Interval type-2 fuzzy sets based multi-criteria decision-making model for offshore wind farm development in Ireland

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Abstract

Offshore wind energy takes up an important place in Ireland's renewable generation portfolio thanks to its abundant offshore wind resource. Optimal offshore site selection and developing site-specific energy policy instruments are of key importance to the success of offshore wind energy investments. In this respect, this study aims at developing a multi-criteria decision-making (MCDM) model considering technical, economic, environmental and social criteria to assess Ireland's most promising offshore wind sites in terms of their sustainable development. An interval type-2 fuzzy sets based MCDM model is developed that integrates the score function with positive and negative solutions to achieve better results. Moreover, advanced energy economic metrics such as levelized cost of electricity with higher resolution are integrated into the decision-making process to make more precise decisions. Case studies are conducted for the five of the offshore sites in development pipeline. Results are compared to those of other state-of-the-art MCDM methods. It is found that Arklow Bank-2 is the most favorable site while Sceirde is the least site. The ranking of other sites is found to be Oriel>Dublin Array>Codling

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Energy, https://doi.org/10.1016/j.energy.2020.117317

Park. It is shown that the proposed approach is superior in terms of stability and implementation as compared to its counterparts.

Keywords: Offshore wind farm, site selection, levelized cost of electricity (LCOE), decision-making, interval type-2 fuzzy sets, renewable energy.

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1. Introduction

The development of offshore wind energy is central to Ireland's energy policy since the country benefits from an extensive offshore territory of $\sim$ 650,000 km^2, ten times larger than its land area, with an unrestricted technical potential of more than 1,000 TWh [1]. Given favourable developments in policy and infrastructure, it is projected that an offshore wind deployment of 30 GW can be achieved by 2050 [2]. As such, the country has built its national renewable energy action plan in line with the 2009 EU Renewable Energy Directive with the target of meeting 16% of its total energy and of 40% of electricity demand from renewable energy sources by 2020. More ambitious EU-wide targets will likely to come into force in coming years. This will require continued growth of the renewable energy sector including offshore wind.

The offshore renewable energy development plan (OREDP) assesses the Irish offshore territories based on the extent of available theoretical and technical resources for offshore wind, wave, and tidal [3]. This document identified that a potential of 12,000 MW from bottom-fixed offshore wind and at least 27,000 MW from offshore floating wind can be developed without likely significant adverse effects on the environment. Thus, Ireland set out an achievable scenario of offshore wind development of 4,500 MW by 2030. However, there has been only one operational offshore wind farm (OWF), rated 25 MW, commissioned in 2014 [4] even though the project was originally proposed with a total installed capacity of 520 MW. Lack of policy clarity and support are claimed to be the main means to be fallen behind the European markets even though Ireland has one of Europe's best offshore wind resource [5].

Considering Ireland's growing electricity market and the targets associated with the use of renewable energy, the need of large-scale offshore deployment is indispensable. Technical and economic feasible recommendations should therefore be provided for the policy makers and investors to help shape the Ireland's offshore wind energy outlook. As the Ireland's energy mix has already a relatively high proportion of variable generation, technical challenges such as system stability and reliability due to increased high wind power integration have been extensively addressed in [6, 7, 8]. From the point of economic perspective, [9] explored the maximum wind penetration level. A number of feasibility studies for wind energy has been also focused [10]. These studies included only onshore wind power development in Ireland. Yet, the cost structure of offshore wind farm is highly dependent on their site conditions [11] that contributes to imbalance price volatility in the energy market. Proper offshore site selection and developing regulations and site-specific supports are therefore key for the offshore wind sector that will help offshore wind auctions. As such, the industry could respond it by investing in the offshore wind energy. In this perspective, this study aims at developing a multi-criteria decision-making (MCDM) model in assessing and ranking Ireland's most promising offshore wind sites in terms of the country's sustainable development. This study contributes to representing and handling higher degrees of uncertainty in the decision process of OWF site selection based on the interval type-2 fuzzy sets (IT2FS). It includes *(i)* identifying and defining 24 criteria in terms of technical, economic, environmental and social aspects, *(ii)* integrating advanced energy economic metrics such as LCOE, DPBP, and NPV to reduce uncertainties and subjectivity associated with complex manner of interdisciplinary approaches, *(iii)* developing a new hybrid IT2FS based MCDM model that integrates the score functions with positive and negative ideal solutions, *(iv)* ranking the selected sites for a sustainable offshore wind development.

The rest of this paper is organized as follows. Section 2 presents relevant literature used in multi-criteria OWF site selection and fuzzy based decision-making models. Section 3 introduces the methodology, the site description, and the decision-making variables selected. The proposed IT2FS model is developed in Section 4. Experimental and comparison results are discussed in Section 5. Finally, Section 6 provides the concluding remarks.

2. Related Work

2.1. OWF Site Selection

MCDM has been a common practice in offshore wind energy development planning since this process incorporates many decision criteria from various perspectives in its nature [12]. This process requires a pre-selection of eligible offshore sites based on multi-criteria site selection analysis [13]. As such, the

Table 1: Overview of studies on OWF site selection analysis

Author(s)	Study Area	Main-criteria	Sub-criteria	Number of alternatives	Method/Tool	Energy Economic Considerations
[17]	Taiwan	-	-	5	GIS	Cost benefit
[22]	North Sea	-	18	Unspecified	GIS	LCOE
[23]	Greece	-	5	10	AHP and GIS	None
[19]	South Korea	5	9	8	Multi-criteria analysis	Cost benefit
[24]	Iran	6	31	4	Fuzzy ANP, DEMATEL and ELECTRE	Cost benefit
[25]	United States	-	8	3	GIS	None
[26]	Germany	-	9	Unspecified	GIS and Ordered Weighted Averaging Method	None
[20]	China	6	22	5	Intuitionistic fuzzy ELECTRE	External Resources
[14]	Europe	6	-	3	GIS	None
[21]	South Korea	4	14	Unspecified	GIS	Cost benefit
[12]	Baltic States	3	6	15	GIS	Only Cost (OPEX / CAPEX)
[15]	Greece	3	8	12	AHP and GIS	None
[27]	China	4	10	5	Fuzzy AHP	None
[11]	Turkey	3	-	3	Multi-criteria analysis	LCOE
[13]	Turkey	-	8	55	Multi-criteria analysis	None

site selection is of key importance to the success of offshore wind energy investments. Primary investigation of technical and regulatory restricted areas is first conducted to eliminate unsuitable sites [14]. Then, the site selection involves qualitative and quantitative evaluations by expert judgements in terms of several perspectives such as technical [14], economic [12], social [13], and environmental [15]. Geographical Information System (GIS) is generally used as a support tool in the analysis [16]. Cost-benefit analysis has been the most common energy economic evaluation method among the site selection studies since it accommodates the most influential technical data about the site in terms of investment decision-making [11, 12, 17, 18, 19, 20, 21]. Levelized cost of electricity (LCOE) is more effective energy economic metric which considers cost, benefits and other financial factors including the interest and inflation rates. Thus, for energy economic feasibility studies, the use of LCOE is more superior than any other simpler metrics such as cost benefit analysis related metrics. Finally, expert judgements are interpreted through analytic hierarchy process (AHP) or fuzzy based decision-making methods. While AHP was originally used to provide a preference ranking, fuzzy based improved decision tools have been later introduced to reduce uncertainties further [16], which are inherently present in decision problems. A summary of various studies applying multi-criteria site selection analysis is reported in Table 1.

2.2. Fuzzy Multi-Criteria Decision Making

Various MCDM based approaches, such as AHP, VIKOR(Vlse Kriterijumska Optimizacija Kompromisno Resenje), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Decision Making Trial and Evaluation Laboratory (DEMATEL), Preference Ranking Organization Method for

Enrichment Evaluations (PROMETHEE), ELimination Et Choix Traduisant la REalitwas (ELECTRE), have been applied in a variety of the renewable energy systems as follows: Kaya and Kahraman [28] proposed a fuzzy VIKOR and AHP for renewable energy planning. Heo et al. [29] assessed renewable energy dissemination program using fuzzy AHP. Choudhary and Shankar [30] applied the fuzzy AHP-TOPSIS to select thermal power plant locations. Ertay et al. [31] presented a fuzzy AHP for evaluation of renewable energy alternatives. San [32] used VIKOR method in the selection of a renewable energy project in Spain. Kabir and Sumi [33] investigated a suitable power substation location selection using fuzzy AHP and PROMETHEE. Yeh and Huang [34] examined the key factors considered in determining the location of wind farms using fuzzy DEMATEL and Analytic Network Process (ANP). Sengul et al. [35] employed fuzzy TOPSIS for ranking renewable energy supply systems. Sanchez-Lozano et al. [36] proposed a fuzzy MCDM for the evaluation of GIS based onshore wind farm site selection in the Southeast of Spain. Ayodele et al. [16] applied a multi-criteria GIS based model which includes interval type-2 fuzzy AHP for onshore wind farm site selection in Nigeria. Hofer et al. [37] conducted a study to evaluate wind farm sites using a spatial AHP approach in Stadteregion Aachen.

