**Loughney, S, Wang, J, Bashir, M, Armin, M and Yang, Y**

**Development and application of a multiple-attribute decision-analysis methodology for site selection of floating offshore wind farms on the UK Continental Shelf**



**Loughney, S, Wang, J, Bashir, M, Armin, M and Yang, Y (2021) Development and application of a multiple-attribute decision-analysis methodology for site selection of floating offshore wind farms on the UK Continental Shelf. Sustainable Energy Technologies and Assessments, 47. ISSN 2213-1388**

# Development and application of a multiple-attribute decision-analysis methodology for site selection of floating offshore wind farms on the UK Continental Shelf

Sean Loughney[1], Jin Wang[1], Musa Bashir[1], Milad Armin[1], Yang Yang[1]

[1]*Liverpool Logistics, Offshore and Marine (LOOM) Research Institute, Liverpool John Moores University, Byrom Street, Liverpool, L3 3AF, UK*

Corresponding Author: Dr. Sean Loughney – s.loughney@ljmu.ac.uk

**ABSTRACT:** This research presents the development of a methodology for determining the most suitable floating offshore wind farm locations for the northern coast of Scotland, through the application of multi-attribute decision-analysis. A large area off the northern coast of Scotland is defined and separated into coordinate grids. The environmental, logistical and facilities factors are first analysed 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 *Logistics, Facilities & Environmental*, and *Met-Ocean* criteria. The logistical criterion consists of such factors as, depth, distance to ports and distance to substations. The *Met-ocean* criterion provides a data analysis of the wind, wave, tidal and current conditions of each site between 2011 and 2016, and the *Facilities & Environmental* criterion analyses the proximity of the sites to such criteria as Marine Protection Areas, Special Areas of Conservation, military training areas and subsea facilities. 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 and correlation with government survey sites.

**Keywords:** Multiple attribute decision analysis; Renewable site selection; Floating offshore wind.

## 1 INTRODUCTION

### 1.1 State of Offshore Wind in the UK

Driven by issues of climate change, security of energy supply and economic development potential, the UK Government set ambitious plans for the growth of offshore wind by 2020. Overall, the UK had nominal targets for around 20 GW of installed offshore wind by 2020, however, the offshore wind capacity, as of December 2020 was approximately 10.5GW, which is 50% of what was projected for 2020. The UK's current goal is to achieve an offshore capacity of 27 GW by 2026, and 40 GW by 2030 (Energy Vice, 2021) (RenewableUK, 2021). The projected level of capacity is required to help deliver the UK's carbon reduction targets through the de-carbonization of electricity production – a means of achieving an overall 15% reduction in carbon-based energy use. This represents a ten-fold increase in

2006 renewable energy consumption (IRENA, 2016) (Offshore Energy, 2018). Furthermore, offshore wind deployment is expected to reach 20-55 GW by 2050, depending on the UK's broader energy mix and carbon reduction strategy (Department for Business, Energy & Industrial Strategy, 2019).

Offshore wind in the UK is a world-leading industry in terms of installed capacity, which is approaching 7.5GW as of September 2018. One UK offshore site has recently begun supplying power while another is in the construction phase, both off the coast of Lincolnshire (See Figure 1), the Hornsea 1 and 2 projects, respectively. Hornsea 1 was completed and installed in early 2020 and has an approximate capacity of 1.2GW (approximately 171 × 7MW turbines). It is the world's first offshore wind farm to produce over a Gigawatt of power, as well as being the largest wind farm in the world. Hornsea 2 was given consent to be constructed in August 2016, and is expected to be operational by 2022, with an approximate capacity of 1.4GW (Orsted, 2018) (Orsted, 2019) (Orsted, 2020) (Orsted, 2021).

All the offshore wind farms around the UK consist of conventional fixed-bottom foundation technology located in relatively shallow water depths (<60m) and near to shore (<30km), except for the Hywind Scotland farm which is floating (see Section 1.2), and the Hornsea Project which is more than 30km from the shore. (James & Ros, 2015) (Orsted, 2019). 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 Floating Offshore Wind (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. Therefore, it can be said that FOW is well suited to some areas of the UK, in particular the northern coast of Scotland. 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 offshore oil and gas industry create the requisite conditions to position the UK, particularly Scotland, as a world leader in floating wind technology (Wind Europe, 2018).

### 1.2 Hywind Scotland

The Hywind Scotland wind farm, operated by Statoil in partnership with Masdar, consists of 5 × 6MW turbines, with a total farm capacity of 30MW, and has the potential to power approximately 20,000 households. Hywind is located 25km offshore from Peterhead in Aberdeenshire, Scotland (See Figure 1). Hywind is a floating wind turbine design based on a single floating cylindrical spar buoy moored by cables or chains to the seabed. Its substructure is ballasted so that the entire construction floats upright. Hywind combines familiar technologies from the offshore and wind power industries into a new design (Statoil, 2015) (Hill, 2018).

The floating design allows Hywind wind turbines to be placed in waters too deep for conventional bottom-fixed turbines. Where a fixed wind turbine can operate in a maximum water depth of 60m, the Hywind design can operate in waters up to 800m deep. The wind farm is currently operating in a water depth of approximately 105m. Hywind uses a ballasted catenary layout with three mooring cables with 60 tonne weights hanging from the midpoint of each anchor cable to provide additional tension. Control software on board constantly monitors the operation of the wind turbine and alters the pitch of the blades to effectively dampen the motion of the tower and maximise production. Electricity produced is taken to shore through subsea cables. Similarly, several logistical challenges were faced regarding the construction and installation of Hywind as it the structures were built in the Navantia Fene shipyard, which is in Ferrol, A Coruña, Spain. Thus, there was a significant distance between the construction site and the final installation site and further adds to the rationale of including the logistics criterion in this research (Statoil, 2015) (Equinor, 2019).

The Hywind Scotland array is a massive step towards implementing FOW farms in much deeper waters and further out to sea. Offshore winds are typically more consistent and stronger over the sea, due to the absence of topographic features that disrupt wind flow. Hence 80% of the wind resources available are located over the open ocean (Statoil, 2015) (Wind Europe, 2018).

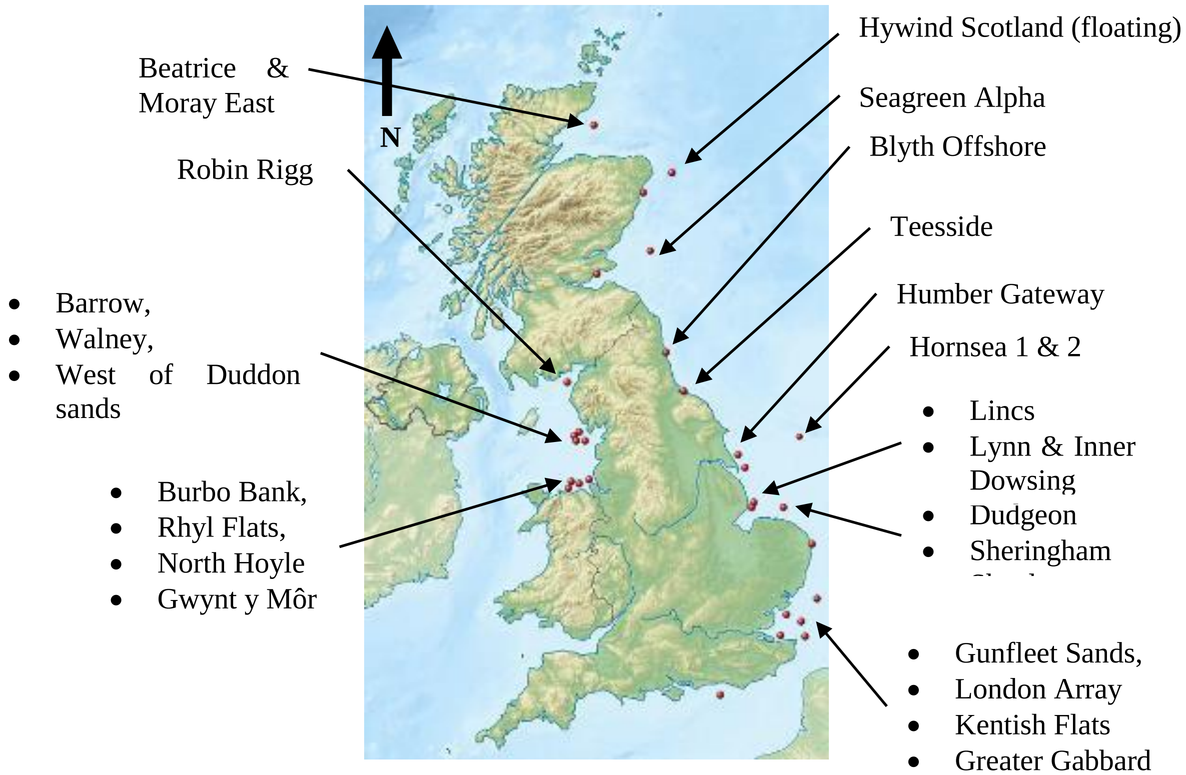


Figure 1: Locations of major operational offshore wind farms on the UKCS

### 1.3 Purpose and Structure

The aim of this research is to develop a Multiple Attribute Decision-Analysis (MADA) methodology for application the selection of a suitable site for Floating Offshore Wind (FOW) farms. This will be conducted through several objectives which are reflected in the steps of the methodology outlined in Section 3. These objectives focus on outlining: 1) a specific area of the United Kingdom Continental Shelf (UKCS) to apply the methodology; 2) a suitable set of qualitative criteria to identify restricted zones, *i.e.* areas that cannot be utilised for FOW development due to environmental or legislative restrictions; 3) a further set of criteria and gather data relative to these criteria in order to apply a MADA algorithm and 4) conduct the quantitative analysis. Subsequently, ideal sites for FOW implementation are produced and partial validation of the model can also be conducted.

This paper is divided into several sections; Section 1 outlines a brief introduction into the current state of offshore wind on the UKCS. Section 2 presents the background into floating offshore wind and State-of-the-Art site selection methodologies. Section 3 outlines the MADA methodology, while Section 4 presents a case study focusing on a specific area of the UKCS. Section 5 provides the data aggregation and utility ranking, along with the validation of the MADA algorithm. Finally, Section 6 provides the conclusions and further work.

## 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 several stages, from screening a whole region to identify suitable sites, down to the point of designing array and detailed cable layouts (Shao, et al., 2020). On a more general scale, national and regional assessments have been reported in the literature. For example, (Cradden, et al., 2016) and (Peters, et al., 2020) 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) 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 utilising 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 UK 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 (Kim, et al., 2016) (Kim, et al., 2018). 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 analysed 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 utilise 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 utilises some MADA approaches through the application Non-dominated Sorting Genetic Algorithm (NSGAII) and two variations of The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). (Mytilinou, et al., 2018) subsequently determined optimum solutions and ranked them based on experts' preferences. In their research Seagreen Alpha was the best option, and Hornsea Project One was the least probable to be selected. However, since the publication of the research of (Mytilinou, et al., 2018), the Hornsea Project One has begun generating power, becoming more than twice the size of the current largest wind farm, the Walney Extension. The final monopile foundation for Hornsea One was completed in April 2019 and as of 3 May 2019, 28 turbines out of 174 had been installed (Orsted, 2019). Similarly, (Chaouachi, et al., 2017) 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). A key feature of utilising a MADA methodology is that most techniques are flexible in terms of their ability to be updated with addition criteria and data. This allows for application across various locations around the world where some criteria may be more favourable or relevant than others. This can also be seen in more recent work presented by (Emeksiz & Demirci, 2019) (Tercan, et al., 2020) (Deveci, et al., 2020) (Ari & Gencer, 2020) and (Lo, et al., 2021) where multiple criteria decision methodologies have been applied in analysis of renewable energy site selection. These literature sources also demonstrate the application of hybrid decision methodologies.

All of the literature examined in this research applies a number of key methodologies, MSP through GIS or MADA or, in some cases, a combination of the two (hybrid). What separates the research presented here with other methodologies is that it utilises a conditional binary formula to exclude sites in a given region based on initial exclusion criteria, outlined in Section 3.2. Subsequently 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.

## 2.1 Novelty Statement

The novelty of the research is found in the combination of the initial exclusion methodology (qualitative) and the ER methodology (quantitative). This technique of combining the two methodologies for site selection is not utilised within the outlined literature. The initial exclusion methodology that is utilised in this manner does not require the uses of any additional third-party software, such as GIS. It can be applied utilising the binary formulas within MS Excel, as demonstrated in this paper. This is a great improvement on the ease of use and accessibility of this type of methodology. The ER approach offers a rational and reproducible methodology to aggregate uncertain, incomplete, and vague data. ER uses the concept of 'degree of belief' to elicit a decision-maker's preference. The degree of belief can be described as the degree of expectation that an alternative will yield an anticipated outcome on a particular criterion. An individual's degree of belief depends on the knowledge of the subject and the experience (Wang, et al., 1995) (Yang & Xu, 2002) (Sadeghi, et al., 2018). The ER approach has been developed particularly for MADA problems with both qualitative and quantitative criteria under uncertainties utilises individuals' knowledge, expertise, and experience in the forms of belief functions. The major advantage of ER is its ability to handle incomplete, uncertain, and vague as well as complete and precise data. However, there are two quantitative parts to ER, one is the belief degrees, and the other is the relative weights of the criteria. AHP is an ideal solution to develop these weights as the data gathering process can incorporate the both the belief degree determination as well as a PC, which is a tremendous advantage in the data gathering process. Particularly when utilising non-probability sampling, as it allows experts to complete the surveys for both ER and AHP at the same time, thus, limiting the level of uncertainty and randomness related to separate surveys for other mixed method approaches (Sönmez, et al., 2012).

