

Research Article

Offshore Wind Energy Potential for Bahrain via Multi-criteria Evaluation

Mohamed Elgabiri ¹, Diane Palmer ^{1,*}, Hanan Al Buflasa ² and Murray Thomson ¹

¹ Loughborough University, Loughborough, UK; mohamed.elgabiri@gmail.com

² University of Bahrain, Kingdom of Bahrain; h.m.albuflasa@gmail.com

* Correspondence: d.palmer@lboro.ac.uk; Tel.: +44 1509 635604. ORCID 0000-0002-5381-0504

Abstract: Current global commitments to reduce emissions of greenhouse gases encourage national targets for renewable generation. Due to its small land mass, offshore wind could help Bahrain to fulfill its obligations. However, no scoping study has yet been carried out. The methodology presented here addresses this research need. It employs Analytical Hierarchy Process and pairwise comparison methods in a Geographical Information Systems environment. Publicly available land use, infrastructure and transport data are used to exclude areas unsuitable for development due to physical and safety constraints. Meteorological and oceanic opportunities are ranked, then competing uses are analyzed to deliver optimal sites for wind farms. The potential annual wind energy yield is calculated by dividing the sum of optimal areas by a suitable turbine footprint, to deliver maximum turbine number. Ten favourable wind farm areas were identified in Bahrain's territorial waters, representing about 4% of the total maritime area, and capable of supplying 2.68 TWh/yr of wind energy or almost 10% of the Kingdom's annual electricity consumption. Detailed maps of potential sites for offshore wind construction are provided in the paper, giving an initial plan for installation in these locations.

Keywords: Offshore wind farm siting; Suitability maps; Geographical Information Systems (GIS); Multi-criteria; Analytic hierarchy process (AHP); Offshore wind energy potential.

1. Introduction

The Kingdom of Bahrain, in common with the majority of the countries of the Gulf Cooperation Council, has committed to the Paris Agreement of the United Nations Framework Convention on Climate Change 2015. This requires initiatives to reduce emissions of greenhouse gases. To fulfill its obligation, Bahrain has set a target for generating 5% of capacity from renewable sources by 2025, and 10% by 2035, as detailed in the National Renewable Energy Action Plan (NREAP 2019). Currently, only 0.15% of generation is renewable energy, including 0.03% of wind (IRENA 2018).

The proposed renewable energy mix comprises solar, wind and energy-from-waste technologies. Offshore renewable energy development could constitute a significant proportion of this mix. Bahrain has limited land mass (765 km² or half the size of Greater London), so offshore wind installation would enable large-scale generation. The territorial waters of Bahrain are comparatively extensive and shallow, with 0.01 km² of sea area per person. This is the same as its neighbour, Saudi Arabia, which is almost 3,000 times larger. Theoretically, then, offshore wind appears to be a feasible option for installation of renewables. This research investigates in detail whether in fact this is the case.

Methods for assessing the potential of both onshore and offshore sites for wind farms have been the subject of research for many years in various countries. Comprehensive reviews are provided by Panagiotidou et al. (2016); Vagiona and Kamilakis (2018); Mahdy and Bahaj (2018). Geographical Information Systems (GIS) which organise, store and link together real-world data via its spatial reference, have been extensively employed for this purpose. Their simple application is described in a well-cited UK example of land-based wind site targeting by Serwan and Parry (2001). Here the authors first consider all criteria (map layers) to be equally important, before grading them by apparent significance. More complex methods of applying multi-criteria decision making (MCDM) methods based on GIS to wind farm prospecting are tested by Villacreses et al. (2017) in continental Ecuador. The researchers initially used the Analytic Hierarchy Process (AHP), which involves pairwise comparisons of ranked criteria, to rank input criteria. Four MCDM methods were then appraised: little difference was found between the MCDM methods.

Focusing on offshore wind studies only, the AHP approach to multi-criteria selection has been applied in the Baltic (Chaouachi et al. 2017) and China (Wu et al. 2018). The most important technoeconomic cost-related factors (wind speed, distance and water depth), have been modelled using genetic algorithms, taking the UK as a case study (Mytilinou and Kolios 2017). However, it has been found that failure to incorporate other factors such as conservation overinflates the number of feasible sites (Kim et al. 2016). The biological effects of offshore wind are investigated by Bray et al. (2016). This group of researchers locate potential offshore wind farm “hotspots” in the Mediterranean by applying the following thresholds: 20–50 m depth and an annual wind speed >5 m/s at a turbine height of 80 m. Sensitive species which may be impacted are then identified. AHP and GIS is used by Loukogeorgaki et al. (2018) to hierarchically score a dozen factors for hybrid wind and wave systems in the Greek marine area, one factor being environmental impact.

To the authors' knowledge, no offshore wind farm site targeting studies have been carried out in Bahrain, to date. One of the closest is that of Mahdy et al. (2017) who assess potential wind farm sites on Saudi Arabia's Red Sea coast, using a simple Boolean Mask technique (map layers suitable/unsuitable for installation) in a GIS environment. Moving to the Persian Gulf, Fetanat and

Khorasaninejad (2015) employ fuzzy set theory to create matrices for six criteria (depth, height, environment, proximity to land, economic implications, wind resource and acceptance) to aid decision-making in coastal Iran. A slightly different set of criteria are analysed by Saleous et al. (2016) in United Arab Emirates (UAE) waters. These are studied in a two-stage process. Firstly, areas where wind farm construction is impossible are combined into a single map layer (marine protected areas, oil extraction platforms and oil pipelines). Then remaining areas are ranked according to average wind speed and water depth.

In the present paper, a sequence of methods for identifying the optimal sea areas for offshore wind deployment in Bahrain's territorial waters is planned and executed. The methodology developed is adapted from Vagiona and Kamilakis (2018) and Mahdy and Bahaj (2018). That is, GIS and AHP are allied in a five-stage process for offshore wind farm site targeting. The stages comprise data collection, exclusion, ranking, analysis of a set of feasible scenario alternatives and calculation of offshore wind power potential. The exclusion stage identifies all constrained areas where wind farms cannot be built based on nautical hazards, shipping, environmental and development criteria. These areas are combined using GIS and excluded from subsequent processing. The ranking stage considers additional factors i.e. average wind speed, water depth and distance from Bahrain Island. These map layers offer varying degrees of opportunity for wind farm installation, depending on their value. They are standardised, weighted via AHP pairwise comparison and overlaid in a GIS grid so that the relative importance of each layer is reflected. In the scenario phase, the collective excluded constraints are subtracted from the weighted amalgamated factors. Next, competing uses of the nearshore seabed are investigated: sand extraction, oil drilling, fishing and conservation. Finally, in the last (fifth) stage, the number of wind turbines in available space is estimated, followed by nameplate capacity and potential output. It should be emphasized that this is the first time the offshore wind potential for Bahrain has been studied and the first time AHP and GIS together have been applied to renewable-energy (RE) siting issues in Bahrain.

The rest of this paper is organized as follows: Section 2 describes the several stages in the method. It details the types and sources of data used and its standardisation, as well as the software employed. Next, exclusion of constraint data layers is described, followed by a comprehensive explanation of weighting of possibilities using the Analytical Hierarchy Process (AHP). After a study of the needs of other seabed users, a final suitability map layer is produced. Calculations of the offshore wind energy potential based on this suitability layer are described. Section 3 illustrates the results obtained. That is, the size of each potential wind farm, number of turbines, nameplate capacity and total possible annual wind energy yield. Section 4 makes international comparisons of the previously derived wind potential in Bahrain. It investigates the extent to which it could contribute to the Kingdom's energy needs and explores how future turbine developments may

change the situation. Finally, Section 5 restates the research objectives and evaluates the success of this study.

2. Methods

The sequence of methods expounded in this journal paper is summarized in Fig. 1. The succeeding sub-sections of this article itemize each stage of the methodology.

