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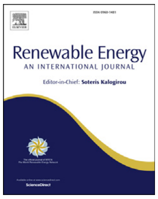

New approach to determine the Importance Index for developing offshore wind energy potential sites: Supported by UK and Arabian Peninsula case studies

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ABSTRACT

A multi-criteria decision-making analysis linked to a Geographical Information System was developed to solve the spatial siting for offshore wind farms taking into account appropriate conflicting factors/constraints. A new approach is presented to solve the conflicting factors by determining the Importance Index (I) for offshore wind farms. This is based on a newly defined parameter *Representative Cost Ratio* (RCR) facilitating the comparison process. The method compares factor pairs and overcomes the issue where the evaluation of “alternatives” and “criteria”, conducted by a number of experts result in reduced accuracy, coherence, and making the process time-consuming. The approach is tested through two case studies (i) UK deployed projects and (ii) determining the offshore wind energy potential around the Arabian Peninsula at scale. The presented method circumvents the literature-highlighted shortcomings with the advantage of considering all restrictions/constraints together at the start of the analysis, arriving at a signally combined Boolean Mask. RCR compares factor pairs to interpret the relationship between Importance Index scale (1–9) and its descriptors. Results from both case studies provided excellent outcomes, confirming the robustness of the RCR approach and its global applicability in addressing the spatial planning of offshore wind farms.

1. Introduction

Offshore wind energy is now considered a mature technology with over 19 GW capacity already installed globally [1,2]. In addition, offshore wind energy costs are declining globally. For instance, the UK’s Department for Business, Energy and Industrial Strategy (BEIS) recently announced the outcome of its 2018 Contracts for Difference (CfD) scheme which incentivise long term investment for supporting low-carbon electricity generation [3]. For offshore wind projects in the UK, the tenders showed a halving of the cost per MWh to £57.50 (US$80) compared to the cost of the previous round [4]. Onshore wind energy is cheaper compared to offshore wind; however, it has some disadvantages. For instance, the lost value of the land used, noise, high vibrations, visual impact, bird path hazards, and shadow flicker effect. Shadow flicker effect is an infrequent event that occurs when the sunlight is at the horizon. This could be responsible for photo-induced seizures or photosensitive epilepsy and other disturbance to people near the turbines [5]. Offshore wind on the other hand, does not suffer these disadvantages and has two other noticeable advantages: (a) offshore wind speeds on average are higher than those onshore and (b) in general, the effect of turbulence is reduced compared to inland projects. Furthermore, turbulences assessment is required when considering intra-array and array-to-array effects, especially under stable atmospheric conditions in offshore wind farms. Reducing turbulence in offshore wind regions could extend the life cycle of wind turbines and reduce the materials used to support the wind turbine, as the fatigue stress is minimised [6]. Furthermore, offshore wind farms need further robust environmental impact assessment around the farm sites. This should include impacts on sea life – such as fish, mammals and birds encompassing noise and vibration etc. Hence, studies to appropriately site offshore wind farms are needed to support technology expansion taking into

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account all local and regional constraints.

Offshore wind energy, similar to most of the other renewable sources, has a low power density, for instance, it could occupy 50 times more space than a comparative gas-fuelled electrical power plants, which makes the spatial siting for offshore wind farms a critical process not only in addressing the appropriate data needs but also for optimised decision-making.

Identifying the most suitable locations for offshore wind energy around a region is a spatial siting decision problem. Spatial problems comprise the analysis of a large number of suitable alternatives and multiple criteria that will need appropriate evaluation. Once these criteria are chosen, they are evaluated and weighted by experts - stakeholders, and/or scholars. The evaluation is normally based on knowledge and experience of the appraisers concerning the specific problem to be solved, and the region under consideration [7]. In such cases, Analytic Hierarchy Process (AHP) is used to identify the problem criteria, to weight them, and then to evaluate each alternative [8,9]. Literature for example [10–14] indicates that such *spatial decision problems* are complex and require innovation. This is because the techniques typically involve a large set of feasible alternatives and multiple evaluation criteria, which are often conflicting.

The Analytic Hierarchy Process (AHP) is a well-known multi-criteria decision analysis technique in engineering to solve complex problems including the spatial planning for siting renewable energy projects – such as offshore wind farms [15–17]. AHP is a structured technique for organising and analysing complex decisions, based on mathematics and psychology. This work utilises AHP for siting offshore wind farms promoting a new approach developed to support coherent analysis, which circumvent the current processes, which have reduced accuracy and are time-consuming.

In comparison, AHP was employed to prioritise the highly suitable areas for solar farms of the regional unit Rethymno, Greece [18], where the study used an inverted scale of suitability - a score of four was considered not suitable and a score zero is suitable area. The work used Geographical Information System (GIS) and established four scenarios and ten factors to find sustainable areas to deploy photovoltaics and concentrated solar power farms.

A further study was conducted to test the hypothesis that onshore wind is the cheapest renewable energy in the UK addressing many of the constraints faced in its deployment [19]. The study used a multi-criteria decision analysis (MCDA) and AHP approach which provided what the authors claimed to be accurate estimation for the UK's onshore potentials which was around 5% of previous estimates.

The GIS-based constraints analyses limited to only restrictions, such as government regulations, are not enough to identify the most suitable locations, for offshore wind energy development. In essence, such analysis is most suitable for small-scale study areas as evidenced in the studies [20–25]. In a recent study addressing techno-economic constraints for small regions, especially islands the authors evaluated the offshore wind energy potentials of the Canary Islands, Spain [25]. The work considered both fixed and floating turbines, for two constraints - minimum speed of 6.5 m/s and exclusion of all protected areas. The study used only constraint analysis and no factors were applied. The results showed that the expected electrical power from the wind farm would be more than 20 times that of the annual electricity demand of the islands. Moreover, the levelised cost of electricity is approximately 9%–40% lower than the current electricity tariff in the islands.

To make it widely and fully applicable, one needs to produce suitability maps which requires an AHP analysis to produce factor weights to score the available areas on the maps to *high*, *moderate* and *not suitable* grades. For example, in the UK, the available areas for offshore wind energy are vast, so, stakeholders and investors do not need just the locations of the available areas only; they need to know the most suitable locations. Hence, appropriate analyses will need to create a descending score of the available areas from the highest to the lowest suitability (i.e. suitability maps). Such suitability maps assist stakeholders in targeting investments by exploiting the most suitable areas first and then the moderate areas and so on.

In essence, currently published work needs to find a robust way to compare factor pairs. As indicated earlier, alternatives and criteria are often evaluated by several individuals (decision-makers, managers, stakeholders, interest groups) who most of the time, have conflicting ideas, preferences, objectives, etc. This current practice, which is based on expert surveys and their subsequent analysis, is a long-winded process, requiring: (a) the generation of appropriate succinct questions to be addressed, (b) ethics approval for data collection, (c) identifying a cohort of experts, (d) once identified pooling them with the survey questionnaires and hoping to get robust sample return from the cohort, and (e) analysis for providing judgment and agreement between experts. This could take 6 months or more, [26–32]. This period is evaluated for academic practise only, as compared to experienced industry development teams where such survey may take shorter time frame. In addition, most literature only mentions the Importance Index (I) parameter without a clear explanation of how they arrive at the outcomes [10,20,33–38].

In this work, we addressed these issues heads on, by providing a new and unambiguous way to compare factor pairs. This new approach is on the *Representative Cost Ratio* (RCR) developed to facilitate the comparison process, which, in our view, is an innovative process to circumvent all the shortcomings highlighted above. Unlike previous offshore wind spatial siting research, for example [38–40], our considerations bring all restrictions together from the beginning of the analysis and then combined these in one Boolean Mask. This approach compares factor pairs to interpret the relationship between the Importance Index (I) sometimes referred to as the (Intensity of Importance) scale and its descriptions (see definitions and details in Section 2).

In order to test the above approach, we have applied it to two case studies covering: (i) analysis of the UK's deployed and planned offshore wind energy farms sites (ii) application across the whole process steps needed to quantify the offshore wind renewable energy potential at regional scale around the shores of the Arabian Peninsula (AP). In the following sections, we discuss the methodology, the two case studies, the results and implications of the analysis, followed by the discussion and the conclusions.

2. Methodology

2.1. Consideration for assessing offshore wind energy potential

The cost of a project is determined to be the most critical aspect of offshore wind energy exploitation. As indicated earlier, AHP is normally based on judgement and experience [15,16], where for offshore and onshore wind spatial siting, the cost is considered to link the factor pairs. In order to avoid such judgments and provide a robust way to compare factor pairs, we propose the *Representative Cost Ratio* to link pairs and provide the relative grading in terms of the Importance Index values needed. This innovation circumvents all the shortcomings previously highlighted in the current literature. Furthermore, our considerations have the advantage of bringing all restrictions together at the start of the analysis and then combining these in one Boolean Mask.

2.1.1. AHP process

A Multi-Criteria Decision-Making (MCDM) analysis linked to a Geographical Information System (GIS) model was developed to solve the spatial siting for offshore wind farms in an efficient manner, which takes into account regional and appropriately defined conflicting factors and constraints. Fig. 1 provides a summary of the steps to be undertaken within the whole AHP process including problem definition, identifying criteria and the needed processing [16,41].

The alternatives of spatial siting problem consist of a small unit called "cell or pixel". The study area map is then divided into an equal size grid where each pixel on the grid is a cell/alternative. The criteria of the problem are then divided into factors and constraints, constraints are explained later in Section 2.1.2.

Factors are the weighted criteria that increase or decrease the suitability of the alternatives (most/least cells). For example, the wind speed factor, where high/low wind speed means most/least suitable cell according to this factor [41].

A standardisation (Non-Boolean Standardisation) step is required to facilitate the final accumulation part. Due to the different magnitude and units of the factors, a standardisation process is used to transform them to a similar scale [42]. For instance, the wind speed has a scale ranging from 3 m/s [Min] to 9 m/s [Max], while water depth has a scale ranging from 5 m [Min] to 60 m [Max]. Therefore, to accumulate the two factors together, a standardisation process is applied by converting the two magnitudes of each factor to similar scales namely: 0 [Min] and 1 [Max] scale. This process is carried out using a fuzzy linear function, which is available as a tool in ArcGIS [43]. In addition, factors also have different weights according to their *importance*, so pairwise comparison method is used to weigh these factors as per the method developed in Refs. [15,16].

