Application of a Multiple-Attribute Decision-Analysis methodology for site selection of floating offshore wind farms off the West coast of Ireland

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ABSTRACT: This research presents the application of multi-attribute decision-analysis methodology for selection the most suitable sites in a region off the West coast of Ireland. A large area off the West Irish coast is defined and separated into coordinate grids. The environmental, wind potential and facilities factors are first analyzed in order to remove sites that fall within restricted areas. Following this, data is gathered for the remaining sites in terms of a set of logistic, facilities & environmental, and met-ocean criteria. The logistical criteria consist of such factors as, depth, distance to ports and distance to substations. The met-ocean criteria provide a data analysis of the wind, wave, tidal and current conditions of each site between 2011 and 2016, and the facilities & environmental criteria analyses the proximity of the sites to such criteria as Marine Protected Areas and Special Areas of Conservation. The compiled data is then applied to a Multiple Attribute Decision-Analysis (MADA) algorithm which aggregates the data for each site and produces a utility ranking in order to determine the most suitable site for floating offshore wind. Validation is conducted through benchmark testing.

1 INTRODUCTION

1.1 *State of offshore wind in Ireland*

Offshore wind in the UK is a world-leading industry in terms of installed capacity, which is approaching 7.5GW as of September 2018. A further two offshore sites are in the construction phase, off the coast of Lincolnshire, the Hornsea 1 and 2 projects. Hornsea 1 is expected to be operational by 2020 and will have a capacity of 1.2GW (approximately 171 x 7MW turbines), the world's first offshore wind farm to produce over a Gigawatt of power. Hornsea 2 was given consent to be constructed in August 2016 (Crown Estate, 2013) (Court & Grimwade, 2014) (Crown Estate, 2018).

While the UK has an abundance of offshore wind farms, Ireland currently has one offshore wind farm producing power. This is the Arklow Bank Wind Park located at approximately 52.8°N 5.95°W in the Irish Sea, as shown in Figure 1, and is owned and operated by GE Renewable Energy (Crown Estate, 2018). Figure 1 also shows the locations of the onshore wind farms in the Republic of Ireland. There are number of sites under consideration at various stages of implementation from planning to concept and development. The lack of offshore wind farms around the Republic of Ireland provides an excellent opportunity to apply a developed methodology presented in this report to determine suitable sites for floating offshore wind implementation. There are a number of sites allocated for planning and concept that are discussed as part of the rationale.

Ireland currently has 25 offshore wind farm projects of which 2 currently operating, none where construction has progressed enough to connect the turbines and generate electricity, none are in the build phase, and 3 are either consented or have applied for consent. As demonstrated by Figure 2 (4COffshore, 2020a) (4COffshore, 2020b) (IWEA, 2020).

Furthermore, Offshore wind energy is at the heart of Ireland's offshore wind plan that will cut CO_2 emissions in the electricity sector by two-thirds and increase the renewable energy share of electricity demand to 70% by 2030 from its current 35% (KPMG, 2018) (IWEA, 2020).