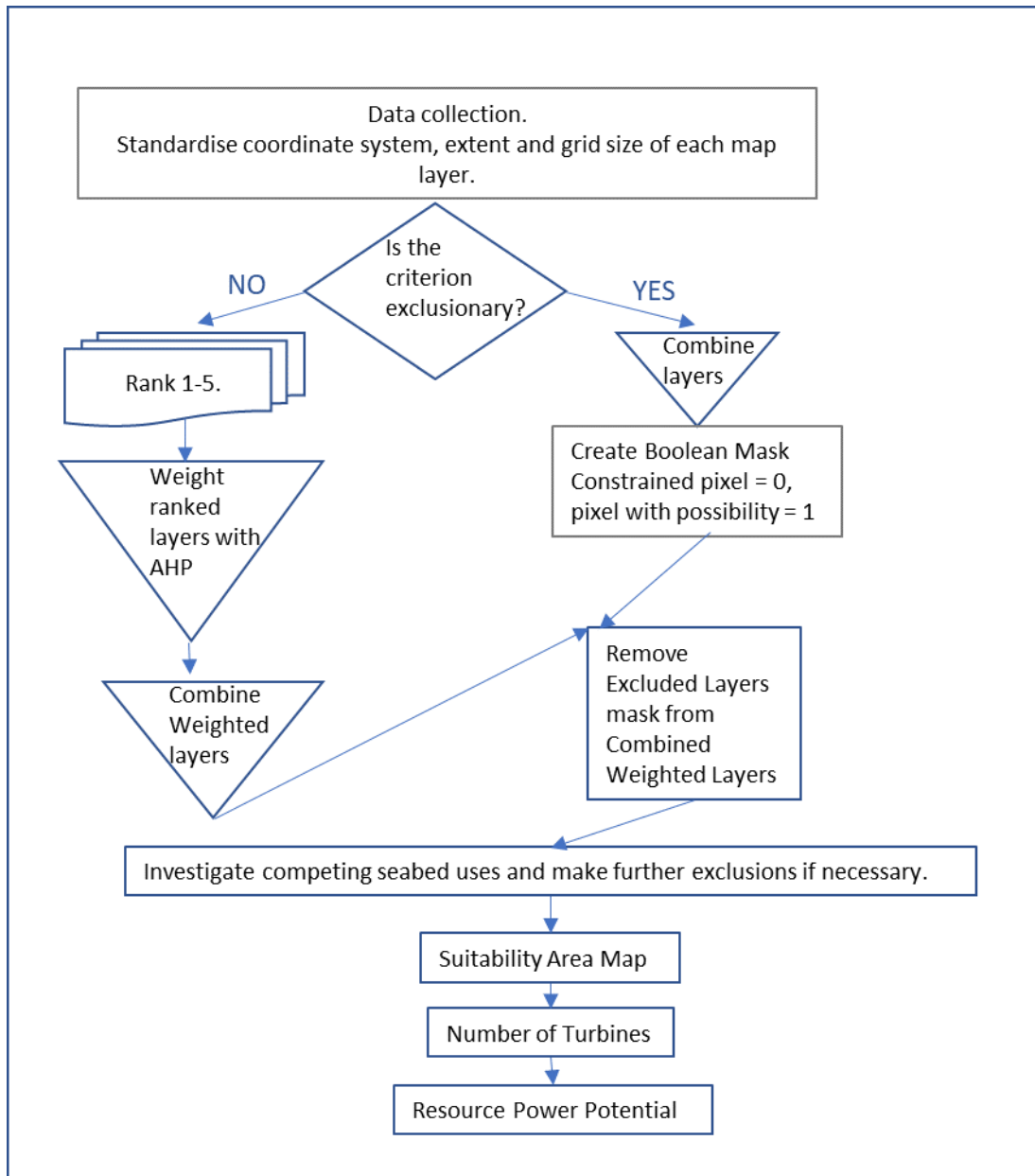


Fig. 1 Diagrammatic representation of the sequence of methods

2.1. Data Collection Stage

An extensive literature review was undertaken, including the above cited references. From the criteria utilized by these authors, a number of constraints (exclusions) were identified as relevant to offshore wind site selection in Bahrain. These are: land and planned land fill; transport (roads,

airport exclusion zones, shipping), submarine cables and pipelines; and protected areas (conservation, military, restricted). The factors (opportunities) are: wind speed; sea depth (bathymetry); and distance from Bahrain Island. Further details of the various constraints and factors used in this methodology, as well as reasons for their selection and ranges of values chosen, are given in subsections 2.2 and 2.3.

2.2. Exclusion Stage

The process of locating prospective areas for siting wind farms was begun by excluding areas deemed incompatible for offshore wind. That is, the spatial footprint of unsuitable areas was blocked out of the map to avoid considering impractical locations for installation. The areas classified as unsuitable for offshore wind construction are:

- Current land area. This was obtained from GADM (2019). Since 1965, Bahrain has had an ongoing programme of reclaiming land from the sea. Approximately 70 km² of land for housing, commerce and industry has been added to the country, the majority of it in the last ten years (Al-Nabi 2012). Therefore, the country outline was updated with recent satellite imagery from World Imagery (2019) to capture its most up-to-date extent.
- Future reclamation areas. These are part of Bahrain's Economic Vision 2030 (Our Vision 2030). Planned land fill was digitized from the National Detail Land Use map 2030 (Bahrain Ministry of Works, Municipalities Affairs and Urban Planning 2016).
- Buoyed shipping channel. The seas around Bahrain are very busy, so an area around the main dredged shipping channel only was excluded from wind turbine installation, otherwise little sea space would remain for wind development. Vessels may be re-routed where wind farms are constructed, as in the case of the Thames Estuary (Rawson and Rogers (2015). The location of the channel was obtained from nautical charts (i-Boating 2019). A buffer zone of 500 m on either side of the buoyed channel, to comply with the United Nations Convention on the Law of the Sea and to avoid navigation interference (Erftemeijer and Boot 2004), was added to the channel exclusion area.
- Oil shipment route. This was recognized and digitized from the marine density maps of marinetraffic.com, a website which provides information about the real-time geographical position of ships from radio signals.
- Sitra port anchorage area. Highlighted by a researcher carrying out site selection for artificial reefs in Bahrain (Erftemeijer and Boot 2004), this was noticed as an artificially deep (due to being dredged) region in bathymetry data (Becker et al. 2009). This feature was captured by digital tracing.

- Current airport height restriction zones. These were digitized from the National Detail Land Use map 2030 (Bahrain Ministry of Works, Municipalities Affairs and Urban Planning 2016).
- Area surrounding proposed airport. Again, digitized from the National Detail Land Use map 2030.
- New roads connecting future reclamation areas. The routes of these were copied from the National Detail Land Use map 2030. An exclusion zone of 500 m either size was added, as used by the artificial reefs researchers (Erftemeijer and Boot 2004) for the King Fahad causeway between Saudi Arabia and Bahrain.
- Submarine cables, oil and gas pipelines. These were digitised from i-Boating. 250 m on each side of this infrastructure network was additionally excluded, the same as applied for wind site selection in UAE (Saleous et al. 2016).
- Proposed oil pipeline. This was traced from the National Detail Land Use map 2030 and buffered as for the existing pipelines.
- Current protected areas. Areas protected for environmental reasons (they contain fish nurseries, oyster beds, mangroves or species including rare seabirds, flamingos, sea cows and turtles) were excluded (Supreme Council for Environment, 2015).
- Bahrain Fort viewing corridor. This historic entrance channel is obvious on the National Detail Land Use map 2030. It is a development exclusion zone, particularly as regards height (Unesco 2014).
- Approximate location of new underwater theme park. Details of position were difficult to ascertain. It was estimated from a travel website (The Travel 2019).
- Area around King Fahad Causeway and Umm an Nasan Island. Nautical charts (i-Boating) show that this area contains no anchorage zones, buoyed and marked channels, piles, obstacles, fish traps and pipelines.
- Bahrain Defence Force area, obtained from the National Detail Land Use map 2030.
- Border areas. Following Erftemeijer and Boot (2004), a 1 km buffer was added to the inside of the territorial waters of Bahrain (the Economic Exclusion Zone, EEZ) to avoid any potential problems with border patrols. The EEZ GIS layer was obtained from marineregions.org.

A GIS database was created initially in QGIS (2015) and transferred to ArcGIS for its advanced mapping functionality (ESRI 2014). The exclusion layers are illustrated in Fig. 2.