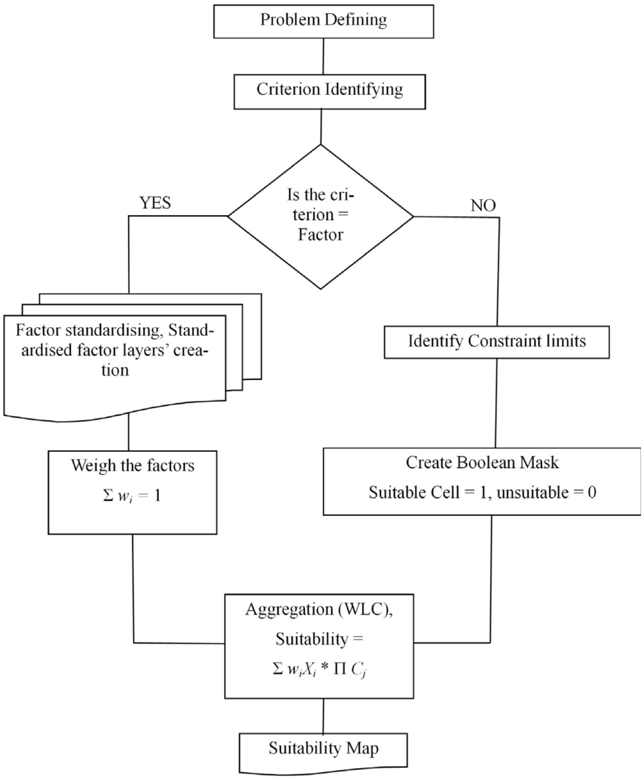

Fig. 1. AHP process stages undertaken including problem definition identifying criteria and the needed processing adopted from Ref. [41].

The required pairwise comparison process is accomplished by building two different matrices. The first matrix is the "pairwise comparison matrix", with an equal number of rows and columns, the number of rows and columns should be equal to the number factors (in this paper, n = 4). The two rules to create the pairwise comparison matrix are given below:

- Rule 1: The matrix element value is equal to the Importance Index value. This is adopted from Table 1, with the condition that the factor named in the left column (A) (Table 2) of the matrix has higher importance compared with the factor named in the top row (B) of the matrix (Table 2).
- Rule 2: Represents the condition when the factor named in the left column (A) of the matrix has lower importance when compared with the factor named in the top row (B) of the matrix (Table 2). In this case, the matrix element is equal to the inverse of the values in Table 1.

Table 1 provides the definitions and descriptions of the Importance Index's scale, which are used to compare factor pairs. The second matrix is the "normalised matrix", which is created by dividing each matrix element by its column sum. The weight of each factor is equal to the average of its row in the new matrix. The total sum of factor weights is one. The final step to complete the pairwise comparison is to validate the comparison assumption, using the following equations adopted from Ref. [15].

$$CR = CI / RI \tag{1}$$

$$CI = (\lambda_{max} - n) / (n - 1) \tag{2}$$

Where, *CR* is the Consistency Ratio having a value less or equal to 0.1 and is used to validate the accuracy of the Importance Index, *I*, values. *CI* is the Consistency Index, *RI* is the Random Consistency Index, with its values adopted from Ref. [15], and $\lambda_{\max}$ is the Principal Eigenvalue. $\lambda_{\max}$ is equal to the products of the factor sum (total) of each column of the pairwise matrix and the determined Factor Weight value.

2.1.2. Restrictions and Boolean Mask

To identify a suitable cell, a Boolean Mask is applied before the aggregation process is conducted, so that restricted cells are eliminated. Constraints are the criteria used in the Boolean Mask, which differentiates between suitable and unsuitable cells. Boolean relations (AND, OR and NOT) are used to sum different constraints into the final Boolean Mask map, see Equation (3).

The government regulations have a role to play in the analysis that will be taken into account by converting the regulations into restrictions in the analysis from the start of site consideration (Boolean Mask). The applied Boolean mask fulfils the role of such regulations, providing a generic approach applicable widely in any jurisdiction. The Boolean mask outcomes are unique outputs that differ from location to location, e.g. UK and Arabian Peninsula models considered in this paper. On the contrary, factors are mostly not affected by government regulations, for example, water depth, distance to grid, distance to shore, and wind speed factors of the offshore wind energy spatial siting are inherent to the sites and therefore represent the technical aspects of the analysis. Further environmental impact assessment is needed after locating the most suitable areas to cover additional government regulation not covered by the analysis. A recent example is the UK offshore wind farm socio/economic/environmental impact statement [44].

The criteria considered as restrictions are oil and gas installations – platforms (OGS), high capacity shipping routes (HCSR), cables paths, maritime natural reverse (MNR), maritime

Table 1
The Importance Index (I) scale adopted from Ref. [16].

Importance Index, *I*	Definition	Description
1	Equal importance	Two activities contribute equally to the objective
2	Weak/slight	
3	Moderate importance	Experience and judgement slightly favour one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgement strongly favour one activity over another
6	Strong plus	
7	Very strong	An activity is favoured very strongly over another
8	Very, very strong	
9	Extreme importance	Evidence favouring one activity over another is of highest possible order

boundaries (MB), military practice and exercises areas (PXEA), fishing zones, existing or planned offshore wind farms (OWF), protected wrecks, and tunnels [33]. A Boolean mask need to be created to eliminate restricted cells, so that constraint cells have a value of zero, and unrestricted cells have a value of one. The final Boolean Mask is produced using Equation (3).

$$\textit{Boolean Mask} = (OGS)\ x\ (HCSR)\ x\ (MNR)\ x\ (MB)\ x\ (PEXA)\ x\ (Fishing)\ x\ (OWF)\ x\ (Wrecks)\ x\ (Tunnels) \tag{3}$$

2.1.3. WLC aggregation process

As indicated in Fig. 1, the final step in the AHP process is the aggregation where the Weighted Linear Combination (WLC) method is used [8]. WLC combines the standardised factors after multiplying each factor by its weight and finally multiply the result map by the Boolean Mask (generated by multiplying all the constraints together). The overall outcome is called the Suitability Map and is estimated using Equation (4).

$$\begin{aligned}\textit{Suitability of any cell/alternative} &= (\textit{Sum of factors weights})\ x\ (\textit{score})\ x\ (\textit{Boolean Mask}) \\ &= \left(\sum_{i=1}^{n} W_i X_i\right) \times \left(\prod_{j=1}^{l} C_j\right)\end{aligned} \tag{4}$$

Where, W_i is the weight assigned to factor i, X_i is the criterion score of factor *i*, *n* is the number of factors, C_j is zero or one score of the constraint j, Π is the product of constraints, and *l* is the number of constraints.

2.2. RCR approach

In order to address the importance of the factors used and compare them in pairs, the Importance Index is introduced [16]. The Importance Index is an integer with scale between 1 and 9 and is critical in determining the relationship and importance between factor pairs that govern a project and its cost. The pairwise comparison process is undertaken by linking factor pairs to the Importance Index and its overall parameters. This process is mainly governed by the contribution of the factors to the cost of a project and associated impacts [41]. In this paper, we introduce the new term *Representative Cost Ratio* (RCR) to facilitate the determination of the Importance Index and the evaluation of offshore wind energy projects overcoming current methods which are time-consuming and less robust. The following steps in the methodology will now provide an approach to estimate these relationships and the values for both the Importance Index and RCR.

The relationship is gained through analysis of the literature and their data to assess the onshore wind energy potentials [45–47], as to the authors' knowledge, this work provides the first consideration of offshore wind energy farm siting using AHP and the RCR. A study of such wind energy potential in the South of the UK [47], which was based on the opinion provided by five experts in the wind energy field will be used to estimate the Importance Index. The study used six factors to evaluate the study area, which are wind speed, distance from historically important areas, distance from residential areas, distance from wildlife designations, distance from transport links, and distance from the electrical network connection. The other two studies [45,46] have used their experience and judgment to arrive at an appropriate and relevant Importance Index of each factor pair related to urban studies. These three studies are independent from each other; their work encompassed generic approach for siting of wind farms at different locations (Kozani of Greece, onshore areas of England, and South Central England of the UK) [45–47]. The authors used similar factors (some with more than ten factors) and the same range of the RCR; see Table 2 and Fig. 2. In essence, these three studies, conducted by different scholars, covered different study areas and periods. These authors did not rely on each other's work, yet the authors arrived at the same range of RCR for the different locations considered. Hence, factors could be applied to any locale.

Table 2 is based on data from the aforementioned studies [45–47] which are used to determine the appropriate range (1–9) of RCR for each Importance Index in terms of factor pairs. The factor pairs determined from these studies is shown in column A of Table 2. RCR is the ratio of factor pairs contribution to the final Levelised Cost of Energy (LCOE) of the project. To estimate RCR for this case we use the LCOE given in Table 3, by using the ratio between pairs. For example, the Wind Speed vs. Residential Areas Proximity is 52.2:16.2 giving a value of 3.2 in Table 2 Column C, and so on. In order to determine the values of the Importance Index in Column B, we used the pairwise comparison method mentioned above. The pairwise matrix and the normalised matrix for onshore wind spatial siting are given in Tables 4 and 5 respectively.

To arrive at the range for RCR, we use the interpolation given in Fig. 2 with the results shown in Column D of Table 2. For example, the Importance Index for the Wind Speed vs. Residential Areas Proximity pair is 4 and from Fig. 2 this is in the RCR range of 3–4,

Table 2
Process of obtaining the RCR range from previous onshore wind studies [45–47].