In addition, no site selection research findings utilise the ER methodology to determine the most optimal/suitable site for offshore wind farm implementation. Furthermore, the majority of site selection research focuses on fixed wind farms whereas the method presented in this research is specifically for floating offshore wind. Similarly, the methodology is applied to the United Kingdom Continental Shelf, where most of the research focuses on fixed offshore wind farms. Further novelty is also found in the outlined criteria. Site selection studies in literature apply either environmental, logistical, or met-ocean criteria individually in the methodologies, occasionally two sets of criteria, whereas this research analyses the performance of potential Floating Offshore Wind Farm sites across all three criteria with a specific set of sub-criteria under each main criterion.

## 2.2 Rationale

The rationale behind applying the methodology to Northern Scotland is to identify areas in the Atlantic Arc region. The Atlantic Arc regions are exposed to the open Atlantic Ocean and given that the study is to be applied to the UK there are limited areas in which to focus. This is for a number of reasons; firstly, the depth around the UK is relatively shallow when compared to the coast lines of other European countries such as France, Spain and Portugal. For FOW to be feasible, the depth should be a minimum of 60m. Secondly, the majority of the waters around the UK are already convoluted in terms of shipping and existing fixed wind farms. Hence, the study cannot focus in the Irish or the North Sea due to congestion and the shallow water depth. Finally, the northern coast of Scotland offers a large

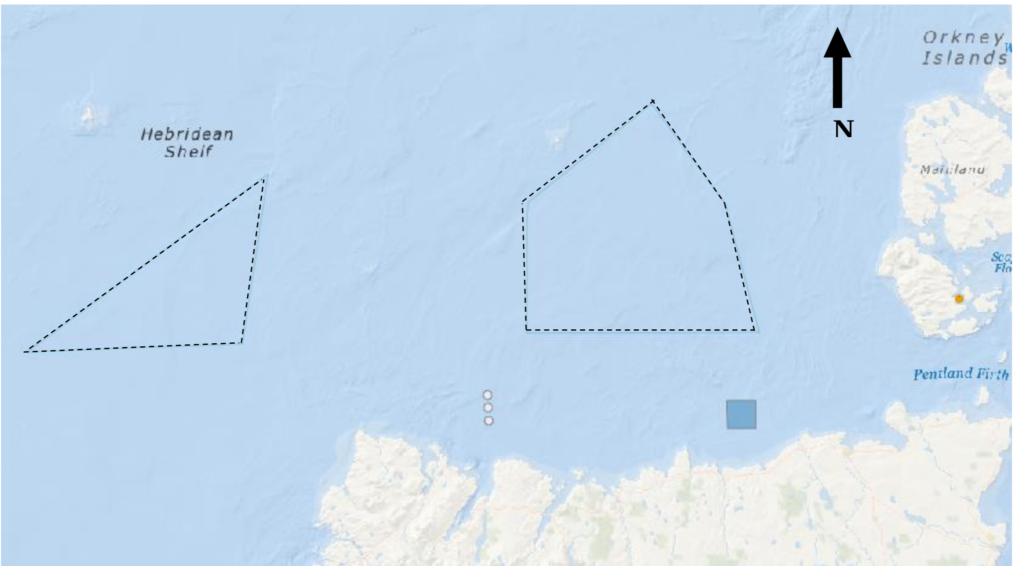


Figure 2: Sites currently under survey for potential offshore wind farms in deeper waters *(4COffshore, 2020)*.

expanse of water in the vicinity of the Island of Orkney where offshore renewable feasibility research is being conducted by European Marine Energy Centre (EMEC), who have also contributed to this research. Figure 2 demonstrates two main sites under survey by the Scottish Government in the region of Orkney and northern Scotland, along with the Dounreay Tri site closer to the coast, represented by the dark blue square.

# 3 METHODOLOGY

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 attribute 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 several steps involved in the procedure for applying a decision-making algorithm to a problem. Having several 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 utilised in this research. In Figure 3 each step of the methodology is outlined with further sub-steps also highlighted. For example, in Step 1 the main objective is to determine the scope and domain of the research application. The sub-steps further detail how this is to be done, i.e., defining a specific area for analysis, and identifying a set of exclusion criteria to exclude unsuitable sites to avoid an unnecessarily complex quantitative assessment.

## 3.1 Establish the domain and definition.

This involves putting boundaries in place to prevent the process from becoming too complex. For this research it has already been stated that the focus is a region off the northern coast of Scotland. However, this does not indicate the size and scope of the area. Therefore, a large area off the northern coast of Scotland is outlined, with the aim to break the large area into sections. These sections can then be ranked according to their suitability regarding the implementation of FOW. The rationale behind applying the methodology to the northern coast of Scotland is to identify areas in the Atlantic Arc region. The Atlantic Arc regions are exposed to the open Atlantic Ocean and given that the study is to be applied to the UK there are limited areas in which to focus. This step corresponds to Step 1a in Figure 3.

## 3.2 Identification of initial exclusion 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 to determine unsuitable

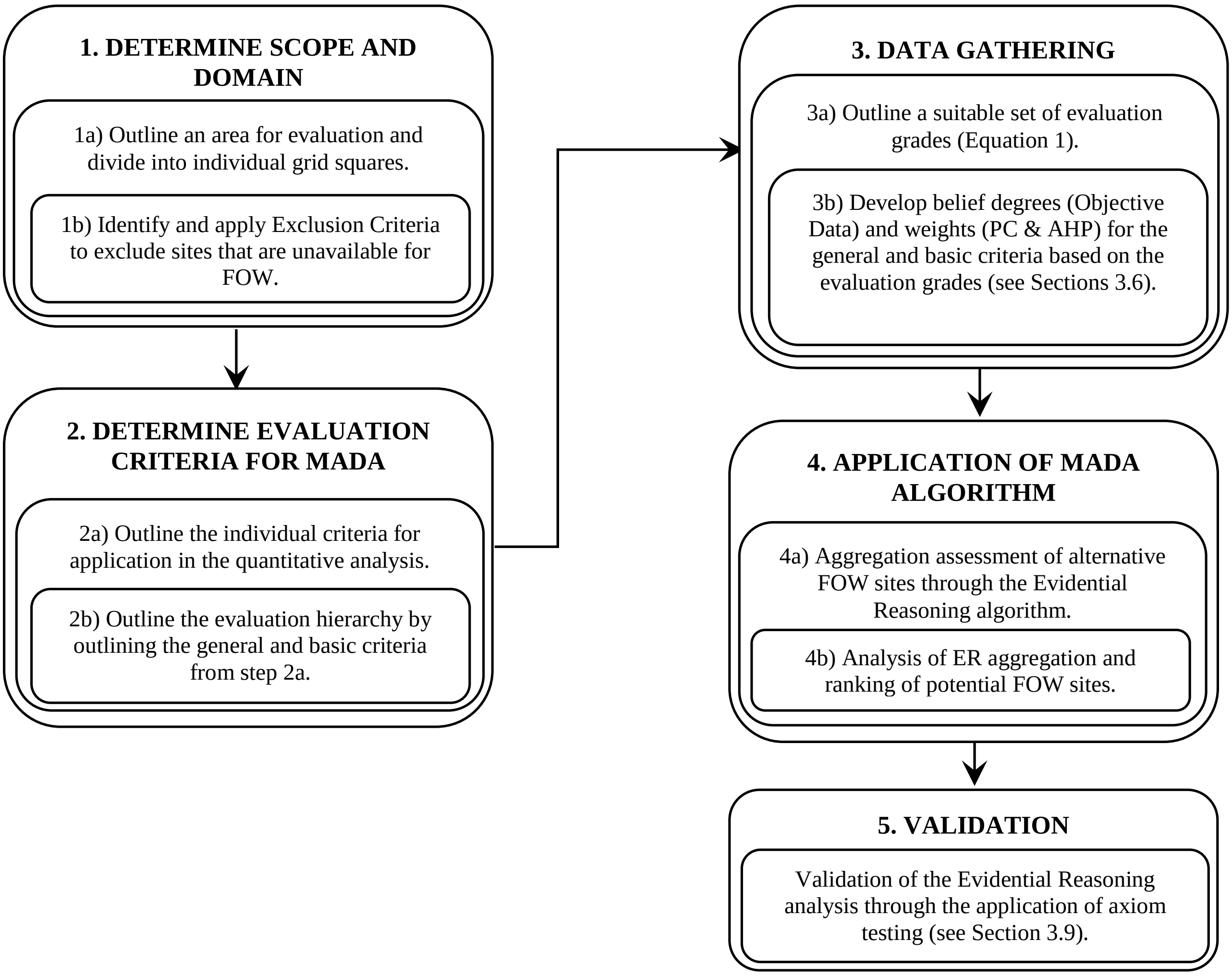


Figure 3: Methodological framework for FOW site selection

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. This step corresponds to Step 1b in Figure 3.

### 3.3 Identify individual criteria for quantitative analysis.

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. This step corresponds to Step 2a in Figure 3.

### 3.4 Develop the evaluation hierarchy.

Once the criteria have been established, a hierarchy must be determined in order to coherently develop a solution to the problem. This hierarchy groups certain criteria under one general criterion. This allows for a smaller number of criteria to be aggregated gradually to reduce the calculation complexity of the decision-making algorithm (Yang, 2001) (Yang & Xu, 2002) (Wang, et al., 1995) (Sadeghi, et al., 2018). This step corresponds to Step 2b in Figure 3.

### 3.5 Outline suitable evaluation grades.

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, indifferent, average, good* or *Excellent* (Yang & Xu, 2002) (Ren, et al., 2005). These five evaluation terms have been outlined, with $H_n$ denoting the $n^{th}$ evaluation grade. This step corresponds to Step 3a in Figure 3, and is demonstrated by Equation 1:

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

### 3.6 Develop the belief degrees and criteria weights for MADA analysis.

The weights of the criteria are calculated through Pairwise Comparison (PC) and Analytical Hierarchy Process (AHP), and are determined by qualitative assessment from expert judgement, using questionnaires. This step is further outlined in the analysis in Section 4.7. PC and AHP are selected as they are efficient methods of applying a qualitative data gathering mechanism to a quantitative methodology. The method of utilising PC and AHP to determine subjective quantitative data for application in a relative weighting system is exceptionally useful in filling gaps in data for additional analysis techniques, such as with the ER or Bayesian Network approaches.

It is supposed that there is a simple two-level hierarchy. Suppose there are $L$ basic criteria $e_j$ $(j=1\ldots L)$ associated with general criterion $E$. Similarly, suppose the normalised weights of each general criterion are given as $\omega_1, \omega_2 \ldots \omega_i \ldots \omega_L$ $(i=1\ldots L)$ where, $\omega_i$ is the relative weight of the $i^{th}$ general criterion $(E_i)$ with $0 \le \omega_i \le 1$ and $\omega_{ij}$ is the weight of the basic criterion $(e_i)$ $0 \le \omega_{ij} \le 1$, where $j$ represents the $j^{th}$ basic criterion under the $i^{th}$ general criterion. For example, the weighing of general criterion, Logistics, is represented by $\omega_1$ and the weight of the 3rd basic criterion under logistics, (Depth, $e_3$) is represented by $\omega_{13}$. See Figure 8 which outlines the evaluation hierarchy and contains the allocated notation related to the weighting of criteria. Furthermore, let $\beta_{n,i}$ denote the belief degree of the basic criterion $e_i$ to the evaluation grade $H_n$, where $\beta_{n,i} \geq 0$ and $\sum_{n=1}^{N} \beta_{n,i} = 1$ Finally, $S(e_i)$ is the assessment of an alternative under criterion $e_i$,. This assessment can be represented by Equation 2 (Yang & Xu, 2002) (Ren, et al., 2005) (Li & Liao, 2007) (Loughney, 2018). This step corresponds to Step 3b in Figure 3.

$$S(e_i) = \{(H_n, \beta_{n,i}), n = 1, \dots, N\} \;\; i = 1, \dots, L \tag{2}$$

The assessment of a criterion, $S(e_i)$ is complete if the sum of the belief degrees is equal to 1, *i.e.* $\sum_{n=1}^{N} \beta_{n,i} = 1$.