As in Table 1, while the type-1 fuzzy sets have been often applied to the offshore site selection problem, the interval type-2 fuzzy hybrid MCDM method which includes positive and negative ideal solutions, and relative assessment matrix has not been used in finding the best offshore site selection. The hybrid model can provide better representation of vagueness with simplified calculations. In addition, the interval type-2 fuzzy captures uncertainty better than type-1 fuzzy sets [38]. This reflects less uncertainty in decision-making assessments.

3. Methodology

The methodology used in the MCDM process includes 4 steps as shown in Fig. 1. Step-1 starts at determining evaluation criteria that turned out to be 3 main and 24 sub-criteria. Studies on the offshore site selection analysis typically relies on the generic data sets specified for each offshore site interested such as wind speed and wind power density [13]. In addition to the typical data set, this study provides the experts with a detailed data set to make more precise decisions. Hence, Step-2 employs a comprehensive techno-economic analysis based on a discounted cash flow model. In Step-3, the evaluations of sub-criteria and alternatives are individually carried out by experts' judgments based on the data set provided in the former step. Analyzing experts' judgements is essential as a final stage of ranking the alternatives. IT2FS is selected in this study as an effective analysis tool and alternative to conventional AHP methods. Finally, the last step includes the IT2FS based MCDM analysis for ranking the alternatives based on a new integrated model developed in Section 4.3.

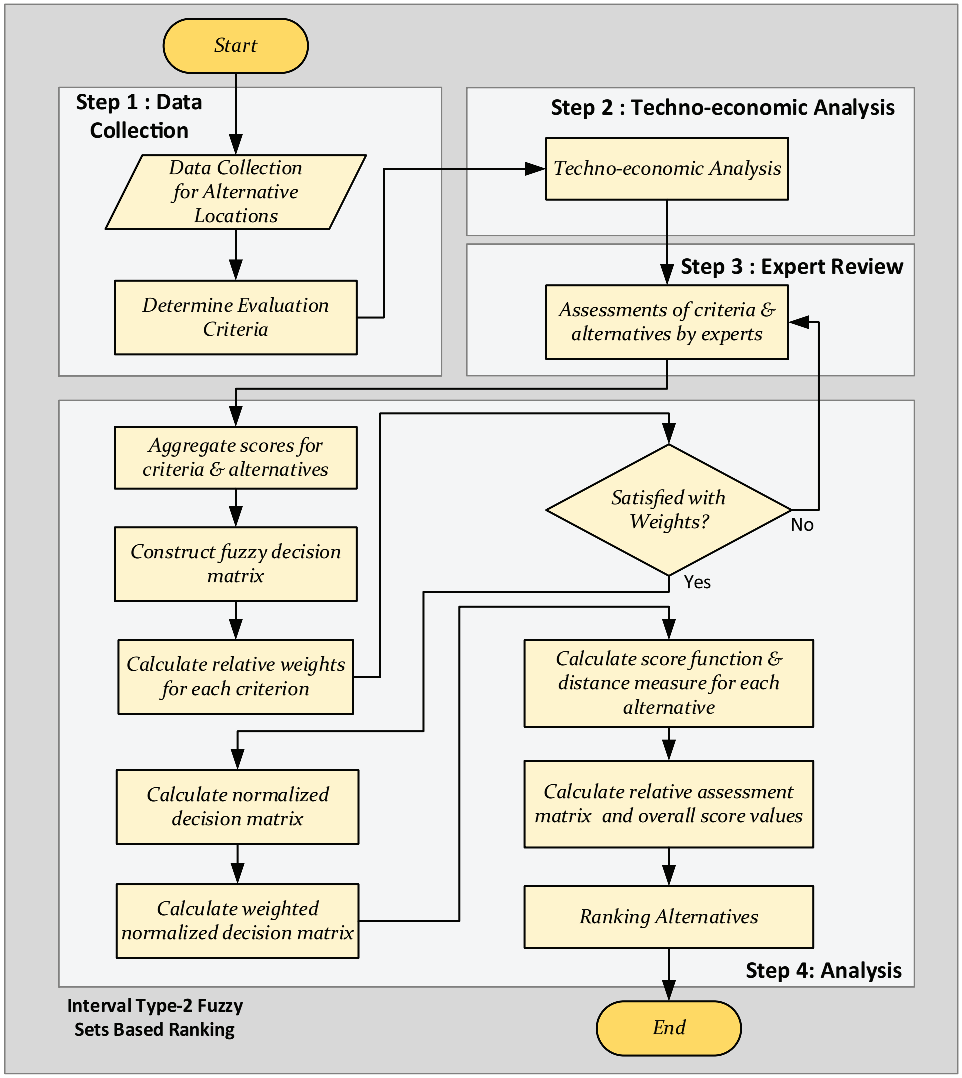


Figure 1: Flow chart of proposed methodology.

3.1. Site description

The OREDP splits the Irish offshore territory into six areas [3]. Among those, the east, the east-north and the west-north are found to be the greatest potential for bottom-fixed offshore wind development. Besides, 9 offshore wind projects with up to 5,375 MW are currently in development pipeline. In this study, 5 offshore sites out of 9 have been selected for the decision-making purpose. The offshore sites selected, Arklow Bank-2 (Alternative 1) and Codling Park (Alternative 2) are located in the east cost and have been approved for the OWF. Other alternatives selected are Dublin Array (Alternative 3) in the east cost, Oriel (Alternative 4) in the east-north, and Sceirde (Alternative5) in the west coast. Their consent applications were proposed but have not been approved yet. The selected alternatives are shown in Fig. 2.

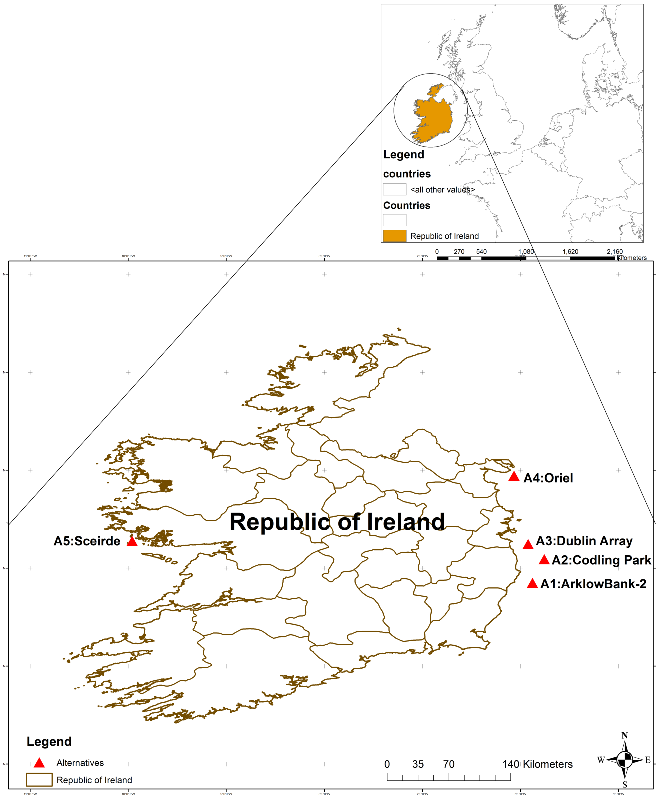


Figure 2: The alternative sites studied for OWF development in Ireland.

3.2. Determination of decision-making variables

In order to assess and rank the alternatives, three main criteria were taken into account that cover technical, economic, environmental, and social aspects. Under the main criteria, 24 sub-criteria were defined as either benefit or cost perspectives to allow qualitative and quantitative evaluations (Fig. 3).

3.2.1. Technical Evaluation:

This study performs the technical evaluation quantitatively through 8 sub-criteria and qualitatively through 2 sub-criteria. *Wind speed* and *wind power density* are used to estimate wind power output which is the main input in annual energy production (AEP) calculations. Using hourly wind speed distribution and turbine manufacturers' power curves, hourly wind speeds are converted to wind power outputs. The Siemens Wind Turbine SWT-4.0-130 was selected for the OWF projects that is one of the most popular ones among OWF developers and operators. The AEP values were estimated using an open source renewable energy resource assessment tool named Virtual Wind Farm (VWF) which uses weather data from satellite observations and the associated global reanalysis models including Modern-Era Retrospective Analysis for Research and Applications (MERRA) [39]. Besides, the Irelands Marine Atlas [40] dataset were used for validating the wind speed values from the VWF model. This study uses the mean offshore wind speed measurements at a height 100m above sea level (Fig. 6a) [40]. *Proximity to grid connection* refers to the transmission line length between OWF and the point of common coupling (PCC) that has impacts on the electrical system costs. Considering a projected OWF in each alternative, rated 100 MW, this study uses 220 kV transmission lines within the Irish power network for the grid connection and their corresponding substations are selected as PCC [41]. *Wave* and *tidal energy potentials* are other offshore renewable energy sources that can form hybrid offshore systems [15]. As operational reliability and economic viability of these offshore technologies are being proved, hybrid offshore renewable energy systems can be deployed in future [42]. However, wave and tidal energy potentials increase with wave height and currents that requires more robust foundations affecting their corresponding costs. This study uses mean annual practicable wave energy resource calculated by the Pelamis Wave Power device based on the wave forecasts (Fig. 6b) [40]. *Tidal resource potential*, on the other hand, refers to technical resource between 10 and 15 km shoreline based on spring tidal current speeds greater than and equal to 1.2 meters/second and by a water depth constraint of 20 to 80 m below mean sea level (Fig. 6c)[40]. *Water depth* and *sea bed type* determine the type of foundation used (e.g., monopile, jacket etc.) affecting the foundation costs [43]. The characteristics of water depth and sea bed are obtained from the INFOMAR's database (Fig. 6d) [44]. The characteristics of the alternatives in terms of quantitative technical evaluation are summarized in Table 2.

