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Multi criteria decision analysis for offshore wind energy potential in Egypt

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ABSTRACT

Offshore wind energy is highlighted as one of the most important resource to exploit due to greater wind intensity and minimal visual impacts compared with onshore wind. Currently there is a lack of accurate assessment of offshore wind energy potential at global sites. A new methodology is proposed addressing this gap which has global applicability for offshore wind energy exploitation. It is based on Analytical Hierarchy Process and pairwise comparison methods linked to site spatial assessment in a geographical information system. The method is applied to Egypt, which currently plan to scale renewable energy capacity from 1 GW to 7.5 GW by 2020, likely to be through offshore wind. We introduce the applicability of the spatial analysis, based on multi-criteria decision analysis providing accurate estimates of the offshore wind from suitable locations in Egypt. Three high wind suitable areas around the Red Sea were identified with minimum restrictions that can produce around 33 GW of wind power. Suitability maps are also included in the paper providing a blueprint for the development of wind farms in these sites. The developed methodology is generalised and is applicable globally to produce offshore wind suitability map for appropriate offshore wind locations.

1. Introduction

Most of onshore wind farms are located in the best resource areas. The exploitation of further land-based onshore areas in many countries is currently impeded due to visual impacts, threats to birdlife, public acceptance, noise and land use conflicts [1]. All these conflicts are likely to hinder future development of onshore wind farm deployment [2–4]. Hence, most major developments worldwide have now shifted towards offshore wind where the resource is high, and less likely to be affected by the drawbacks of land-based wind farms mentioned earlier. The advantage of offshore wind is that despite being 150% more costly to install than onshore wind, the quality of the resources is greater as is the availability of large areas to build offshore wind farms (OWFs). Furthermore, scaling up is likely to result in cost reductions propelling offshore wind on a trajectory that will be on par with onshore wind in the future [5].

However, to our knowledge, there is no general approach to accurately assess wind resources. This work provides a new methodology to address this lack of knowledge which has global applicability for offshore wind energy exploitation. It is based on Analytical Hierarchy Process (AHP) defined as an organised process to generate weighted factors to divide the decision making procedure into a few simple steps and pairwise comparison methods linked to site spatial assessment in a Geographical Information System (GIS). GIS based multi-criteria decision analysis (MCDA) is the most effective method for spatial siting of wind farms [6]. GIS-MCDA is a technique used to inform decisions for spatial problems that have many criteria and data layers and is widely used in spatial planning and siting of onshore wind farms. GIS is used to put different geographical data in separate layers to display, analyse and manipulate, to produce a new data layers and/or provide appropriate land allocation decisions [7]. The MCDA method is used to assess suitability by comparing the developed criteria of the alternatives [8]. The alternatives are usually a number of cells that divide the study area into an equally dimensioned grid. The most popular and practical method to deploy MCDA is the *Analytical Hierarchy Process* (AHP). AHP was defined as an organised process to generate weighted factors to divide the decision making procedure into a few simple steps [9]. Each criterion could be a factor or a constraint. A *factor* is a criterion that increases or decreases the

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suitability of the alternatives, while a *constraint* approves or neglects the alternative as a possible solution. AHP has two main steps: “Pairwise” comparison and *Weighted Linear Combination* (WLC). Pairwise comparison method is used to weight the different factors that are used to compare the alternatives [9] while WLC is the final stage in AHP evaluating the alternatives [10].

In order to establish a pathway for exploiting offshore wind resources, a systematic analysis for such exploitation is needed and this is at the core of this work. Our aim is to address the paucity of generalised modelling to support the exploitation of offshore wind energy. In order to do this, this work will utilise a countrywide case study where the developed methodology will be used to investigate the wind energy potential, specify appropriate locations of high resources with no imposed restrictions and generate suitability maps for offshore wind energy exploitation. The development methodology will appropriately identify the essential criteria that govern the spatial siting of offshore wind farms.

The work is structured as follows: in the first section we develop the literature review further, followed by the detailed methodology considerations, description of Egyptian offshore wind, analysis and criteria followed by detailed results and discussion and then conclusions.