(A) Factor Pair	(B) Importance Index [47]	(C) RCR [48]	(D) Appropriate RCR Range
Wind Speed vs. Residential Areas Proximity	4	52.2/16.2 = 3.2	3–4
Wind Speed vs. Wildlife Designations Proximity	5	52.2/12.8 = 4.1	4–7
Wind Speed vs. Network Connection Proximity	5	52.2/10.3 = 5.1	4–7
Wind Speed vs. Transport Links Proximity	6	52.2/7.3 = 7.2	7–10
Wind Speed vs. Historical Areas Proximity	9	52.2/1.2 = 44	>18
Residential Areas vs. Wildlife Designations	2	16.2/12.8 = 1.3	1–2
Residential Areas vs. Network Connection	2	16.2/10.3 = 1.6	1–2
Residential Areas vs. Transport Links	3	16.2/7.3 = 2.2	2–3
Residential Areas vs. Historical Areas	8	16.2/1.2 = 14	13–18
Wildlife Designations vs. Network Connection	2	12.8/10.3 = 1.5	1–2
Wildlife Designations vs. Transport links	3	12.8/7.3 = 2.1	2–3
Wildlife Designations vs. Historical Areas	7	12.8/1.2 = 11	10–13
Network Connection vs. Transport Links	2	10.3/7.3 = 1.4	1–2
Network Connection vs. Historical Areas	6	10.3/1.2 = 8.5	7–10
Transport links vs. Historical Areas	5	07.3/1.2 = 6.1	4–7
Approaches and data from Refs. [45,46]			
Land Use vs. Road Network Proximity	3	16.2/7.3 = 2.2	2–3
Land use vs. Natural Areas Proximity	2	16.2/12.8 = 1.3	1–2
Natural Areas vs. Road Network Proximity	3	16.2/7.3 = 2.2	2–3
Urban Areas vs. Historic Sites	7	16.2/1.2 = 14	10–13
Roads vs. Historic Sites	6	10.3/1.2 = 8.5	7–10

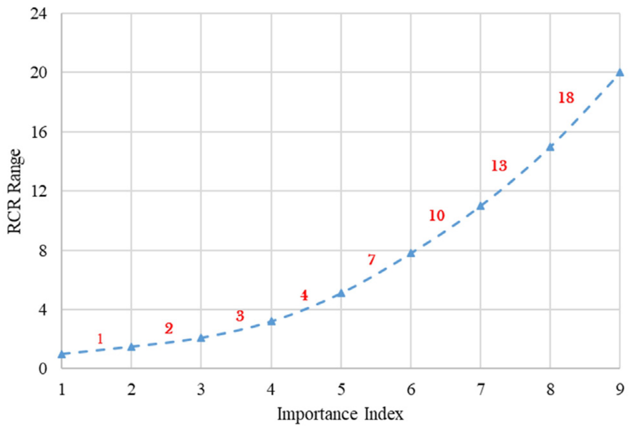

Fig. 2. The interpolation curve to determine the RCR range (red numbers show RCR range).

and so on. It must be noted that the last five rows of Table 2 are from Refs. [45,46] and are included here to illustrate the process of estimating RCR, based on factor pairs representing land use and urban areas, etc.

The Principal Eigenvalue λ_{max} is determined by the product of the factor sum (total) of each column of the pairwise matrix (Table 4) and the Factor Weight value (Table 5) determined earlier. For example, for the wind speed factor, $\lambda_{max} = 1.93 \times 0.512 = 0.99$ and so on for the other values.

In order to ascertain the validity of the assumptions made, the magnitude range of the Consistency Ratio CR (Eq. (1)) should be less than or equal to 0.1. The Consistency Index, *CI*, using Equation (2) has a value of 0.0185 since $\Sigma\ \lambda_{max} = 6.09$ from Table 5 and $n = 6$. The Random Consistency Index, *RI*, for the six factors has a value of 1.24, [15]. Using these values in Equation (1), *CR* has a value of 0.0149, which is < 0.10. Hence, the assumptions in Table 4 are correct [16]. The final range of RCR and the corresponding Importance Index are shown in Table 6, the table will be used later in Section 2.2.1 to calculate the factor weights that control the decision making of offshore wind energy spatial siting.

2.2.1. *Offshore wind energy factors weighting*

As indicated earlier, using the *Representative Cost Ratio (RCR)* as the new approach to calculate factor weighs will reduce time and

Table 3
The LCOE contribution to a 2.16 MW Land-Based Turbine, adopted from Ref. [48].

	Wind Speed	Residential Area Proximity	Wildlife Proximity	Network Proximity	Transport Links	Historical Sites	Total Cost
LCOE[a] [$/kW]	830	258	116	164	203	19	1590
LCOE [%] = (Factor/Total Cost)	52.2	16.2	7.3	10.3	12.8	1.2	

[a] LCOE [$/kW] = The Redistribution readjustment number to meet the total capital expenditures.

Table 4
The pairwise matrix for onshore wind spatial siting.

	Wind Speed	Residential Area Proximity	Wildlife Proximity	Network Proximity	Transport Links	Historical Sites
Wind Speed	1	4	5	5	6	9
Residential Areas Proximity	1/4	1	2	2	3	8
Wildlife proximity	1/5	1/2	1	2	3	7
Network Proximity	1/5	1/2	1/2	1	2	6
Transport Links	1/6	1/3	1/3	1/2	1	5
Historical Sites	1/9	1/8	1/7	1/6	1/5	1
Sum	1.93	6.46	8.98	10.7	15.20	36.00

Table 5
The normalised matrix for onshore wind spatial siting.

	Wind Speed	Residential Area Proximity	Wildlife Proximity	Network Proximity	Transport Links	Historical Sites	Factor Weight	λ_{max}	Error
Wind Speed	0.52	0.62	0.56	0.47	0.39	0.25	0.512	0.99	0.04
Residential Areas Proximity	0.13	0.15	0.22	0.19	0.20	0.22	0.178	1.15	0.07
Wildlife Proximity	0.10	0.08	0.11	0.19	0.20	0.19	0.135	1.22	0.01
Network Proximity	0.10	0.08	0.06	0.09	0.13	0.17	0.092	0.99	0.05
Transport Links	0.09	0.05	0.04	0.05	0.07	0.14	0.058	0.88	0.01
Historical Sites	0.06	0.02	0.02	0.02	0.01	0.03	0.024	0.88	0.02
Sum	1.00	1.00	1.00	1.00	1.00		1.00	6.09	

Note: Average Error is 0.01.

Table 6
The Importance Index and the corresponding RCR range.

Importance Index (Definition and description in Table 1)	1	2	3	4	5	6	7	8	9
RCR Range	(0–1):1	(1–2):1	(2–3):1	(3–4):1	(4–7):1	(7–10):1	(10–13):1	(13–18):1	18>:1

effort to rank the criteria for offshore wind spatial siting. Table 7 identifies the Importance Index, *I*, of each possible factor pair, using the definition given in Table 1 and the RCR range in Table 6. The selected values for the Importance Index are chosen based on the contribution to the final Levelised Cost of Energy (LCOE) as shown in Table 6 [40,41]. In these published articles, the contribution to the LCOE for wind speed is 50%, water depth is 20% and distance to shoreline is 5% and distance to grid is 2% [40,41] (Table 7). To arrive at the RCR value the contribution of these pairs in relation to each other will need to be established.

That is, the Wind Speed (WS) will need to be paired with other factors (Water Depth (WD), Distance to Shore (DS) and Distance to the Grid (DG)) and so on. Hence, the Importance Index score will be dependent on these combined contributions and the range of RCR given in Table 6, also shown in Table 7 for the specific RCR. For example, the Importance Index (I) for Wind Speed compared to Water Depth is determined by their contribution to the LCOE as follows: WS:WD = 50%:20% = 2.5 this falls in the RCR range to 2–3:1 (Table 6) and hence was given a value of 3 (Table 7). Similarly, WS:DG = 50%:2% = 25, this falls in the RCR range 18>:1 (Table 6) and hence *I* given is 9 (Table 7) and so on.

The values in Table 7 were then used to establish the pairwise comparison matrix (Table 8), using the two rules discussed earlier. The normalised matrix (Table 9) is determined by dividing each matrix element of Table 8 by its column sum (described above). For instance, the wind speed value in the normalised matrix is determined by $1 \div 1.59 = 0.63$ and so on for the other values. The Factor Weight values in Table 9 are the average of all values determined in the row for each factor.

The Principal Eigenvalue λ_{max} is determined by the product of the factor sum (total) of each column of the pairwise matrix (Table 8) and the Factor Weight value (Table 9) determined earlier. For example, for the wind speed factor, $\lambda_{max} = 1.59 \times 0.58 = 0.93$ and so on for all other values.

In order to ascertain the validity of the assumptions made, the magnitude range of the Consistency Ratio CR (Eq. (1)) should be less than or equal to 0.1. The Consistency Index, *CI*, using Equation (2) has a value of 0.077 since $\Sigma\ \lambda_{max} = 4.23$ from Table 9 and $n = 4$. The Random Consistency Index, *RI*, for the four factors has a value of 0.9, [15]. Using these values in Equation (1), *CR* has a value of 0.085, which is < 0.10. Hence, the assumptions in Table 7 are correct [16].

In order to apply the above analysis to the two case studies, a consideration of the membership limitations for the factors to be used in each study area is needed. These limitations are depicted in Table 10. A Fuzzy Membership tool will be applied to produce a new linear standardised layer for each factor. Such a process will be accomplished for each case study separately.

3. Analysis and results

This section provides analysis to test the methodology and its resilience through application to two case studies undertaken for siting offshore wind energy farms sites. The first case study (Section 3.1) addresses the UK wind energy programme where most of the projects are already in place or being commissioned. The UK is at the forefront of offshore wind energy and most of the analysis undertaken is for the UK projects at their specific sites. These projects were funded under the various UK mechanisms (called "Rounds") for offshore wind energy deployments [33]. The second case study was geared to test and provide the outcomes from the methodology at a regional scale. This considers seven countries covering an area of approximately 3.1 million km^2 and coastline stretch of 9180 km. To the authors' knowledge, this is the largest scale considered by any study in the offshore wind energy field.

3.1. Case study 1: UK offshore wind energy round projects

The UK has an ambitious programme for offshore wind. This is normally managed through the Crown Estate, which is an independent authority, with responsibility of overseeing the seabed of the UK including the promotion and the exploitation of the resources around and within the UK's shores. For offshore wind energy, such exploitation was undertaken through a process called "leasing rounds" or "Rounds" for short. The Crown Estate utilised a Marine Resource System (MaRS) tools based on a GIS database to identify potential offshore wind areas under various government investments stages to support each Round. There are three Rounds - 1 to 3 - where offshore wind farm projects are tendered for deployment at various locations around the UK [33]. It must be noted that Rounds 1 and 2 have already been deployed whilst Round 3 is in partial deployment.