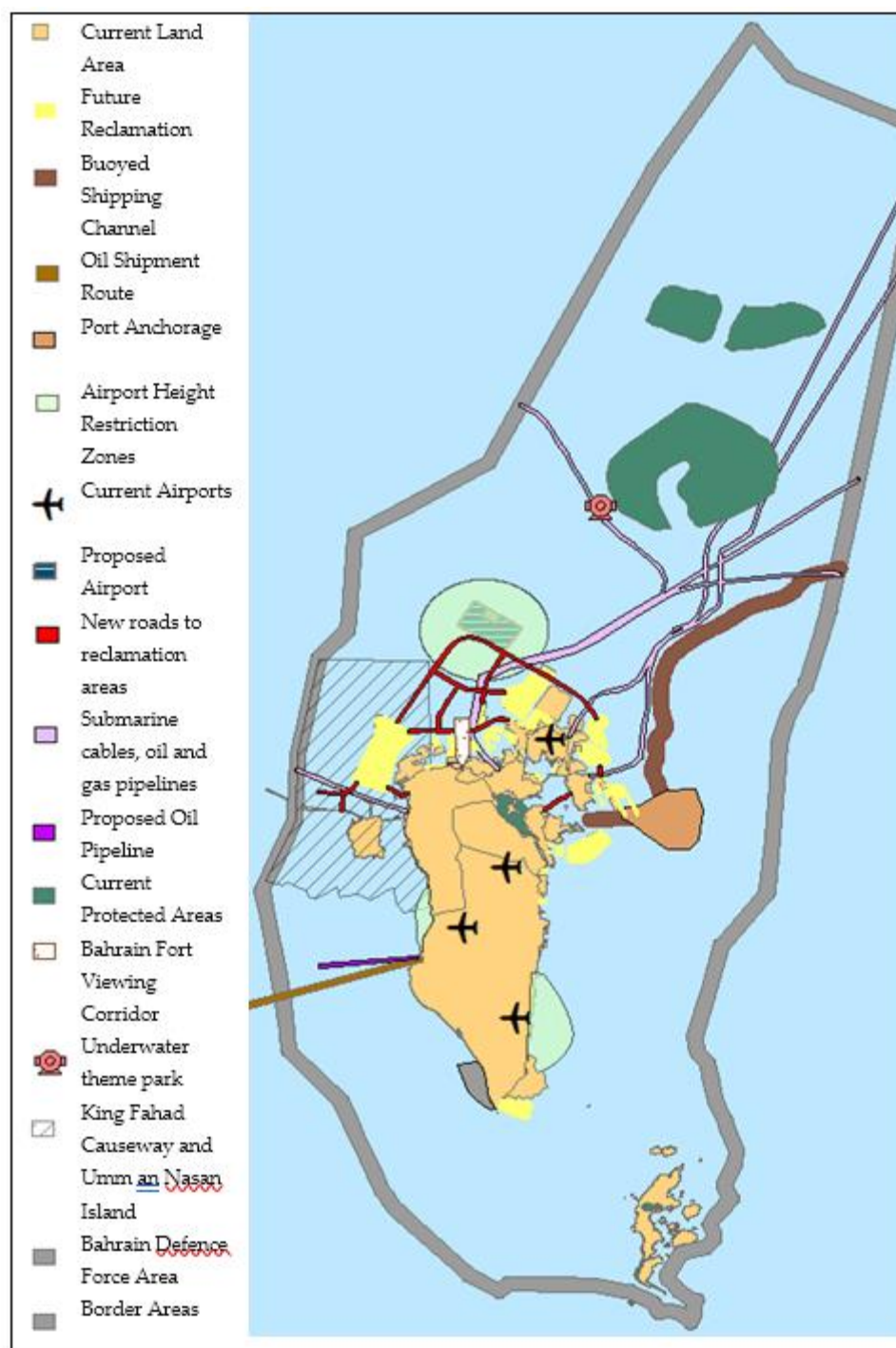


Fig. 2 Constraints for selection of sea areas suitable for wind farm construction

All datasets were converted from their original format (grid coordinates, pdf or GIS polygon shapefile) into GIS raster (grid) format. The map layers were standardized in geographic coordinate system, extent and spatial resolution as follows:

- The well-known WGS84 coordinate system (used by the Global Positioning System, GPS) was chosen to ensure identical features in the layers correctly coincide.
- The spatial extent of all maps was limited to the Bahrain EEZ.

- The raster grid square (pixel) size for all was set to 1.0 x 1.0 km which is the resolution of the bathymetry layer (Becker et al. 2009) (see Section 2.3).

All the areas (listed above) identified as exclusions were combined into a total exclusion mask. This is in the form of a Boolean mask, where constrained pixels have value 0 and pixels where wind installation is possible have value 1. This was achieved by reclassifying each layer (0 or 1) and unifying them into a single exclusion area using ArcGIS Raster Calculator. The resultant exclusion mask covers about 60% of Bahrain's territorial waters (Fig. 6).

2.3. Ranking Stage

The factors identified in the literature review and employed in this research were converted to GIS raster (where necessary) and changed to a coordinate system, extent and grid size which conformed with that of the constraints (Section 2.2). The following paragraphs particularise the factors and describe their ranking according to the level of opportunity they offer for offshore wind installation. The various factors have different values and scales, so to make them directly comparable they are reclassified to a common linear scale of 1-5, with 5 being the most preferred.

2.3.1 Wind Speed

GIS polygon shapefiles of wind speed for Bahrain were downloaded from the Wind Atlas (EMD 2017). This was prepared using mesoscale and microscale modelling by a consultancy commissioned by the Sustainable Energy Unit of the Kingdom of Bahrain. The input data is ECMWF ERA-Interim data 1997-2016 (satellite reanalysis data). This dataset agrees well with the Global Wind Atlas which is also generated by downscaling atmospheric re-analysis data. It is also consistent with the Coastal Information System Database at Kuwait Institute for Scientific Research (Al-Salem et al. 2018). This database is mathematically modelled and validated with instrumental records from Kuwait International Airport. However, lower values are obtained by Khonkar (2009). This author based his results on sparse voluntary ship observations. Thus the wind data utilised in this research should be used as a guide only. Measurements at potential sites using masts or vertical LiDAR should be undertaken before commencement of any construction.

The wind speed was selected for 150 m height. This is the closest to the present average wind turbine hub height of 133 m in 2018 (Fraunhofer 2018a). The wind speed at 150 m in Bahrain's maritime area ranges from 6.3 m/s to 7.5 m/s (Fig. 3). By European standards this is considered insufficient for profitable energy production (minimum of 8 m/s at 100 m (BVG 2017)). Yet wind turbines commence electricity generation at wind speeds of 3 m/s and achieve full capacity at 12 m/s (Rampion 2019). Researchers have employed minimum offshore wind speeds of 5 m/s in India

(Murali et al. 2014) and 4.5 m/s in UAE (Saleous et al. 2016). Hence, in this paper, the whole of Bahrain EEZ is designated as possessing adequate winds. Wind speed is divided into five equal classes, the stronger the better (Table 4).

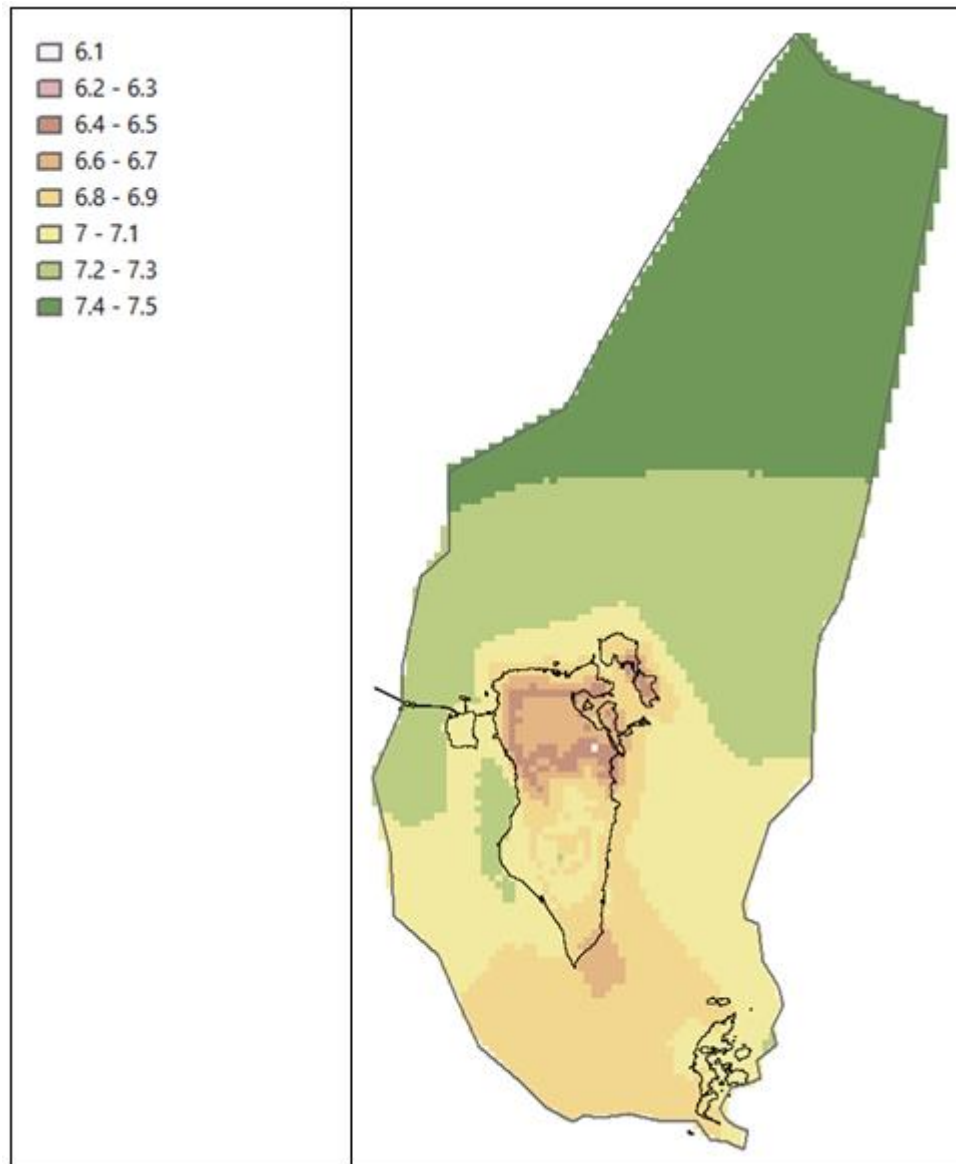


Fig. 3 Bahrain wind speed at 150 m in m/s from Wind Atlas (EMD 2017)

2.3.2 Sea Depth

The bathymetry layer was obtained from (Becker et al. 2009). It comprises satellite data calibrated by soundings and is the most detailed and accurate publicly available for the region. The seas surrounding Bahrain are generally very shallow, reaching a maximum depth of 70 m at the northern extremity of the territorial waters (Fig. 4). Following a survey of reports and scientific articles, the depth layer was divided into the classes itemized next and summarized in Table 4. Waters between 30 and 50 m are the most favourable. These allow installation of fixed monopile

turbines which are a mature technology (Scottish Government, 2018). Second in order of preference are 5-10 m and 30-40 m. In less than 5 m water depth, wind turbine construction is possible but requires dredging or a specialist vessel (for instance as described by Mammoet (2018)). Therefore 0-5 m takes the next lowest ranking. Fewer turbines are installed in depths greater than 40 m (Fraunhofer 2018b). When the seabed exceeds 50 m below the surface, it becomes necessary to deploy floating structures. Currently, this is associated with a step up in costs but as the technology evolves, expenses are expected to fall. However, as of today (June 2019) just one floating wind farm is actually operational (OffshoreWind.biz 2019). Therefore, depths greater than 50 m were categorized as least preferable.