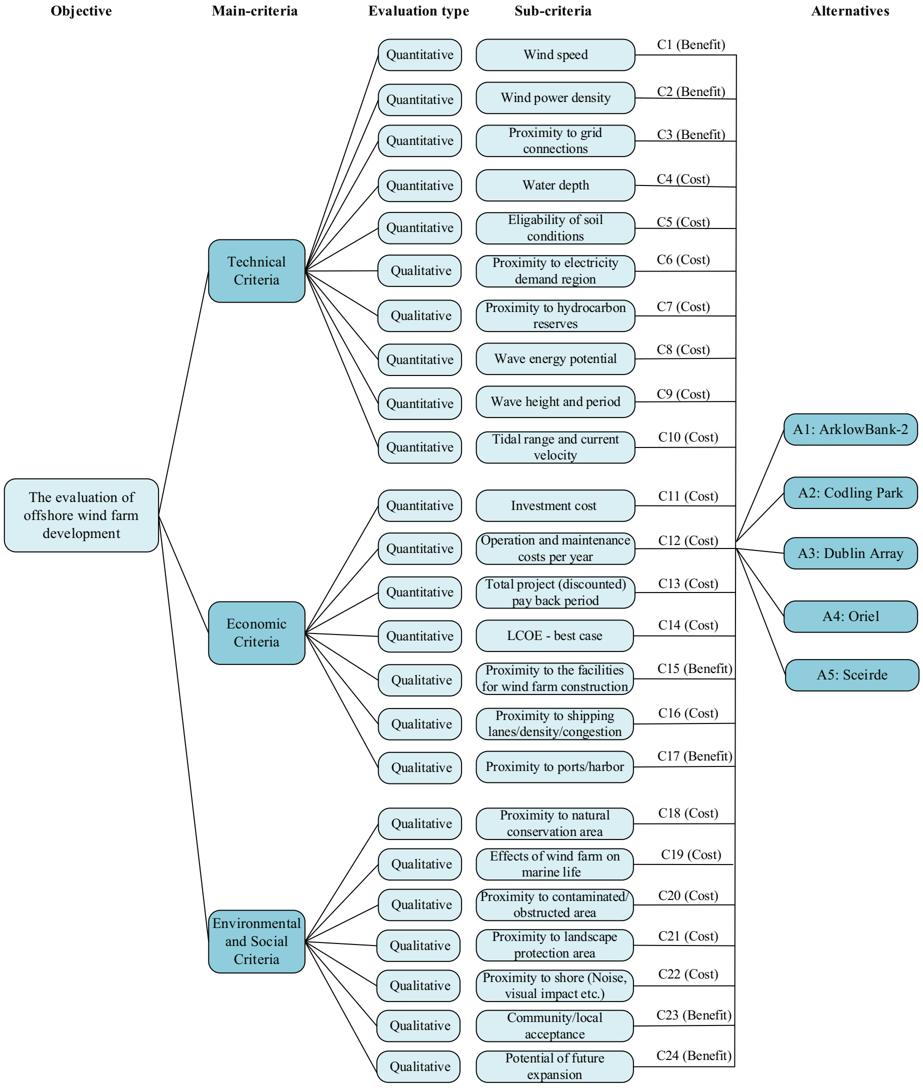


Figure 3: The designed decision hierarchy for OWF site selection problem.

Table 2: Characteristics of the alternatives for technical evaluation.

No	Criteria	Unit	Alternative sites				
			A1	A2	A3	A4	A5
C1	Mean offshore wind speed at 100m	m/s	8.8	8.9	9.0	8.6	10.0
C2	Wind power density at 100m	W/m^2	1,100	1,100	1.100	1,150	1,400
C3	Proximity to grid connections	m	15	25	16	33	74
C4	Water depth	m	39	36	31	18	70
C5	Sea bed type	NA	gravel	gravel	sand	rock	rock
C8	Mean annual wave energy potential	GWhe/km	8	8	6	6	22
C9	Mean annual wave height & period	m & s	0.75 & 5.75	0.75 & 5.75	0.50 & 5.25	0.75 & 4.75	2.0 & 7.50
C10	Tidal resource potential	NA	Moderate	Moderate	Moderate	Low	Low

The qualitative evaluation, on the other hand, included *proximity to the electricity demand region* and *proximity to hydrocarbon reserves /energy exploration. Proximity to electricity demand region* is considered from transmission line losses perspective. The line losses decreases as OWF is installed closer to the demand region which make them favorable from the transmission system operator perspective. *Proximity to hydrocarbon reserves /energy exploration* is another parameter considered which prevents potential OWFs being extended in future. This study considers the locations of current petroleum exploration and production authorized by the Minister for Communications, Energy and Natural Resources (Fig. 6e) in [40].

3.2.2. Economic Evaluation:

Economic evaluation yields the major investment indicators such as LCOE, discounted payback period (DPBP) [11]. This study performs a quantitative economic evaluation through 4 sub-criteria and qualitative evalution through 3 sub-criteria. First, an economic model is developed for projected OWFs in each alternative. Then, a detailed cash flow analysis is done to estimate the economic variables which are *total investment cost, operational and maintenance cost (OPEX), DPBP,* and *LCOE.*

It is considered that the studied OWFs have 25 wind turbines rated at 4MW each. The layout includes 5 turbines both in a row and column with 5 rotor diameter (D) and 10 D spacing, respectively as recommended in [45]. Among several electrical layout configurations, radial design is used in this study since it is the most straightforward design that requires a single cable to connect turbines in a feeder [46]. It is also assumed that the offshore substation is connected to a nearest substation of the power grid without additional onshore substation requirement. The layout is given in Fig. 4.

The total investment cost is sum of capital expenditures (CAPEX) and OPEX. CAPEX have four main cost components [43]: (i) turbines, (ii)

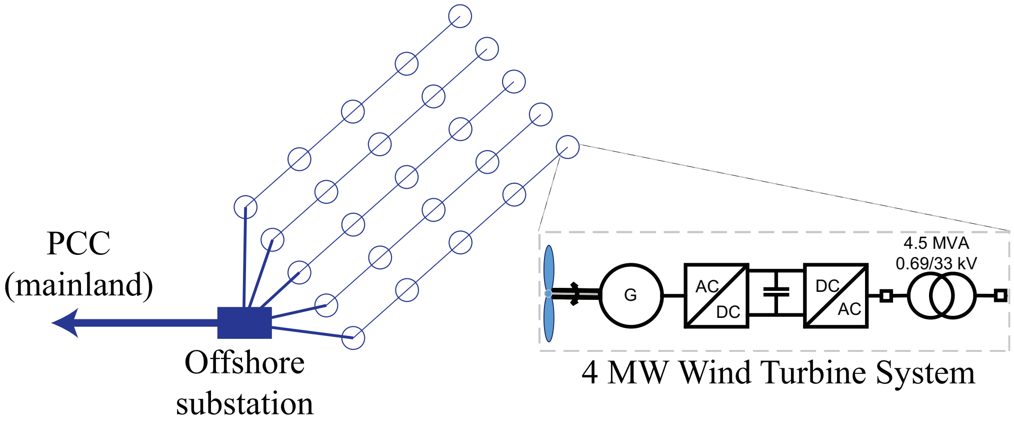


Figure 4: Electrical layout of projected OWF in selected alternative sites.

support system, (iii) electrical system, (iv) project development and management including insurance. The OPEX is considered to be 1.9% of the CAPEX to include operational, maintenance, administrative, insurance premiums and royalty costs over a lifespan of 20 years [19]. Cost models of each above mentioned components are taken from [47] that gathers various models from literature.

The $LCOE$ is a per unit cost measure which represents the net present value of the power plant over its lifetime and is calculated by:

$$LCOE = \frac{\sum_{t=0}^{T} \frac{C_{CAPEX}(t)+C_{OPEX}(t)}{(1+r)^t}}{\sum_{t=0}^{T} \frac{netAEP}{(1+r)^t}}, \tag{1}$$

where, $\forall t \in \{1..T\}$ $C_{CAPEX}(t) = 0$ and $C_{OPEX}(0) = 0$. $C_{OPEX}(t)$ is the operational expenditure for the year of t and r is discount rate. The net AEP is the estimated amount of energy yielded by the plant for one year. The net cash flow for a year is found by subtracting the net present value of expenditures from the net present value of annual cash benefits. Another economic variable studied, $DPBP$, considers the time value of money and refers to the length of time in which the cumulative profit equals to the cumulative cost. DPBP is expressed by Eq. 2 [11].

$$DPBP = \frac{ln\left(\frac{1}{1-\frac{r \cdot C_{CAPEX}}{NetCashFlow}}\right)}{ln(1+r)}. \tag{2}$$

Table 3: Estimated values of economic variables obtained from the economic model run.