### 3.7 Evidential Reasoning Algorithm and Data Aggregation

Suppose $m_{n,i}$ is the probability mass representing the degree to which $e_i$ supports the hypothesis that the general criterion $E$ is assessed to $H_n$, and is calculated by Equation 3 (Yang & Xu, 2002) (Li & Liao, 2007) (Loughney, 2018).

$$m_{n,i} = \omega_i \beta_{n,i} \quad n = 1, \dots, N \tag{3}$$

Similarly, for basic criteria, Equation 3 is rewritten as Equation 4:

$$m_{n,j} = \omega_{ij} \beta_{n,i} \quad n = 1, \dots, N \tag{4}$$

where, $m_{n,j}$ is the probability mass of the basic criteria $e_j$ assessed to $Hn$. Also, $E_{I(j)}$ must be defined as the subset of the $j$ basic criteria under the $I^{th}$ general criterion, as given by Equation 5.

$$E_{I(j)} = \{e_1 \;\; e_2 \dots e_j\} \tag{5}$$

$m_{n,I(i)}$ is the probability mass defined as the degree to which all criteria in $E_{I(i)}$ support the hypothesis that $E$ is assessed to the grade $H_n$. Similarly, $m_{H,I(i)}$ is the remaining probability mass which is unassigned to individual grades after all the basic criteria in $E_{I(i)}$ have been assessed. The terms $m_{n,I(i)}$ and $m_{H,I(i)}$ can be determined by combining the basic probability masses $m_{n,}$ and $m_{H,j}$ for all values of $n=1, \dots, N$ and $j=1, \dots, i$ (Yang & Xu, 2002) (Li & Liao, 2007) (Loughney, 2018). Thus, the Evidential Reasoning algorithm is expressed through Equations 6, 7, 8 & 9.

$$K_{I(i+1)} = \left[1 - \sum_{t=1}^{N} \sum_{\substack{z=1 \\ z \neq t}}^{N} m_{t,I(i)} m_{z,i+1}\right]^{-1} \quad i = 1, \dots, L-1 \tag{6}$$

$$m_{n,I(i+1)} = K_{I(i+1)} \begin{pmatrix} m_{n,I(i)}m_{n,i+1} + m_{n,I(i)}m_{H,i+1} \\ +m_{H,I(i)}m_{n,i+1} \end{pmatrix} \quad n = 1, \ldots, N \tag{7}$$

$$m_{H,I(i+1)} = K_{I(i+1)}m_{H,I(i)}m_{H,i+1} \tag{8}$$

$$\beta_n = \frac{m_{n,I(L)}}{1 - m_{H,I(L)}}, \qquad n = 1, \ldots, N, \qquad i = 1, \ldots, L \tag{9}$$

where $K_{I(i+1)}$ is a normalising factor so that $\sum_{n=1}^{N} m_{n,I(i+1)} + m_{H,I(i+1)} = 1$ and $\beta_n$ is the combined belief degree of the aggregated assessment for the criteria (Yang & Xu, 2002) (Li & Liao, 2007). This step corresponds to Step 4a in Figure 3.

### 3.8 Utility Assessment and 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 grades are assumed to be equidistant as follows, with $u(H_1)=0$, $u(H_2)=0.25$, $u(H_3)=0.5$, $u(H_4)=0.75$ and $u(H_5)=1$ (Yang, 2001). The estimated utility for the general and basic criteria, $S(e_i)$, is given by Equation 9 and corresponds to Step 4b in Figure 3. (Yang & Xu, 2002) (Loughney, 2018):

$$u\big(S(e_i)\big) = \sum_{n=1}^{N} u(H_n)\beta_n\,(e_i) \tag{10}$$

### 3.9 Validation of the decision-making process.

Validation is a key aspect to the methodology, as it provides a reasonable amount of confidence to the results. In current literature, there is an axiom-based validation procedure, which is useful for validation of the process. The aggregation process may not be rational or meaningful if it does not follow certain axioms. The application of 4 axioms is consistent with the partial validation procedure applied to the ER approach and is heavily utilised in literature (Yang & Xu, 2002) (Durnbachm, 2012) (Loughney, 2018). This step is outlined by Step 5 in Figure 3, and the four axioms to be assessed are as follows:

- *Axiom 1.*
  A general criterion must not be assessed to $H_n$ if the basic criteria are not assessed to $H_n$.
- *Axiom 2.*
  The general criterion should be precisely assessed to $H_n$, provided all basic criteria are assessed to $H_n$.
- *Axiom 3.*

If all basic criteria, under a general criterion completely assessed to a given subset of evaluation grades, then the general criterion should be assessed to the same subset of grades.

- *Axiom 4.*

  If an assessment for basic criteria is incomplete, then the assessment for the general criterion should be incomplete to a certain degree.

# 4 APPLICATION OF METHOLOGY TO A CASE STUDY

## 4.1 Establish the domain and objective.

To determine the size and location of the larger area for analysis, conversations and meetings were held with experts in the area of renewable energy and the legislation that surrounds implementing an offshore wind farm. These meetings (which formed part of the ARCWIND project) were held with experts from industry and academia who are heavily involved in the development and implementation of offshore wind farms. These experts consisted of members from the following renewable energy companies:

- Two offshore wind farm structural development and construction companies from Spain,
- Two offshore wind testing companies in the UK and Ireland, specialising in both simulated and real environmental loading conditions,
- An offshore wind farm mooring development and construction company in Spain,
- A company specialising in the connection of offshore wind farms to national grids in Portugal,
- A company specialising Met ocean data gathering and analysis from France,
- Several academics from universities from UK, Ireland, France, Spain, and Portugal.

These conversations led to the selection of an area off the northern coast of Scotland, which is approximately 170km East to West ($3^o$ – $6^o$ West) by 83km North to South ($58.75^o$ – $59.5^o$ North and was divided into grids. This site can be seen in Figure 4. This area has subsequently been divided into 450 individual grid squares, each with an approximate area of $30km^2$ (5.5km×5.5km). If there are twenty 10 MW turbines in two rows of 10 and given the distance for separation (at least the topple distance of 120m), the grids are of sufficient size to contain a wind farm. These grids have been allocated a reference code depending on their location in the larger area. There is a scale running west to east from A to AD, and a scale running north to south from 1 to 15. Hence, the most North-Westerly grid is referenced as Site A1. For further reference to the site's location, the island of Orkney can be seen on the right side of Figure 4, with the Scottish mainland located at the bottom.

## 4.2 Identification and application of initial exclusion criteria.

The set of exclusion criteria is outlined in Table 1, along with an explanation as to why the criteria are necessary and being applied to this research. This process is conducted in Microsoft Excel utilising the IF and binary functions to produce a grid identifying the areas for further analysis. Figure 5 and Figure 6 outline the breakdown of the large region into areas where the initial evaluation criteria has been applied. Figure 7 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.

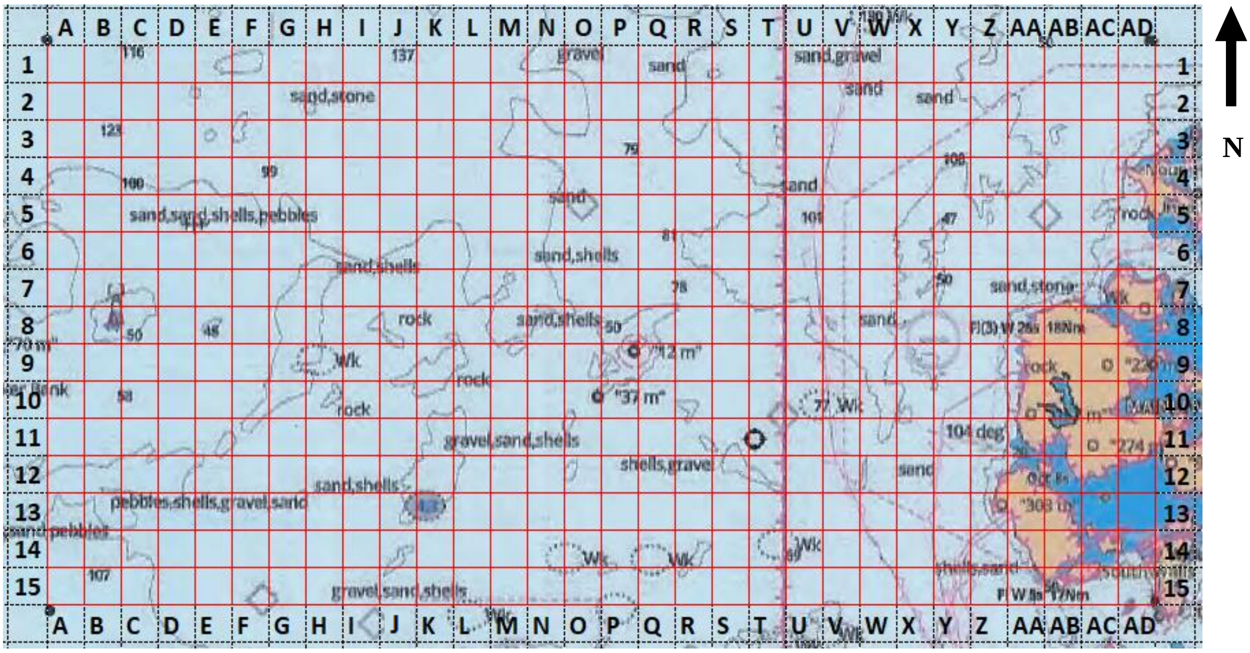

Figure 4: Large area, north of Scotland for FOW site selection analysis.

Table 1: Outline of the initial evaluation criteria for determining suitable sites for FOW

| Criteria | Description |
|---|---|
| Land Mass ($x_1$) | 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). |
| Landmarks ($x_2$) | These small rocky islands in the middle of the ocean, usually too small for human habitation. In most cases it is simply as rocky reef, also known as a Skerry or Sea Stack. An example of this is the Sule Skerry at 59.08°N 4.41°W and covers grid references P8, G8, P9 and Q9 in Figure 5. (Johnson & Webb, 2007) (Bist LLC, 2019). |
| Wrecks ($x_3$) | In this instance a shipwreck is the remains of a ship that has been wrecked and remains on the seabed. Designated shipwrecks of Scotland are protected under the Protection of Wrecks Act 1973 and the Ancient Monuments and |

| | |
|---|---|
| | Archaeological Areas Act 1979, which are UK-wide Acts that apply also in England, Wales, and Northern Ireland. (legislation.gov.uk, 1973) (legislation.gov.uk, 1979) (Bist LLC, 2019). |
| Fisheries ($x_4$) | 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 unauthorised access (European Union, 2013) (Marine Institute, 2019). |
| Military Training Areas ($x_5$) | These are areas outlined for training by the Ministry of Defence (MOD). These areas are to be excluded as they are utilised periodically by the MOD (Scottish Government, 2018) (Bist LLC, 2019). |
| Subsea Facilities ($x_6$) | This criterion includes the avoidance of subsea cables in the allocated area. There is a 500m restricted radius around offshore facilities and structures that break the surface at any state of the tide. It is an offence (under section 23 of the Petroleum Act 1987) to enter a safety zone except under the special circumstances (Legislation.gov.uk, 1987) (Bist LLC, 2019). |
| Marine Protection Area (MPA) ($x_7$) | MPAs are geographically distinct zones for which conservation objectives can be set. Marine reserves are MPAs where human impact is kept to a minimum, therefore, the extraction of resources is not permitted (EEA, 2015) (EEA, 2019) (Marine Scotland, 2019) (Bist LLC, 2019). |
| Special Area of Conservation (SAC) ($x_8$) | A SAC protects one or more special habitats and/or species, terrestrial or marine, listed in the Habitats Directive (European Union Council Directive 92/43/EEC). The Habitats Regulations implement the Habitats Directive in Scotland and provide protection to European protected species and Natura sites. (EEA, 2015) (EEA, 2019) (Marine Scotland, 2019) (Marine Institute, 2019) (Bist LLC, 2019). |
| Maximum Depth (m) ($x_9$) | The minimum depth for a potential site cannot be 60m or less as this is the minimum depth required to implement FOW structures. Fixed offshore wind structures operate to a maximum of 50-60m water depth (Bist LLC, 2019). |
| Wind Potential (m/s) ($x_{10}$) | 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 (Ifremer, 2019). |
| Extreme Wave Height (m) ($x_{11}$) | The extreme wave height shall exclude any areas with a Significant Wave Height ($H_s$) of ≥8m. This value is based upon the testing of a FOW structure conducted by Esteyco. (Esteyco, 2018) (Ifremer, 2019). |

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z | AA | AB | AC | AD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| 4 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 |
| 7 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 8 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 9 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

LAND MASS | WRECKS | FISHERY ZONE | LANDMARK | MILITARY AREAS | SUBSEA CABLES

Figure 5: Separation of the larger region through the application of initial evaluation criteria $x_1$, $x_2$, $x_3$, $x_4$, $x_5$ and $x_6$

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z | AA | AB | AC | AD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 6 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 |
| 7 | 1 | 1 | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 11 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |
| 15 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 |

LAND MASS | MPA | SAC

Figure 6: Separation of the larger region through the application of initial evaluation criteria $x_1$, $x_7$ and $x_8$

It can be seen in Figure 7 that the vast majority of sites have been excluded following the application of the initial evaluation criteria outlined in Table 1. Out of possible 450 sites, 45 have been identified for further analysis and ranking based upon their suitability for FOW implementation. It should be mentioned that the proximity to shipping lanes can be considered (Wu, et al., 2018), however, the majority of vessels in the area are fishing and recreational. Vessels such as medium to large containers or bulk carriers rarely venture into the region, they mainly stay close to the main coastline. Similarly, as fishing vessels dominate the region it is difficult to ascertain a consistent shipping route (ABP Marine Environmental Research, 2014). In the event a FOW farm is to be implemented, further legislative approaches would have to be carried out to satisfy the requirements of the fishing vessels and the FOW farm. Thus, shipping lanes and traffic density are not considered as a criterion for this research.

| | A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y | Z | AA | AB | AC | AD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 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 | 1 | 1 | 1 | 1 | 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 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 7 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 8 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 9 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 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 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 13 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 14 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 15 | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Figure 7: The result of the application of all initial evaluation criteria outlined in Table 1.

### 4.3 Identify individual criteria for quantitative analysis.

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 sixteen basic criteria.

- *Logistics (X)* is defined as the proximity of the site to key ports for installation and maintenance as well as the proximity to the nearest sub-station for grid connections and the maximum and minimum depth range of the site. The difference between ports for installation and maintenance is dependent on the size of the port. Ports that can cope with the installation, *i.e.* the housing and assembly of parts are known as category A ports and ports that are suitable for housing and transporting parts for maintenance are category B ports.

    - *Vicinity to Ports for Maintenance ($e_1$)*: This is the proximity of a site to category A+B ports. There are two ports that are suitable for maintenance purposes for the sites, these are Londonderry and Hunterston. There are three ports that are suitable for Installation (Category A), Stornoway, Belfast and Stranraer (IPORES, 2014) (Bist LLC, 2019).