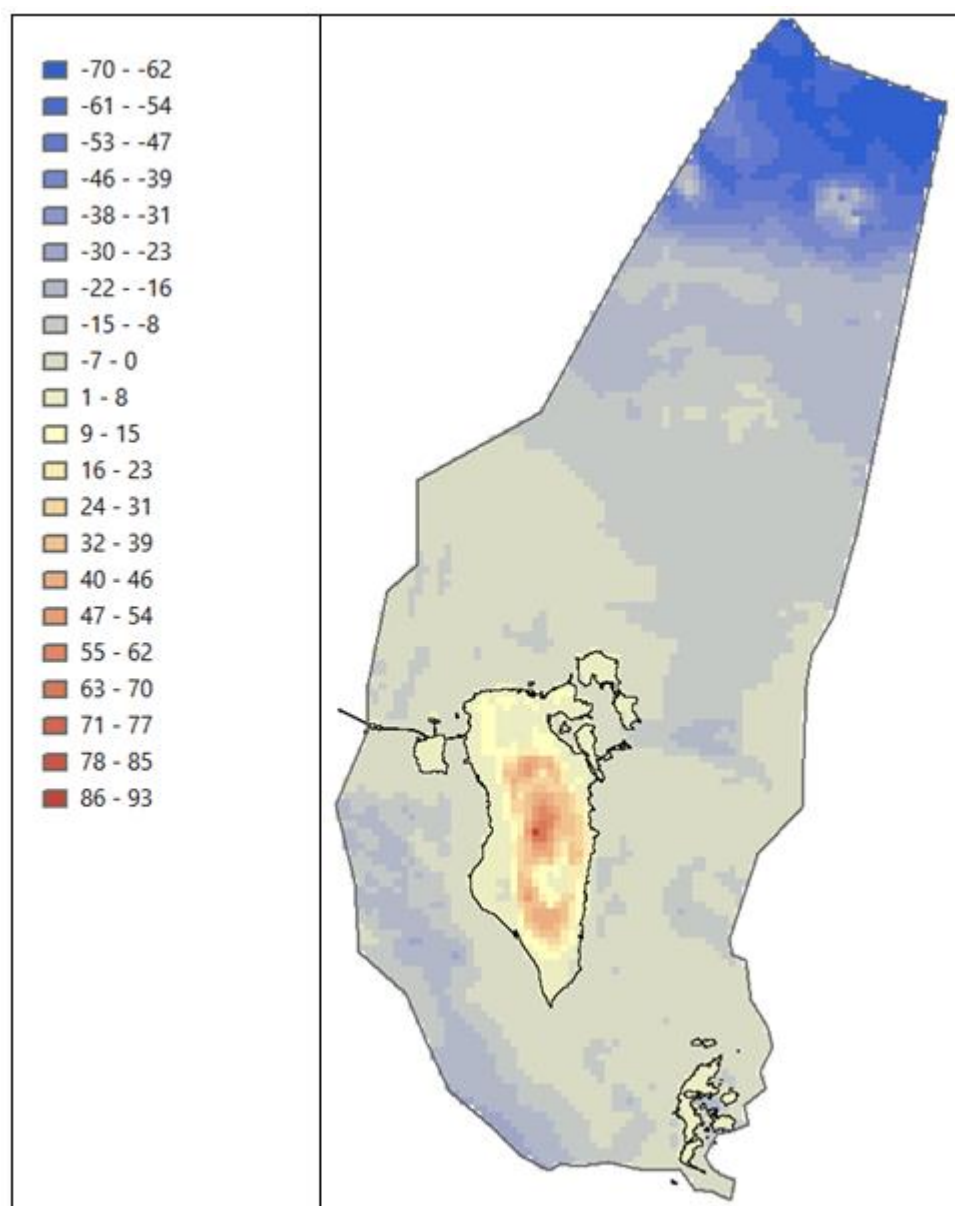


Fig. 4 Bahrain land elevation and sea depth in metres SRTM30_PLUS (Becker at al. 2009)

2.3.3 Distance from Bahrain Main Island

The Euclidean Distance tool of ArcGIS Spatial Analyst (ESRI 2014) was used to create a raster where each grid cell contains the measurement of straight-line distance from the cell itself to Bahrain Main Island (Fig. 5). That is to the mainland where main infrastructure is located. The cell distances were then reclassified 1-5 (Table 4). Cells within 10 km of the main coastline were allocated a low score because many are visible from tourist beaches and urban areas. (Average visibility is 10 km in Bahrain (Manama Monthly Climate Averages 2019). The remaining distances were divided into four equal classes with rank decreasing as distance increases. It has been found that leveled cost of wind energy production rises in an almost linear fashion, as distance to land increases (Myhr et al. 2014).

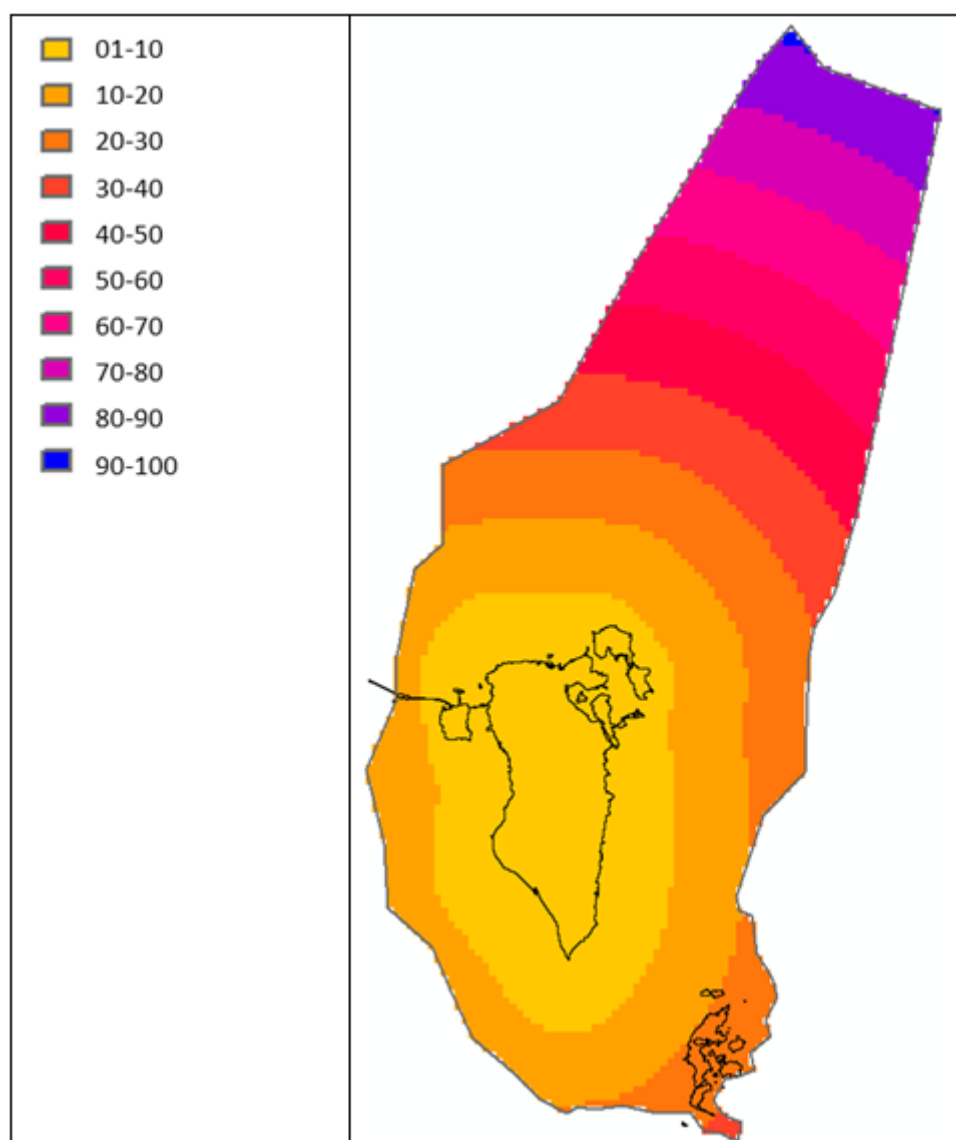


Fig. 5 Distance in km to Bahrain Main Island

2.3.4 Additional Factors

Further factors identified in the literature review as important for offshore wind construction are seabed conditions and tide. Regarding the seabed type, renewable developers choose sites with dense marine sand to facilitate burying cables and laying foundations (Mahdy and Bahaj 2018). No detailed data about the subsea soils surrounding Bahrain exists. Sand dredging is carried out to the north of Bahrain main island (National Detail Land Use map 2030). A textbook on coral reefs describes the southern gulf as mostly hardground (from echo-sounder), topped by fine windblown material (Riegl and Purkis 2012), which is very suitable for turbine construction. It is acknowledged that seabed type is significant for offshore wind, but due to lack of spatially resolved data, this factor will be not be examined by this paper. Any construction activity should be preceded by a geotechnical site investigation.

Tidal range dictates accessibility of turbines by maintenance boat crews (Fraunhofer 2018c). It also impacts on wind shear profile (Khan et al. 2003). However, Bahrain has a low variation in the tide (Riegl and Purkis 2012), because of the proximity of coral reefs, sand banks and the gulf amphidromic point. Thus, tide is not included as a factor in this analysis.