The UK's Round 3, announced in mid-2008 covered an approximate area of 27,000 km^2 and aimed to exploit more than 32 GW of offshore wind energy. However, by the end of 2018 only 30% of this area has been exploited. Nevertheless, this represents 49% of Europe's gross offshore wind installed capacity in 2018, with the UK representing the highest installed capacity in the world [49].

For the development of these projects, the Crown Estate has only published the location maps for the three Rounds and has not disclosed details of the methodology used for the spatial siting of the wind farms in the selected locations [33,50–53]. However, their reports state the criteria and the scenarios/iterations considered

Table 7
Importance Index *I* of each possible factor pair, using definition given in Table 1 and RCR range in Table 6.

Contribution to LCOE, %	*Representative Cost Ratio* (RCR) = (Contribution to LCOE/other pair contribution)		Importance Index, *I* Equal Importance 1	Weak or slight 2	Moderate importance 3	Moderate plus 4	Strong importance 5	Strong plus 6	Very strong 7	Very, very strong 8	Extreme importance 9		Contribution to LCOE, %
50	2.5	Wind Speed (WS)			x							Water Depth (WD)	20
	10								x			Distance to Shoreline (DS)	5
	25										x	Distance to Grid (DG)	2
20	4	Water Depth (WD)					x					Distance to Shoreline (DS)	5
	10							x				Distance to Grid (DG)	2
5	2.5	Distanced to Shoreline (DS)			x								2

when approving projects [33,50–53]. Such considerations are useful to allow us to undertake analysis to compare the effectiveness of our methodology with that of the results achieved through the Crown Estate considerations.

The Factor Weight values in Table 9, which were calculated using the introduced *Representative Cost Ratio* approach, were used to create a suitability map for the UK's offshore regions. The UK has the rights to exploit their shores out to 200 miles of the seabed for renewable energy power generation. In this section, we provide the analysis undertaken which is geared to check the appropriateness and validity of our proposed methodology and its assumption. This is accomplished by applying it to assess the suitability of the locations of the UK offshore wind farms' ongoing deployments.

Four suitability factor maps were produced using the available information from the Crown Estate Maps and their GIS Data website, which was updated in 2019 [53]. The source shape files of the water depth, grid connection, wind speed, and shoreline were converted to a raster format, with a cell size of 200 × 200 m, and its Geographic Coordinate System was "WGS 1984 UTM Zone 31N". The data for different factors were established in different dimensions (wind speed, water depth, distance to shore, and distance to grid – referred to as layer) and scales of values. Therefore, to arrive at the Weighted Linear Combination (WLC) step (last step in Fig. 1 as we already have the information for the previous steps in Fig. 1 from the Crown Estate published data), linear fuzzy limits were applied to unify their scales and dimensions to a scale from (1–0) (see methodology). These new layers called factor suitability maps represent: (a) Water depth factor, (b) Distance to electricity grid line, (c) Distance to UK shorelines, and (d) Wind speed factor. The four maps are processed using the Fuzzy-membership Tool in ArcGIS programme with the resulting suitability maps for these four factors shown in Fig. 3.

The Boolean mask was not used in this analysis as the Crown Estate had already eliminated the constraints criteria from the mapping of the three Rounds. The four suitability maps shown in Fig. 3 were integrated using ArcGIS Raster Calculator Tool, applying Equation (3), (Weighted Linear Combination (WLC) method). The final UK suitability score for each map cell equals [0.28 x water depth suitability + 0.05 x distance to grid suitability + 0.09 x distance to shorelines suitability + 0.58 x wind speed suitability], where the factors weight values are those given in Table 9.

These considerations resulted in the offshore wind suitability map for the UK shown in Fig. 4. The suitability score shown in Fig. 4 ranged from 0 (least suitability) to 1 (highest suitability). The results indicate that around 26% of the UK's offshore areas have high suitability (Fig. 4 legend range - 0.6 to 1.0) for offshore wind and that these areas are concentrated in the East of England and most of Scottish waters.

To validate the new approach, the suitability of the operational and planned UK's offshore wind farms under Rounds 1, 2 and 3, were identified using their original locations and boundaries derived from Crown Estate maps, which were superimposed onto the newly generated UK offshore wind suitability map. The appropriate validation is to ascertain whether all the cells identified by the Crown Estate to develop the offshore wind energy Rounds through the last two decades, coincide within the high and moderate suitability areas generated through our methodology, shown in Fig. 4.

Fig. 5 shows the locations of three Rounds of the UK's offshore wind energy farms superimposed on our resultant analysis of Fig. 4. Fig. 5 is the same as Fig. 4 but enlarged to show more details. The Clipping Tool in ArcGIS was used to clip the suitability map of the UK resulting in the outlines shown in the figure covering three sets: (i) Round 1 and 2 operating wind farms (shown in grey), and (ii) Round 3 operational wind farms areas outlined in red and (iii)

Table 8
Pairwise comparison matrix.

A	B			
	Wind Speed	Water Depth	Distance to Shoreline	Distance to Grid
Wind Speed	1	3	7	9
Water Depth	1/3	1	5	6
Distance to Shoreline	1/7	1/5	1	3
Distance to Grid	1/9	1/6	1/3	1
Total (Σ)	1.59	4.37	13.33	19

Table 9
Normalised matrix and final factors weight value.

	Wind Speed	Water Depth	Shoreline	Grid	Factor Weight	λ_{max}
Wind Speed	0.63	0.69	0.53	0.47	0.58	0.93
Water Depth	0.21	0.23	0.38	0.32	0.28	1.23
Shoreline	0.09	0.05	0.08	0.16	0.09	1.23
Grid	0.07	0.04	0.03	0.05	0.05	0.84
Σ	1.00	1.00	1.00	1.00	1.00	4.23

Round 3 under construction or planned shown dotted. It is clear from the results in Fig. 5 that the UK offshore wind Rounds are within the high and medium suitability areas generated by our analysis.

In order to estimate the suitability percentage distribution for the three sets, (i), (ii) and (iii) mentioned above, the Attribute Table which identifies the geographic feature of an ArcGIS Layer for each set was used to arrive at the number of cells for every suitability score range (0–1). The Attribute Table and the scores for these sets are given in appendix A. Table 11, depicts the suitability percentages for all the three Rounds of the UK offshore wind projects. The table shows the estimated areas for each Round as well as the predicted suitability determined by the methodology presented here. The cell suitability distribution in Table 11 is divided into three ranges - unsuitable cells (0.0–0.39 score), moderately suitable cells (0.4–0.59), and highly suitable (0.6–1.0). As can be seen from the results in Table 11, all the UK's operational or planned offshore wind locations are in moderate and high suitability ranking. For Rounds 1

Table 10
Fuzzy membership limitations and related values.

Factor	Max	Min	Condition	Value	Condition	Value
Wind Speed	7 m/s	3 m/s	> Max	1.0	< Min	0.0
Water Depth	- 60.0 m	- 5.0 m	< Max	0.0	> Min	0.0
Distance to Shoreline	140 km	5.0 km	> Max	1.0	< Min	0.0
Distance to the Grid	180 km	10.0 km	> Max	0.0	< Min	1.0

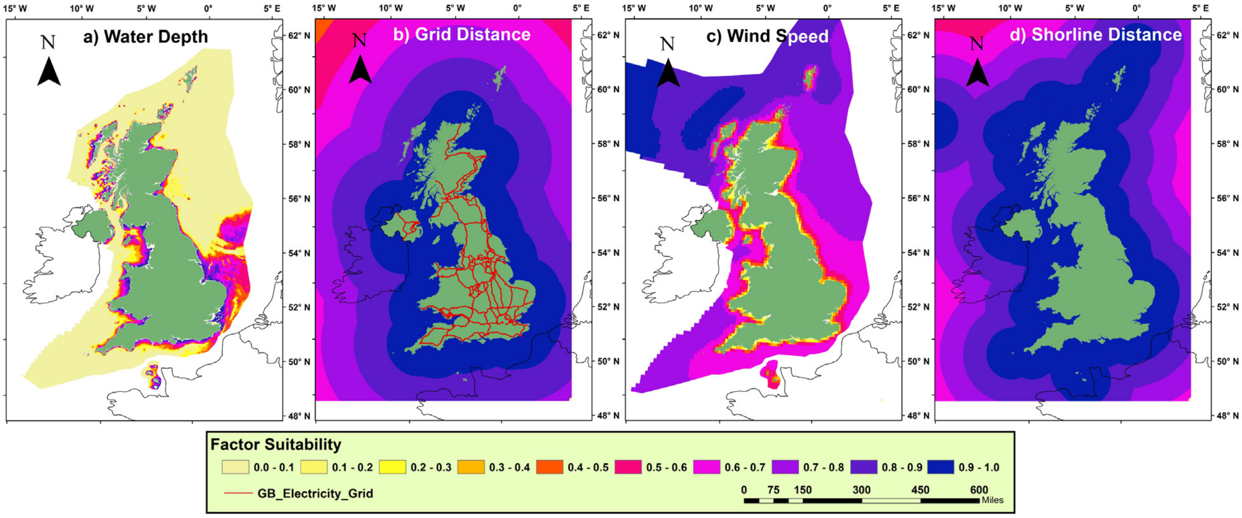

Fig. 3. The suitability maps for the four considered factors: (a) Water depth factor, (b) Distance to electricity grid line, (c) Distance to UK shorelines, and (d) Wind speed factor.

