0.85	1.29	0.56	0.92	1.80	0.33	0.70	1.29	0.56	0.85	3.00	0.14	0.87	2.33
MDF	2.78	7.10	9.00	0.33	1.13	9.00	0.71	1.53	3.00	0.71	1.77	9.00	0.33	0.90	1.80	1.67	5.40	9.00	0.14	0.87	2.33
Floating OWC	1.67	4.26	7.00	0.43	1.13	3.00	0.56	1.21	3.00	0.56	1.00	1.80	0.33	0.70	1.29	0.56	2.56	5.00	0.11	0.62	1.40
Fixed OWC	0.56	2.56	5.00	0.60	3.40	9.00	1.67	7.67	9.00	1.67	7.67	9.00	1.00	6.33	9.00	3.89	7.67	9.00	0.14	1.18	7.00
Floating Overtopping	1.67	6.53	9.00	0.33	0.63	1.29	0.56	1.10	1.80	0.56	1.00	1.80	0.33	0.70	1.29	0.56	0.85	3.00	0.11	0.52	1.40
Fixed Overtopping	1.67	6.53	9.00	0.60	3.40	9.00	1.00	4.60	9.00	1.67	7.67	9.00	1.00	6.33	9.00	3.89	7.67	9.00	0.20	2.60	7.00
A*	2.78	7.1	9	0.6	3.4	9	1.667	7.67	9	1.67	7.7	9	1	6.33	9	3.89	7.667	9	0.2	2.6	7
A-	0.56	2.56	5	0.333	0.63	1.3	0.556	0.85	1.29	0.56	0.9	1.8	0.33	0.7	1.286	0.56	0.852	3	0.111	0.52	1.4

The next step is to calculate the distance from each alternative to the FPIS (d_i^*) and to the FNIS (d_i^-) as illustrated in Table 5 and Table 6; respectively. Then, the closeness coefficient (CC_i) for each alternative is determined and based on it the WECs alternatives are ranked such that the higher the closeness coefficient the better the alternative as illustrated in Table 7 and Figure 3.

Table 5. Distance from each alternative to the FPIS

	Efficiency	Establishing Cost	Operational Cost	Failure Rate	Mean time to repair	Ease of maintenance	Environmental impact
Point Absorber	1.460	3.734	5.069	5.177	4.606	2.617	3.440
Attenuator	0.656	3.704	4.984	5.701	5.527	3.707	3.449
Terminator	2.105	4.434	5.977	5.733	5.527	5.584	2.874
MDF	0.000	1.318	4.984	3.449	5.220	1.835	2.874
Floating OWC	2.105	3.704	5.129	5.701	5.527	4.212	3.430
Fixed OWC	3.723	0.000	0.000	0.000	0.000	0.000	0.819
Floating Overtopping	0.720	4.735	5.664	5.701	5.527	5.584	3.449
Fixed Overtopping	0.720	0.000	1.812	0.000	0.000	0.000	0.000

Table 6. Distance from each alternative to the FNIS

	Efficiency	Establishing Cost	Operational Cost	Failure Rate	Mean time to repair	Ease of maintenance	Environmental impact
Point Absorber	2.73	1.01	1.03	0.70	1.02	3.10	0.03
Attenuator	3.29	1.03	1.07	0.05	0.00	2.51	0.00
Terminator	1.65	0.30	0.00	0.00	0.00	0.00	0.58
MDF	3.72	4.46	1.07	4.19	0.32	4.39	0.58
Floating OWC	1.65	1.03	1.01	0.05	0.00	1.52	0.06
Fiixed OWC	0.00	4.73	5.98	5.73	5.53	5.58	3.26
Floating Overtopping	3.32	0.00	0.33	0.05	0.00	0.00	0.00
Fixed Overtopping	3.32	4.73	4.96	5.73	5.53	5.58	3.45

Table 7. Closeness coefficient and ranking of WECs

	Closeness Coefficient	Rank
Point Absorber	**0.269**	**4**
Attenuator	**0.223**	**5**
Terminator	**0.073**	**8**
MDF	**0.488**	**3**
Floating OWC	**0.151**	**6**
Fixed OWC	**0.872**	**2**
Floating Overtopping	**0.105**	**7**
Fixed Overtopping	**0.929**	**1**

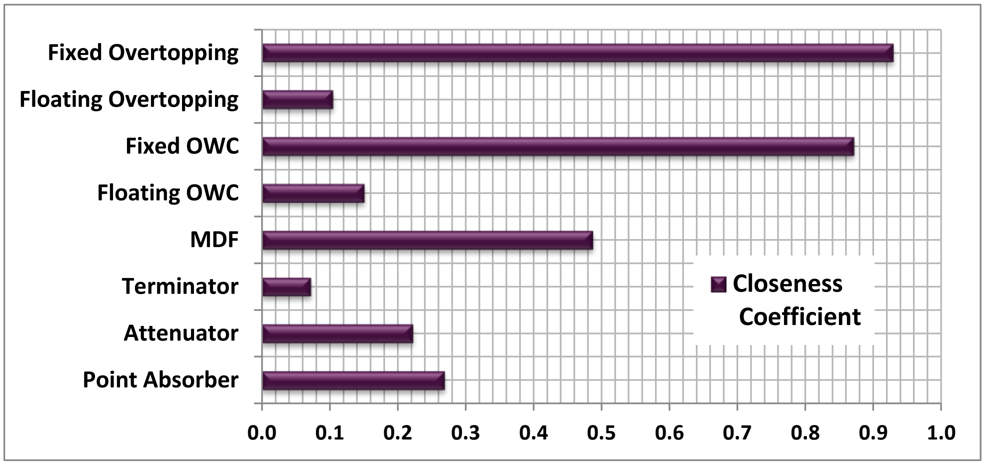

Figure 3 - Ranking of WECs Alternatives

The results reveal that the Fixed Overtopping WEC is best alternative according to the specified criteria and their assigned weights, closely followed by the Fixed Oscillating Water Column WEC. Then, the Multi-Degree of freedom is ranked as the third WEC, while the Terminator WEC has the lowest rank.

5. Conclusion

In this paper, the fuzzy TOPSIS as one of the most widely employed multi criteria decision making methodologies under fuzzy environment has been adopted for ranking different wave energy converters. In the context of selecting a wave energy converter in a real world scenario, the decision is challenging as the problem is associated with several vagueness and incomplete information. The employed fuzzy TOPSIS with triangular fuzzy numbers has been capable of coping with these difficulties. The proposed model has effectively incorporated the opinion of three decision makers and the linguistic expression was initially used to capture the decision makers' feedback. The developed model has considered eight wave energy converters alternatives; namely, Point Absorber Converters, Attenuator Converters, Terminator Converters, MDF Converters, Floating OWC Converters, Fixed OWC Converters, Floating Overtopping Converters, and Fixed Overtopping Converters. These alternatives have been assessed against seven critical selection criteria; namely, efficiency, establishing cost, operational cost, failure rate, mean time to repair, ease of maintenance, and adverse environmental impact. The results of the model implementation provided the decision maker with a ranking for the considered converters alternatives. According to the specified criteria and their assigned weights, it has been realized that the Fixed Overtopping converter is best alternative, closely followed by the Fixed OWC converter. Then, the Multi-Degree of freedom is ranked as the third WEC, while the Terminator WEC has the lowest rank. The attained results provide a general insight on the superiority of the considered alternatives; however, it is highly recommended to perform a sensitivity analysis to test the sensitivity of the obtained results against variations in the weights of the considered criteria.

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