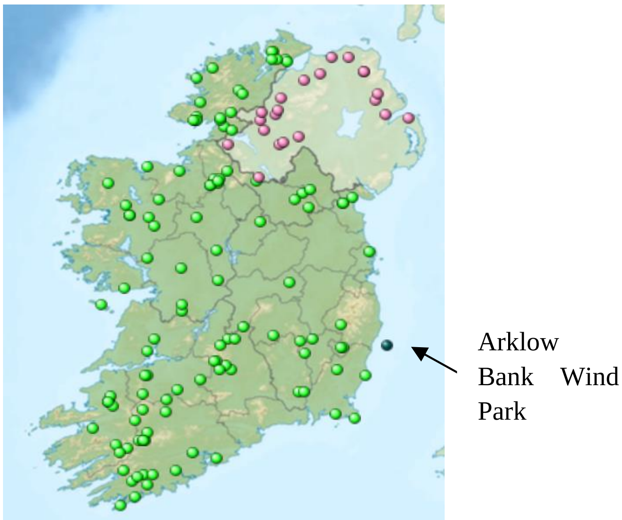


Figure 1. Location of the Arklow Bank Wind Park in the Irish Sea

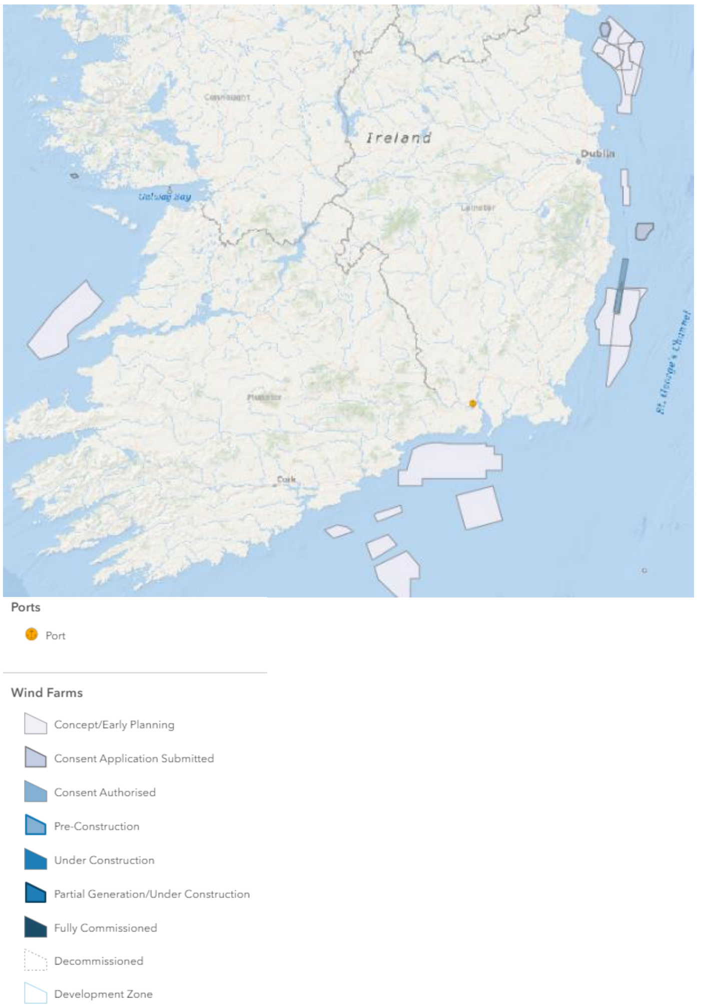


Figure 2. Locations of offshore wind farm projects around Ireland.

1.2 *Purpose*

The aim of this research is to apply a MADA methodology for application to the selection of a suitable site for Floating Offshore Wind (FOW) farms around Ireland. This will be conducted through a number of objectives which are reflected in the steps of the methodology outlined in Section 3. These objectives focus on outlining specific areas of the Republic of Ireland to apply the methodology. To outline a suitable set of qualitative criteria to identify restricted zones, *i.e.* areas that cannot be utilized for FOW development due to environmental or legislative restrictions. To outline further criteria and gather data relative to these criteria in order to apply the multiple-criteria decision-making algorithm and conduct the quantitative analysis. Subsequently, ideal sites for FOW implementation shall be outlined and validation of the model can also be conducted.

2 BACKGROUND

2.1 *Floating offshore wind*

Offshore wind has been identified as one of the leading technology options to decarbonize Ireland's energy system, with deployment expected to reach 3.5 GW by 2030, depending on Ireland's broader energy mix and carbon reduction strategy (Department for Business, Energy & Industrial Strategy, 2019). While the UK is the current market leader in offshore wind power, with ~7.5 GW of installed capacity (as previously stated), Ireland's first, and only, operational Offshore wind farm was installed in 2004; the Arklow Bank Wind Park (James & Ros, 2015). This wind farm, like much of the UK's farms (except Hywind Scotland) consists of a conventional fixed- bottom foundation technology located in relatively shallow water depths (<60m) and near to shore (<30km) (IWEA, 2020) (4COffshore, 2020b). As installed capacity increases and the availability of near-shore sites is exhausted, it is inevitable that wind farms will need to be developed further from shore in deeper water. This poses great technical challenges and efforts to reduce costs. Hence, the application of FOW is gaining momentum along with unlocking the potential in near-shore deep water sites at a lower cost of energy than far-shore fixed- bottom locations (Halkyard, 2005) (IRENA, 2016).

Therefore, it can be said that FOW is well suited to some areas of Ireland, in particular the West Coast where the water depth increases rapidly further into the Atlantic. A combination of high wind speeds, abundant near-shore deep water sites, and the ability to leverage existing infrastructure and supply chain capabilities from the Large ports along the South and West coasts create the requisite conditions to position Ireland as a world leader in floating wind technology(IPORES, 2014) (KPMG, 2018) (Wind Europe, 2018).

2.2 *Offshore site selection methods and State-of-the-Art*

During the planning and development of offshore wind farms, the technical aspects and the design of the wind turbine structures tends to be at the forefront. However, the identification of areas where the energy resources are sufficient, and the environment is ideal for offshore wind development can be somewhat overlooked when considering floating devices. This can result in poor site selection which can be damaging not only in terms of underestimated economic performance and subsequent stakeholder conflict, but also in terms of the effects on local eco-systems and habitats, as well as societal issues and dissatisfactions (Court & Grimwade, 2014).