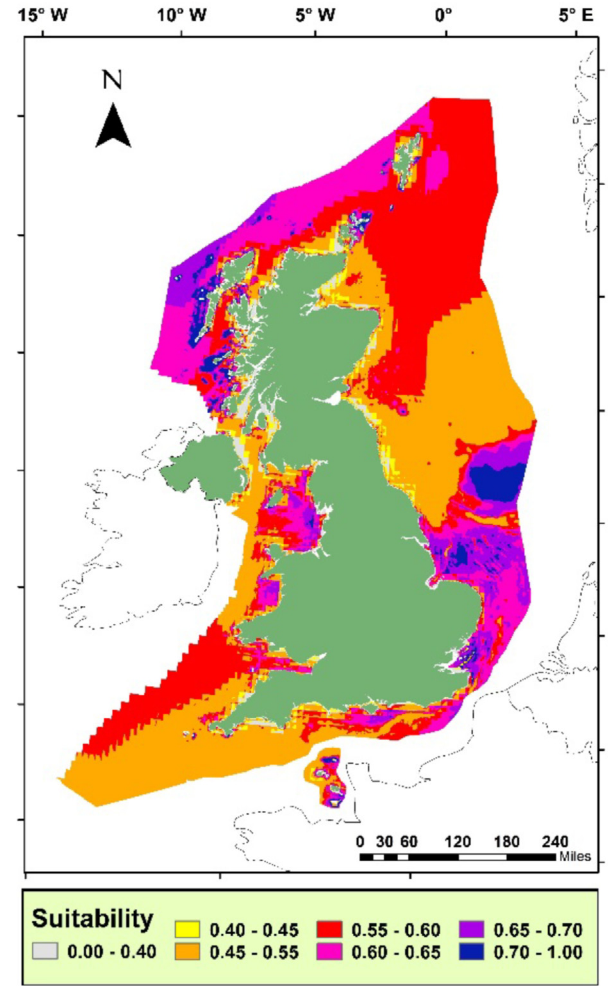

Fig. 4. UK's offshore wind suitability map produced by the methodology presented here. The suitability score is ranged from 0 (least suitability) to 1 (highest suitability). The results in the figure is also duplicated in Fig. 5 opposite where it is enlarged to allow more details to be shown including superimposing the 3 Rounds of the current and future offshore wind farms.

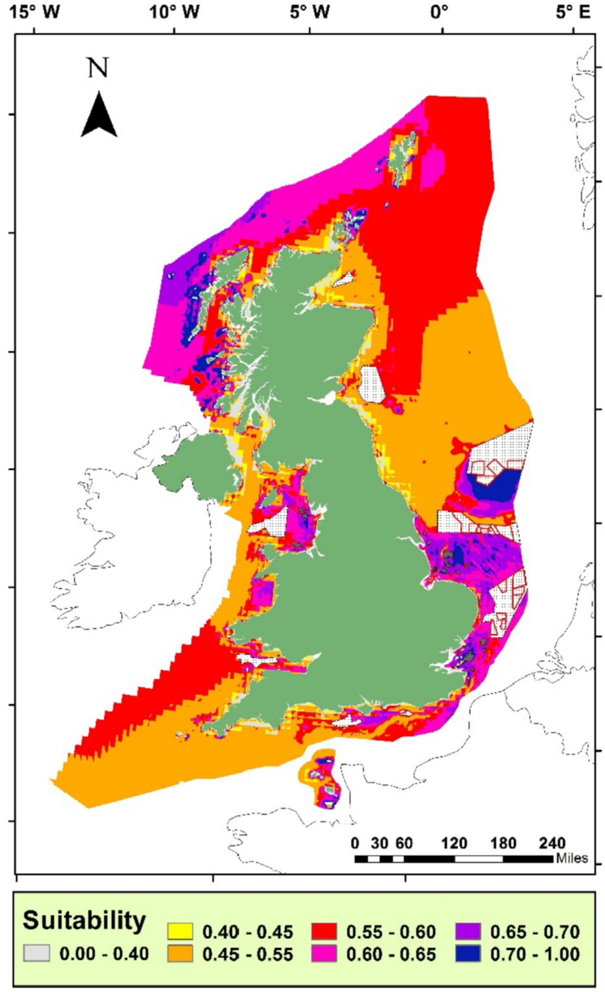

Fig. 5. Same suitability distribution map as Fig. 4. However here we also show the UK 3 Rounds – Rounds 1 and 2 in grey and Round 3 dotted areas with current wind farms outlines in red.

and 2, 92.4% of the farms were found to be in the high suitability areas with an estimated area of 1342 km^2. While for operational farms in Round 3, 85.8% were in high suitability areas, with an estimated area of 8565 km^2. For under construction or planned farms in Round 3 only 64.2% are within highly suitable areas, while the remaining (35.8%) areas are in moderately suitable areas, covering an estimated area of 27,039.9 km^2. The reason for this split is the high water depth average that exceeds 39.4 m, which will reduce the percentage of high suitability cells for the wind farms planned in Round 3.

The spatial siting verification was performed using the pre-planned UK offshore wind energy projects announced under Rounds 1 to 3. As can be seen from the results, the verification proved that the new *Representative Cost Ratio* (RCR) approach is very accurate as all of the cells of these farms are located in either moderate or high suitability categories (Table 11). Furthermore, this verification is significant, as we have simulated the data used by the UK, the country with highest installed capacity of offshore wind farms coupled with unmatched experience in planning, financing, and constructing such farms globally.

Considering that, the UK's Crown Estate is spending around £90k per MW for the cost of the offshore wind spatial planning process alone [40], which means that their commissioned maps are highly precise and accurate. The proposed new approach will save on such expenditure and reduce the time and effort needed to achieve the optimal spatial siting plan decision. We, therefore, conclude, that the results given in Figs. 4 and 5 and Table 11 confirm the quality of the different assumptions and calculation of the new RCR approach to accurately estimate the suitability of offshore wind energy farms. This approach will now be tested further by applying it to the analysis of the potential for offshore wind energy at a regional scale, in un-investigated areas around the shores of the Arabian Peninsula.

3.2. *Case study 2: Arabian Peninsula*

The Arabian Peninsula (AP) is bounded between 10^{o}N and 35^{o}N latitude and 35^{o}E and 60^{o}E longitude with a spatial extent, which includes the offshore areas of the Red Sea, the Gulf of Aden, the Arabian Gulf, and the northern part of the Arabian Sea. AP encompasses the countries of Bahrain, Kuwait, Oman, Qatar, Kingdom of Saudi Arabia (KSA), United Arab Emirates (UAE), and Yemen. Most of these countries rely on fossil fuel for their electricity supply. Table 12 depicts various characteristics of the AP including areas, population, and installed fossil fuel power capacities. The Gulf Cooperation Council (GCC) countries sit on more than 500 billion

Table 11
Percentages of suitability distribution for the UK offshore wind projects.

Round/[Location Source]	Estimated Area (km^2)	Installed Capacity (GW)	Predicted Suitability Distribution [%][a]		
			Unsuitable	Moderate	High
Round 1 and 2/[54]	1342.4	7.5	0	7.6	92.4
Round 3 operating wind farms until the end of 2018/[53]	8565.8	10.1	0	14.2	85.8
Round 3 under construction/planned/[37]	27039.9	32	0	35.8	64.2

[a] Cell scores: Unsuitable < 0.39; Moderate 0.4 to 0.6; High > 0.6 (suitability maps Figs. 4 and 5).

Table 12
Some characteristic of the Arabian Peninsula countries (GCC and Yemen) adopted from the references shown, power derived from fossil fuels.

Country/[Reference]	Area (10^6 km^2)	Coastline [km]	Population [Million]	Installed Power Capacity [GW]
Bahrain/[56]	0.008	161	1.41	3.93
Kuwait/[57]	0.017	499	2.88	16.0
Oman/[58]	0.310	2092	3.42	7.87
Qatar/[59]	0.012	563	2.31	8.80
KSA/[21,60]	2.148	2640	28.6	69.1
UAE/[61,62]	0.084	1318	6.07	28.9
Yemen/[63]	0.528	1906	28.0	1.50
Total	3.09976	9179	72.69	136.1

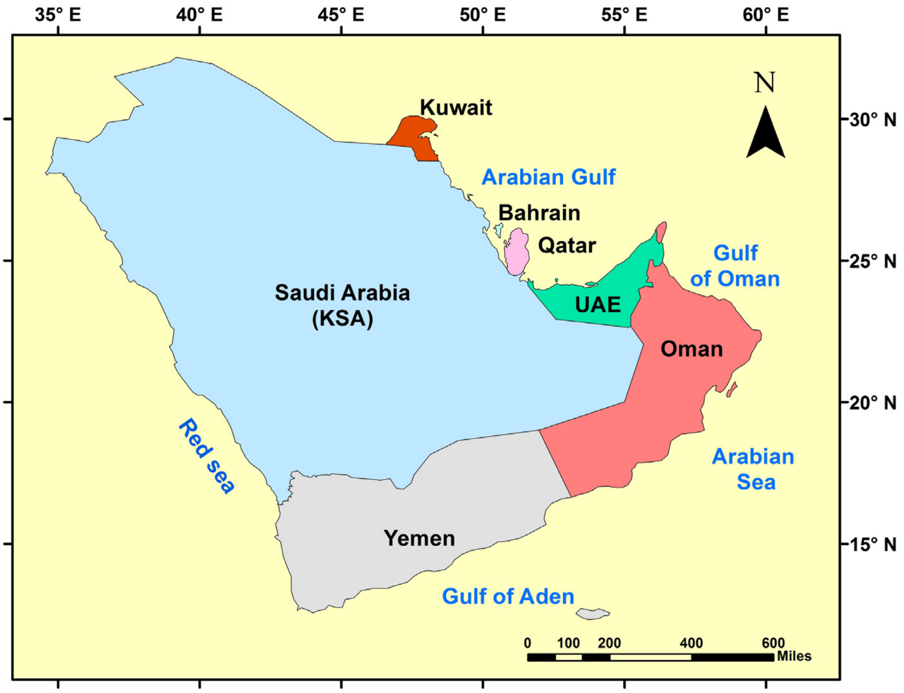

Fig. 6. Arabian Peninsula countries considered in this study, created using ArcGIS programme.

barrels of oil reserves ($^1/_3$ of the total known global reserves), hence most of their electricity is generated using fossil fuels [55].