2.3.5 Weighting of Factors

So far, all the factors have been standardised. For example: if a location for the wind layer is allocated a rank of 5, then this factor will have the same influence as cells in the depth and distance layers with values of 5. However, this is not the real situation. Some factors are more important than others. It remains to assign a relative importance to each of the ranked factors so as to form a weighted ranking. Each layer is multiplied by its weight before all the factor layers are combined. At the end of this process the grid cells in the combination layer with the highest rank represent the optimal locations for offshore wind. This weighted overlay combination goes by various names in the statistical literature. It is known as “weighted sum” in ArcGIS (ESRI 2014).

The question arises as to what weight to give each factor. The most widely used and pragmatic solution is the Analytical Hierarchy Process (AHP) (Mahdy and Bahaj 2018), developed by Saaty (1980). AHP commences by placing the three factors (wind speed, depth and distance from shore) in a three-by-three matrix (Tables 1 and 2). The matrix is completed by initially assigning a score of one where both factors are equally important. That is, where each factor is compared to itself, resulting a left-to-right diagonal of one's across the matrix. To the right of this diagonal, a judgement value is allocated. This ranges from 1 for a pair of factors of equal importance, to 9 where the first factor is extremely important in comparison to the second. The score of 1 to 9 may be selected according to own judgement, seeking expert opinion, or knowledge. Here, the score is based on cost. Wind speed is designated three times as important as depth, using projects costs obtained from Cavazzi and Dutton (2016). Distance from shore is treated as half as important as depth, following Mahdy and

Bahaj (2018) and Cavazzi and Dutton (2016). The lower left of the matrix is filled with the reciprocal of the judgement value in the pairwise comparison.

Table 1. Pairwise Comparison Matrix.

| FACTOR | Wind Speed | Depth | Distance from shore |
|---------------------|------------|-------|---------------------|
| Wind Speed | 1 | 3 | 6 |
| Depth | 1/3 | 1 | 3 |
| Distance from Shore | 1/6 | 1/3 | 1 |
| Sum | 1 | 4 | 10 |

Table 2. Results of Pairwise Comparison Matrix.

| FACTOR | Wind Speed | Depth | Distance from shore |
|---------------------|------------|-------|---------------------|
| Wind Speed | 1.00 | 3.00 | 6.00 |
| Depth | 0.33 | 1.00 | 3.00 |
| Distance from Shore | 0.17 | 0.33 | 1.00 |
| Sum | 1.50 | 4.33 | 10.00 |

The next step in AHP is to normalize the matrix by totaling the columns. Each matrix cell in the column is divided by the column total to yield its normalized score. Finally, the weight of each factor is obtained by summing each row in the new normalized matrix (Table 3) and dividing the sum by the number of columns i.e. factors in the matrix. (Three in this case.) The sum of the rightmost factor weights columns is one. A summary of the ranks assigned and weights calculated for all factors is given in Table 4.

Table 3. Normalised matrix and weight determination.

| FACTOR | Wind Speed | Depth | Distance from shore | Weight |
|---------------------|------------|-------|---------------------|--------|
| Wind Speed | 0.67 | 0.69 | 0.60 | 0.65 |
| Depth | 0.22 | 0.23 | 0.30 | 0.25 |
| Distance from Shore | 0.11 | 0.08 | 0.10 | 0.10 |

Table 4. Ranking and Weighting of Factors.

| Factor | Relative Weighting % | Class | Score |
|---------------------|----------------------|---------------|-----------|
| Wind Speed | 65 | < 6.8 m/s | 1 (worst) |
| | | 6.8 – 7.0 m/s | 2 |
| | | 7.0 – 7.2 m/s | 3 |
| | | 7.2 – 7.4 m/s | 4 |
| | | > 7.4 m/s | 5 (best) |
| Depth | 25 | 0 – 5 m | 2 |
| | | 5 – 10 m | 4 |
| | | 10 – 30 m | 5 (best) |
| | | 30 – 40 m | 4 |
| | | 40 – 50 m | 3 |
| | | > 50 m | 1 (worst) |
| Distance from shore | 10 | 0 – 10 km | 1 (worst) |
| | | 10 – 30 km | 5 (best) |
| | | 30 – 50 km | 4 |
| | | 50 – 70 km | 3 |
| | | > 70 km | 2 |

To ensure the pairwise comparisons are consistent and to validate them, the consistency ratio (CR) is calculated. The consistency vector is calculated by multiplying each row in the original pairwise matrix (Table 2) by the weights column in Table 3 (matrix multiplication) and dividing by the weight. The average of these values is λ_{max} . The consistency index (CI) is calculated as: $CI = (\lambda_{max} - n)/(n - 1)$. The CR is then: $CR = CI/RI$; where RI is the Random Consistency Index, i.e. the CI of a randomly-generated pairwise comparison matrix obtained from Saaty (1980). The CR should be less than 10%, if judgements are consistent and assumptions are valid. In this instance it was found to be 1.9%. This justifies the AHP just performed. The method also agrees with those employed by FOWIND (2019) and Scottish Government (2018), who also treat distance as half as important as depth.

The last step in AHP is to multiply the standardized factors by their weights using the Weighted Sum tool in ArcGIS. The resultant single combined map layer of reclassified standardized weighted factors is illustrated in Fig. 6.

2.4. Scenario Analysis Stage

In this stage, the Weighted Sum layer was multiplied by the Boolean exclusion mask layer, using the Raster Calculator tool in ArcGIS. The needs of other users of Bahrain's territorial waters were then investigated. Sand extraction activities, oil drilling, the fishing industry and conservation areas were examined.

Sand extraction is valuable to Bahrain's development. It is necessary to support the high urbanization rate because it is used in building construction and land reclamation (Trade Arabia 2013). In the UK, the Crown Estate recommends that sand extraction takes precedence over wind energy areas to supply elevation of land levels. There are no similar guidelines for Bahrain. Sand extraction areas (also known as sand mining or borrow areas because sand will eventually flow back) were digitized from the National Detail Land Use map 2030. In practice they were found to be close inshore, in lower wind speed regions and in shallow water. Therefore, there is no conflict with potential wind farm locations (Fig. 6).

There are currently no offshore oilfields in Bahrain's territorial waters. (The Abu Safah field just beyond the maritime border is joint with Saudi Arabia.) However, in April 2018 Bahrain's Higher Committee for Natural Resources and Economic Security revealed that a reserve of shale oil and deep gas had been discovered in the Khaleej Al Bahrain Basin, which curves around the west and south-west coast of the main island (Fig. 6). The deposits are estimated to comprise 80 billion barrels of oil and 10 - 20 trillion cubic feet of natural gas. Compared to Bahrain's onshore oil reserve of 125 million barrels, this is potentially of great economic importance (Ellyat 2018). The technology for exploiting these unconventional resources has yet to be established. The exact locations of the deposits are not public. The entire Basin does not coincide with areas identified as best for wind, so the new oilfield is not treated as a competitor for maritime area by this research. On the other hand, exploratory drilling has recently been permitted (13 January 2019) in the northern EEZ, until now unexplored as far as hydrocarbon capacity is concerned (Eni 2019). This could be in the same position as potential wind farms but since the location of any future oilfields is as yet unknown, the possibility is not taken into account.

Legislation pertaining to the co-existence of fishing activities and offshore wind varies from country to country. In Belgium, fishing vessels must remain at least 500 m from wind parks but in the UK, access is permitted. Although even in the UK, offshore wind is not popular with fishermen due to the risk of fishing gear becoming trapped on underwater cables and potential collisions with

turbines. A map layer of Bahrain's current fishing grounds was created by capturing the density map of fishing vessel signals from Global Fishing Watch. Fishing grounds were in shallow water close to the port of Sitra, so problems with wind installation is unlikely.

The Kingdom of Bahrain is a signatory to the UN Convention on Biological Diversity (CBD) and as such is dedicated to promoting sustainability. Expansion of the existing network of protection areas is proposed. A strategy to identify new protection areas based on four possible scenarios which meet different objectives (biodiversity, fishing, habitat type and cumulative) has been developed by the Supreme Council for Environment (2015b). This research captures the very high conservation priority areas from the cumulative scenario, in addition to the Hayrat Buffer, and rules them out for wind installation. Thus, in addition to the range of habitats and fish feeding/nursery grounds, key bird species, including one of the world's biggest Socotra Cormorant colonies, Greater Flamingo, and Black-headed Gulls are protected, as well as sea turtles and dugongs (sea cows). Most of the areas reserved for conservation are in shallow water, but inclusion of the Hayrat Buffer does reduce sea area for potential offshore wind. Nevertheless, the national commitment to the environment is honoured.

The final suitability map layer is shown in Fig. 6 (cross-hatching). It may be seen that this is the area weighted "5" of the reclassified factors (dark pink), with the Hayrat Buffer removed. Weight 5 represents sea area that is: of sufficient depth but not too deep; far enough offshore to avoid visibility issues; not so far as to increase transport/cable costs. In order to meet these requirements a compromise on wind strength is employed. The areas selected as suitable have 7.2 – 7.4 m/s wind speed and not the highest speed available (> 7.4 m/s).