In many literature studies relating to site selection, Geographical Information Systems (GIS) are commonly applied to the issue of renewable energy resource analysis and site selection. Developers might typically employ GIS at a number of stages, from screening a whole region to identify suitable sites, down to the point of designing array and detailed cable layouts. On a more general scale, national and regional assessments have been reported in the literature. For example, (Cradden, et al., 2016) examined a wide range of issues surrounding site selection for offshore renewable energy platforms and demonstrated the use of GIS with additional tools to assess multiple sites with multiple selection criteria. Similarly, (Fonseca, et al., 2018) have developed a methodology for comprehensive evaluation of feasible areas for floating offshore wind farms, useful to support the strategic spatial planning around the Madeira Islands utilizing marine spatial techniques based on GIS. The work conducted by (Fonseca, et al., 2018) is part of the Interreg project; ARCWIND, as is the research presented in this paper. In addition to this (Goke, et al., 2018) applied Marxan for testing the influence of different energy production targets on the site selection of suitable offshore wind production areas in the Baltic Sea. In this case Marxan was used as a support tool to identify suitable sites for offshore wind power, along with an informed Marine Spatial Planning (MSP) decision making approach.

While the research presented in this paper is focused on the Irish offshore wind market, the methodology can be applied to any area of the world given sufficient input data. This is key as there has been an increase in the offshore wind development in Asia (Kim, et al., 2013) (Gadad & Deka, 2016), particularly China and South Korea (Liu, et al., 2016) (Liu, et al., 2017) . There are a number of studies relating to site selection for floating offshore wind in this area, such as work presented by (Kim, et al., 2018) where a decision-making support tool was applied that can be used to select the most preferable sites for offshore wind farms on the southwest coast of South Korea. Their decision-making tool analyzed social, environmental, and economic factors using various databases and assessed the suitability of sites for offshore wind farms. Similarly, Kim, *et al.* 2016 presented an offshore wind farm site selection strategy and applied it to a case study around Jeju Island. They also utilizes multiple-criteria assessment in their research by dividing the criteria considered for offshore wind farm site selection into four categories: i) energy resources and profitability, ii) conservation areas and view protection, iii) human activities, and iv) the marine environment and ecology.

Further sites selection methodologies have also been presented in literature, such as the method developed by (Mytilinou, et al., 2018) for site selection on the UK for fixed platforms considering the Round 3 available zones in the UK. This methodology utilizes some MADA approaches through the application NSGAII and two variations of TOPSIS. (Mytilinou, et al., 2018) subsequently determined optimum solutions and ranked them based on experts' preferences. Similarly, (Chaouachi, et al., 2017) have also developed a methodology for renewable energy site selection through an MADA approach. They proposed a new framework for offshore wind farm site assessment based on multi-criteria selection through application of the Analytical Hierarchy Process (AHP).

All of the literature examined in this research applies two key methodologies, MSP through GIS or MADA or, in some cases, a combination of the two. What separates the research presented here with other methodologies is it utilizes a conditional binary formula to exclude sites in a given region based on an initial set of exclusion criteria, outlined in Section 4.2. Then a MADA methodology is applied to areas, in a given region that pass the initial conditional assessment. Furthermore, this research applies the Evidential Reasoning (ER) approach in the MADA assessment.

The ER approach is a generic evidence based MADA approach for dealing with problems having both quantitative and qualitative criteria under various uncertainties including ignorance and randomness. Furthermore, ER has been applied to Environmental Impact Assessment (EIA) (Wang, et al., 2006), which is a key factor in FOW site selection. However, ER has yet to be applied as a site selection methodology for FOW, which is where the novelty lies within this research. Similarly, the methodology also incorporates logistical and environmental assessments in order to provide input data to the ER algorithm.

3 METHODOLOGY

3.1 *Rationale*

As the Atlantic Arc also includes Ireland, a number of sites where hypothesized based upon a number of factors, such as, areas already outlined for concept/planning of offshore wind farms, areas that are mostly in >60m of water and that are in proximity of a sufficient grid connection. A number of areas were initially identified based upon the location of a sufficient grid connection. A number of these areas are located in the Irish Sea which is already heavily congested and contains a number of already allocated sites. These sites include an expansion of the already commission Arklow Bank Wind Farm.

Furthermore, the areas off the south coast of Ireland, in the vicinity of the city of Cork were also initially investigated. While the water is much deeper in this location, there are also a number of sites allocated for offshore wind farm implementations, including a site for FOW. These sites are also in the concept/planning phase, as shown in Figure 2.

Finally, areas off the west coast of Ireland were investigated. There are two sites currently under construction or at early concept/planning off the coast of County Mayo, as shown in Figure 2. One of these sites is an Atlantic Marine Energy Test Site (AMETS) to facilitate testing of full-scale wave energy converters in an open ocean environment. The other is part of AFLOWT (Accelerating market uptake of Floating Offshore Wind Technology), where the plan is to develop a full scale FOW turbine by 2022. However, this site in the concept/planning stage is in shallow water and is focused more on the testing of the design rather than the selection process for a full-scale farm. Furthermore, the grid connections in this region of Ireland are not sufficient to cope with the addition of a FOW farm without major modifications. On the other hand, there are a couple of sufficient sub-stations located at Galway (Cashla) and at the Shannon Foynes River (Prospect).

What is also apparent around the Galway Bay area is the allocation of a small testing site for renewable energy in very shallow waters, and also a site near Bertraghboy Bay, called Sceirde (Skerd) Rocks. This site has had a consent application submitted so far for 20 × 5MW turbines (100MW capacity).