    - *Sub-station Vicinity ($e_2$):* This criterion is based upon the distance of the sites to the available grid connections. On the northern coast of Scotland there is on location for grid connections. This sub-station is located at Dounreay and is currently the site of a nuclear facility. The average distance to the sub-station is 100km. This distance does not seem ideal however, given the distance from the coast that the FOW farms would be located, this situation is somewhat unavoidable (British Business energy, 2010) (Bist LLC, 2019).

- *Depth Range ($e_3$):* This criterion is associated with the maximum and minimum depth ranges at each suitable site. The assessment scale for the depth range is simpler to define with the worse scenario being 50m or less. (Bist LLC, 2019).

- *Vicinity to Ports for Installation ($e_4$):* This is the proximity of a site to only category A ports. This is a separate criterion as the preparation and installation of the wind farms is an extensive process and it is key that each site be evaluated given its range to this category of port in particular (IPORES, 2014) (Bist LLC, 2019).

- *Met-Ocean (Y)* is defined as the state of the environment at each site. This criterion includes five basic criteria relating to the wind speed, significant wave height, current speed, tidal range and the potential power output. The potential power has been included here as it directly relates to the wind speed.

  - *Wind Speed (m/s) ($e_5$):* This criterion relates to the potential wind speed at each site over a given time period. Each site is evaluated given the cut-in and cut-out speed of the previously outlined turbine. The data for the analysis is evaluated for each site given the average 10m 10minute wind speed, recorded four times a day, every day from 2011 – 2016 (Ifremer, 2019). The scale for wind speed is incremental between the cut-in and cut-out speed, with the lowest rating either greater than the cut-out or less than the cut-in (Esteyco, 2018).

  - *Potential Power Output (MW) ($e_6$):* This criterion relates to the wind speed and applies an equation for available power output, which is demonstrated by Equation 11 (Sarkar & Behera, 2012) (npower, 2018).

$$P = \frac{1}{2} . \rho . A . v^3 . C_p \tag{11}$$

where, $P$ is the available power, $\rho$ is the density of air at sea level, $A$ is the swept area of the turbine ($A = \pi . (rotor\ radius)^2$), $v$ is the wind speed and $C_p$ is the power coefficient. Some of these values are specific for a given turbine. As previously stated, the specification for the turbine is taken from testing conducted by Esteyco on a 10MW turbine of rotor diameter of 120m and a $C_p$ 0.43 (43%) (Esteyco, 2018) (Sarkar & Behera, 2012).

- *Significant Wave Height (SWH) (m) ($e_7$):* This criterion relates to the range of significant wave heights at each site from 2011 to 2016 (Ifremer, 2019). The data range is very much the same as the wind speed, it is the SWH per day per month per year. The scale for the assessment of this criterion is based on the best practice for the operation, and thus the grade of average is to be 5m ≤ x < 8m (Esteyco, 2018).

- *Tidal Range (m) ($e_8$):* This criterion is not vital for fixed wind farms but can be an influential factor for FOW structures as the tide will influence the depth in which the turbine will operate and hence affects the mooring system. In this research the tidal range is determined for each site based upon data from a tide and current software package, POLPRED (National Oceanography Centre, 2019). The average grade in the scaling for analysis is set to a total tidal range (positive and negative) of 4m ≤ x < 7m (Esteyco, 2018).

- *Current Speed (m/s) ($e_9$):* This criterion is again not vital to fixed wind turbines but can be key for FOW turbines. This is the velocity of the subsea currents and can affect the subsea sections of a FOW structure. In this research the current speed is determined in the same manner as the tidal range (National Oceanography Centre, 2019). The average grade in the scaling for analysis is set to a current speed of 1m/s ≤ x <1.75m/s (Esteyco, 2018).

- *Facilities and Environment (Z)* consists of a set of criteria that determine the proximity of the potential site to various facilities and areas in the vicinity. The basic criteria $e_{11}$ and $e_{13}$ are to be evaluated at the same grade, with the average grade in the scaling to be 30km < x ≤ 50km. This is due to the minimum distance, of 35km, from land where offshore wind farm are not considered too heavily impact the view from shore. Similarly, given the nature of the military training area, it was concluded that allocating this attribute the same scale was appropriate. All other criteria in this category follow the same evaluation scale with 0.5 km the worst possible grade and the scale increases incrementally from this value.

  - *Proximity to Sub-Sea Cables ($e_{10}$):* This criterion defines the proximity to undersea cables and the data within this abided by the minimum distance of 500m, hence avoiding the unauthorised zone (Bist LLC, 2019).

  - *Minimum Distance to Land ($e_{11}$):* This criterion defines the minimum distances from each site to either a large land mass, *i.e.* the northern coast of Scotland and the island of Orkney; or either of the landmarks located in the large area, *i.e.* Sule Skerry (Bist LLC, 2019).

- *Proximity to Fisheries ($e_{12}$):* This criterion defines the minimum distances of each available site to the two large fisheries outlined in Figure 5 (Bist LLC, 2019) (Marine Scotland, 2019) (EEA, 2019).

- *Proximity to Military Training Areas ($e_{13}$):* This criterion defines the minimum distance of each site to the designated military training area in the larger site (Scottish Government, 2018) (Bist LLC, 2019).

- *Proximity to Known Ship-Wrecks ($e_{14}$):* This criterion outlines the minimum distances to the known shipwrecks in the area, as outlined in Figure 5 (Bist LLC, 2019).

- *Proximity to MPAs ($e_{15}$):* This criterion determines the minimum distances of the available sites to the two outlined MPAs in Figure 6 (Bist LLC, 2019).

- *Proximity to SACs ($e_{16}$):* This criterion determines the minimum distance of the individual sites to the SAC located in the larger area (Bist LLC, 2019).

### 4.4 Develop the evaluation hierarchy.

The evaluation hierarchy is presented in Figure 8 where the notations are allocated based upon the explanations in Section 3.6. Based upon the initial evaluation criteria, all 45 identified sites are analysed against this set of criteria. This evaluation hierarchy denotes the sequence in which the 45 alternatives are to be assessed. They are each aggregated against the basic criteria, under each general criterion initially, then they assessed against the aggregated beliefs of the general criteria to determine one set of overall belief degrees. This set of overall belief degrees are then processed by Equation 9 to produce a rank of each alternative.

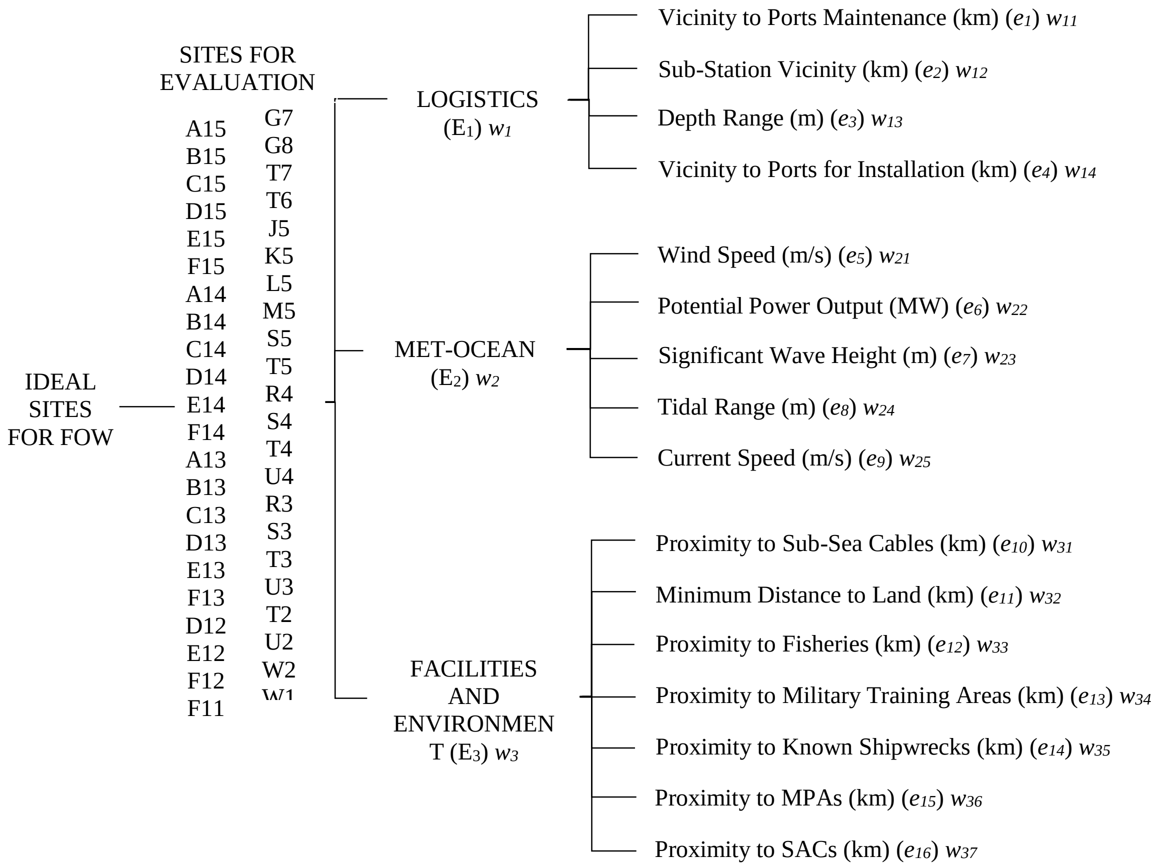


Figure 8: Evaluation Hierarchy for the available sites for FOW

### 4.5 Outline suitable evaluation grades.

As previously stated, the general criteria, such as *Logistics* are not easy to analyse directly due to the vast number of possible variables, so it is defined by four basic criteria. Hence, by assessing the basic criteria, the general criteria can also be assessed. In hierarchical assessment, higher level criteria are assessed through lower-level criteria. For example, if the criteria $e_1$, $e_2$, $e_3$ and $e_4$ are all deemed to be graded as *good* for a particular site, then the general attribute *logistics (X)* is also deemed to be *good*. Furthermore, following from the assessment of the basic criteria, for each alternative site, under a given general criterion, a belief structure is determined for the general criterion. This is the case for each general criterion; thus, the general criteria can be aggregated for each alternative site to produce an overall belief structure highlighting the suitability of each site for FOW implementation (Yang & Xu, 2002). It is important to note that in this analysis objective data sources are to be utilised, such as satellite met-ocean databases and navigational charts.

### 4.6 Determining the Belief Degrees

The belief degrees in this analysis are determined from a number of sources. For determining the proximity to various ports, navigational charts have been used to determine the distances in kilometres from the specified port to the centre of each individual site. This approach has also been employed for determining the proximity to facilities, restricted and protected areas. The met-ocean data has been determined from two distinct databases. The wind speed and wave height have been determined from satellite data provided by Ifremer from 2011 to 2016 (Ifremer, 2019). Similarly, the tidal and current data has been determined from Hindcast data provided by NOC in the form of their own in-house software, POLPRED (National Oceanography Centre, 2019).

### 4.7 Developing the relative weights of the criteria

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 PC and AHP, and are determined by qualitative assessment from expert judgement, using questionnaires. As outlined previously, three general criteria are considered, which are *Logistics, Met-ocean,* and *Facilities & Environment*. These criteria are generic and difficult to assess directly, therefore, sets of basic criteria are required.

Nine experts and their judgements were used to complete the qualitative questionnaire across the discipline of offshore wind structure and farm development within industry. The nine experts are to remain anonymous, however, all experts are currently in the employment of companies which develop and implement fixed and floating offshore wind structures. All experts have a MSc or PhD degree qualification and have 5 or more years' experience within the offshore renewable energy industry. The same experts provided data in interviews for the exclusion criteria, outlined in Section 4.1. The expertise of the experts are outlined as follows:

- 3 experts from an offshore wind farm structural development and construction company.
- 2 experts from an offshore wind testing company, specialising in both simulated and real environmental loading conditions.
- 2 experts from an offshore wind farm mooring development and construction company.
- 1 expert from a company specialising in the connection of offshore wind farms to national grids.
- 1 expert from a company specialising Met ocean data gathering and analysis.

Sample sizes in this type of research can be small to support the depth of case-oriented analysis that is fundamental to this mode of inquiry. Additionally, these samples are purposive, that is, selected by virtue of their capacity to provide richly textured information, relevant to the phenomenon under investigation. Furthermore, it is highlighted by Cohen et al. (2018) that non-probability sampling (demonstrated in this research) is useful in small scale research where a specific level of knowledge is required. This is the case in this study where specific knowledge of Floating Offshore Wind Farms in the Atlantic Arc region is vital and pivotal to the research (Cohen, et al., 2018) (Vasileiou, et al., 2018).

The PC and AHP methodologies and calculations are not demonstrated here, however some applications and examples can be found in the following studies (Saaty, 1980) (Saaty, 1990) (Saaty, 1994) (Ahmed, et al., 2005) (Koczkodaj & Szybowski, 2015). However, while the AHP methodology is not to be outlined in this paper, the Consistency Ratios (CR) are presented to indicate the validity and consistency of the data gathering process. To be regarded as consistent results, according to Saaty (1989 & 1990), the CR of the PC must be less than 0.1. The weights of the general and basic criteria are outlined in Table 3 and the consistency ratios are outlined as follows:

- General Criteria (X, Y and Z) – CR = 0.006 < 0.1
- Logistics (X) Basic Criteria ($e_1$ to $e_4$) – CR = 0.013 < 0.1
- Met-Ocean (Y) basic criteria ($e_5$ to $e_9$) – CR = 0.074 < 0.1
- Facilities & Environment (Z) basic criteria ($e_{10}$ to $e_{16}$) – CR = 0.031 < 0.1

The CR values for the PC following the AHP analysis, to determine relative weights, are all less than 0.1. This demonstrates the consistency and validity of the PC and AHP analysis applied in this research. Furthermore, the range of the weights across each expert is outlined in Table 2 where the range of Eigen Values of the matrices produced by each expert can also be found. This further solidifies the validity of the results, given the sample size.