No	Criteria	Unit	Alternative sites				
			A1	A2	A3	A4	A5
C11	Investment cost	Million $	309	318.1	309.3	329.3	351.1
C12	Annual operation and maintenance costs	$	293,595	302,203	293,814	312,880	333,586
C13	Discounted payback period	year	11	11	11	12	15
C14	LCOE	$/MWh	71.27	73.17	71.51	79.27	89.80

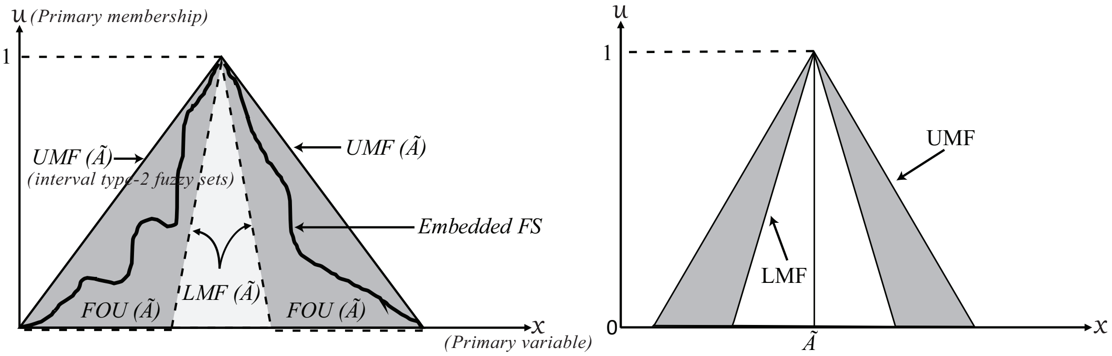
The estimated values of quantitative economic variables from the economic model are summarized in Table 3. The qualitative economic evaluation included three components: *proximity to the facilities for wind farm construction*, *proximity to ports/harbor* and *proximity to shipping lanes/density/congestion* (Fig. 6f). The first two aspects make offshore installations favorable due to their relatively less CAPEX and OPEX, while the last is not preferred as it delays the commissioning and maintenance operations and thus increases costs.

3.2.3. Environmental and Social Evaluation:

The alternatives are evaluated qualitatively through 7 sub-criteria in terms of environmental and social aspects. The environmental evaluation included *proximity to natural environment conservation area*, *effects of wind farm on marine life*(Fig. 6g), *proximity to contaminated/obstructed area*, and *proximity to landscape protection area*. These areas are specified from [40]. The natural environment conservation area refers to prime wildlife conservation areas with offshore special area conservation (Fig.6i) while the contaminated area covers baseline, geographical and temporal trend monitoring of contaminants and parameters in biota, water, and sediments in the marine environment undertaken by Ireland's Marine Institute (Fig. 6h). The social evaluation criteria included *proximity to the shore (noise, visual impact etc.)*, *community/local acceptance*, and *potential of future expansion.*

4. Preliminaries

This section provides an overview of fuzzy sets used in this study and developes an integrated model.



(a) the functions of IT2FS $\tilde{A}$ (b) lower and upper memberships.

Figure 5: IT2FS $\tilde{A}$.

4.1. Interval Type-2 Fuzzy Sets

Fuzzy sets can be broadly categorized into type-1 and type-2. The membership function (MF) of the type-1 fuzzy sets is crisp. The concept of type-2 fuzzy set is an extension version of classical fuzzy sets to capture uncertainty of grade of membership. It provides additional design degree of freedom [38]. Type-2 fuzzy set has the potential to provide better performance as compared to the type-1 [48, 38].

A simpler type-2 fuzzy set, called IT2FS is characterized by two primary MFs that are upper membership function (UMF) and lower membership function (LMF) and each element of these functions is a fuzzy set in $[0, 1]$. Fig. 5 presents an IT2FS where the blue shaded region indicates the footprint of uncertainty [38]. Some basic definitions are given as follows [38, 49]:

Definition 1. $\tilde{A}$ is a type-2 fuzzy set belonging to X universal set, and $\mu_{\tilde{A}}$ is a type-2 fuzzy MF, expressed by [50]:

$$\tilde{A} = \{(x, u), \mu_{\tilde{A}}(x, u))|\ \forall x \in X, \quad \forall u \in J_x \subseteq [0, 1], \quad 0 \leq \mu_{\tilde{A}}(x, u) \leq 1\}, \tag{3}$$

where, J_x denotes a range of $[0, 1]$.

Definition 2. Let $\mu_{\tilde{A}}$ denotes a type-2 MF defining $\tilde{A}$ type-2 fuzzy set belonging to X universal set. When all $\mu_{\tilde{A}}(x, u) = 1$, then the set $\tilde{A}$ is called to be the IT2FS. An IT2FS is regarded as a special case of $\tilde{A}$ type-2 fuzzy set and expressed as by [38]:

$$\tilde{A} = \int_{x \in X} \int_{u \in J_x} 1/(x, u), \tag{4}$$

where, $J_x \subseteq [0, 1]$.

Definition 3. The LMF and UMF of IT2FS are type-1 membership functions. Chen and Lee [51] proposed a new approach for solving fuzzy MCDM problems based on the IT2FS. According to this approach, the reference points and heights of ITF2S including LMF and UMF are used to characterize the IT2FS. For example, a trapezoidal IT2FS can be presented as $\tilde{A}_i = (\tilde{A}_i^U, \tilde{A}_i^L) = ((a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u; h_1(\tilde{A}_i^U), h_2(\tilde{A}_i^U)), (a_{i1}^l, a_{i2}^l, a_{i3}^l, a_{i4}^l; h_1(\tilde{A}_i^L), h_2(\tilde{A}_i^L))$ [49], where, $\tilde{A}_i^U$ and $\tilde{A}_i^L$ denote type-1 fuzzy sets, $a_{i1}^u, a_{i2}^u, a_{i3}^u, a_{i4}^u; a_{i1}^l, a_{i2}^l, a_{i3}^l$ and a_{i4}^l denote the reference points of trapezoidal IT2FS. $H_j(\tilde{A}_i^U)$ indicates the membership value of the element $a_{i(j+1)}^U$ in upper trapezoidal MF and $H_j(\tilde{A}_i^L)$ indicates the membership value of the element $a_{i(j+1)}^L$ in lower trapezoidal MF, while $0 \leq j \leq 1$.

The basic algebraic operations used in this study are defined as follows [49]:

Let $\tilde{C}_1$ and $\tilde{C}_2$ be two trapezoidal IT2FS numbers:
$\tilde{C}_1 = (\tilde{C}_1^U, \tilde{C}_1^L) = ((c_{11}^u, c_{12}^u, c_{13}^u, c_{14}^u; H_1(\tilde{C}_1^U), H_2(\tilde{C}_1^U)), (c_{11}^l, c_{12}^l, c_{13}^l, c_{14}^l; H_2(\tilde{C}_1^L), H_2(\tilde{C}_1^L)$
$\tilde{C}_2 = (\tilde{C}_2^U, \tilde{C}_2^L) = ((c_{21}^u, c_{22}^u, c_{23}^u, c_{24}^u; H_2(\tilde{C}_2^U), H_2(\tilde{C}_2^U)), (c_{21}^l, c_{22}^l, c_{23}^l, c_{24}^l; H_2(\tilde{C}_2^L), H_2(\tilde{C}_2^L)$

Definition 4. The addition of $\tilde{C}_1$ and $\tilde{C}_2$ trapezoidal IT2FS can be written by

$$\begin{aligned}\tilde{C}_1 \oplus \tilde{C}_2 = (\tilde{C}_1^U, \tilde{C}_1^L) \oplus (\tilde{C}_2^U, \tilde{C}_2^L) = ((&c_{11}^u + c_{21}^u, c_{12}^u + c_{22}^u, c_{13}^u + c_{23}^u, c_{14}^u + c_{24}^u;\\ &min(H_1(\tilde{A}_1^U), H_1(\tilde{A}_2^U)), min(H_2(\tilde{A}_1^U), H_2(\tilde{A}_1^U))),\\ &(c_{11}^l + c_{21}^l, c_{12}^l + c_{22}^l, c_{13}^l + c_{23}^l, a_{14}^l + c_{24}^l;\\ &min(H_1(\tilde{C}_1^L), H_1(\tilde{C}_2^L)), (H_2(\tilde{C}_1^L), H_2(\tilde{C}_2^L)))\end{aligned} \tag{5}$$

Definition 5. The subtraction of $\tilde{C}_1$ and $\tilde{C}_2$ trapezoidal IT2FS can be presented as

$$\begin{aligned}\tilde{C}_1 \ominus \tilde{C}_2 = (\tilde{C}_1^U, \tilde{C}_1^L) \ominus (\tilde{C}_2^U, \tilde{C}_2^L) = ((&c_{11}^u - c_{24}^u, c_{12}^u - c_{23}^u, c_{13}^u - c_{22}^u, c_{14}^u - c_{21}^u;\\ &min(H_1(\tilde{C}_1^U), H_1(\tilde{C}_2^U)), min(H_2(\tilde{C}_1^U), H_2(\tilde{C}_1^U))),\\ &(c_{11}^l - c_{24}^l, c_{12}^l - c_{23}^l, c_{13}^l - c_{22}^l, c_{14}^l - c_{21}^l;\\ &min(H_1(\tilde{C}_1^L), H_1(\tilde{C}_2^L)), (H_2(\tilde{C}_1^L), H_2(\tilde{C}_2^L)))\end{aligned} \tag{6}$$