Given all of the various factors relating to each area around Ireland, it was concluded that a large area off the coast of Galway would be investigated for FOW implementation. This was due to the fact that i) there are no large sites currently in concept, planning or under considerations, ii) there are good grid connections in close proximity, iii) there is a larger area off the coast with a greater water depth that the other areas, and iv) it fulfils the criteria of being part of the Atlantic Arc region for the ARCWIND Project.

3.2 *Research Framework*

When developing a decision-making methodology, it is important to clearly define the domain that it is to represent. The criteria must be appropriately allocated, which careful attention being paid to what each criterion shall represent and where they shall rank in the evaluation hierarchy. The fundamental part of developing a coherent decision-making method, with the ability to deliver coherent results, lies in its evaluation hierarchy and the allocation the belief degrees and weights. To ensure that a coherent method is established, knowledge is obtained through reviewing literature. There are a number of steps involved in the procedure for applying a decision-making algorithm to a problem. Having a number of steps is key for maintaining consistency throughout the process and offers and element of confidence to the final analysis. There are key elements that the procedure must follow, and these elements shall be outlined in the following sections. Figure 3 also outlines the methodological framework utilized in this research.

4 ANALYSIS

4.1 *Scope and Domain*

In order to determine the size and location of the larger area for analysis, further conversations and

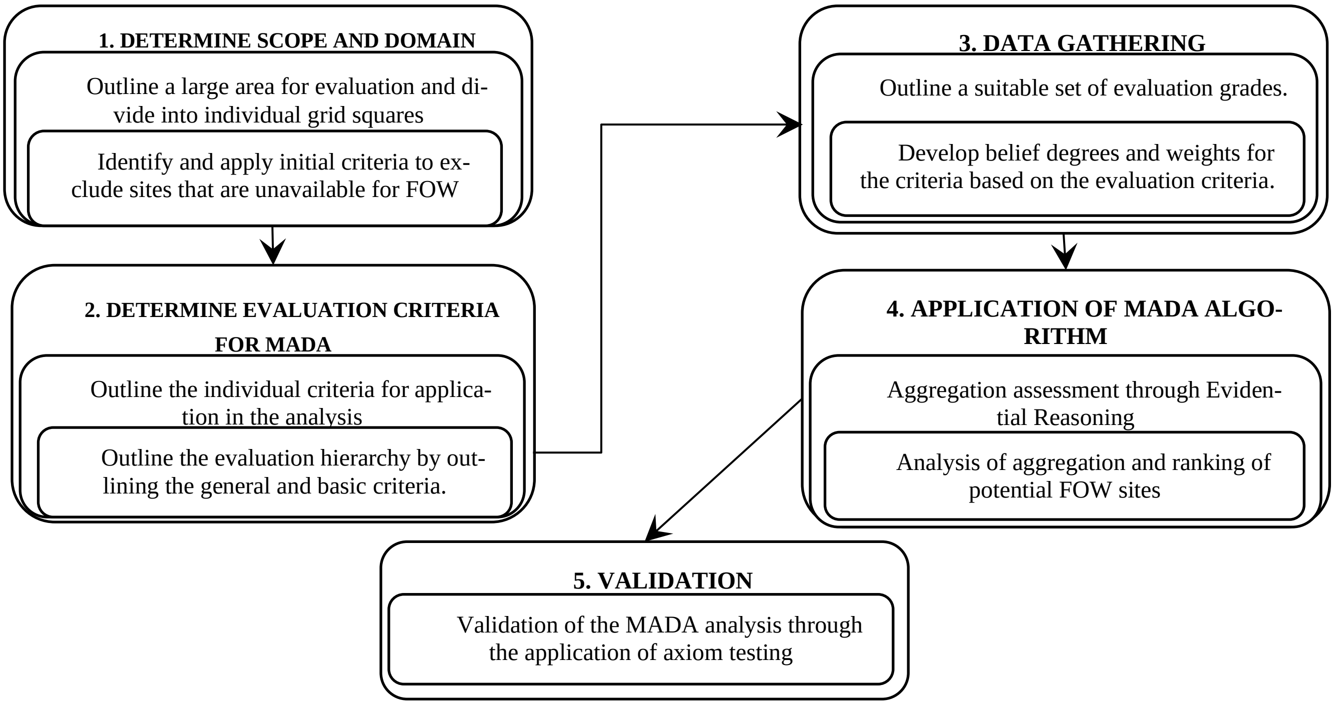
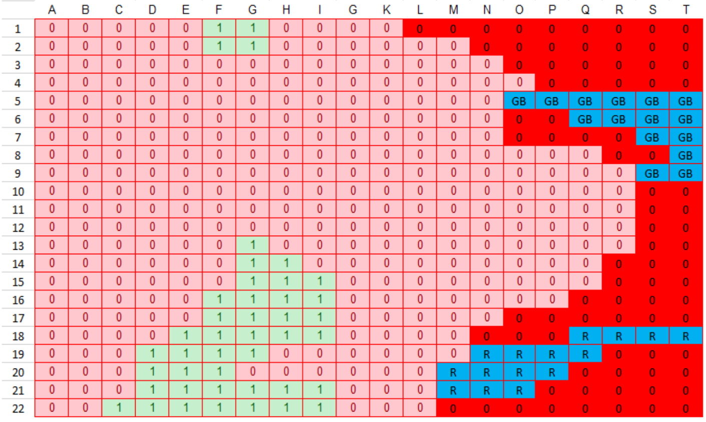