The Arabian Peninsula is surrounded by water (Fig. 6), where Saudi Arabia has two shorelines; - Arabian (Persian) Gulf and the Red Sea, Bahrain, Kuwait, Qatar and UAE have shorelines on the Arabian Gulf. Oman has shorelines laying on the Arabian Gulf and the Arabian Sea whilst Yemen has shorelines on the Red Sea and the Arabian Sea. Hence, these countries would benefit from identifying the offshore wind energy potential around their shores.

To our knowledge, offshore wind energy potential in the AP region has not been fully investigated. In addition to testing the methodology, the research will also provide the quantification of the potential of offshore renewable wind energy for these countries contributing to both knowledge and understanding. The outcomes of the research based on the optimised methodology applied at scale could also assist in the speedy achievement of the regional renewable energy targets.

The following section outlines the steps undertaken to produce an overall outcome for offshore wind farm spatial siting in the AP region. Due to the wide-area footprint of the region and the different conditions presented by the considered countries, the analysis was conducted using nine criteria. Four of these criteria are factors covering: (i) wind speed (m/s), (ii) water depth in (m), (iii) distance from alternative cells to the shoreline in (km), and (iv) distance to the grid lines in (km). While the constraints used, which were selected due to their appropriateness for the region, are (a)

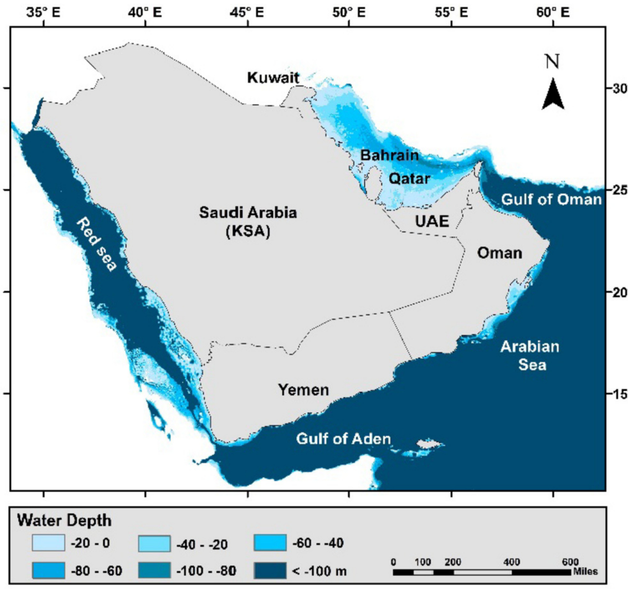

Fig. 7. Bathymetry (water depth) map around the Arabian Peninsula.

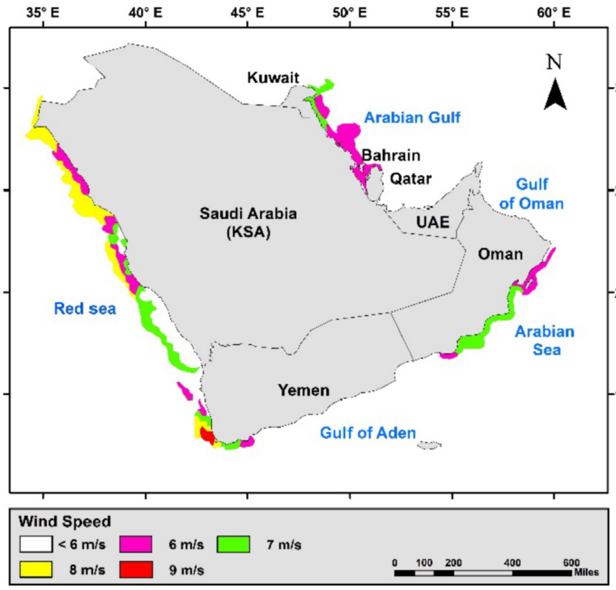

Fig. 8. Wind Speed [m/s] map around offshore areas of the Arabian Peninsula.

maritime boundaries, (b) oil and gas extraction areas, (c) reserved maritime natural parks, (d) shipping routes paths, and (e) underwater (sea) cables paths.

Table 13
Maritime reserved parks for Arabian Peninsula countries.

Country	Park name	Source
Oman	Daymaniyat Islands Nature Reserve, Jabal Samhan Nature Reserve, Ras Al Jinz Turtle Reserve, The Khawrs of the Salalah Coast Reserve	[69]
Yemen, Qatar, UAE, Bahrain, Kuwait	N/A	[70,71]
KSA	Umm al-Qamari Islands Farasan Islands	[72]

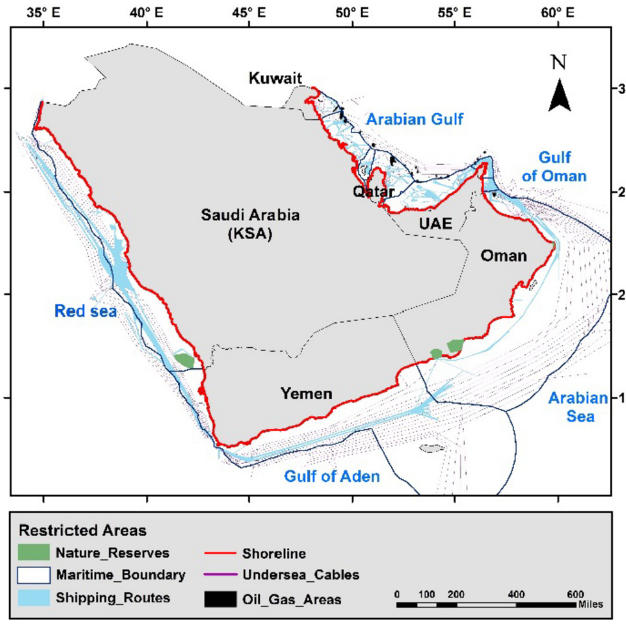

Fig. 9. Restricted areas raster layer around the offshore areas of the Arabian Peninsula.

In order to carry out the analysis, an ArcGIS [43] map layer for each criterion was created utilising available and relevant published spatial data. The bathymetry (water depth) data for the offshore areas around GCC countries and Yemen were adopted from Ref. [64]. The source file of the bathymetry data was created in raster format, with a cell size of 800 × 800 m, and its Geographic Coordinate System was “GCS_WGS_1984”. The results for the water depth for the considered countries are shown in Fig. 7. It must be noted that all other criteria layers were also confined to the same cell size and coordination system type as that of the bathymetry source file.

Wind speed data was adopted from the “Wind Atlas for Egypt” [65] and from the Global Atlas for Renewable Energy [66]. The

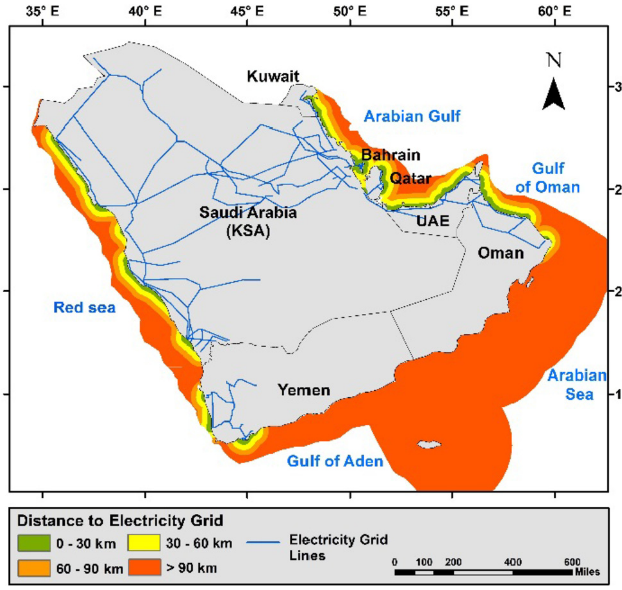

Fig. 10. Distance between representative cells of the offshore wind resources and electricity grid lines.

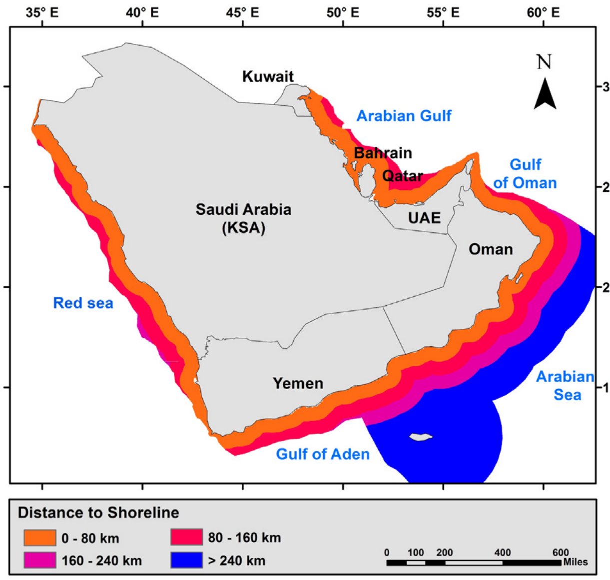

Fig. 11. Layer map of the distance between representative cells of the offshore wind resources and shoreline.

determined values were then verified using data available from Refs. [67,68]. The map layer in Fig. 8 shows the results of the average wind speed in [m/s] at a height of 50m over a flat and uniform sea.

All layers for area restrictions were adopted from different sources. Locations, shapes, dimensions of maritime reserved parks were taken from the official websites of different Wildlife Authorities of these countries, as documented in Table 13. All oil extraction areas are located on the Arabian Gulf, according to data from Saudi Aramco [73]. Shipping Routes within the study area were identified using the data available from ship density maps of the Marine Traffic website [74]. Undersea submerged cable locations and paths were extracted from the submarine cable map given in Ref. [75].