Table 2: Range of weights and eigen values from the AHP analysis across all experts.

| Criteria | Criteria Notation | Weight Ranges |
|---|---|---|
| General Criteria | X | 0.48 |
| | Y | 0.33 |
| | Z | 0.51 |
| Eigen Value Range (General Criteria) | | 0.25 |
| Logistics | e1 | 0.23 |
| | e2 | 0.42 |
| | e3 | 0.38 |
| | e4 | 0.26 |
| Eigen Value Range (Logistics) | | 0.76 |
| Met-Ocean | e5 | 0.23 |
| | e6 | 0.43 |
| | e7 | 0.17 |
| | e8 | 0.06 |
| | e9 | 0.09 |
| Eigen Value Range (Met-Ocean) | | 0.55 |
| Facilities & Environment | e10 | 0.05 |
| | e11 | 0.10 |
| | e12 | 0.10 |
| | e13 | 0.09 |
| | e14 | 0.12 |
| | e15 | 0.11 |
| | e16 | 0.11 |
| Eigen Value Range (Facilities & Environment) | | 0.52 |

Utilising the PC and AHP methods, the weights for all the basic and general criteria are calculated and are demonstrated in Table 3. Table 4 is an example of part of the complete data table which consists of 5 grades for each set of 16 basic criteria, for all 45 sites in the analysis.

Table 3: Calculated weights for the general and basic criteria for use in the analysis of the sites in northern Scotland

| General criteria | Weights | Basic Criteria | Notation | Weights |
|---|---|---|---|---|
| LOGISTICS (X) | 17.56% | Vicinity to Cat. B ports | e1 | 16.17% |
| | | Vicinity to Sub-stations | e2 | 23.84% |
| | | Depth | e3 | 44.04% |
| | | Vicinity to Cat. A ports | e4 | 15.96% |
| | | | SUM | 100.00% |
| MET-OCEAN (Y) | 51.50% | Wind Speed | e5 | 34.51% |
| | | Power Output | e6 | 31.22% |
| | | Significant Wave Height | e7 | 22.79% |
| | | Tidal Range | e8 | 4.83% |
| | | Current Speed | e9 | 6.65% |
| | | | SUM | 100.00% |
| FACILITIES & ENVIRONMENT (Z) | 30.94% | Proximity to Subsea cables | e10 | 7.92% |
| | | Minimum distance to land | e11 | 6.69% |
| | | Proximity to fisheries | e12 | 6.88% |
| | | Proximity to Military Training Areas | e13 | 24.19% |
| | | Proximity to known shipwrecks | e14 | 4.24% |
| | | Proximity to MPAs | e15 | 23.50% |
| | | Proximity to SACs | e16 | 26.58% |
| SUM | 100.00% | | SUM | 100.00% |

Table 4: An example of a generalised decision matrix for site selection assessment with relative weights and basic attribute belief degrees

| General Attribute | Weight | Basic Attribute | Sites: A15 | B15 | C15 | D15 | E15 | F15 | Evaluation grade | Grading Scale |
|---|---|---|---|---|---|---|---|---|---|---|
| LOGISTICS | $w_{11}$= 0.1617 | Vicinity to Ports Maintenance (km) ($e_1$) | 0 | 0 | 0 | 0 | 0 | 0 | Poor | ≤ 700km |
| | | | 0.6 | 0.6 | 0.6 | 0.6 | 0.8 | 0.8 | Indifferent | 500km ≥ x < 700km |
| | | | 0.2 | 0.2 | 0.2 | 0.2 | 0 | 0 | Average | 300km ≥ x < 500km |
| | | | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | 0.2 | Good | 100km ≥ x < 300km |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | Excellent | >100km |
| | $w_{12}$= 0.2384 | Sub-Station vicinity (km) ($e_2$) | 0 | 0 | 0 | 0 | 0 | 0 | Poor | ≥ 175km |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | Indifferent | 125km ≥ x <175km |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | Average | 75km ≥ x < 125km |
| | | | 1 | 1 | 1 | 1 | 1 | 1 | Good | 25km ≥ x < 75km |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | Excellent | <25km |
| | $w_{13}$= 0.4404 | Depth (m) ($e_3$) | 0 | 0 | 0 | 0 | 0 | 0 | Poor | <50m |
| | | | 0 | 0 | 0 | 0.5 | 0.5 | 0.5 | Indifferent | 50m ≤x< 100m |
| | | | 0.5 | 0.5 | 0.5 | 0 | 0 | 0 | Average | 100m ≤x< 150m |
| | | | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | Good | 150m ≤x< 250m |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | Excellent | ≥ 250m |
| | $w_{14}$= 0.1596 | Vicinity to Ports for Installation (km) ($e_4$) | 0 | 0 | 0 | 0 | 0 | 0 | Poor | ≤ 700 |
| | | | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | 0.67 | Indifferent | 500 ≥ x < 700km |
| | | | 0 | 0 | 0 | 0 | 0 | 0 | Average | 300km ≥ x < 500km |
| | | | 0 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | Good | 100km ≥ x < 300km |
| | | | 0.33 | 0 | 0 | 0 | 0 | 0 | Excellent | >100km |

# 5 RESULTS AND DISCUSSION

## 5.1 Aggregation Assessment through Evidential Reasoning Algorithm

The problem now is how the belief degrees can be aggregated to arrive at an assessment as to the most suitable site for FOW implementation. To demonstrate the procedure of the ER algorithm the detailed steps of the calculation shall be shown for generating the assessment for the criterion *Logistics (X)*, by aggregating two basic criteria, *Depth* ($e_3$) and *Vicinity to Ports for Installation* ($e_4$), for site A15. The evaluation grades have been defined in Equation 1, and from Table 4 the following belief degrees can be stated:

$$\beta_{1,1} = 0, \quad \beta_{2,1} = 0, \quad \beta_{3,1} = 0.5, \quad \beta_{4,1} = 0.5, \quad \beta_{5,1} = 0$$

$$\beta_{1,2} = 0, \quad \beta_{2,2} = 0.67, \quad \beta_{3,2} = 0, \quad \beta_{4,2} = 0, \quad \beta_{5,2} = 0.33$$

As the weight have been determined the basic probability masses can be calculated through Equation 4, as this calculation deals with the aggregation of the basic criteria.

$$m_{1,1} = 0, \quad m_{2,1} = 0, \quad m_{3,1} = 0.5 \times 0.4404, \quad m_{4,1} = 0.5 \times 0.4404, \quad m_{5,1} = 0,$$
$$\sum_{n=1}^{N} m_{n,1} = 0.4404, \quad \therefore m_{H,1} = 0.5596$$

$$m_{1,2} = 0, \quad m_{2,2} = 0.67 \times 0.1596, \quad m_{3,2} = 0, \quad m_{4,2} = 0, \quad m_{5,2} = 0.33 \times 0.1596,$$
$$\sum_{n=1}^{N} m_{n,2} = 0.1596, \quad \therefore m_{H,2} = 0.8404$$

where, $m_{H,i}$ is the remaining probability mass unassigned to any individual grade after all grades have been considered (Yang & Xu, 2002) (Sadeghi, et al., 2018) (Li & Liao, 2007).

It is now possible apply the ER algorithm. Firstly, criteria $e_3$ and $e_4$ are to be aggregated using Equation 6 to find $K_{I(2)}$.

$$\sum_{\substack{t=1 \\ Z\neq t}}^{5} m_{t,I(1)} m_{z,2} = (m_{1,1}m_{2,2}) + (m_{1,1}m_{3,2}) + (m_{1,1}m_{4,2}) + (m_{1,1}m_{5,2})$$
$$= (0) + (0) + (0) + (0) = 0$$

$$\sum_{\substack{t=2 \\ z\neq t}}^{5} m_{t,I(1)} m_{Z,2} = (m_{2,1}m_{1,2}) + (m_{2,1}m_{3,2}) + (m_{2,1}m_{4,2}) + (m_{2,1}m_{5,2})$$
$$= (0) + (0) + (0) + (0) = 0$$

$$\sum_{\substack{t=3 \\ z\neq t}}^{5} m_{t,I(1)} m_{z,2} = (m_{3,1}m_{1,2}) + (m_{3,1}m_{2,2}) + (m_{3,1}m_{4,2}) + (m_{3,1}m_{5,2})$$
$$= (0) + \left((0.5 \times 0.4404).(0.67 \times 0.1596)\right) + (0)$$
$$+ \left((0.5 \times 0.4404).(0.33 \times 0.1596)\right) = 0.035$$

$$\sum_{\substack{t=4 \\ z\neq t}}^{5} m_{t,I(1)} m_{z,2} = (m_{4,1}m_{1,2}) + (m_{4,1}m_{2,2}) + (m_{4,1}m_{3,2}) + (m_{4,1}m_{5,2})$$
$$= (0) + \left((0.5 \times 0.4404).(0.67 \times 0.196)\right) + (0)$$
$$+ ((0.5 \times 0.4404).(0.33 \times 0.1596)) = 0.035$$

$$\sum_{\substack{t=5 \\ z\neq t}}^{5} m_{t,I(1)} m_{z,2} = (m_{5,1}m_{1,2}) + (m_{5,1}m_{2,2}) + (m_{5,1}m_{3,2}) + (m_{5,1}m_{4,2})$$
$$= (0) + (0) + (0) + (0) = 0$$

$$K_{I(2)} = [1 - (0.035 + 0.035)]^{-1} = 1.082$$

Given that the value of $K_{I(2)}$ has been determined, Equations 7 and 8 are utilised, as follows:

$$m_{1,I(2)} = K_{I(2)}\big(m_{1,1}m_{1,2} + m_{1,1}m_{H,2} + m_{H,1}m_{1,2}\big) = 0$$

$$m_{2,I(2)} = K_{I(2)}\big(m_{2,1}m_{2,2} + m_{2,1}m_{H,2} + m_{H,1}m_{2,2}\big) = 0.06$$

$$m_{3,I(2)} = K_{I(2)}\big(m_{3,1}m_{3,2} + m_{3,1}m_{H,2} + m_{H,1}m_{3,2}\big) = 0.2$$

$$m_{4,I(2)} = K_{I(2)}\big(m_{4,1}m_{4,2} + m_{4,1}m_{H,2} + m_{H,1}m_{4,2}\big) = 0.2$$

$$m_{5,I(2)} = K_{I(2)}\big(m_{5,1}m_{5,2} + m_{5,1}m_{H,2} + m_{H,1}m_{5,2}\big) = 0.032$$

$$m_{H,I(2)} = K_{I(2)}m_{H,1}m_{H,2} = 0.51$$

Finally, the combined belief degrees for this aggregation are determined through Equation 9.

$$\beta_1 = \frac{m_{1,I(2)}}{1 - m_{H,I(2)}} = \frac{0}{1 - 0.51} = 0$$

$$\beta_2 = \frac{m_{2,I(2)}}{1 - m_{H,I(2)}} = \frac{0.06}{1 - 0.51} = 0.12$$

$$\beta_3 = \frac{m_{3,I(2)}}{1 - m_{H,I(2)}} = \frac{0.2}{1 - 0.51} = 0.41$$

$$\beta_4 = \frac{m_{4,I(2)}}{1 - m_{H,I(2)}} = \frac{0.2}{1 - 0.51} = 0.41$$

$$\beta_5 = \frac{m_{5,I(2)}}{1 - m_{H,I(2)}} = \frac{0.032}{1 - 0.51} = 0.65$$

$$\sum_{n=1}^{5} \beta_n = 1$$

The outlined calculation represents an example of the calculations required for the aggregation assessment of the basic criteria. Given the basic criteria under the general criterion *Logistics*, the results from the outlined example would be utilised to form the assessment of a third basic criterion, and then the fourth ($e_1$, $e_2$, $e_3$ and $e_4$). Following the complete aggregation of the basic criteria $e_1$, $e_2$, $e_3$ and $e_4$, Equation 10 can be applied to determine the overall assessment of the general criterion *Logistics*, for site A15.

$$S(Logistics) = S(e_1 \oplus e_2 \oplus e_3 \oplus e_4) = \{(Poor, 0), (Indifferent, 0.1545), (Average, 0.2682),$$
$$(Good, 0.5398), (Excellent, 0.0376)\}$$

It is important to note that changing the aggregation order does not change the final results in any way. This process is applied to all of the 45 outlined sites, for all basic and general criteria through the application of the Intelligent Decision System (IDS) software. The calculations demonstrated in Section 4.2 for the assessment of site A15 in terms of *Logistics* were repeated for the other basic criteria for each of the 45 proposed sites. The results were then aggregated further to give the overall beliefs for the general criteria for each of the sites. All of the calculations were completed using IDS software as it is a reputable ER software package and displays the results clearly. All 45 sites have been assessed in the same manner.