Figure 3: Methodological framework for FOW site selection

meetings were held with experts in the area of renewable energy and the legislation that surrounds implementing an offshore wind farm. These conversations led to the selection of an area off Galway/Shannon Foynes Bay, which was divided into grids. This site can be seen in Figure 4, where red is the Irish Mainland and blue is inland water (Galway Bay and the River Shannon). The area shown in Figure 4 is approximately 100km East to West (9.4° – 10.9° West) by 110km North to South (52.4° – 53.4° North). This area has subsequently been divided into 440 individual grid squares, each approximately 5km×5km, with an area of approximately 25km^2. These grids have been allocated a reference code depending on their location in the larger area. It can be seen that there is a scale running west to east from A to T, and a scale running north to south from 1 to 22. Hence, the most North-Westerly grid is referenced as Site A1. For further reference to the site's location, the Irish Mainland can be seen on the right side of Figure 4, with the River Shannon located at the bottom right.

4.2 *Identification and application of initial evaluation criteria*

Before the process of ranking each individual site in the area in terms of its suitability for FOW implementation, the area must first be evaluated against an initial set of criteria specific to the area of the coast of Ireland to determine unsuitable areas. This part of the analysis is mainly qualitative and identifies a range of criteria to initially exclude areas from later evaluation. Similarly, some criteria involve met-ocean data, where areas will be excluded if they regularly experience extreme environments, *i.e.* consistently large waves or high wind speeds. The set of criteria is outlined in Table 1, along with an explanation as to why the criteria is necessary and being applied to this research. This process is conducted in Microsoft Excel utilizing the IF and binary functions to produce a grid identifying the areas for further analysis. Figure 4 shows the large area outlined for the study along with the results of the binary analysis in Excel where the any area allocated a "1" is suitable for further analysis, and "0" indicates that the area fails in the assessment of one or more of the initial criteria.



	A	B	C	D	E	F	G	H	I	G	K	L	M	N	O	P	Q	R	S	T
1	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GB	GB	GB	GB	GB	GB
6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GB	GB	GB	GB
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GB	GB
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GB
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	GB	GB
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	R	R	R	R
19	0	0	0	1	1	1	1	0	0	0	0	0	0	R	R	R	R	0	0	0
20	0	0	0	1	1	1	0	0	0	0	0	0	R	R	R	R	0	0	0	0
21	0	0	0	1	1	1	1	1	1	0	0	0	R	R	R	0	0	0	0	0
22	0	0	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0

Figure 4: The final result of the application of all initial evaluation criteria outlined in Table 1

Table 1: Outlines of the initial evaluation criteria for determining suitable sites for FOW off Galway Bay

Criteria	Description
Land Mass (y_1)	Any areas that include land masses such as the Island of Orkney. The location of this criterion is determined through the application of navigational charts and interactive maps (Bist LLC, 2019).
Wrecks (y_2)	In this instance a shipwreck is the remains of a ship that has been wrecked and remains on the seabed. (legislation.gov.uk, 1973) (legislation.gov.uk, 1979) (Bist LLC, 2019).
Fisheries (y_3)	Most commonly, a fishery (aquaculture or aquafarming) is an area designated for the raising and/or harvesting of aquatic organisms and is determined by some authority as a fishery. Therefore, these areas are to be avoided due to the legislative and legal implications attached (European Union, 2013) (Marine Institute, 2019).
Shipping Lanes (y_4)	This criterion includes the avoidance of shipping lanes in the allocated area.
Marine Protection Area (MPA) (y_5)	MPAs are geographically distinct zones for which conservation objectives can be set. (EEA, 2015) (EEA, 2019) (Marine Scotland, 2019) (Bist LLC, 2019).
Aquatic habitats (y_6)	Marine habitats are habitats that support marine life.
Minimum Depth (m) (y_7)	Some floating designs have a draft of more than 60m, therefore the minimum depth of the sites is to be 100m. Fixed offshore wind structures operate to a maximum of 50-60m water depth (Bist LLC, 2019).
Wind Potential (m/s) (y_8)	The wind potential will feature in the further analysis however, for the initial evaluation, sites will be excluded if the wind speed is consistently outside of the range for cut-in and cut-out speeds of a turbine. cut-in speed of 4m/s and a cut-out speed of 25m/s. the rated speed is 11.4m/s. (Ifremer, 2019).
Extreme Wave Height (m) (y_9)	The extreme wave height shall exclude any areas with a Significant Wave Height (H_s) of ≥8m. (Ifremer, 2019).