Definition 6. The multiplication of $\tilde{C}_1$ and $\tilde{C}_2$ trapezoidal IT2FS can be presented as

$$\begin{aligned}\tilde{C}_1 \otimes \tilde{C}_2 =&(\tilde{C}_1^U, \tilde{C}_1^L) \otimes (\tilde{C}_2^U, \tilde{C}_2^L) = ((c_{11}^u \times c_{21}^u, c_{12}^u \times c_{22}^u, c_{13}^u \times c_{23}^u, c_{14}^u \times c_{24}^u;\\ &min(H_1(\tilde{C}_1^U), H_1(\tilde{C}_2^U)), min(H_2(\tilde{C}_1^U), H_2(\tilde{C}_2^U))),\\ &(c_{11}^l \times c_{21}^l, c_{12}^l \times c_{22}^l, c_{13}^l \times c_{23}^l, c_{14}^l \times c_{24}^l;\\ &min(H_1(\tilde{C}_1^L), H_1(\tilde{C}_2^L)), (H_2(\tilde{C}_1^L), H_2(\tilde{C}_2^L))).\end{aligned} \tag{7}$$

Definition 7. The arithmetic processes between trapezoidal IT2FS and crisp value δ are presented as follows:

$$\begin{aligned}\delta\tilde{C}_1 =&((\delta \times c_{11}^u, \delta \times c_{12}^u, \delta \times c_{13}^u, \delta \times c_{14}^u; H_1(\tilde{C}_1^U), H_2(\tilde{C}_1^U)),\\ &(\delta \times c_{11}^l, \delta \times c_{12}^l, \delta \times c_{13}^l, \delta \times c_{14}^l; H_1(\tilde{C}_1^L), H_2(\tilde{C}_1^L))).\end{aligned} \tag{8}$$

$$\begin{aligned}\frac{\tilde{C}}{\delta}_1 =&((\frac{1}{\delta} \times c_{11}^u, \frac{1}{\delta} \times c_{12}^u, \frac{1}{\delta} \times c_{13}^u, \frac{1}{\delta} \times c_{14}^u; H_1(\tilde{C}_1^U), H_2(\tilde{C}_1^U)),\\ &(\frac{1}{\delta} \times c_{11}^l, \frac{1}{\delta} \times c_{12}^l, \frac{1}{\delta} \times c_{13}^l, \frac{1}{\delta} \times c_{14}^l; H_1(\tilde{C}_1^L), H_2(\tilde{C}_1^L))),\end{aligned} \tag{9}$$

where $\delta > 1$.

Definition 8. The distance between $\tilde{C}_1$ and $\tilde{C}_2$ of trapezoidal IT2FS can be calculated as [52]

$$D(\tilde{C}_1, \tilde{C}_2) = \sqrt{\tilde{D}_1 + \tilde{D}_2}, \tag{10}$$

where, D denotes the distance of IT2FS.

$$\begin{aligned}\tilde{D}_1 =& (c_{11}^u - c_{21}^u)^2 + (c_{12}^u H_1(\tilde{C}_1^U) - c_{22}^u H_1(\tilde{C}_2^U))^2\\ &+(c_{13}^u H_2(\tilde{C}_1^U) - c_{23}^u H_2(\tilde{C}_2^U))^2 + (c_{14}^u - c_{24}^u)^2,\end{aligned} \tag{11}$$

$$\begin{aligned}\tilde{D}_2 =& (c_{11}^l - c_{21}^l)^2 + (c_{12}^l H_1(\tilde{C}_1^L) - c_{22}^l H_1(\tilde{C}_2^L))^2\\ &+(c_{13}^l H_2(\tilde{C}_1^L) - c_{23}^l H_2(\tilde{C}_2^L))^2 + (c_{14}^l - c_{24}^l)^2.\end{aligned} \tag{12}$$

4.2. IT2FS Score Function

In this section, we use a score function of IT2FS based on the concept proposed by [53] regarding the ranking value of IT2FS [54].

Definition 9. Let $\tilde{h}_i = \{\tilde{C} \in \tilde{h} \mid \tilde{C} = ((c_1^u, c_2^u, c_3^u, c_4^u; h_1(\tilde{C}_i^U), h_2(\tilde{C}_i^U)), (a_1^l, a_2^l, a_3^l, a_4^l; h_1(\tilde{C}_i^L), h_2(\tilde{C}_i^L))$ be an IT2FS. Then the score function are defined by

$$\begin{aligned} d(\tilde{h}_i) &= \frac{1}{*\tilde{h}} \sum_{\tilde{C} \in \tilde{h}} score(\tilde{C}) \\ &= \frac{1}{*\tilde{h}} \sum_{\tilde{C} \in \tilde{h}} \left[\frac{a_1^u + a_4^u}{2} + \frac{H_1(\tilde{C}_1^U) + H_1(\tilde{C}_1^U) + H_2(\tilde{C}_1^L) + H_2(\tilde{C}_1^L)}{4} \right] \\ &\quad \times \frac{a_1^u + a_2^u + a_3^u + a_4^u + a_1^l + a_2^l + a_3^l + a_4^l}{8}, \end{aligned} \tag{13}$$

where, $*(\tilde{h}_i)$ is the number of the IT2FS $\tilde{C}$ in $\tilde{h}$ and $score(\tilde{h}_i)$ is a crisp score.

4.3. Proposed Decision Model

In the proposed hybrid model, a classical fuzzy set is first extended to the IT2FS. Second, the score function with positive and negative ideal solutions is applied to achieve better results. Finally, the relative assessment matrix [55] is applied to aggregate the ranking results. The steps of the proposed approach are given in order as follows:

Step 1. Construct the fuzzy decision matrix $\tilde{X} = (x_{ij})_{m \times n}$. x_{ij} is the evaluation values of the alternatives k_i $(i = 1, 2, ..., m)$ with respect to the criteria $l_j (j = 1, 2, ..., n)$,

$$\tilde{X} = (\alpha_{ij})_{m \times n} = \begin{array}{c} \\ k_1 \\ k_2 \\ \vdots \\ k_m \end{array} \begin{array}{c} \begin{array}{cccc} l_1 & l_2 & \cdots & l_n \end{array} \\ \begin{pmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{1m} & \alpha_{2m} & \cdots & \alpha_{mn} \end{pmatrix} \end{array}, \tag{14}$$

where, m and n denote the number of alternatives and criteria, respectively.

Step 2. Determine the fuzzy weights of each criterion from each decision-maker, $(p = 1, 2, ..., q)$. Then, the average fuzzy weights are calculated as follows:

$$\tilde{W}_j = [\tilde{w}_{jq}]_{1 \times n} = \begin{array}{c} \begin{array}{cccc} \alpha_1 & \alpha_2 & \cdots & \alpha_n \end{array} \\ \begin{pmatrix} w_1, & w_2, & \cdots & w_n \end{pmatrix} \end{array}, \tag{15}$$

$$\tilde{\alpha}_{ij} = (\frac{\alpha_{ij}^{1} \oplus \alpha_{ij}^{2} \oplus \cdots \oplus \alpha_{ij}^{q}}{q}), \tag{16}$$

where, $\tilde{W}_j$ denotes fuzzy weight of j^{th} criterion that is an IT2FS $j \leq 1 \leq n$.

Step 3. Calculate the normalized decision matrix with respect to type of each criterion and the decision matrix $X = (c_{ij})_{m\times n}$ into $P = [p_{ij}]_{m\times n}$. For the *benefit* and *cost* types considered for the criteria, they are defined as follows:

$$\tilde{P} = [\tilde{p}_{ij}]_{m\times n}, \tag{17}$$

$$\tilde{p}_{ij} = \begin{cases} \alpha_{ij}/max\{\alpha_{ij}\} & \forall_i \quad \text{if } j \in Benefit \\ 1 - \alpha_{ij}/max\{\alpha_{ij}\} & \forall_i \quad \text{if } j \in Cost \end{cases}, \tag{18}$$

where, $\tilde{r}_{ij}$ shows normalized values, which are obtained from α_{ij}.

Step 4. Determine the fuzzy weighted normalized decision matrix. it is defined by

$$\tilde{V} = [\tilde{v}_{ij}]_{m\times n} \quad \text{and} \quad \tilde{v}_{ij} = \tilde{w}_{ij} \otimes \tilde{p}_{ij}, \tag{19}$$

where, $\tilde{v}_{ij}$ denotes the weighted normalized IT2FS.