## 5.2 Utility Ranking

Each individual site can be ranked based on their aggregated belief degrees in Table 4, and this is accomplished through utility assessment. In this section Equation 9 is applied and the rank of each site can be determined. One utility value can be determined for each site and they can subsequently be ranked in descending order to outline the most suitable to the least suitable. By applying the aggregated belief data calculated in the previous section and Equation 9, the overall utility ranking of site A15, in terms of *Logistics*, can be determined.

$$\begin{aligned} u\big(S(Overall)\big) &= (u(H_1)\beta_1) + (u(H_2)\beta_2) + (u(H_3)\beta_3) + (u(H_4)\beta_4) + (u(H_5)\beta_6) \\ &= (0 \times 0) + (0.25 \times 0.1545) + (0.5 \times 0.2682) + (0.75 \times 0.5398) + (1 \times 0.0376) \\ &= 0.6151 \end{aligned}$$

This utility assessment is conducted for each individual site for each general criterion and the overall suitability. Table 5 demonstrates the utility assessment results for the general criterion *Logistics*.

Table 5: Utility assessment results for the general criterion *logistics*

| LOGISTICS | | | | | |
|---|---|---|---|---|---|
| Rank | value | Loc. | Rank | Value | Loc. |
| 1 | 0.6273 | T7 | 24 | 0.5342 | A13 |
| 2 | 0.6151 | A15 | 25 | 0.5342 | B13 |
| 3 | 0.6082 | B15 | 26 | 0.5342 | C13 |
| 4 | 0.6082 | C15 | 27 | 0.5342 | T5 |
| 5 | 0.6082 | A14 | 28 | 0.5342 | R4 |
| 6 | 0.6082 | B14 | 29 | 0.5342 | S3 |
| 7 | 0.6040 | T3 | 30 | 0.5342 | S4 |
| 8 | 0.6040 | U3 | 31 | 0.5342 | U4 |
| 9 | 0.6040 | W2 | 32 | 0.5342 | T4 |
| 10 | 0.6040 | T6 | 33 | 0.5254 | F15 |
| 11 | 0.6025 | K5 | 34 | 0.5254 | E14 |
| 12 | 0.6025 | L5 | 35 | 0.5254 | F14 |
| 13 | 0.6025 | G7 | 36 | 0.5254 | D13 |
| 14 | 0.5979 | M5 | 37 | 0.5254 | X1 |
| 15 | 0.5871 | J5 | 38 | 0.5254 | X1 |
| 16 | 0.5722 | U2 | 39 | 0.5254 | F13 |
| 17 | 0.5722 | W1 | 40 | 0.5254 | F11 |
| 18 | 0.5722 | X1 | 41 | 0.5254 | D12 |
| 19 | 0.5722 | T2 | 42 | 0.5254 | F12 |
| 20 | 0.5437 | S5 | 43 | 0.5254 | E12 |
| 21 | 0.5342 | D15 | 44 | 0.5254 | E15 |
| 22 | 0.5342 | C14 | 45 | 0.5097 | R3 |
| 23 | 0.5342 | D14 | | | |

It can be seen in Table 5 that sites T7, A15, B15, C15, A14 and B14 make up the top 6 sites in terms of logistics. All of the sites, with the exception of T7 are all located to the south western corner of the larger area off the coast of Scotland. The proximity of site T7 to the grid connection on the mainland may have increased the performance of this site under the criterion of *Logistics*. Similarly, a key factor in this hypothesis is that the weighting for the criterion related to sub-station vicinity is the second highest under the general criterion of *Logistics* at 23.84%. Table 6 shows the results of the utility assessment for the general criterion *Met-ocean*.

Table 6: Utility assessment results for the general criterion *Met-ocean*

| MET-OCEAN | | | | | |
|---|---|---|---|---|---|
| Rank | value | Loc. | Rank | Value | Loc. |
| 1 | 0.7233 | T7 | 24 | 0.6917 | C14 |
| 2 | 0.7230 | T6 | 25 | 0.6917 | A13 |
| 3 | 0.7168 | R4 | 26 | 0.6917 | B13 |
| 4 | 0.7086 | A15 | 27 | 0.6917 | C13 |
| 5 | 0.7008 | U2 | 28 | 0.6917 | J5 |
| 6 | 0.7008 | W2 | 29 | 0.6917 | K5 |
| 7 | 0.7008 | X1 | 30 | 0.6917 | L5 |
| 8 | 0.6989 | S5 | 31 | 0.6917 | M5 |
| 9 | 0.6989 | T5 | 32 | 0.6911 | D14 |
| 10 | 0.6989 | S4 | 33 | 0.6911 | D13 |
| 11 | 0.6989 | T4 | 34 | 0.6911 | E13 |
| 12 | 0.6989 | U4 | 35 | 0.6911 | D12 |
| 13 | 0.6989 | R3 | 36 | 0.6911 | E12 |
| 14 | 0.6989 | S3 | 37 | 0.6911 | E14 |
| 15 | 0.6989 | T3 | 38 | 0.6805 | F11 |
| 16 | 0.6989 | U3 | 39 | 0.6685 | F12 |
| 17 | 0.6989 | T2 | 40 | 0.6682 | F15 |
| 18 | 0.6975 | G8 | 41 | 0.6682 | F14 |
| 19 | 0.6940 | W1 | 42 | 0.6682 | F13 |
| 20 | 0.6917 | B15 | 43 | 0.6389 | G7 |
| 21 | 0.6917 | A14 | 44 | 0.6129 | D15 |
| 22 | 0.6917 | C15 | 45 | 0.6067 | E15 |
| 23 | 0.6917 | B14 | | | |

It can be seen in Table 6 that six sites (*i.e.* T7, T6, R4, U2, W2 and X1) have a utility value more than 0.7 with a vast number of sites just under this 0.7 value at 0.6989. Furthermore, the rest of the sites up to rank 19, are all located in the approximate center of the larger site. This suggests that the ideal met-ocean conditions are in this region. This may be due to the fact that, it is the open sea, and the conditions are not greatly affected by obstructions, such as land, thus the conditions are consistent all year round. This is further verified by the fact that sites closer to the coast, D15 and E15 demonstrate the lowest ranks (44 & 45 respectively). Similarly, sites close to landmarks, such as G7 also demonstrate a low rank at 43. Site T7 also ranked in the top five sites in terms of *Logistics*. This demonstrates that it could be potentially one of the most suitable sites in the region. Table 7 demonstrates the utility assessment for the general criterion *Facilities & Environment*.

Table 7: Utility assessment results for the general attribute *Facilities & Environment*

| FACILITIES AND ENVIRONMENT | | | | | |
|---|---|---|---|---|---|
| Rank | value | Loc. | Rank | Value | Loc. |
| 1 | 0.8966 | A14 | 24 | 0.7646 | U4 |
| 2 | 0.8954 | A15 | 25 | 0.7534 | S5 |
| 3 | 0.8862 | A13 | 26 | 0.7504 | E13 |
| 4 | 0.8836 | X1 | 27 | 0.7504 | E13 |

| | | | | | |
|---|---|---|---|---|---|
| 5 | 0.8561 | B14 | 28 | 0.7443 | T6 |
| 6 | 0.8561 | B15 | 29 | 0.7425 | C13 |
| 7 | 0.8553 | W1 | 30 | 0.7352 | T7 |
| 8 | 0.8530 | W2 | 31 | 0.7304 | E15 |
| 9 | 0.8520 | B13 | 32 | 0.7241 | R4 |
| 10 | 0.8397 | R3 | 33 | 0.7241 | R4 |
| 11 | 0.8306 | S3 | 34 | 0.7023 | E12 |
| 12 | 0.8293 | T3 | 35 | 0.6874 | F14 |
| 13 | 0.8161 | T5 | 36 | 0.6812 | F15 |
| 14 | 0.8160 | S4 | 37 | 0.6598 | F13 |
| 15 | 0.8145 | T2 | 38 | 0.6439 | F12 |
| 16 | 0.8068 | T4 | 39 | 0.6367 | K5 |
| 17 | 0.7752 | U2 | 40 | 0.6302 | L5 |
| 18 | 0.7752 | U2 | 41 | 0.6300 | M5 |
| 19 | 0.7720 | U3 | 42 | 0.6285 | F11 |
| 20 | 0.7716 | U2 | 43 | 0.6231 | J5 |
| 21 | 0.7705 | S5 | 44 | 0.5855 | G8 |
| 22 | 0.7705 | S5 | 45 | 0.5726 | G7 |
| 23 | 0.7649 | D12 | | | |

Nine sites demonstrate a utility value of more than 0.85: A14, A15, A13, X1, B14, B15, W1, W2, and B13. However, the site T7, which was ranked first in both the *Logistics* and *Met-ocean* criteria, is now ranked 30th out of 45. This is most likely because it is very close to fisheries, an MPA and sub-sea cables. Furthermore, all of the sites that have a utility value of 0.85 or higher are either located at the Southwestern or north eastern extremes of the larger region. This can be attributed to a number of factors. The sites in the south west (A14, A15, A13, B14, B15, and B13) are far away from MPAs, SACs and marginally far away from military areas. Similarly, the north eastern sites (X1, W1 and W2) are far away from SACs and Military areas but are quite close to the MPAs. This is key as this would mean that these sites will have a high belief degree in the evaluation grades of *good* and *excellent*. Then this is coupled with the high relative weights for SACs, military areas and MPAs, 26.58%, 24.19% and 23.5% respectively. Thus, there is sound reasoning from the data as to why these sites are the best performers in this criterion. Table 8 demonstrates the overall utility assessment of the 45 individual sites.

Table 8: Results of the overall utility assessment for each individual site

| OVERALL ASSESSMENT | | | | | |
|---|---|---|---|---|---|
| Rank | value | Loc. | Rank | Value | Loc. |
| 1 | 0.7565 | A15 | 24 | 0.7002 | C15 |
| 2 | 0.7461 | A14 | 25 | 0.6981 | D14 |
| 3 | 0.7449 | X1 | 26 | 0.6970 | D13 |
| 4 | 0.7439 | W2 | 27 | 0.6953 | D12 |
| 5 | 0.7337 | A13 | 28 | 0.6918 | C14 |
| 6 | 0.7332 | T3 | 29 | 0.6894 | C13 |
| 7 | 0.7330 | B15 | 30 | 0.6834 | R4 |
| 8 | 0.7330 | B14 | 31 | 0.6834 | R4 |
| 9 | 0.7329 | W1 | 32 | 0.6764 | E12 |
| 10 | 0.7252 | S3 | 33 | 0.6648 | K5 |
| 11 | 0.7248 | T7 | 34 | 0.6622 | L5 |
| 12 | 0.7245 | T6 | 35 | 0.6618 | M5 |
| 13 | 0.7228 | B13 | 36 | 0.6596 | J5 |
| 14 | 0.7226 | T2 | 37 | 0.6571 | F14 |
| 15 | 0.7219 | R3 | 38 | 0.6551 | F15 |
| 16 | 0.7206 | S4 | 39 | 0.6513 | D15 |
| 17 | 0.7201 | T5 | 40 | 0.6487 | F13 |
| 18 | 0.7189 | R4 | 41 | 0.6466 | F11 |
| 19 | 0.7171 | T4 | 42 | 0.6439 | F12 |

| | | | | | |
|---|---|---|---|---|---|
| 20 | 0.7163 | U3 | 43 | 0.6438 | G8 |
| 21 | 0.7112 | U2 | 44 | 0.6325 | E15 |
| 22 | 0.7050 | U4 | 45 | 0.6153 | G7 |
| 23 | 0.7028 | S5 | | | |

Finally, the potential offshore sites for the site in northern Scotland are ranked, in Table 8, based upon their overall performance from the aggregation and utility assessments. It can be seen that site A15 is deemed to be the most favourable of the 45 potential sites. This is not unexpected as this site has ranked consistently in the top 5 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. The relative weights of the general criteria are 17.56%, 30.94 and 51.5% for *Logistics*, *Met-Ocean* and *Facilities & Environment* respectively. This influence can be seen in the aggregated assessment as site A14 ranks 21st in terms of *Met-ocean* suitability but ranks 1st in term of *Facilities & Environment*. Similarly, the criterion of *Met-ocean* 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 2nd in terms of overall suitability. This is also evident by the fact that two of the sites (W2 and X1) that ranked in the top 10 in the two highly weighted criteria, also ranked in the top 5 overall. This effect of the weighting of the general criteria can be seen across the analysis and results.

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

$$A15 > A14 > X1 > W2 > A13$$

It can be seen from Figure 9 that the top 5 sites are either in southwestern area or the northeastern 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 9 that the most suitable collective areas are the southwestern or the north-northeastern areas, which collectively follows with the locations of the top 5 sites. The results clearly demonstrate that moving further into 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 due to the close proximity of landmarks, there is a disruption of continuous air flow. Thirdly, while they are increasingly further from the mainland, they are also further away from the nearest sub-station.