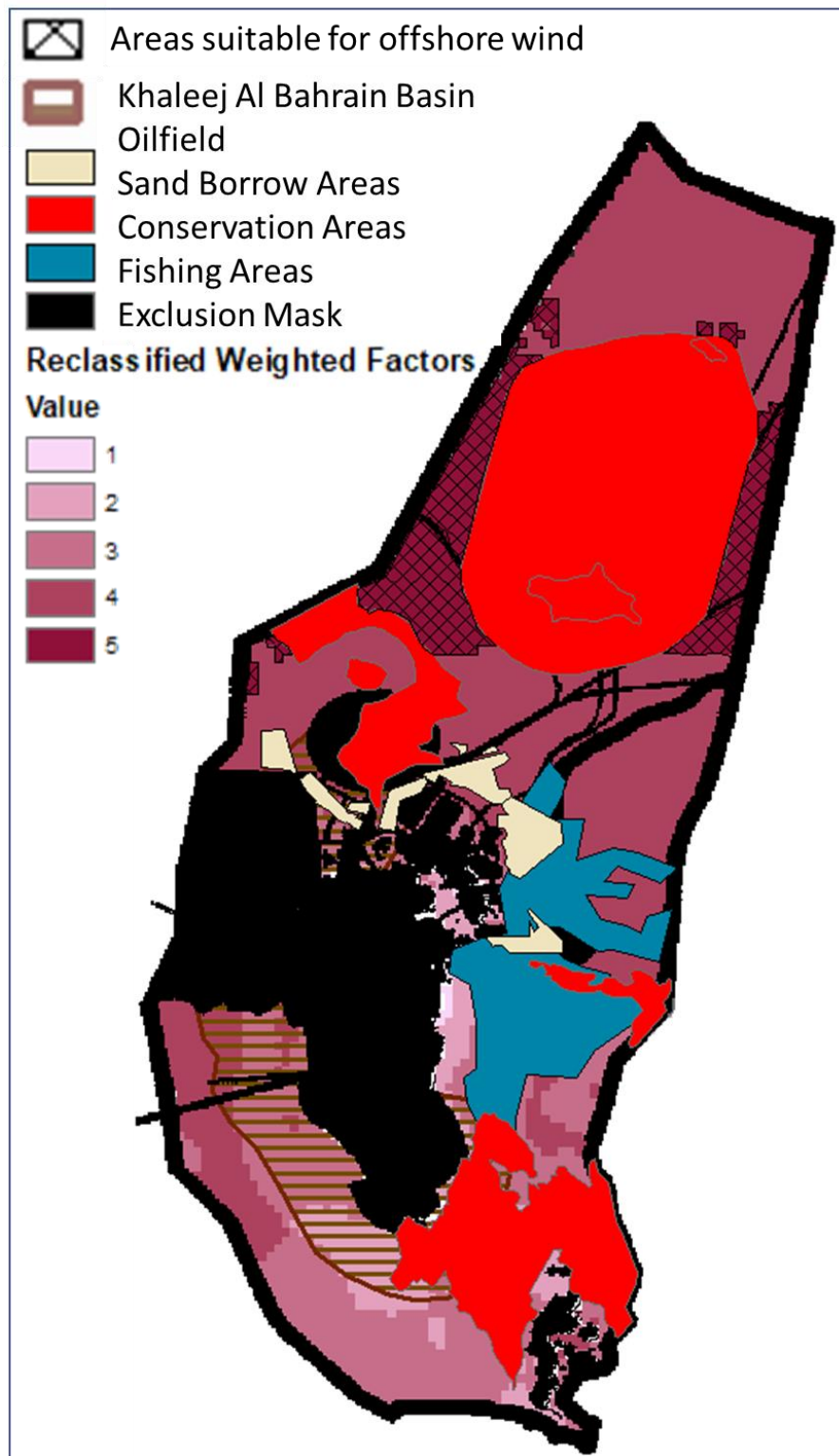


Fig. 6 Map of exclusion mask, reclassified weighted factors, competing seabed uses and areas selected as suitable for offshore wind

2.5. Offshore Wind Potential Stage

In this last stage of the sequence of methods, the number of wind turbines which will fit into the areas identified as suitable is calculated, as well as their nameplate capacity and potential output.

Bahrain has a prevailing wind, the Shamal, which blows from the northwest. Therefore, Sheridan's method of calculating turbine placement which utilizes the benefit of directional wind patterns is employed (Sheridan 2012). Total energy output is optimized by placing turbines in rows, with five rotor diameters between each turbine crosswind and ten rotor diameters between downwind. The following equations (1 and 2) are used to obtain the footprint per turbine and total number of turbines in the suitable areas. (Size of suitable areas computed using ArcGIS).

$$\text{Turbine footprint} = (\text{rotor diameter})^2 \times \text{crosswind spacing factor (5)} \times \text{downwind spacing factor (10)} \quad (1)$$

$$\text{Number of turbines} = \text{total available area} \div \text{turbine footprint} \quad (2)$$

The turbine Vesta V150 (Vestas 2018) is used for power calculations in this research. In low wind sites, it is better to choose a turbine with a large rotor diameter and a smaller generator which even in low speeds allows enough torque to be produced by the rotor to drive the generator (Schaarup 2001). The Vesta V150 has a rated power of 4.2MW, a rotor diameter of 150 m and a specific rotor power of 237.68W/m². Thus, it is appropriate for the low (by European standards) offshore wind conditions surrounding Bahrain.

The nameplate capacity of each suitable windfarm area is calculated by multiplying the number of turbines by the rated power (4.2 MW). Annual energy production per turbine is obtained from the manufacturers' manual (Vestas 2018), assuming 100% availability, 0% losses, standard air density and yearly average wind speed of 7.3 m/s. (All the potential Bahraini wind farm areas have the same average wind speed.) This is an idealized situation where the capacity factor (CF) (average power generated divided by peak rated power) is equal to one. For this reason, two more CFs were employed to estimate annual energy production. Firstly, the capacity factor was calculated from the manufacturers' annual energy yield for the Vesta V150 divided by the rated energy yield (4.2MW*365*24). Secondly, because the answer returned seems rather optimistic (CF = 0.448 matches the best European conditions), a bias-corrected simulated CF of 0.3 was obtained from Renewables.ninja. This is nearly the same as that estimated by Jowder (2009) who takes Bahrain specific air density into the equation.

The outcomes of the number of offshore turbines and energy yield calculations are portrayed in the Results section.

3. Results

Ten marine areas were found to be suitable for construction of offshore windfarms in Bahrain's EEZ. The size of each area, number of turbines and nameplate capacity of the windfarm is illustrated in Fig. 7.

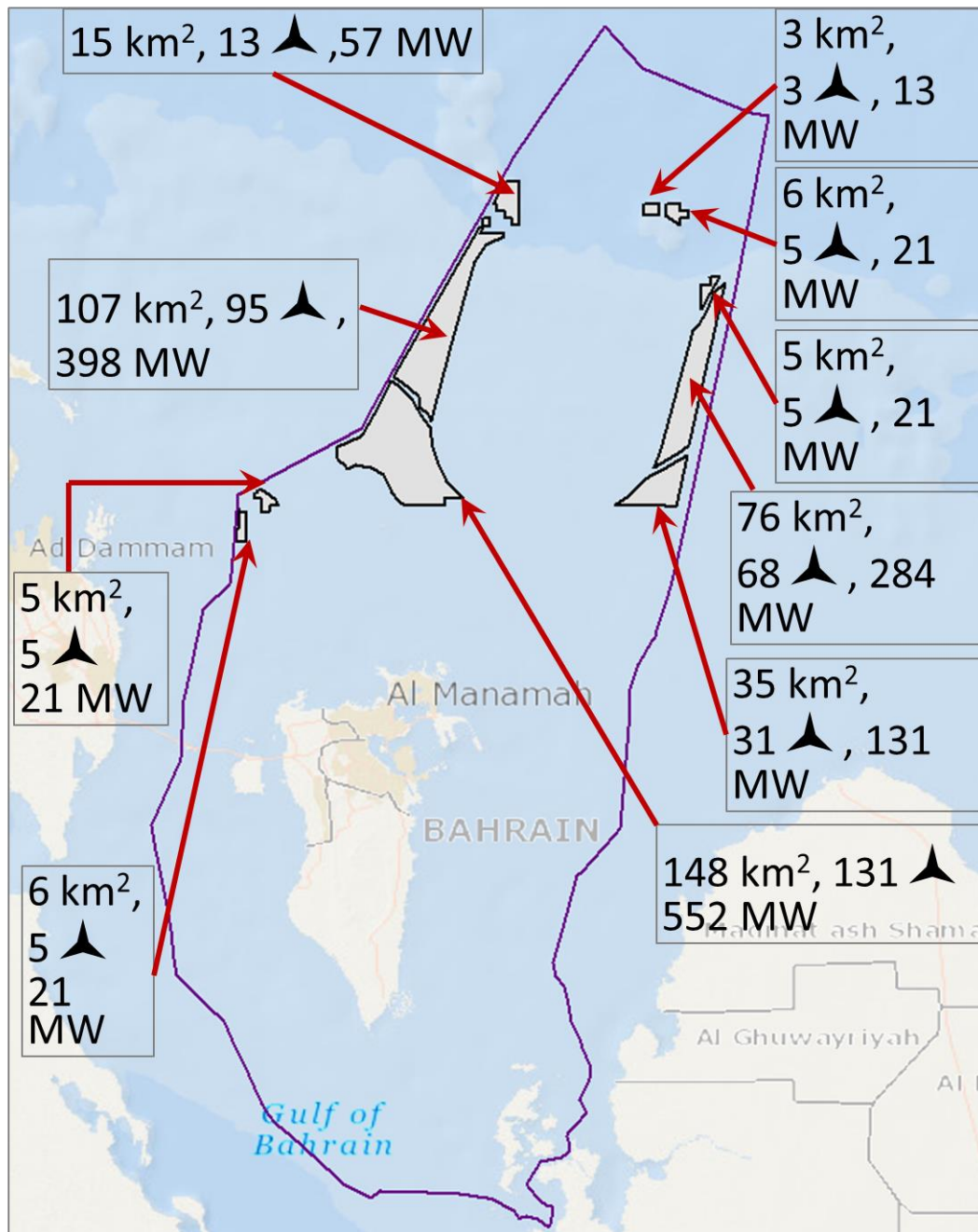


Fig. 7 Map of potential offshore windfarms for Bahrain, showing sea area, number of turbines and nameplate capacity.