Step 5. Calculate the score function of the overall IT2FS for each alternative in terms of criteria as follow:

$$d(\tilde{h}_{ij}) = \frac{1}{*\tilde{h}} \sum_{\tilde{C}\in\tilde{h}} \left[\frac{a_1^u + a_4^u}{2} + \frac{H_1(\tilde{C}_1^U) + H_1(\tilde{C}_1^U) + H_2(\tilde{C}_1^L) + H_2(\tilde{C}_1^L)}{4} \right] \times \frac{a_1^u + a_2^u + a_3^u + a_4^u + a_1^l + a_2^l + a_3^l + a_4^l}{8} . \tag{20}$$

Step 6. Calculate the distances of each alternative from positive-ideal and negative-ideal solutions, that are

$$d_j^* = max\{d_{ij}\} \quad \text{and} \quad \tilde{d_j^-} = min\{d_{ij}\}, \tag{21}$$

where, d_j^* and d_j^- denote max and min values of the score function for each criteria.

Then, euclidean (Δ_i^*) and hamming distances (Δ_i^-) are calculated by using the positive and negative-ideal solutions as follows [56]:

$$\Delta_i^* = \sqrt{\frac{1}{2}\sum_{j=1}^{n}(d_{ij} - d_j^*)^2} \quad \text{and} \quad \Delta_i^- = |\frac{1}{2}\sum_{j=1}^{n}(d_{ij} - d_j^-)^2|. \tag{22}$$

Step 7. Obtain the relative assessment matrix (θ) that is [55]:

$$\theta = [\tilde{v}_{it}]_{m\times m} \quad \text{and} \quad \rho_{it} = (\Delta_i^* - \Delta_t^*) + (\lambda(\Delta_i^* - \Delta_t^*) \times (\Delta_i^- - \Delta_t^-)), \quad (23)$$

where, $t \in \{i = 1, 2, \ldots, m\}$ and λ denotes a threshold function that can be defined by

$$\lambda(\alpha) = \begin{cases} 1 & \text{if } |x| \geq \beta \\ 0 & \text{if } |x| < \beta \end{cases} \quad (24)$$

where, β is the threshold parameter of λ function, which can be set by decision makers. The degree of closeness of euclidean distance is determined by a β.

Step 8. Determine the overall score values of each alternative as follow:

$$OS_i = \sum_{t=1}^{m} \rho_{it}, \quad (25)$$

Step 9. Finally, the alternatives are ranked according to the decreasing order of OS_i. The highest score shows the most desirable alternative.

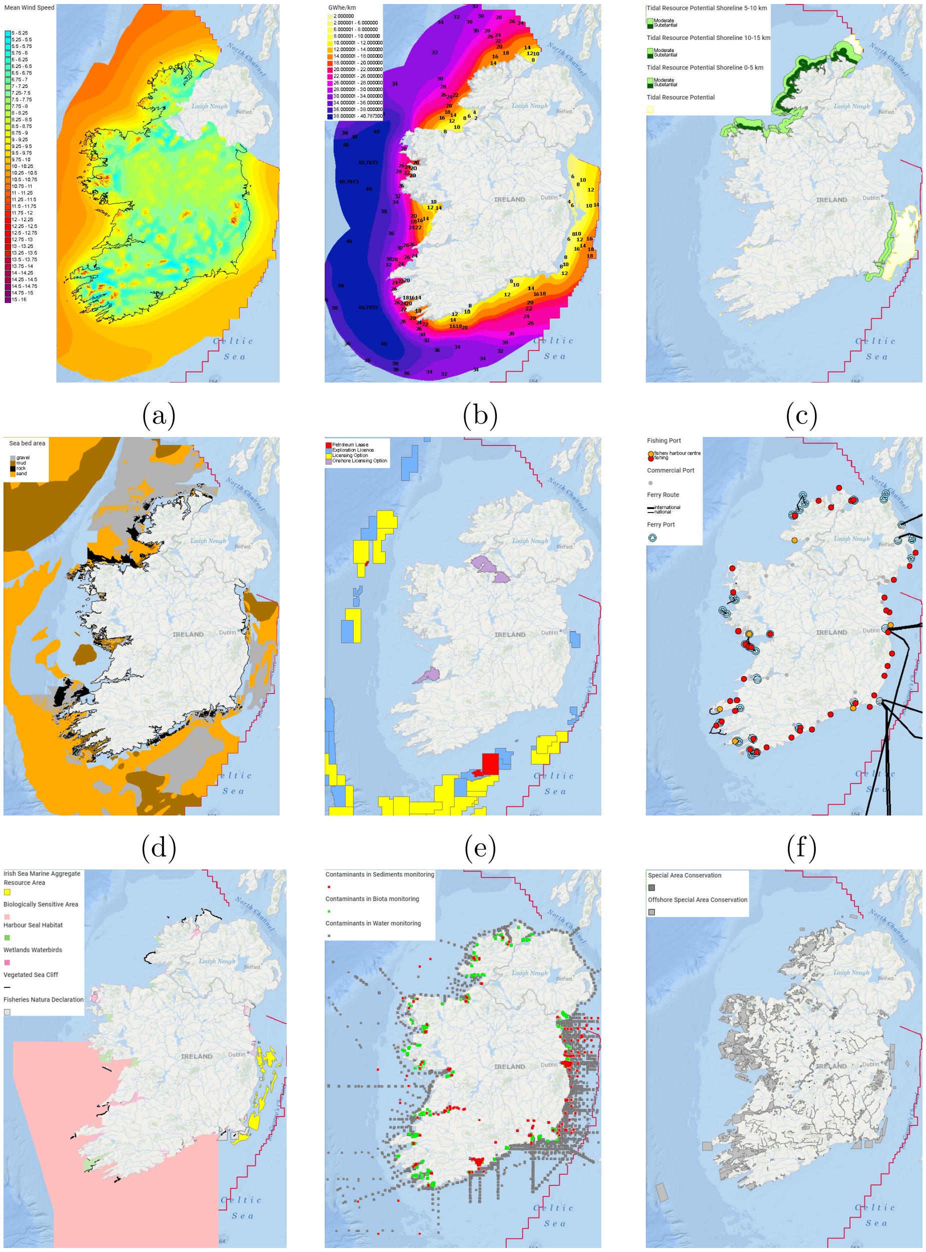
5. Experimental Results

The alternatives are evaluated independently by a set of decision makers. The expertise of the decision makers includes offshore wind energy, energy economics, project management, techno and socio-economics, and business modelling. Pairwise evaluations of criterion and alternatives are not carried out in this study. Instead, each criterion and alternative are individually evaluated using linguistic variables. Seven linguistic terms are used for rating purpose that are *very low (VL), low (L), medium low (ML), medium (M), medium high (MH), high (H)*, and *very high (VH)*. The experts are supported with both available relevant data and outputs of the economic model run. Some of the technical, environmental and social data interpreted by the experts are given in Fig. 6. The results regarding to the experts' evaluations and hence IT2FS analysis are given in the following.

5.1. Alternatives and Criteria Evaluations

Fig. 7 illustrates the upper and lower values of the linguistic variables in sub-criteria and alternative evaluations. The linguistic assessments and ratings of the criteria and alternatives are presented in Table S1 and Table S2, respectively.

The linguistic ratings are then converted to fuzzy numbers to form an aggregated fuzzy decision matrix using Eq. (14). The fuzzy decision matrix is, thus, obtained as given in Table S3. The weights of the criteria are calculated using Eq. 15 through Eq. 16 and presented in Table 4. According to the table, wind speed, DPBP, wind power density, LCOE, and the proximity to shore are found to be the most important siting criteria.

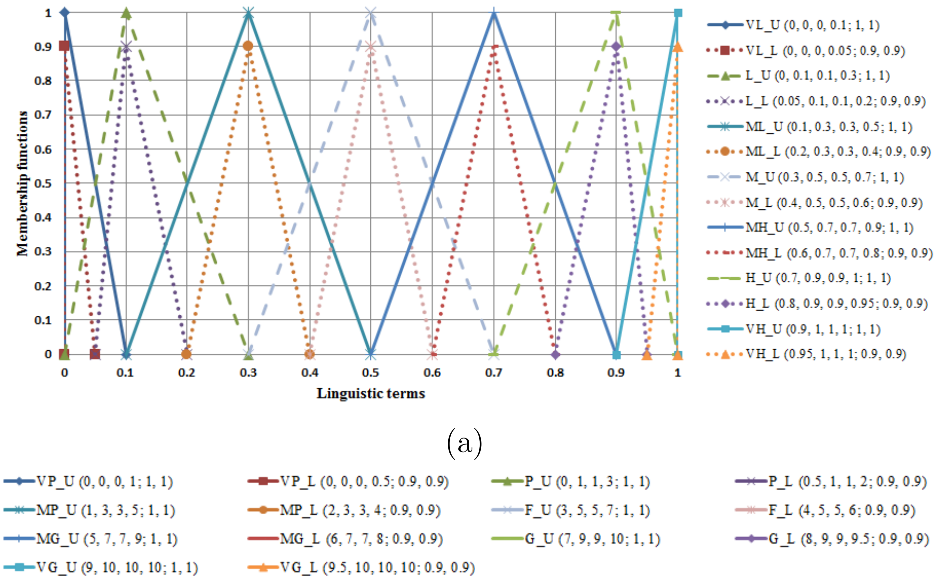


(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 6: GIS based map layers for evaluation criteria, a) wind speed at 100 m, b) practicable wave energy potential, b) technical tidal energy potential, d) sea bed properties, e) authorized energy exploration areas, f) ports and shipping lanes, g) marine life, h) marine contaminants, i) offshore conservation areas. Data accessed through Ireland's Marine Atlas under the related themes in [40]



(a)

(b)

Figure 7: Linguistic variables for the ratings of (a) the criteria, (b) alternatives, their representations ordered by IT2FS numbers.