4.3 *Quantitative analysis criteria and evaluation hierarchy*

This section of the methodology involves filtering possible criteria that are relative to the description and the objective. For this problem, the criteria were devised from literature studies based upon the key requirements of FOW implementation. It is necessary to keep the criteria to a sensible number at this stage to avoid over complications when applying the decision-making algorithm.

In order to apply the ER algorithm to the decision of the most suitable site for FOW implementation, a set of variables and a hierarchical structure of general and basic criteria must first be defined. The variables and hierarchical structure are based upon the initial evaluation criteria but apply a more intricate quantitative approach with an increased number of criteria. In this analysis, there are three general criteria outlined and thirteen basic criteria, as shown in Figure 5.

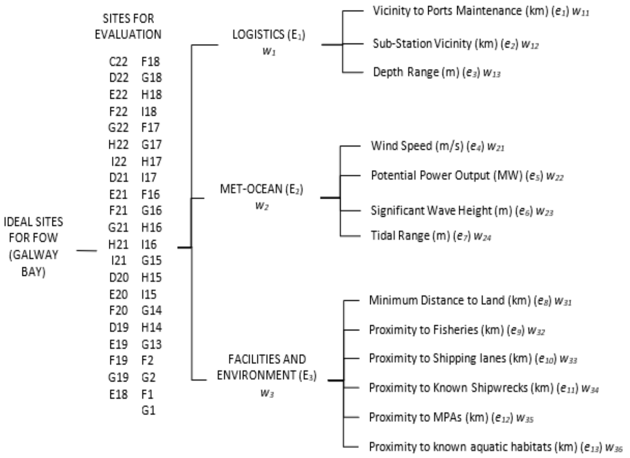


Figure 5: Evaluation Hierarchy for the available sites for FOW off the coast of Galway Bay

4.4 *Outline suitable evaluation grades*

A sensible set of evaluation grades was established to maintain consistency throughout the problem-solving process. In the end five grades are selected in order to accurately determine each individual site's suitability and to assist with the qualitative to quantitative assessment.

Subjective judgements may be used to distinguish one alternative from another in terms of qualitative criteria. However, in this research it is possible to use objective data to determine the belief degrees. For example, to evaluate the *Logistics* the data may suggest that the *logistics* of a site is *poor*, *average* or *Excellent*. In this case the terms *poor*, *average* and *excellent* represent clear grades of the criteria, However, when applying a MADA approach such as Evidential Reasoning, three evaluations grades are not sufficient (Yang & Xu, 2002) (Ren, et al., 2005). Therefore, five evaluation terms have been outlined, with H_n denoting the n^{th} evaluation grade. This is demonstrated by Equation 1:

$$H_n = \{Poor\ (H_1), Indifferent\ (H_2), Average\ (H_3), Good\ (H_4), Excellent\ (H_5)\} \qquad (1)$$

Logistics is not an easy criterion assess directly, so it is defined by four basic criteria, as previously stated. Hence, by assessing the basic criteria, the general criteria can also be assessed.

4.5 *Obtain data to develop the belief degrees and relative weights*

The Pairwise Comparison (PC) and Analytical Hierarchy Process (AHP) methodologies and calculations are not demonstrated here, however some applications and examples can be found in the following studies (Loughney & Wang, 2017) (Saaty, 1980) (Saaty, 1990) (Saaty, 1994) (Ahmed, et al., 2005) (Koczkodaj & Szybowski, 2015)

Before the analysis can be conducted, the weights of each criterion, both general and basic must be determined. The weights of the criteria are calculated through Pairwise Comparison (PC) and AHP, and are determined by qualitative assessment from expert judgement, through the use of questionnaires.

As outlined previously, three general criteria are considered, which are Logistics, Metocean and Facilities & environment. These criteria are generic and difficult to assess directly, therefore, sets of basic criteria are required. Five experts and their judgements were used to complete the qualitative questionnaire across the discipline of offshore wind structure and farm development within industry. The five experts are to remain anonymous, however, their expertise and experience are outlined as follows. All 5 experts are currently in the employment of fixed and floating offshore wind structures and turbine development companies located within the Atlantic Arc region. All experts have a degree classification to MSc or PhD level and have 5 or more years' experience within the offshore renewable energy industry. Table 2 shows the weights of each criteria. The belief degrees are obtained through the application of navigational charts, literature review and databases. The completed belief degrees for 1 of the 43 sites in the analysis for the basic criteria, under the general criterion *logistics*, are demonstrated in

Table 3.

Table 3 is an example of part of the complete data table which consists of 5 grades for each 13 basic criteria, for all 43 sites in the analysis.