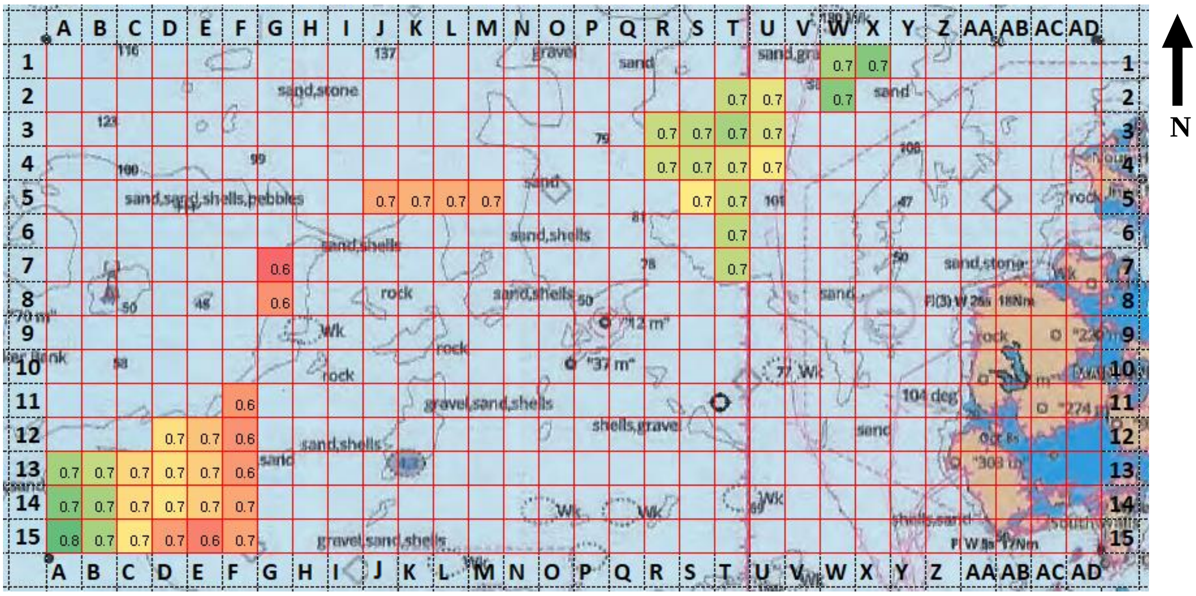


Figure 9: Graphical representation of the most suitable sites for floating offshore wind (Green = Best, Red = Worst)

## 5.3 Validation

In order to verify the method of applying the ER algorithm to the decision-making process, it must first satisfy the four axioms stated in Section 3.9. The overall beliefs and the general criteria beliefs are very much reliant on the magnitude of the belief degrees of the basic criteria. Each axiom shall be identified, and cross examined individually.

*The independence axiom:* This axiom can be said to be satisfied because when the aggregation of the general criterion *Logistics* is analysed, for site A15. It can be seen that none of the basic criteria are assessed to the grade *poor*, *i.e.* $\beta_{(n,i)}=0$ for $i = 1, \ldots, L$. Thus, the belief degree of the evaluation grade, *poor*, for the general criterion, *Logistics*, should also be equal to 0, *i.e.* $\beta_n = 0$, which it does.

*The consensus axiom:* This axiom can be said to be satisfied by the example of the aggregation of the basic criteria of *Logistics* for site A15. The initial belief degrees for the evaluation grades, *poor*, *indifferent* and *excellent* of the basic criteria $e_1$, $e_2$, $e_3$ and $e_4$ are *poor* (0, 0, 0, 0), *indifferent* (0.6, 0, 0, 0.67), *average* (0, 0.2, 0.5, 0), *good* (0.2, 1, 0.5, 0) and *excellent* (0, 0, 0, 0.33) respectively. The axiom is satisfied, in this case, by the magnitude of the aggregated belief degrees of the basic criteria. Given the belief degrees outlined it would be expected that poor would be 0, as all belief degrees in this evaluation grade are 0. Similarly, based on the beliefs, the highest value, once aggregated, would be attributed to the grade good due to consistent values and somewhat large values. Therefore, the aggregated belief structure for site A15 under the attribute *Logistics* is poor (0), indifferent (0.1583), average (0.268), good (0.5395) and excellent (0.0341). This trend can be seen across all of the data aggregation for all of the criteria. Hence, the ER analysis satisfies the consensus axiom.

*The completeness axiom*: This is true throughout the entire analysis where all criteria are assessed to the same set of evaluation grades of: *poor, indifferent*, *average*, *good* and *excellent.* Therefore, this axiom can be said to be satisfied.

*The incompleteness axiom:* This is consistent throughout the analysis as there are not any incomplete belief degrees, and all belief degrees sum to equal one for each criterion.

Further validation of the methodology can be seen when the grid of the site, with the most suitable areas highlighted, is overlaid onto the map shown in Figure 2 (4COffshore, 2020) which demonstrates the areas under initial survey for offshore wind implementation. Figure 10 (4COffshore, 2020) shows the locations of the identified sites and the sites under survey. It can be seen that the sites to the south west of the area fall quite well within the ranges of the site under survey by the Scottish government (the left most triangle). There appears to be a small discrepancy with the sites in the south west, but this could be due to the size and configuration of the grid allocation in the methodology. What is also key is that the cluster of sites in the south west form the same shape as the survey area outlined by the Scottish government. However, the site in the centre of the large area is currently in an area where the depth is not suitable for FOW (<60m). Thus, this is area is excluded from the analysis at the initial stage due to the insufficient depth. Given this, the only sites that would be suitable for FOW, in this region would be to the South-West, in deeper water, which have been allocated by the Scottish government and reinforced by the results of this research. This correlation with actual governmental offshore wind development surveys gives further validation to the methodology.

However, the sites identified to the north and the north east do not fit into any areas outlined for survey. This may be to unforeseen restrictions not allocated in the methodology or because the government simply does not wish to survey in these areas. Nevertheless, it is an area for further study and development of the methodology. Similarly, the survey site in the centre is within MPAs and SACs which is allocated as a restricted site in the methodology. However, in Scotland, it is possible to survey and plan offshore wind farms within MPAs and SACs with caution. The reason this factor was not included in the methodology was purely precautionary. The methodology was designed to be generic and applicable to any area in the world given available data. It can simply be the case that the MPA restriction are removed and it will be possible to identify potential sites in these outlined survey areas.

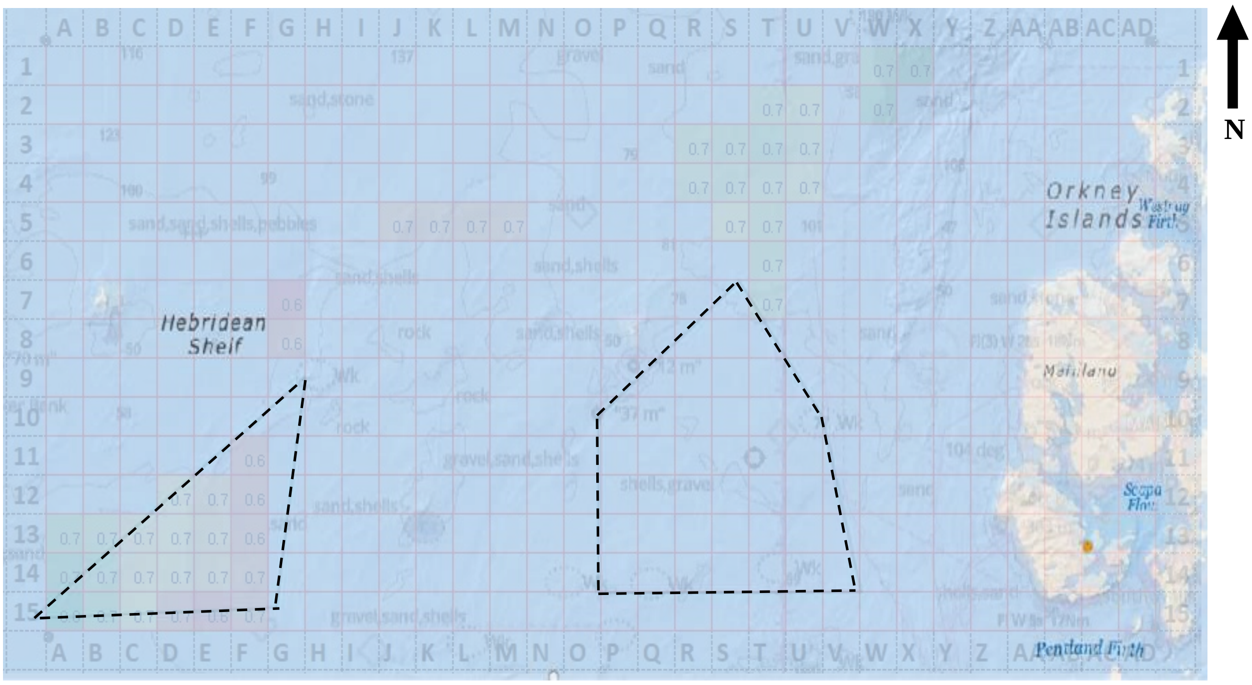


Figure 10: The identified sites in Scotland overlaid onto a map of areas under survey for FOW by the Scottish Government

## 6 CONCLUSION

This research set out to develop a MADA methodology for suitable site selection for floating offshore wind farms on the UK continental shelf. A large site was selected off the north coast of Scotland and was subsequently divided into a grid system with 450 individual sites. Initially, 11 evaluation criteria were determined in order to remove sites that fell into areas that are restricted for offshore development. The evaluation criteria included marine protected, military areas, landmass and subsea facilities. The application of the initial criteria identified 45 sites where a floating offshore wind farm may be implemented. These 45 sites were quantitatively analysed against a set of 16 basic criteria under 3 general criteria. In order to conduct the analysis, an evaluation hierarchy was established based upon the basic and general criteria outlined. Data was then gathered for each site given each basic criterion, in order to apply the ER algorithm. For this analysis, the weights within the ER methodology were calculated utilising PC and AHP and the belief degrees under the general criteria *Logistics* and *Facilities & Environment* were determined from navigational charts, government reports and EU reports, as well as environmental databases such as Natura2000. The data for the belief degrees under the general criterion *Met-ocean* was determined from two separate databases from National Oceanography Centre (POLPRED Software) and Ifremer. This data was then applied to the ER algorithm and the results of the case study were obtained.

This case study was then validated against a 4-axiom benchmark test and comparison to planned surveys for FOW implementation in the area. Both procedures gave some validation to the model by fulfilling the 4 axioms and demonstrating some correlation with the government sites outlined for survey. It was determined that in Scotland site A15 (approximately 58.8$^O$ N 6$^O$ W) and 3 adjacent sites (A14, A14 and A13) along with 2 other sites (X1 and W2) at approximately 59.45$^O$ N 3.7$^O$ W were the most ideal for the implementation of a floating offshore wind farm. The results of the ER analysis were then validated against 4 axioms. Similarly, the ranking order of all 45 sites is produced.

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 PC 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 presented mixed method approach, utilising ER, can accurately be used as a viable decision-making tool in the site selection for floating offshore wind farms.

## DECLARATION OF CONFLICTING INTERESTS

The authors declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: This paper is the opinion of the authors and does not represent the belief and policy of their employers.


## FUNDING

Thanks are given to the EU for its financial support under a European Commission funded project ARCWIND 2017 – 2021 (EAPA_344/2016), as well as to the European Marine Energy Centre (EMEC), the National Oceanography Centre (NOC) Liverpool and Ifremer (French Research Institute for the Exploitation of the Sea) for their data contributions. This research is also partially supported by EU H2020 RISE 2016 RESET – 730888.


## NOMENCLATURE

| | |
|---|---|
| $\beta_{n,i}$ | belief degree of the basic criterion, $e_i$ |
| $E$ | General criterion. |
| $E_{I(i)}$ | Subset of the $i^{th}$ basic criteria under the $I^{th}$ general criterion. |
| $e_i$ | $i^{th}$ basic criterion. |
| $H_n$ | $n^{th}$ evaluation grade to which the basic and general criteria are assessed. |
| $K_{I(i+1)}$ | is a normalising factor. |
| $m_{H,i}$ | Remaining probability mass unassigned to any individual grade after all grades have been considered. |
| $m_{H,I(i)}$ | Remaining probability mass which is unassigned to individual grades after all the basic criteria in $E_{I(i)}$ have been assessed. |

| | |
|---|---|
| $m_{n,i}$ | Probability mass representing the degree to which $e_i$ supports the hypothesis that the attribute $E$ is assessed to $H_n$. |
| $m_{n,I(i)}$ | Probability mass defined as the degree to which all criteria in $E_{I(i)}$ support the hypothesis that $E$ is assessed to the grade $H_n$. |
| $m_{n,j}$ | probability mass of the basic criteria $e_j$ assessed to $Hn$. |
| $u(H_n)$ | The utility value of an evaluation grade, $H_n$, used to determine the ranking of alternatives. |
| $\omega_i$ | the relative weight of the $i^{th}$ general criterion. |
| $\omega_{ij}$ | the weight of the $j^{th}$ basic criterion under the $i^{th}$ general criterion. |
| ARCWIND | Adaptation and implementation of floating wind energy conversion technology for the Atlantic region |
| AHP | Analytical Hierarchy Process |
| ER | Evidential Reasoning |
| FOW | Floating Offshore Wind |
| GW | Giga-Watts |
| MADA | Multiple attribute Decision Analysis |
| MPA | Marine Protected Areas |
| MW | Mega-Watt |
| SAC | Special Area of Conservation |
| UKCS | United Kingdom Continental Shelf |

**REFERENCES**

4COffshore, 2020. *Global Offshore Map.* [Online] Available at: https://www.4coffshore.com/offshorewind/

ABP Marine Environmental Research, 2014. *Mapping UK shipping Density and Routes from AIS,* London: Marine Management Organisation.

Ahmed, A. et al., 2005. Application of Analytical Hierarchy Process and Bayesian Belief Networks for Risk analysis. *Complexity International,* Volume 12, pp. 1-10.

Ari, E. S. & Gencer, C., 2020. The use and comparison of a deterministic, a stochastic, and a hybrid multiple-criteria decision-making method for site selection of wind power plants: An application in Turkey. *WIND ENGINEERING,* 44(1), pp. 60-74.

Bist LLC, 2019. *GPSNautical Charts.* [Online] Available at: http://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-

charts-navigation.html#4.29/35.454/-121.153
[Accessed January 2018].

British Business energy, 2010. *Map of The UK's Electricity Supply System Network Grid.* [Online] Available at: https://britishbusinessenergy.co.uk/electricity-supply-system/
[Accessed January 2019].

Chaouachi, A., Covrig, C. F. & Ardelean, M., 2017. Multi-criteria selection of offshore wind farms: Case study for the Baltic States. *Energy Policy,* Volume 103, pp. 179-192.