At first glance it appears that only a small amount of Bahrain's maritime area is suitable for offshore wind. However, this quantity actually totals 407 km² which provides sufficient space for the installation of hundreds of turbines and 1.52 GW of wind capacity.

Estimated number of turbines and annual energy yield under three CFs are shown in Table 5. Naturally, the CF has a significant influence on eventual energy production.

Table 5. Energy Production under 3 Capacity Factors.

| Average wind speed (m/s) | Number of turbines | Manufacturer's Energy production per turbine (GWh/yr) | Total energy production (TWh/yr) Capacity Factor = 1 | Total energy production (TWh/yr) Capacity Factor = 0.448 ^a | Total energy production (TWh/yr) Capacity Factor = 0.3 ^b |
|--------------------------|--------------------|---|--|---|---|
| 7.3 | 362. | 16.5 | 5.97 | 2.68 | 1.79 |

^a CF = manufacturers' annual energy yield divided by the rated energy yield.

^b CF from Renewables.ninja.

4. Discussion

1.52 GW of installed capacity would place Bahrain in a similar position to Norway (installed capacity 1.68 GW in 2018). Norway is 29th by capacity out of 61 world countries with installed wind power capacity. Put another way, this capacity would be similar to what the UK had in 2005 (1.35 GW) (Wikipedia).

As can be seen from Fig. 7, potential windfarm size in Bahrain ranges from 21 to 552 MW. To place some of the sizes in context, Hornsea One is the world's biggest offshore wind farm at present with 1218 MW (1.2 GW), London Array (phase 1) is 630 MW and London Array (phase 2) 270 MW (Renewable UK). The Hywind Scotland Pilot Park has a total installed capacity of 30 MW comprised of five 6MV floating turbines (Offshorewind.biz 2019), while the one-year-old Nissum Bredning near shore wind farm in Denmark has 4 × 7 MW turbines placed in 3 m deep water by submersible barge (Mammoet 2018).

Bahrain used 27.81 TWh of energy in 2016 (IEA 2016). This represents the 67th largest energy consumption out of 254 world countries, despite being 188th in terms of size. Causes of this high energy consumption rate include rapid population expansion, growing urbanization, industrialization, commercialization, energy subsidies and the increasing visitor rate. There is also more need of air conditioning due to warming (Ahmad 2018). However, if all the sea area identified as suitable was allocated to offshore wind production, 10% of consumption could be supplied by this single renewable resource. The NREAP target for generating 5% of capacity from renewable sources by 2025 appears to be achievable.

Wind is an intermittent resource. Assuming a CF of 0.448, the potential 2.68 TWh annual wind energy yield could theoretically satisfy one-tenth of consumption. However, peak production and

demand times may seldom match. Future research should investigate storage or solar-wind combination to meet Bahrain's energy needs.

Anticipated developments in floating turbines mean that this research will soon need to be repeated because this possibility will significantly change the optimal areas and locations for offshore wind farms. Floating foundations will enable construction in deep-water sites, further from land and with higher wind strength. As costs come down, they may also be introduced into mid-depth (30 – 50 m) areas, where they have less environmental impact than fixed foundation structures. Floating wind farms are expected to become commercially viable between 2020 and 2025 (IRENA 2016).

5. Conclusions

The potential of the wind energy resource in Bahraini waters has been analyzed. It was found that a substantial contribution to the supply of the Kingdom's energy requirements from offshore wind is feasible. The objectives of this study were to: investigate whether construction of wind farms offshore of Bahrain is an achievable renewable energy option; to pinpoint optimal sites for these installations via mapping of constrained areas and identification of opportunities; and to estimate potential power production from offshore wind.

GIS was used as an efficient means to prepare and assess map layers of spatial variables. This was the first step in a five-stage multi-criteria model. The consecutive steps were: area exclusion; area suitability ranking with AHP; investigation of competing uses of Bahrain's territorial waters; and lastly calculation of potential wind energy yield. The process presented was successful in providing a suitability map for offshore wind farms in Bahrain.

This research fills a gap in knowledge. No detailed studies of potential energy production from offshore renewables have previously been conducted for Bahrain. The model sequence employed in the present study enables the scientific and objective selection of 407 km² (~4% of territorial waters) as optimal locations for offshore windfarms in Bahrain.

Acknowledgments: This work was conducted within 'Technical Integration of Sustainable Energy and Water (TISEW)', a collaboration between Loughborough University and the University of Bahrain, supported by grant ID 279332548, under the UK-Gulf Institutional Links Programme. The grant is funded by the UK Department for Business, Energy and Industrial Strategy and delivered by the British Council. The projects funders were not directly involved in the writing of this article.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

- Ahmad, R (2018) Energy Conservation in Bahrain. Ecomena
<https://www.ecomena.org/energy-conservation-bahrain/> (accessed on 1 July 2019).
- Al-Nabi, MN (2012) The History of Land Use and Development in Bahrain, Information Affairs Authority, Bahrain, ISBN 978-99958-0-129-8, www.housing.gov.bh/en/.../6681%20book%20resized.pdf
- Al-Salem, K; Neelamani, S; Al-Nassar, W (2018) Wind Energy Map of Arabian Gulf, Natural Resources, 9: 212-228
- Bahrain Ministry of Works, Municipalities Affairs and Urban Planning, National Detail Land Use map 2030, 11/1/2016 https://www.mun.gov.bh/ppd/images/maps/SOM_bahrain.jpg (accessed on 4 June 2019).
- Becker, J J; Sandwell, DT ; Smith, WHF; Braud,J; Binder,B; Depner, J; Fabre, D; Factor, J; Ingalls, S; Kim, S.H; Ladner, R; Marks, K; Nelson, S; Pharaoh, A; Trimmer, R; Von Rosenberg, J; Wallace, G; Weatherall, P (2009) Global Bathymetry and Elevation Data at 30 Arc Seconds Resolution: SRTM30_PLUS, Marine Geodesy 32:4, 355-371.
- Bray, L; Reizopoulou,S; Voukouvalas, E; Soukissian, T; Alomar, C; Vázquez-Luis, M; Deudero, S; Attrill, MJ; Hall-Spencer, JM (2016) Expected Effects of Offshore Wind Farms on Mediterranean Marine Life, J Mar Sci Eng 4(1):18-25
- BVG Associates Wind Europe (2017) Unleashing Europe's offshore wind potential A new resource assessment <https://windeurope.org/wp-content/uploads/files/about-wind/reports/Unleashing-Europes-offshore-wind-potential.pdf> (accessed on 18 June 2019)
- Cavazzi, S; Dutton, A (2016) An Offshore Wind Energy Geographic Information System (OWE-GIS) for assessment of the UK's offshore wind energy potential, Renew Energy 87: 212-228.
- Chaouachi, A; Covrig, C.F; Ardelean, M (2017) Multi-criteria selection of offshore wind farms: Case study for the Baltic States, Energy Policy 103:179–192
- Ellyatt, H (2018) Bahrain discovery of 80 billion barrels of oil, CNBC, 08 May 2018 <https://www.cnbc.com/2018/05/08/bahrain-discovery-of-80-billion-barrels-of-oil.html> (accessed online 21 June 2019)
- EMD International A/S (2017) Wind Prospecting <http://bahrain.windprospecting.com/> (accessed on 18 June 2019)
- Eni (2019) Eni signs MoU for conducting Petroleum Exploration in Block 1 Offshore Bahrain 13 January 2019 https://www.eni.com/docs/en_IT/enicom/media/press-release/2019/01/PR_Eni_Block1_MOU_Bahrain.pdf (accessed 17 July 2019)
- Erfteimeijer, P; Boot, G (2004) Site Selection for Artificial Reefs in Bahrain, Journal of Marine Science and Environment, C2, 29-38
- ESRI (2014, ArcGIS Desktop: Release, 10.3, www.arcgis.com.
- Fetanat, A; Khorasaninejad, E; (2015) A novel hybrid MCDM approach for offshore wind farm site selection: A case study of Iran, Ocean & Coastal Management 109:17-28
- FOWIND (2019) European Union Pre-feasibility Study for Offshore Wind Farm Development in Gujarat 2019, <https://issuu.com/dnvgi/docs/180614091800-a6e4849958f043e380a9b6207f4904a8> (accessed 21 June 2019)

Fraunhofer (2018). Turbine Size

http://windmonitor.iee.fraunhofer.de/windmonitor_en/3_Onshore/2_technik/4_anlagengroesse/ (accessed on 18 June 2019)

Fraunhofer (2018) Distance to shore and water depth

http://windmonitor.iee.fraunhofer.de/windmonitor_en/4_Offshore/2_technik/2_Kuestenentfernung_und_Wass_ertiefe/ (accessed on 18 June 2019).