4.6 *Aggregation assessment through Evidential Reasoning algorithm*

Forty-three sites were determined from the application of the initial exclusion criteria are ranked based upon their performance in the decision-making analysis. The overall belief degrees of each site were determined and ranked in terms of their suitability for FOW implementation. These utility intervals are ranked from greatest to smallest. The

Table 2: Calculated weights for the general and basic criteria for use in the analysis of the sites off the west coast of Ireland

General criteria	Weights	Notation	Weights
E_1	17.56%	e_1	32.12%
		e_2	23.84%
		e_3	44.04%
		SUM	100.00%
E_2	51.50%	e_4	36.97%
		e_5	33.44%
		e_6	24.41%
		e_7	5.18%
		SUM	100.00%
E_3	30.94%	e_8	6.69%
		e_9	6.88%
		e_{10}	27.22%
		e_{11}	4.24%

		e_{12}	27.74%
		e_{13}	27.22%
SUM	100.00%	SUM	100.00%

Table 3: An example of a generalized decision matrix for site selection assessment with basic criteria belief degrees

Basic Criteria	Beliefs Site C22	Evaluation Grade	Grading Scale
Vicinity to All Ports (Maintenance + Installation)	0	Poor	≤ 175km
	0.5	Indifferent	150km ≥ x < 175km
	0.5	Average	125km ≥ x < 150km
	0	Good	100km ≥ x < 125km
	0	Excellent	>100km
Sub-Station vicinity	0.5	Poor	≤ 175km
	0	Indifferent	150km ≥ x < 175km
	0	Average	125km ≥ x < 150km
	0.5	Good	100km ≥ x < 125km
	0	Excellent	>100km
Depth	0	Poor	<50m
	0	Indifferent	50m ≤x< 100m
	0.5	Average	100m ≤x< 150m
	0.5	Good	150m ≤x< 250m
	0	Excellent	≥ 250m

site with the greatest value is the most suited for FOW implementation. The utility ranking method is to be outlined here but for further information regarding the application of the ER algorithm can be found at the following references (Li & Liao, 2007) (Ren, et al., 2005) (Yang, 2001) (Yang & Xu, 2002) (Wang, et al., 1995).

It is important to note that changing the aggregation order does not change the final results in any way. In other words, the criteria can be aggregated in any order and the same result would still be achieved. This process is applied to all of the 43 outlined sites, for all basic and general criteria through the application of the Intelligent Decision System (IDS) software.

4.7 *Utility Ranking*

The criteria must be ranked based upon their aggregated belief degrees from the ER algorithm. Suppose the utility of an evaluation grade, H_n, is denoted by $u(H_n)$. The utility of the evaluation grade must be determined beforehand, with $u(H_1) = 0$ and $u(H_5) = 1$ assuming there are five evaluation grades (Yang, 2001). If there a lack of information available then the values of $u(H_n)$ can be assumed to be equidistant, as shown by Equation (2):

$$u(H_n) = \{u(H_1) = 0;\ u(H_2) = 0.25;\ u(H_3) = 0.5;\ u(H_4) = 0.75;\ u(H_5) = 1\} \tag{2}$$

The estimated utility for the general and basic criteria, S(z(ei)), given the set of evaluation grades is given by Equation (3) (Yang & Xu, 2002):

$$u\left(S(z(e_i))\right) = \sum_{n=1}^{N} u(H_n)\beta_n\,(e_i) \tag{3}$$

In Equation (2) the term $\beta_n(e_i)$ determines the lower bound of the likelihood, that e_i is assessed to a grade H_n (Yang, 2001).

4.8 *Results*

The utility assessment is conducted for each individual site to determine the overall suitability for FOW implementation. Table *4* demonstrates the utility ranking of the overall suitability of the sites for FOW implementation. For the locations of each site see Figure 4.

Table 4: Overall assessment results for the 43 identified sites off the west coast of Ireland

Rank	value	Loc.	Rank	Value	Loc.
1	0.6193	F16	23	0.5692	I17
2	0.6171	G15	24	0.5662	E22
3	0.6148	G14	25	0.5662	E20
4	0.6111	G13	26	0.5662	E21
5	0.6088	H15	27	0.5657	G18
6	0.6047	H14	28	0.5653	I16
7	0.6004	D20	29	0.5640	G1
8	0.6002	D22	30	0.5637	F22
9	0.5985	D21	31	0.5637	F20
10	0.5983	F17	32	0.5637	F21
11	0.5978	D19	33	0.5637	F19
12	0.5900	C22	34	0.5631	E19
13	0.5846	G17	35	0.5619	F18
14	0.5835	I15	36	0.5595	G2
15	0.5820	H18	37	0.5578	H21
16	0.5802	G16	38	0.5578	H22
17	0.5780	F2	39	0.5562	G22
18	0.5780	F1	40	0.5552	G21
19	0.5770	E18	41	0.5532	G19
20	0.5757	I18	42	0.5504	I21
21	0.5707	H17	43	0.5421	I22
22	0.5707	H16			

The potential offshore sites for the site off the west coast of Ireland are ranked based upon their overall performance from the aggregation and utility assessments. It can be seen that site F16 is deemed to be the most favorable of the 43 potential sites. This is not unexpected as this site has ranked consistently in the top 10 across the three general criteria. However, some sites in the Top 10 overall have not consistently ranked high in the other general criteria. This is clearly where the relative weights of the general criteria has had an effect on the outcome. This influence can be seen in the aggregated assessment as site G14 ranks 12th and 19th in terms of *metocean* and *Fac. & Env.* suitability but ranks 1st in terms of *logistics*. Similarly, the criterion of *metocean* accounts for more than 50% of the weighing in this assessment. Therefore, the combination weighting has a great effect on the outcome as the site A14 ranks 3rd in terms of overall suitability. This is also evident by the fact that two of the sites (G13 and G15) that ranked outside of the top 10 in the two highly weighted criteria, also ranked in the top 5 for overall performance. This effect of the combined weighting of the general criteria can be seen across the analysis and results.