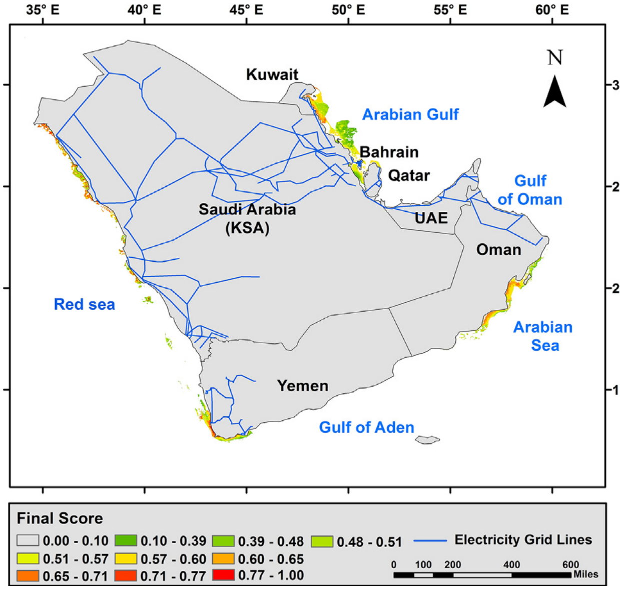

Fig. 12. Offshore wind energy Suitability Map around the Arabian Peninsula. Where 0.0 score is not a suitable area, while a score of 1.00 represents areas of the highest possible suitability. Grid availability, blue line.

Fig. 9 maps the overall results of restrictions for the region covering: natural reserves, oil and gas areas, shipping routes and undersea cables.

Fig. 10 shows the results map layer of the National Electricity Transmission Grid of the GCC and Yemen. The data were adopted from the Global Energy Network Institute [76] and the GCC Interconnection Authority [77]. The Euclidean Distance Tool in ArcGIS [43] was deployed to calculate the distance between the nearest electricity line to each cell, and the results are depicted in Fig. 10. Fig. 11 illustrates the results of the distance from each cell considered in the analysis to the coastline utilising data from Ref. [43].

A Boolean mask was created to eliminate restricted cells, so that constraint cells have a value of zero, and unrestricted cells have a value of one. The Raster Calculator tool in ArcGIS was used to produce the final Boolean Mask given by Equation (3).

All considered criteria were aggregated using Weighted Linear Combination (WLC) given by Equation (3), to create the final suitability map for offshore wind for the AP case study. Four standardised layers were first multiplied by their Factor Weight from Table 9 (Section 2.2.1), then summed together, using the Raster Calculator tool in ArcGIS by applying Equation (3). Finally, restricted cells were removed from the WLC layer using the Boolean Mask layer.

As indicated earlier, the modelling was undertaken using an 800 × 800 m cell size confined to the source file of the bathymetry map. Four factors and five constrained criteria were chosen to evaluate the alternatives/cells around the countries of the Arabian Peninsula. The model solved the spatial siting for offshore wind farms dealing with the chosen conflicted factors and constraints efficiently.

The suitability map for the studied area (Fig. 12) represents the cells around the shores of the AP where the cells final scores and their corresponding areas are graded as follows:

(i) $0.0 < \text{Cell Score} < 0.39$ - not suitable. This represents 20,935 km^2 of the studied regions (the 0 score assigned by the Boolean Mask is not accounted in this area).
(ii) $0.4 < \text{Cell Score} < 0.59$ - moderately suitable. This represents 23,080 km^2 of the studied regions.
(iii) $\text{Cell Score} > 0.6$ – highly suitable. This represents around 3251 km^2 of the studied regions.

The results for the overall suitability map of the Arabian Peninsula is shown in Fig. 12 with high resolution details of the regional sites given in Fig. 13. It must be noted that in the final suitability map, the UAE has no suitable cells (due to low wind speeds and dense shipping routes as indicated by Figs. 8 and 9 respectively), while Qatar and Bahrain have moderate suitability cells and no high suitable cells. In addition, the suitable areas for Yemen and Oman are centred on one area of their shoreline due to the lack of wider electricity grids provisions, (see Fig. 10). Yemen, Kuwait, Oman, and KSA have the most suitable sites for offshore wind, with KSA having the highest suitable areas in the region (due to high wind speeds in the Red Sea).

4. Discussion

A mathematical approach including the utilisation of an Analytic Hierarchy Process (AHP) was developed to solve the spatial siting for offshore wind farms. This is achieved by reducing the conflict between factors and constraints (restrictions) as follows:

(a) A Boolean Mask is produced to eliminate the restricted areas at the start of the analysis where the Mask is different for different locations, e.g. UK and Arabian Peninsula.

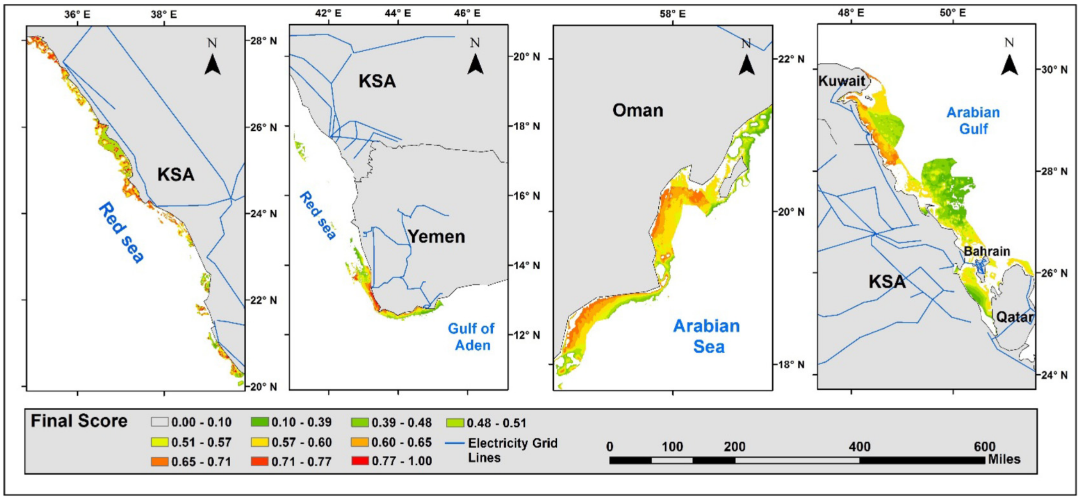

Fig. 13. High-resolution offshore wind energy Suitability Map for the countries with highest offshore wind energy potential - KSA, Yemen, Oman, Qatar, Bahrain, and Kuwait - around the AP. Where a 0.0 score indicates areas which are not suitable, while a score of 1.00 represents areas of the highest possible suitability.

(b) In the methodology, an appropriate Representative Cost Ratio (RCR) was introduced to reduce time, cost, and complexity encountered in previous approaches to analyse offshore wind energy potential.
(c) This new approach was validated using the actual UK offshore wind energy location maps, and the methodology and our analysis predicted this with high accuracy. Furthermore, the methodology also identified future regions of offshore wind energy potential in the UK which are currently being considered for commercialisation.
(d) The methodology can be applied at large scale as evidenced by the outcome for offshore wind energy potential around the Arabian Peninsula.

The methodology and its resilience were tested through application to two case studies. The first case study considered the matured UK wind energy programme where most of the projects are already in place/being commissioned or sites to be utilised (Section 3.1). The methodology and our analysis predicted this with high accuracy. Furthermore, the methodology also identified future regions of offshore wind energy potential in the UK which are currently being considered for commercialisation.

The second case study provided outcomes at regional scale of the Arabian Peninsula (AP) covering an area ~3.1 million km^2 and coastline of 9180 km with Fig. 13 showing the results map for offshore wind energy potential in the region. The outcomes in the figure is used to estimate the suitability distribution for the seven countries in the AP as shown in Table 14. As can be seen from Table 14, the KSA has more than 25,000 km^2 of unrestricted areas, which represents 54% of the total available area for offshore wind energy potential in the Arabian Peninsula region. Despite the high wind potentials in KSA around the Red Sea region (Fig. 8), less than 3.5% of the total available area of the region is considered to be of high suitability. This is due to the fact that most of the Red Sea region of the KSA has a water depth of 60m or more (Fig. 7) which is beyond current turbine foundations technologies. So to extend suitability, it is feasible for the KSA to consider investigating floating offshore wind turbines, which are more suitable for deeper water.

Oman's share of the total available area of the region is around 18%, and only 8.7% of that is highly suitable for offshore wind, which is surprising at it has a shoreline of 2092 km, which is not too dissimilar to that of the KSA (Table 12). Despite this, Oman has a significant average wind speed on the Arabian Sea, but unfortunately, this is remote, located over 90 km from the nearest electricity grid in the area. Nevertheless, Oman does, however, have a well-established national power grid near the Gulf of Oman (Fig. 10), but the wind speed in this location is less than desirable. Kuwait has around 14% of the total available unrestricted area, with a similar percentage of the highly suitable area within the region. These numbers are relatively high when compared to its short shoreline (around 5% of the total coastlines of the region considered). Kuwait has high offshore wind potentials compared to its footprint since it has minimum restriction on the Arabian Gulf (Fig. 9), average wind speed of 6.2 m/s (Fig. 8), and a shallow water depth range of 35m (Fig. 7).

Yemen's offshore wind potential and grid proximity are concentrated in the same area (Figs. 8 and 10), which justifies its 441 km^2 of high suitability areas, despite its current poor infrastructure when compared to others in the Gulf States. Qatar and

Table 14
Suitability distribution for the Arabian Peninsula countries offshore wind sites.

	Unsuitable Suitable Area (km^2)	Moderate Suitable Area (km^2)	High Suitable Area (km^2)	Total Available Area (km^2)
KSA	14732	9204	1586	25522
Oman	493	7410	769	8672
Kuwait	2800	3319	455	6574
Yemen	2742	2843	441	6026
Qatar	162	220	0	382
Bahrain	6	84	0	90
UAE	0	0	0	0
Total	20935	23080	3251	47266

Table 15
National installed electrical power capacities in Arabian Peninsula countries compared with estimated power capacity achieved from offshore wind high suitability sites from an 8 MW capacity turbine in these countries.

	National installed capacity (GW) [81]	High Suitable Area (km^2)	Estimated offshore wind Capacity (GW)	No. of turbines	Potential offshore wind contribution to capacity (%)
KSA	69.1	1586	17.06	2125	24.7
Oman	7.87	769	8.28	1031	105.2
Kuwait	16.0	455	4.90	610	30.6
Yemen	1.5	441	4.75	591	316.5
Qatar	8.8	*0*	–	–	–
Bahrain	3.93	*0*	–	–	–
UAE	28.9	0	0.00	0	0.0
Total	136.1	3555	35	4765	25.7

Bahrain have no high suitable offshore wind areas. UAE has more than 23 seaports; seven of them are mega container ports, resulting in a high volume shipping route density (Fig. 9) and hence zero availability for offshore wind.