Fraunhofer (2018) Wave heights and accessibility

http://windmonitor.iee.fraunhofer.de/windmonitor_en/4_Offshore/3_externer_Bedingungen/3_Wellen/ (accessed on 19 June 2019).

GADM, the Database of Global Administrative Areas <https://gadm.org/> (accessed on 4 June 2019).

Global Fishing Watch <https://globalfishingwatch.org/map/> (accessed 21 June 2019)

Global Wind Atlas <https://globalwindatlas.info/about/method> (accessed on 18 June 2019)

i-Boating: Free Marine Navigation Charts and Fishing Maps

<http://fishing-app.gpsnauticalcharts.com/i-boating-fishing-web-app/fishing-marine-charts-navigation.html#10.97/26.2769/50.7037> (accessed on 4 June 2019).

IEA (2016) Key stats for Bahrain, 1990-2016 <https://www.iea.org/countries/Bahrain/> (accessed on 1 July 2019).

International Renewable Energy Agency (IRENA) (2018), Renewable Capacity Statistics 2018, IRENA, Abu Dhabi, 2018

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2018/Mar/IRENA_RE_Capacity_Statistics_2018.pdf (accessed on 23 May 2019).

International Renewable Energy Agency IRENA (2016) Floating foundations: a game changer for offshore wind power.

https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_Offshore_Wind_Floating_Foundations_2016.pdf (accessed on 1 July 2019)

Joweder, F.A.L (2009) Wind power analysis and site matching of wind turbine generators in Kingdom of Bahrain, *Applied Energy*, 86: 538–545

Khan, D; Watson, SJ; Infield, D.G (2003) Identifying the Effect of Tidal Height on Offshore Wind Speed Profiles, *Wind Energy* 6(4): 405-412

Khonkar, H (2016) Complete Survey of Wind Behavior over the Arabian Gulf, *JKAU: MarSci.*, 20:31-47.

Kim, T; Park, J; Maeng, J (2016) Offshore wind farm site selection study around Jeju Island, South Korea, *Renewable Energy*, 94: 619-628

Loukogeorgaki, E; Vagiona DG; Vasileiou, M (2018) Site Selection of Hybrid Offshore Wind and Wave Energy Systems in Greece Incorporating Environmental Impact Assessment, *Energies* 11: 2095- 2111

Mahdy, M; Bahaj, ABS (2018) Multi criteria decision analysis for offshore wind energy potential in Egypt, *Renewable Energy* 118: 278-289

Mahdy, M; Bahaj, ABS; Alghamdi, AS (2017) Offshore wind energy potential around the east coast of the Red Sea, KSA, Proceedings of the IEA SHC International Conference on Solar Heating and Cooling for Buildings and Industry, Abu Dhabi, UAE, 29 Oct – 2 Nov 2017.

Mammoet (2018) Mammoet installs four wind turbines off Denmark coast 2018
<https://www.mammoet.com/news/mammoet-installs-four-wind-turbines-at-nisum-bredning-near-shore-wind-farm/> (accessed on 18 June 2019).

Manama Monthly Climate Averages (2019)

<https://www.worldweatheronline.com/manama-weather-averages/al-manamah/bh.aspx> (accessed on 19 June 2019).

Marine Traffic <https://www.marinetraffic.com> (accessed on 4 June 2019).

marineregions.org [marineregions.org](https://www.marineregions.org) (accessed 6 June 2019).

Murali, M; Pj, V; Modi, P; Seelam, JK (2014) Site selection for offshore wind farms along the Indian coast, Indian Journal of Geo-Marine Sciences 43(7):1401-1406

Myhr, A; Bjerkseter, C; Ågotnes, A; Nygaard, T.A (2014) Levelised cost of energy for offshore floating wind turbines in a life cycle perspective, Renewable Energy 66: 714-728

Mytilinou, V; Kolios, A.J (2017) A multi-objective optimisation approach applied to offshore wind farm location selection, J Ocean Eng Mar Energy, 3:265–284

Offshorewind.biz (2019) Floating Wind Turbines, Promising Future

<https://www.offshorewind.biz/2019/05/01/floating-wind-turbines-promising-future/> (accessed on 18 June 2019).

Our Vision 2030

<https://www.bahrain.bh/wps/wcm/connect/38f53f2f-9ad6-423d-9c96-2dbf17810c94/Vision%2B2030%2BEnglish%2B%28low%2Bresolution%29.pdf?MOD=AJPERES> (accessed on 4 June 2019).

Panagiotidou, M; Xydis, G; Koroneos, C (2016) Environmental Siting Framework for Wind Farms: A Case Study in the Dodecanese Islands, Resources 5: 24.

QGIS Development Team (2015) QGIS Geographic Information System Open Source Geospatial Foundation Project <http://qgis.osgeo.org>

Rampion Wind Turbines <https://www.rampionoffshore.com/wind-farm/components/turbines/> (accessed on 18 June 2019)

Rawson, A; Rogers, E (2015) Assessing the impacts to vessel traffic from offshore wind farms in the Thames Estuary, Scientific Journals of the Maritime University of Szczecin 43 (115):99-107

Renewable UK Wind Energy Statistics

<https://www.renewableuk.com/page/UKWEDhome/Wind-Energy-Statistics.htm> (accessed on 1 July 2019).

Renewables.ninja <https://www.renewables.ninja/> (accessed on 1 July 2019).

Riegl, B; Purkis, SJ (2012) Coral Reefs of the Gulf: Adaptation to Climatic Extremes in the World's Hottest Sea Springer-Verlag, pp5-33

Saaty, TL (1980) The analytic hierarchy process. McGraw-Hill, New York

Saleous, N; Issa, S; Al Mazrouei, J (2016) GIS-based wind farm site selection model offshore Abu Dhabi Emirate, UAE In The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XLI-B8, Proceedings of the XXIII ISPRS Congress, Prague, Czech Republic, 12–19 July 2016

Schaarup, J; Krogh, T (2001) DNV-Risø "Guidelines for design of wind turbines" Abstract from Risø vinddag 2001, Roskilde, Denmark.

- Scottish Government (2018) Scoping 'Areas of Search' Study for offshore wind energy in Scottish Waters <https://www2.gov.scot/Resource/0053/00536637.pdf> (accessed 21 June 2019)
- Serwan MJB; Parry, T (2001) Developing and applying a GIS-assisted approach to locating wind farms in the UK, *Renewable Energy* 24: 59–71
- Sheridan, B; Baker, SD; Pearre, NS; Firestone, J; Kempton, W (2012) Calculating the offshore wind power resource: robust assessment methods applied to the US Atlantic Coast, *Renew Energy*, 43: 224-233.
- Supreme Council for Environment, Kingdom of Bahrain (2015) An Assessment and Mapping of the Potential Values of Ecosystem Services in the Kingdom of Bahrain, [https://www.recyclepointsbh.com/A%20Protected%20Area%20Strategy%20for%20the%20Kingdom%20of%20Bahrain%20Final%20v11%20Abdulla%2020151125%20\(Received%20201215\).pdf](https://www.recyclepointsbh.com/A%20Protected%20Area%20Strategy%20for%20the%20Kingdom%20of%20Bahrain%20Final%20v11%20Abdulla%2020151125%20(Received%20201215).pdf)
- Supreme Council for Environment, Kingdom of Bahrain (2015) *A Protected Areas Strategy for the Kingdom of Bahrain*,
- Sustainable Energy Unit, National Renewable Energy Action Plan (NREAP), SEU, Manama, 2017 <http://www.seu.gov.bh/nreap/> (accessed on 23 May 2019).
- The Travel (2019) Bahrain Will Debut World's Largest Underwater Theme Park <https://www.thetravel.com/bahrain-will-debut-worlds-largest-underwater-theme-park/> (accessed 6 June 2019).
- Trade Arabia (2013) Bahrain to introduce sand dredging law, Manama, February 12, 2013 http://www.tradearabia.com/news/MISC_230565.html (accessed online 21 June 2019)
- Unesco (2014) Qal'at al-Bahrain – Ancient Harbour and Capital of Dilmun <https://whc.unesco.org/en/list/1192> (accessed on 6 June 2019).
- Vagiona, DG; Kamilakis, M (2018) Sustainable Site Selection for Offshore Wind Farms in the South Aegean—Greece, *Sustainability* 10: 749-759
- Vestas Wind Systems A/S (2018) MW Platform, Aarhus
- Villacreses, G; Gaona, G; Martínez-Gomez, J; Jijon, DJ (2017) Wind farms suitability location using geographical information system (GIS), based on multi-criteria decision making (MCDM) methods: The case of continental Ecuador, *Renewable Energy* 109: 275-286
- Wikipedia. Wind Power by Country https://en.wikipedia.org/wiki/Wind_power_by_country (accessed 16 July 2019).
- World Imagery https://services.arcgisonline.com/ArcGIS/rest/services/World_Imagery/MapServer/0 (accessed on 23 May 2019).
- Wu, B; Yip, TL; Xie, L; Wang, Y (2018) A fuzzy-MADM based approach for site selection of offshore wind farm in busy waterways in China, *Ocean Engineering* 168: 121–132