The normalized fuzzy decision matrix is constructed by using Eq. 17 through Eq. 18 for the five alternatives. The corresponding results are presented in Table S4.

To calculate the fuzzy weighted decision matrix for each criteria with respect to alternatives, p_{ij} values in Table S3 and w_j values in Table 4 are utilized in Eq. 19. Table S5 presents the fuzzy weighted normalized values. Then, the score function of criteria in terms of alternatives is calculated by Eq. 20. The score function values are given in Table 5. Next, to calculate the distance matrices, the positive and negative solutions are determined by Eq. 21 as given in Table 5. Afterwards, using Eq. 22, the euclidean and hamming distances of each alternative from the positive and negative solutions are calculated that are provided in Table 6.

Pairwise comparison matrix and threshold function with respect to the euclidean distance are obtained as given in Table 7. In this study, the threshold value was determined to be ($\beta = 0.06$) with the help of parameter analysis. The relative assessment matrix is calculated based on Tables 6 and 7 and using Eq. 23 through Eq. 24. The results are presented in Table 8.

Table 4: The importance fuzzy weights of criteria.

Criteria	$\tilde{A}_i^U$						$\tilde{A}_i^L$					
	a_{i1}^u	a_{i2}^u	a_{i3}^u	a_{i4}^u	$h_1(\tilde{A}_i^U)$	$h_2(\tilde{A}_i^U)$	a_{i1}^l	a_{i2}^l	a_{i3}^l	a_{i4}^l	$h_1(\tilde{A}_i^L)$	$h_2(\tilde{A}_i^L)$
C1	0.90	1.00	1.00	1.00	1.0	1.0	0.95	1.00	1.00	1.00	0.90	0.90
C2	0.85	0.98	0.98	1.00	1.0	1.0	0.91	0.98	0.98	0.99	0.90	0.90
C3	0.38	0.55	0.55	0.73	1.0	1.0	0.46	0.55	0.55	0.64	0.90	0.90
C4	0.40	0.60	0.60	0.78	1.0	1.0	0.50	0.60	0.60	0.69	0.90	0.90
C5	0.35	0.55	0.55	0.75	1.0	1.0	0.45	0.55	0.55	0.65	0.90	0.90
C6	0.53	0.70	0.70	0.83	1.0	1.0	0.61	0.70	0.70	0.76	0.90	0.90
C7	0.48	0.65	0.65	0.80	1.0	1.0	0.56	0.65	0.65	0.73	0.90	0.90
C8	0.40	0.58	0.58	0.73	1.0	1.0	0.49	0.58	0.58	0.65	0.90	0.90
C9	0.45	0.63	0.63	0.78	1.0	1.0	0.54	0.63	0.63	0.70	0.90	0.90
C10	0.45	0.63	0.63	0.78	1.0	1.0	0.54	0.63	0.63	0.70	0.90	0.90
C11	0.65	0.80	0.80	0.88	1.0	1.0	0.73	0.80	0.80	0.84	0.90	0.90
C12	0.50	0.70	0.70	0.85	1.0	1.0	0.60	0.70	0.70	0.78	0.90	0.90
C13	0.90	1.00	1.00	1.00	1.0	1.0	0.95	1.00	1.00	1.00	0.90	0.90
C14	0.85	0.98	0.98	1.00	1.0	1.0	0.91	0.98	0.98	0.99	0.90	0.90
C15	0.23	0.40	0.40	0.60	1.0	1.0	0.31	0.40	0.40	0.50	0.90	0.90
C16	0.55	0.73	0.73	0.88	1.0	1.0	0.64	0.73	0.73	0.80	0.90	0.90
C17	0.28	0.45	0.45	0.63	1.0	1.0	0.36	0.45	0.45	0.54	0.90	0.90
C18	0.40	0.60	0.60	0.78	1.0	1.0	0.50	0.60	0.60	0.69	0.90	0.90
C19	0.65	0.83	0.83	0.95	1.0	1.0	0.74	0.83	0.83	0.89	0.90	0.90
C20	0.28	0.45	0.45	0.65	1.0	1.0	0.36	0.45	0.45	0.55	0.90	0.90
C21	0.40	0.60	0.60	0.78	1.0	1.0	0.50	0.60	0.60	0.69	0.90	0.90
C22	0.38	0.55	0.55	0.73	1.0	1.0	0.46	0.55	0.55	0.64	0.90	0.90
C23	0.30	0.50	0.50	0.70	1.0	1.0	0.40	0.50	0.50	0.60	0.90	0.90
C24	0.75	0.93	0.93	1.00	1.0	1.0	0.84	0.93	0.93	0.96	0.90	0.90

Table 5: The score function of IT2FS, PIS and NIS.

Criteria	A1	A2	A3	A4	A5	PIS	NIS
C1	1.717	1.596	1.596	1.527	1.864	1.864	1.527
C2	1.654	1.539	1.427	1.346	1.793	1.793	1.346
C3	0.825	0.682	0.800	0.587	0.207	0.825	0.207
C4	0.168	0.230	0.049	0.000	0.049	0.230	0.000
C5	0.075	0.050	0.158	0.229	0.000	0.229	0.000
C6	1.122	1.122	1.122	0.878	0.428	1.122	0.428
C7	0.185	0.000	0.000	0.716	0.493	0.716	0.000
C8	0.478	0.586	0.636	0.667	0.000	0.667	0.000
C9	0.485	0.713	0.649	0.477	0.000	0.713	0.000
C10	0.000	0.000	0.074	0.522	0.588	0.588	0.000
C11	0.624	0.291	0.551	0.101	0.000	0.624	0.000
C12	0.518	0.293	0.518	0.120	0.000	0.518	0.000
C13	0.000	0.000	0.000	0.268	0.902	0.902	0.000
C14	0.877	0.586	0.877	0.201	0.000	0.877	0.000
C15	0.536	0.551	0.551	0.391	0.156	0.551	0.156
C16	0.089	0.000	0.000	0.603	0.753	0.753	0.000
C17	0.555	0.630	0.630	0.494	0.274	0.630	0.274
C18	0.590	0.654	0.475	0.295	0.000	0.654	0.000
C19	0.921	0.662	0.468	0.354	0.000	0.921	0.000
C20	0.106	0.067	0.067	0.000	0.137	0.137	0.000
C21	0.108	0.127	0.000	0.197	0.365	0.365	0.000
C22	0.118	0.039	0.000	0.217	0.553	0.553	0.000
C23	0.362	0.362	0.343	0.700	0.725	0.725	0.343
C24	0.880	0.773	0.773	1.654	1.219	1.654	0.773

Table 6: The euclidean and hamming distances.

	A1	A2	A3	A4	A5
Δ_i^*	1.676	1.879	1.850	1.742	2.013
Δ_i^-	3.971	3.251	3.355	3.746	2.726

Table 7: The pairwise comparison matrix.

	A1-A1	A1-A2	A1-A3	A1-A4	A1-A5
$\lambda(\Delta_i^* - \Delta_t^*)$	0.00	0.203	0.175	0.066	0.337
$\lambda(\alpha)$	0	1	1	1	1
	A2A1	A2A2	A2A3	A2A4	A2A5
$\lambda(\Delta_i^* - \Delta_t^*)$	0.203	0.00	0.028	0.137	0.135
$\lambda(\alpha)$	1	0	0	1	1
	A3A1	A3A2	A3A3	A3A4	A3A5
$\lambda(\Delta_i^* - \Delta_t^*)$	0.175	0.028	0.00	0.109	0.163
$\lambda(\alpha)$	1	0	0	1	1
	A4A1	A4A2	A4A3	A4A4	A4A5
$\lambda(\Delta_i^* - \Delta_t^*)$	0.066	0.137	0.109	0.00	0.271
$\lambda(\alpha)$	1	1	1	0	1
	A5A1	A5A2	A5A3	A45A4	A5A5
$\lambda(\Delta_i^* - \Delta_t^*)$	0.337	0.135	0.163	0.271	0.00
$\lambda(\alpha)$	1	1	1	1	0

Table 8: The relative assessment matrix and ranking of the alternatives.

	A1	A2	A3	A4	A5	Total	Rank
A1	0.000	0.518	0.441	0.159	0.907	2.025	1
A2	-0.518	0.000	0.028	-0.358	0.390	-0.458	4
A3	-0.441	-0.028	0.000	-0.282	0.466	-0.285	3
A4	-0.159	0.358	0.282	0.000	0.748	1.229	2
A5	-0.907	-0.390	-0.466	-0.748	0.000	-2.511	5

5.2. Comparison of IT2FS Results

In this section, the proposed approach is compared with other state-of-the-art MCDM methods. The first and second methods (*M1* and *M2*) are based on techno-economic metrics. *M3* is a fuzzy based MCDM approach based on positive and negative-ideal solutions. Herein, for the comparison study, an improved version of the ITF2S, called, IT2FS based TOPSIS and

Table 9: Ranking of the alternatives with respect to various MCDM methods.