Cohen, L., Manion, L. & Morrison, K., 2018. Chapter 12 Sampling. In: *Research Methods in Education.* New York: Routledge 8th Edition, pp. 202 - 227.

Court, R. S. & Grimwade, J., 2014. *Offshore renewable energy standardization review,* bsi & InnovateUK - Technology strategy board.

Cradden, L. et al., 2016. Multi-criteria site selection for offshore renewable energy platforms. *Renewable Energy,* Volume 87, pp. 791-806.

Crown Estate, 2013. *Round 3 Offshore WInd Site Selection at National and Project Levels,* The Crown Estate.

Crown Estate, 2018. *Offshore Wind Operational Report,* The Crown Estate.

Department for Business, Energy & Industrial Strategy, 2019. *UK National Energy and Climate Plan (NECP),* London: Gov.uk.

Deveci, M. et al., 2020. A study on offshore wind farm siting criteria using a novel interval-valued fuzzy-rough based Delphi method. *JOURNAL OF ENVIRONMENTAL MANAGEMENT,* Volume 270, p. online.

Durnbachm, I. N., 2012. An empirical test of the evidential reasoning approach's synthesis axioms. *Expert Systems with Applications,* 39(12), pp. 11048 - 11054.

EEA, 2015. *Marine protected areas in Europe's seas - An overview and perspectives for the future,* Luxembourg: European Environment Agency (EEA) - Report No.: 3/2015.

EEA, 2019. *Natura2000 Network Viewer - European Environment Agency.* [Online] Available at: http://natura2000.eea.europa.eu/
[Accessed April 2019].

Emeksiz, C. & Demirci, B., 2019. The determination of offshore wind energy potential of Turkey by using novelty hybrid site selection method. *Sustainable Energy Technologies and Assessments,* Volume 36, pp. 1-21.

Energy Vice, 2021. *UK renewable energy capacity set to double by 2026, when offshore wind will overtake onshore.* [Online]
Available at: https://www.energyvoice.com/renewables-energy-transition/wind/uk-wind/274960/uk-renewable-energy-capacity-double-2026/#:~:text=From%2010.5%20GW%20in%202020,2021%20from%208.9%20GW%20today.
[Accessed February 2021].

Equinor, 2019. *hywind-up-close-and-personal.* [Online]
Available at: https://www.equinor.com/en/what-we-do/hywind-where-the-wind-takes-us/hywind-up-close-and-personal.html
[Accessed April 2019].

Esteyco, 2018. *ARCWIND - Model description and inputs,* Esteyco for Liverpool John Moores University - ARCWIND-WP5-RPT-NAV-001-VA.

European Union, 2013. REGULATION (EU) No 1380/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL. *on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC,* 11 September.

Fonseca, R. B., Díaz, H. & Soares, C. G., 2018. *Site selection process for floating offshore wind farms in Madeira Islands.* Lisbon, Portugal, Advances in Renewable Energies Offshore: Proceedings of the 3rd International Conference on Renewable Energies Offshore (RENEW 2018), October 8-10, 2018..

Gadad, S. & Deka, P. C., 2016. Offshore wind power resource assessment using Oceansat-2 scatterometer data at a regional scale. *Applied Energy,* Volume 176, pp. 157 - 170.

Goke, C., Dahl, K. & Mohn, C., 2018. Maritime Spatial Planning supported by systematic site selection: Applying Marxan for offshore wind power in the western Baltic Sea. *PLOS ONE,* 13(3 https://doi.org/10.1371/journal.pone.0194362), pp. 1 - 13.

Halkyard, J., 2005. Chapter 7 - Floating Offshore Platform Design. In: S. K. Chakrabarti, ed. *Handbook of Offshore Engineering.* Plainfield, Illinois, USA: Elsevier Science, pp. 419-661.

Hill, J., 2018. *Hywind Scotland, World's First Floating Wind Farm, Performing Better Than Expected.* [Online]
Available at: https://cleantechnica.com/2018/02/16/hywind-scotland-worlds-first-floating-wind-farm-performing-better-expected/
[Accessed April 2019].

Ifremer, 2019. *Marine Data Portal.* [Online] Available at: http://data.ifremer.fr/pdmi/portalssearch/main [Accessed January 2019].

IPORES, 2014. *A review of irish prots offshore capability in relation to requirements for the marine renewable energy industry,* Dublin: Irish Maritime Development Office - Irish Ports Offshore Renewable Energy Services (IPORES).

IRENA, 2016. *Floating Foundations: a Game Changer for Offshore Wind Power,* Abu Dhabi: The International Renewable Energy Agency.

James, R. & Ros, M. C., 2015. *Floating Offshore Wind: Market and Technology Review,* London: Carbon Trust.

Johnson, M. E. & Webb, G. E., 2007. Outer Rocky Shores of the Mowanbini Archipelago, Devonian Reef Complex, Canning Basin, Western Australia. *The Journal of Geology,* 115(5), pp. 583 - 600.

Kim, C.-K., Jang, S. & Kim, T. K., 2018. Site selection for offshore wind farms in the southwest coast of South Korea. *Renewable Energy,* Volume 120, pp. 151 - 162.

Kim, J.-Y., Oh, K.-Y., Kang, K.-S. & Lee, J.-S., 2013. Site selection of offshore wind farms around the Korean Peninsula through economic evaluation. *Renewable Energy,* Volume 54, pp. 189 - 195.

Kim, T., Park, J.-I. & Maeng, J., 2016. Offshore wind farm site selection study around Jeju Island, South Korea. *Renewable Energy,* Volume 94, pp. 619- 628.

Koczkodaj, W. & Szybowski, J., 2015. Pairwise Comparison Simplified. *Applied Mathematics and Computation*, Volume 253, pp. 387-394.

legislation.gov.uk, 1973. *Protection of Wrecks Act 1973,* legislation.gov.uk & the National Archives.

legislation.gov.uk, 1979. *Ancient Monuments and Archaeological Areas Act 1979,* Legislation.gov.uk & the National Archives.

Legislation.gov.uk, 1987. *Petroleum Act 1987,* London: Legislation.gov.uk & the National Archives.

Li, Y. & Liao, X., 2007. Decision support for risk analysis on dynamic alliance. *Decision support systems,* Volume 42, pp. 2043-2059.

Lo, H., Hsu, C., Chen, B. & Liou, J., 2021. Building a grey-based multi-criteria decision-making model for offshore wind farm site selection. *Sustainable Energy Technologies and Assessments,* Volume 43, pp. 1-13.

Loughney, S., 2018. *Asset Integrity Case Development for Normally Unattended Offshore Installations.* Liverpool: Doctoral Thesis, Liverpool John Moores University.

Marine Institute, 2019. *Biologically Sensitive Area.* [Online] Available at: https://www.marine.ie/Home/site-area/areas-activity/fisheries-ecosystems/biologically-sensitive-area-0
[Accessed April 2019].

Marine Scotland, 2019. *Maps NMPI part of scotlands Environment.* [Online] Available at: https://marinescotland.atkinsgeospatial.com/nmpi/default.aspx?layers=844
[Accessed April 2019].

Mytilinou, V., ozano-Minguez, E. & Kolios, A., 2018. A Framework for the Selection of Optimum Offshore Wind Farm Locations for Deployment. *Energies*, 11(7), pp. 1855 - 1878.

National Oceanography Centre, 2019. *Offshore - POLPRED Offshore Tidal Software.* [Online] Available at: https://noc.ac.uk/business/marine-data-products/offshore
[Accessed January 2019].

npower, 2018. *Wind Turbine Power Calculations,* The Royal Academy of Engineering & npower.

Offshore Energy, 2018. *The future's floating,* Offshore Energy - Friends of floating offshore wind.

Orsted, 2018. *Orsted Annual Report 2018,* Orsted.

Orsted, 2019. *The world's biggest offshore wind farm, Hornsea One, generates first power.* [Online] Available at: https://hornseaprojectone.co.uk/News/2019/02/The-worlds-biggest-offshore-wind-farm-Hornsea-One-generates-first-power
[Accessed May 2019].

Orsted, 2020. *Annual Report 2020,* Orsted.

Orsted, 2021. *https://hornseaprojectone.co.uk/.* [Online] Available at: https://hornseaprojectone.co.uk/
[Accessed January 2021].

Peters, J. L., Remmers, T. & Wheeler, A. J., 2020. A systematic review and meta -analysis of GIS use to reveal trends in offshore wind research and offer on best. *RENEWABLE & SUSTAINABLE ENERGY REVIEWS,* Volume 128.

Ramakrishnan, T. V., 2007. *Marine & Offshore Engineering.* 1 ed. Gene-Tech Books.

RenewableUK, 2021. *Wind Energy Statistics.* [Online] Available at: https://www.renewableuk.com/page/UKWEDhome
[Accessed February 2021].

Ren, J. et al., 2005. an offshore safety assessment framework using fuzzy reasoning and evidential synthesis approaches. *Journal of Marine Engineering and Technology,* 4(1), pp. 3 - 16.

Saaty, T., 1980. *The Analytical Hierarchy Process.* NY: McGraw-Hill Book Co..

Saaty, T., 1990. How to Make a Decision: The Analytical Hierarchy Process. *Journal of Operational Research,* Volume 48, pp. 9-26.

Saaty, T., 1994. *Fundamentals of Decision Making.* Pittsburgh, PA: RWS Publication.

Sadeghi, A., Farhad, H., Moghaddam, A. M. & Qazizadeh, M. J., 2018. Identification of accident-prone sections in roadways with incomplete and uncertain inspection-based information: A distributed hazard index based on evidential reasoning approach. *Reliability Engineering & System Safety,* Volume 178, pp. 278 - 289.

Sarkar, A. & Behera, D. K., 2012. Wind Turbine Blade Efficiency and Power Calculation with Electrical Analogy. *International Journal of Scientific and Research Publications,* 2(2), pp. ISSN 2250-3153.

Scottish Government, 2018. *Sectoral marine plan for offshore wind energy: social and economic impact assessment scoping report,* Edinburgh: Scottish Government (gov.scot) - ISBN: 978-1-78851-961-8.

Shao, M., Han, Z., Sun, J., Xiao, C., Zhang, S. & Zhao, Y., 2020. A review of multi-criteria decision making applications for renewable energy site selection. *Renewable Energy,* 157, pp. 377-403.

Sönmez, M., Yang, J., Graham, G. & Holt, G., 2012. An Evidential Reasoning based Decision Making Process for Pre-qualifying Construction Contractors. *Journal of Decision Systems* , 11(3-4), pp. 355-381.

Statoil, 2015. *Hywind Scotland Pilot Park - Environmental Statement,* : Assignment Number: A100142-S35, Document Number: A-100142-S35-EIAS-001-015.

Tercan, E. et al., 2020. A GIS-based multi-criteria model for offshore wind energy power plants site selection in both sides of the Aegean Sea. *Environmental Monitoring and Assessment volume* , 192(625).

Thomsen, K., 2011. *Offshore Wind: A Comprehensive Guide to Successful Offshore Wind Farm Installation.* 1st ed. Elsevier .

Vasileiou, K., Barnett, J., Thorpe, S. & Young, T., 2018. Characterising and justifying sample size sufficiency in interview-based studies: systematic analysis of qualitative health research over a 15-year period.. *MC Med Res Methodol,* 18(148), pp. 1-18 [online].

Wang, J., Yang, J. B. & Sen, P., 1995. Safety analysis and synthesis using fuzzy sets and evidential reasoning. *Reliability Engineering & System Safety*, 47(2), pp. 103 - 118.

Wang, Y.-M., Yang, J.-B. & Xu, D.-L., 2006. Environmental impact assessment using the evidential reasoning approach. *European Journal of Operational Research*, 174(3), pp. 1885 - 1913.

Wind Europe, 2018. *Floating offshore wind energy: a policy blueprint for Europe.* [Online] Available at: https://windeurope.org/policy/position-papers/floating-offshore-wind-energy-a-policy-blueprint-for-europe/#
[Accessed April 2019].

Wu, B., Yip, T. L., Xie, L. & Wang, Y., 2018. A fuzzy-MADM based approach for site selection of offshore wind farm in busy waterways in China. *Ocean Engineering*, Volume 168, pp. 121-132..

Yang, J., 2001. Rule and Utility based evidential reasoning approach for multiattribute decision analysis under uncertainties. *European Journal of operational Research*, Issue 131, pp. 31 - 61.

Yang, J. & Xu, D., 2002. On the Evidential Reasoning Algorithm for Multiple Attribute Decision analysis Under Uncertainty. *IEEE Transactions on Systems, Man and Cybernetics - Part A: Systems and Humans*, 32(3), pp. 289 - 304.

# Highlights – Application of a Multiple-Attribute Decision-Analysis methodology for site selection of floating offshore wind farms on the UKCS

- Qualitative and quantitative methodology outlined for floating wind site selection
- Case study applied to Northern coast of Scotland; 45/450 sites identified
- sites are analysed and ranked against 3 main criteria and 16 basic criteria
- top 4 sites found to be adjacent, hence large site identified for floating wind
- Evidential Reasoning is a viable tool in offshore wind energy site selection

# CRediT Author Statement

**Sean Loughney:** Conceptualization, Methodology, Investigation, Data curation, Software Writing-Original draft preparation

**Jin Wang:** Conceptualization, Data curation, Supervision, Funding acquisition, Writing- Original draft preparation.

**Musa Bashir:** Funding acquisition, Supervision, Writing- Reviewing and Editing.

**Milad Armin:** Validation, Software, Data curation.

**Yang Yang:** Validation, Writing- Reviewing and Editing,