Therefore, it can be said that the top 5 sites in the region off the northern coast of Scotland are:

F16 > G15 > G14 > G13 > H15

It can be seen from Figure 6 that the top 5 sites are located in the central area. Furthermore, there is a colour coded representation (Green = Best to Red = Worst) which highlights which areas collectively suitable for FOW implementation and those that are not. Therefore, it can be seen from Figure 6 that the most suitable collective area is in the center of the region, which collectively follows with the locations of the top 5 sites. The results clearly demonstrate that moving further out from the center of the region hinders suitability for FOW implementation. This is due to a number of factors: firstly, they are in closer proximity to a number of restricted areas and landmarks, secondly as one progresses east, the depth reduces due to proximity to the coast, and thirdly, if one moves out to the west of the center of the region, the wind condition becomes less hindered and the water is deeper but the sites run the risk of becoming too far from a sub-station connection and from ports.

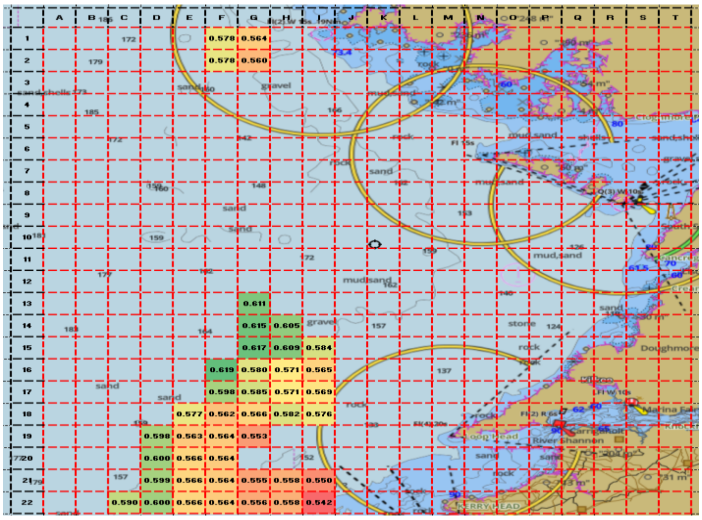


Figure 6: Graphical representation of the most suitable sites for floating offshore wind (Green = Best, Red = Worst)

4.9 *Validation*

This case study was validated against a 4-axiom benchmark test. This procedure gave some validation to the model by fulfilling the 4 axioms. These axioms are named as follows:

The independence axiom: where a general criterion must not be assessed to an evaluation grade, H_n, if none of the basic criteria, under the general criterion, are assessed to H_n.

The consensus axiom: where the general criteria should be precisely assessed to a grade H_n, if all of the basic criteria in E are assessed to H_n.

The completeness axiom: Where if all basic criteria, under a general criterion, *are* completely assessed to a subset of evaluation grades, then the general criteria should be completely assessed to the same subset of grades.

The incompleteness axiom: where if an assessment for any basic criterion in E is incomplete, then the assessment for the general criterion should be incomplete to a certain degree.

5 CONCLUSIONS

This research set out to apply a MADA methodology for suitable site selection for floating offshore wind farms on the west coast of Ireland. The methodology was applied to a large area off of Galway, where a set of 9 evaluation criteria was applied to exclude sites that were not suitable for FOW and further analysis. This identified 43 out of 440 sites within the outlined region. These sites were again quantitatively analyzed against 3 general criteria (Logistics, |Metocean and Facilities & Environment) with 13 basic criteria, as outlined in Section 4. This analysis and aggregation utilizing the ER algorithm allowed for the ranking of the 43 sites off the coast of Galway.

It was determined that the most suitable site in Ireland is F16 (approximately 52.72^{O} N 10.53^{O} W) along with 4 adjacent sites (G15, G14, G13 and H15) in the center of the larger outlined region.

The ER approach establishes a nonlinear relationship between an aggregated assessment for general criteria and an original assessment of basic criteria. This approach was combined with Pairwise Comparison and AHP to determine the relative weights of each criterion. The numerical analysis of the research dealt with the design selection problem outlined previously with key information and data taken from literature, various databases and subjective reasoning (PC and AHP). It has demonstrated that the ER approach can accurately be used as a viable decision-making tool in the site selection for floating offshore wind farms.

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