To estimate the offshore wind power potential for the investigated sites, one needs to provide a spatial siting of the turbines and their inter turbine spacing in an array or farm. To estimate the array spacing between offshore wind turbines, Equation (5) developed in Ref. [78] was used:

$$S = (R_d)^2.\ L_d.\ L_c \tag{5}$$

Where S is the array spacing giving the footprint for each offshore wind turbine in an array, R_d is the rotor diameter, L_d is the downwind spacing, L_c is the crosswind spacing.

To reduce turbulence interaction between turbines, the ideal turbine spacing is in the range of 5–8 times the turbine rotor diameter [79]. In our analysis, L_c was given the value 5 and L_d the value 8. Hence a wind turbine footprint $S = 5 \times 8 \times 164^2$ for an 8 MW turbine (rotor diameter 164 m [80]). The estimated number of wind turbines for 8 MW configuration given in Table 15, is derived by dividing the Suitable Area (km^2) by S for the turbine size used.

The estimated offshore wind power capacities for each country using the turbine type in combination with Equation (5) are shown in Table 15. The table also provides details of the Arabian Peninsula countries currently installed power capacity and the percentage contribution from the estimated offshore wind capacities established here.

As can be seen from Table 15, the estimated overall total cumulative capacity of offshore wind power contribution (from the high suitability areas only) to these countries is approximately 35 GW for an 8 MW turbine capacity. The results indicate that for the 8 MW turbine case around 25.7% of the overall Arabian Peninsula countries power capacity can be achieved from offshore wind. In terms of country, specific offshore wind capacity potential determined in this study, Saudi Arabia has 17 GW, Oman 8 GW, Kuwait 4.9 GW, and Yemen 4.8 GW. Bahrain and Qatar have moderate offshore wind energy capacities of 2.37 GW and 0.9 GW respectively. The United Arab Emirates (UAE) has small forefront to the sea and has many restrictions especially around shipping lanes (Dubai being a world commercial centre). When combined with the limited wind resources around its shores the analysis indicates that UAE has very limited suitable areas and hence negligible wind power potential. This latter outcome provides more rigorous analysis providing stronger evidence than [82], where only two factors were used to select a suitable site for offshore wind around Abu Dhabi, only in the UAE.

It must be noted that the markets, especially in Europe, are now leaning towards the 8 MW capacity turbine with some developers now upgrading these turbines to 9.5–10 MW and are thinking about 12 MW turbines in the next two years with research now being directed towards 13–15 MW turbines [83]. In the case of the countries studied here, it is imperative that any development of the sites highlighted should bear these developments in mind. In our view, the 8 MW option seems to be the most sensible option to go for at this stage.

However, it must be noted that in this new approach the cost ratios need to be updated constantly, and that in some cases some of the factors cannot be easily costed, for example, environmental impacts (if considered as a factor).

Spatial siting models are sensitive to the data quality and availability for the analysis. In this case, factor layers needed to be available at 500–1000 m resolution (cell size). Hence, the spatial siting investigations accuracy is dependent on the data availability and quality. The analysis has considered cost-related criteria as factors, while other criteria, such as environmental and social impacts were considered as restrictions.

Unlike other studies, the presented approach considered more factors in its designed methodology. These included the main four factors (requiring appropriate weights) affecting the offshore siting process, which are wind speed, water depth, distance to land, and distance to the electricity grid. These are augmented by constraints criteria affecting the offshore areas such as Marine Protected Areas, Marin Boundaries, Undersea Cables, Shipping Routes, Military Restricted Areas, and Oil and Gas Extraction Areas, which are combined in one Boolean Mask. Other studies tend to use one or two factors to identify the suitable areas.

This new approach is quick and less complex. It was validated using the actual UK offshore wind energy location maps, and the methodology and predicted outcomes matched well with the "costly mapping" determined by the Crown Estate for their projects for the three UK's Rounds. Furthermore, the methodology also identified future regions of offshore wind energy potential in the UK which are currently being considered for commercialisation. This gives confidence that the RCR approach is accurate as all of the cells for these projects are located in either moderate or high suitability categories determined by this study.

The final suitability maps produced by the methodology provide stakeholders (e.g. governments) the suitable zones for offshore wind energy exploitation. Development of such zones will require further in-depth detail study to address local issues.

The paper introduced the new parameter termed the "Representative Cost Ratio" (RCR) to support the quantification (weighing) of the spatial siting of offshore wind potential areas. This parameter coupled with the approach are also applicable to other renewable energy sources spatial planning. However, it should be noted that the weighting process is to distinguish between compatible zones within the site(s) considered – defining the most/least suitable areas for renewable energy conversion technologies. This weighting must take into account the type of energy and the territory where it is applied. Thus, for example, if all study areas have enough wind to install wind power plants, the wind factor, in this case, is not applicable, and therefore only the other factors should be weighted. Furthermore, when conducting detailed studies, local expertise will be needed to address regional specificity and characteristic to support the study.

In summary, due to the nature of the problem, the work integrates modelling and engineering approaches coupled with regional considerations. The proposed new approach (i) overcomes many of the shortcoming of previous studies (ii) has been verified by the UK offshore wind programme projects and (iii) has predicted the sites and capacities of the Arabian Peninsula offshore wind potential at a large scale. However, it is not tested, as it cannot be compared with previous analysis.

5. Conclusions

Multiple-criteria decision-making (MCDM) analysis coupled with AHP are widely used to solve complex renewable energy spatial planning problems. Here we proposed a new approach to use the *Representative Cost Ratio* (RCR) to assist in the rapid and accurate determination of offshore wind energy potential areas. This approach was quantified through a robust methodology and was used in two case studies to support its applicability and usefulness. The spatial results obtained for the UK offshore wind programme matched well with the “costly mapping” determined by the Crown Estate for their projects (£90k/MW) for the three Rounds [40]. This gives confidence that the RCR approach is accurate as all of the cells for these projects are located in either moderate or high suitability categories determined by this study.

In the second case study, we consider the regional area of the Arabian Peninsula to test the methodology across the whole process (Fig. 1) and to provide detailed indication of the offshore wind energy potential in this region. The analysis and modelling covered seven countries, for which final suitability maps were generated using appropriate factors and weights of relevance to the region’s countries. The identified sites were analysed in terms of potential power capacities based on an 8 MW wind turbine which now seems to be the standard capacity being deployed in Europe and elsewhere. The results shown in Table 15 indicate a cumulative regional capacity of up to 35 GW for the turbine capacity selected. This Middle East region has not seen any significant or meaningful development to exploit its offshore wind energy potential and this work and its outcomes has also addressed this gap in knowledge. To the authors’ knowledge, the outcomes represent the first detailed assessment of the offshore wind energy potential for the Arabian Peninsula countries. This work will contribute to the stimulation of interest in the region of the importance of offshore wind as part of a regional energy mix.

It must be noted that this work does not compare the various attributes of the available renewable energy resources in the region, but provides seminal work for understanding the offshore wind energy potential. The outcomes also show the effective aspect of the presented methodology and its utilisation at such a large regional scale.

In summary, the proposed new approach has been verified by the UK offshore wind programme projects and has predicted the sites and capacities of the Arabian Peninsula offshore wind potential at a large scale. The use of the *Representative Cost Ratio* to assist in the rapid and accurate determination of offshore wind energy potential regions will save money and reduce the time and effort taken to achieve the optimal spatial siting decisions for offshore wind energy farms.

Author contributions

The authors contributed to the paper as follows:

AbuBakr S Bahaj designed, led and directed the overall research of the paper and subsequent revisions; Mostafa Mahdy, obtained essential research data, modelling, design and analysis;

Abdulsalam S. Alghamdi contributed to the KSA side of the research and.

David Richards contributed to the editing and critiquing of manuscript.

All authors contributed to the writing, proof reading, and revisions of the manuscript.

Data accessibility

The datasets supporting this article have been implemented as part of the main manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A
Attribute tables for the three sets of the UK's offshore wind areas.

set a. Round 1 and 2			Set b. Round 3 all operating			Set c. Round 3		
ID	Suitability Value [x 100]	Cells Count	ID	Suitability Value [x 100]	Cells Count	ID	Suitability Value [x 100]	Cells Count
1	41	140	1	40	215	1	42	163
2	42	129	2	41	429	2	43	236
3	44	49	3	42	314	3	44	417
4	45	110	4	43	297	4	45	471
5	46	882	5	44	438	5	46	675
6	47	61	6	45	240	6	47	423
7	48	354	7	46	1081	7	48	113
8	49	65	8	47	240	8	49	380
9	50	81	9	48	267	9	50	1244
10	51	23	10	49	104	10	51	2981
11	52	44	11	50	396	11	52	5343
12	53	4	12	51	664	12	53	7656
13	54	109	13	52	887	13	54	23030
14	56	106	14	53	727	14	55	38889
15	57	7	15	54	2190	15	56	37240
16	59	389	16	55	5117	16	57	43640
17	60	617	17	56	4553	17	58	42704
18	61	1120	18	57	3542	18	59	36686
19	62	1264	19	58	4324	19	60	32195
20	63	1020	20	59	4672	20	61	42883
21	64	1002	21	60	4692	21	62	43159
22	65	2052	22	61	6844	22	63	44510
23	66	2854	23	62	8619	23	64	62563
24	67	3736	24	63	13518	24	65	54082
25	68	3165	25	64	26100	25	66	32675
26	69	5418	26	65	35765	26	67	46389
27	70	3887	27	66	11893	27	68	13139
28	71	1798	28	67	12573	28	69	10860
29	72	1117	29	68	8702	29	70	13526
30	73	781	30	69	10447	30	71	19247
31	74	529	31	70	12728	31	72	17132
32	75	652	32	71	16562	32	73	1347
			33	72	13023			
			34	73	1703			
🟨	Moderate Suitability		35	74	185			
🟦	High Suitability		36	75	95			

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