Approaches	Evaluation	Alternatives				
		ArklowBank 2 (A_1)	Codling Park (A_2)	Dublin Array (A_3)	Oriel (A_4)	Sceirde (A_5)
M1: Ranking based on only mean wind speed	Wind speed	4	3	2	5	1
M2: Ranking based on only LCoE	Energy economics	1	3	2	4	5
M3: IT2FS based TOPSIS [51]	MCDM	1	2	4	3	5
M4: Proposed approach (ITF2S)	MCDM	1	4	3	2	5
M5: Improved IT2FS with TOPSIS and CODAS	MCDM	1	4	3	2	5

CODAS ($M5$) is applied. $M5$ is based on ranking function while the proposed method ($M4$) uses score function. The ranking results of the various decision-making methods employed are reported in Table 9.

In *M1*, the decision-making is performed straight forward based on the wind speed potential. Hence, $M1$, yields the ranking of the alternatives as ($A_5 > A_3 > A_2 > A_1 > A_4$) based on the wind speed in Table 2. *M2* realizes the decision-making based on LCOE analysis which accommodates multiple technical and economic criteria by definition. A viable investment decision shall not be based only technical data, but also energy economic parameters. Hence, $M2$ is more valuable to $M1$ in terms of investment decision-making. According to $M2$, the ranking of the alternatives can be found to be ($A_1 > A_3 > A_2 > A_4 > A_5$) based on the LCOE values in Table 3. Having said that, 89.80 $\$/MWh$ appears to be a feasible techno-economic figure in comparison to other European commercial offshore wind power investments.

Even though, especially $M2$ provides very critical information regarding a decent decision-making approach, large scale OWF investments require more detailed investigations including other technical, economic, environmental and social perspectives using advanced decision-making approaches. Thus, IT2FS based TOPSIS (*M3*) and an improved version of IT2FS (*M5*) approaches were used alongside the proposed approach (*M4*).

As reported in Table 9, $M3$, $M5$ and the proposed method yield the same best and worst alternative options while $M3$ returns to different ranking order for the other three alternatives. Although, $A5$ has the highest offshore wind speed and power density, the followings make it the least favorable option in the decision-making. The offshore site is located in less populated area which is far from the high electricity demand region as well as the grid connection. Also, the grid is relatively weak in this side of the island which prevents the deployment of large-scale OWF [41]. Moreover, the water depth in the site is considerable deep which has higher wave energy potential. This significantly increases foundation costs. The offshore is located in the

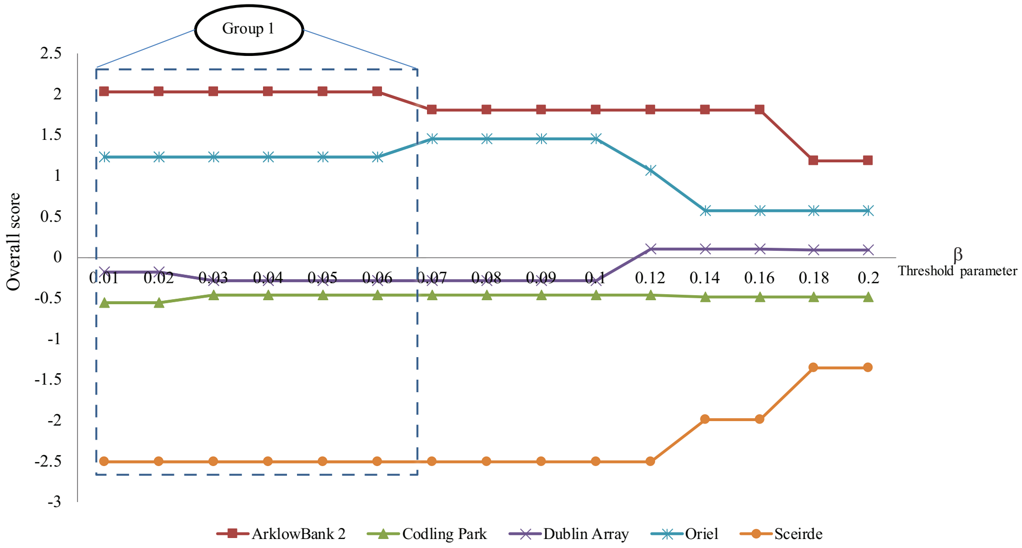


Figure 8: The impact of β on the score values of the alternative sites.

biologically sensitivity areas as well. $A1$, $A2$, and $A3$ have similar techno-economic metrics, while $A4$ has higher LCOE due to its further location from the grid connection. However, $A1$ and $A4$ become prominent sites thanks to their environmental and social aspects. $A3$ is highly affected by environmental and social criteria such as proximity to natural conservation and contaminated areas, effects on marine life. It is also in the vicinity of a licensed exploration area. Moreover, the community/public acceptance might be of interest for $A3$ as it is located in view of the most populated area of the island. $A2$ has slightly higher economic metrics as compared to $A1$ and $A3$ since it is further away from the shore. Even though $A1$ is more affected by environmental and social aspects as compared to $A2$, it is found to be the most feasible option. This is mainly due to the potential of future expansion and economic aspects. $A2$ is suited in the border of Irish offshore territory which strictly prevents the potential expansion of any OWF. It is also located further from ports, shipping lanes, electricity demand region and the grid connection which turned out to be higher LCOE as compared to $A1$.

As shown in Table 9, the proposed method and its improved versions gives the same ranking order. The proposed method *(M4)* is more realistic and stable in terms of defuzzification values and weights. It is also easier to implement as compared to $M5$.

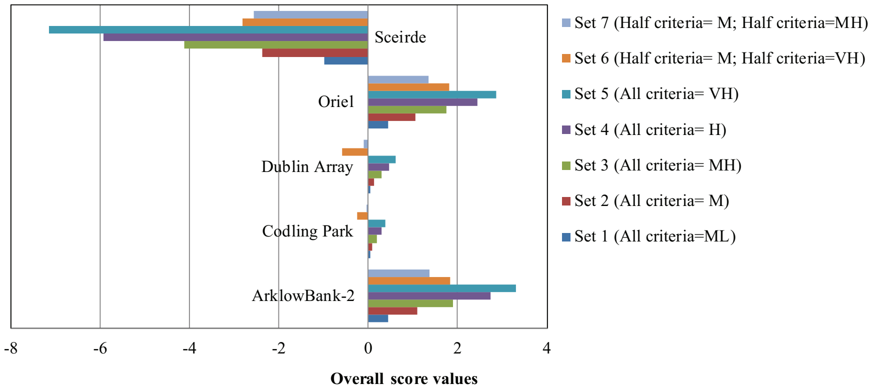


Figure 9: The impact of criteria weights on the ranking of the alternatives.

5.3. Sensitivity analysis

The impact of the threshold parameter, β, and criteria weights on the ranking of alternatives is explored through a sensitivity analysis. The threshold value is changed from 0 to 0.2 with an increment value of 0.1. The impact of changing threshold values on the scores of the alternatives is shown in Fig. 8. As shown, the ranking of the alternatives is not changed for all threshold values studied. As β increases, the overall score decreases which makes the distinctiveness of alternatives weaker. β is suggested to be small values such as 0.02 in [55]. Any value in $Group-1$ in the figure can therefore be chosen for β. A value of 0.06 is selected in this study.

The sensitivity analysis is conducted to reveal the impact of the weights of criteria selected on the alternatives. Seven sets of the criteria weights are generated to demonstrate the stability of the results. Fig. 9 illustrates the sensitivity analysis results. As shown, the ranking is not changed for all weightings. Although the results for Arklow Bank-2 ($A1$) and Oriel ($A4$) are highly close, Arklow Bank-2 is still superior to other four alternatives.

6. Conclusion

Based on the interval type-2 fuzzy sets, this study presents a new decision-making model that integrates the score functions with positive and negative ideal solutions to find the best offshore site among the five authorized offshore sites in Ireland. Moreover, advanced energy economic metrics such as LCOE, DPBP, and NPV are newly integrated into the decision-making process to reduce uncertainties and subjectivity in the expert review phase. Then, the alternatives have been evaluated qualitatively and quantitatively by experts' judgments through linguistic variables for 24 sub-criteria in terms of technical, economic, environmental, and social aspects. Finally, the MCDM model has been applied to rank the alternatives. The ranking results were compared to those of other state-of-the-art methods.

Arklow Bank-2 was found to be the best alternative site while Sceirde was the least favorable. The ranking of other alternatives was found to be $Oriel > DublinArray > CodlingPark$.This ranking is a result of decision-making model considering multiple criteria for the projected OWFs in each alternative site which are the same size (e.g., 100 MW) with resulting different power outputs based on the sites' wind potential. It was shown that the proposed IT2FS and the improved version of IT2FS with TOPSIS and CODAS yielded the same ranking results. However, the proposed approach is superior in terms of implementation (e.g., computational speed) that make the decision-making easier and more reliable. The sensitivity analysis also revealed that the ranking remains the same in response to changes of the weightings.

Floating offshore wind system appears to reduce techno-economic competitiveness of offshore wind investments by reducing capital expenditures and any environmental negative impacts. Therefore, emerging advances including floating offshore wind shall be integrated to the future MCDM studies. On the other hand, various IT2FS based on pythagorean, intuitionistic or neutrosophic sets can be used for offshore site selection problem.

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