2. Relevant literature

GIS based MCDA is widely used in the spatial planning of onshore wind farms and siting of turbines. Below are highlights of some of the literature for these methods and Table 1 provides a brief comparison between the relevant approaches discussed in the literature.

In a study of onshore wind farm spatial planning for Kozani, Greece, sufficient factors and constraints were used to produce a high-resolution suitability map with grid cell (150 by 150 m) [11]. The study focussed on three different scenarios: (a) scenario 1 were all factors are of equal weight, (b) scenario 2, environmental and social factors have the highest weights, and (c) scenario 3, technical and economic factors have more weights than other factors. It was found that more than 12% of the study area has a suitability score greater than 0.5 i.e. suitable for wind farms, and all previously installed wind farms were located in areas with a high suitability score, which emphasised and validated their results. Their suitability map was found to be reliable by stakeholders and was used to inform the siting of new wind farms in Greece. However, in our opinion, scenario 1 is unrealistic, because normally factors normally have different relative importance.

A further study elucidated the methodology for choosing a site for new onshore wind farms in the UK, taking the Lancashire region as a case study [15]. In order to identify the problems and the different criteria involved, the authors undertook a public and industrial sector survey (questionnaire) soliciting community/stakeholders' views on wind farms. From the survey results, they constructed their own scoring matrix from 0 to 10 to standardise the different criteria and then used two scenarios to calculate suitability. In scenario 1 the same weight was assigned to all criteria, while in scenario 2 the criteria were divided into 4 grades. Pairwise comparisons to weight the grades were used. The study then aggregated the criteria producing two different maps. The results showed that roads and population areas had the dominant influence on the final decision and the available area for wind farms represented only 8.32% of the total study area. The study is advanced and accurate despite the fact that it was performed in 2001. However, the fact that they scale the “distance to roads factor” from 1 to 0, without applying the same scaling to the other factors will have implications on the accuracy the final results.

Another research group [12] addressed suitable sites for wind farms in Western Turkey. They found the satisfaction degree for a 250 m by 250 m grid cells, using environmental and social criteria such as noise, bird habitats, preserved areas, airports, and population areas, as well as wind potential criterion. Cells that had satisfaction degree >0.5 in both environmental objectives and wind potentials were designated as a priority sites for wind farms. The study produced a powerful tool to choose new locations for wind farms.

A completed spatial planning [13] study was performed to site new wind farms in Northern Jutland in Denmark. This included most criteria to arrive at a suitability score for grid cell of 50 by 50 m. Although the research is well presented, the method used to weight the factors was not indicated and the weight values were absent. Hence, it is difficult to ascertain from the final suitability map the methodology used to reach the conclusion.

Rodman and Meentemeyer [14], developed an approach to find suitable locations for wind farms in Northern California in the USA. They considered a 30 by 30 m grid and used a simpler method to evaluate alternatives which only included 3 factors - wind speed, environmental aspects, and human impact. The factors were scored on a scale from unsuitable = 0 to high suitability = 4, based on their own experience to judge the factors. They then weighted the three factors by ranking them from 1 to 3, to arrive at final suitability. The suitability map was created by summing the product of each scored factor and its weight, and dividing the sum on the weights summation. Although the method was simple, their results could have been greatly improved in terms of accuracy and applicability had they used the AHP method and considered other important factors such as land slope, grid connection, and land use.

In the UK, for the offshore wind competition “Rounds”, a Marine Resource System (MaRS), based on a GIS decision-making tool was used to identify all available offshore wind resources [16]. After successfully completing Rounds 1, and 2 of the competition, the tool was used to locate 25 GW in nine new zones for Round 3. The MaRS methodology had 3 iterations (scenarios): (i) it considered many restrictions taking advantages of the datasets from Rounds 1 and 2. The study excluded any unsuitable areas for wind farms, then weighted the factors depending on their expertise from previous rounds, (ii) the same as the first iteration but included stakeholder input, and (iii) alligning Round 3 zones with the territorial sea limits of the UK continental shelf. The Crown Estate responsible for these projects did not publish details of the methodology used stating only the criteria and the scenarios used in the spatial sitting process. Capital cost was taken into account in the above studies of offshore wind [17]. The work indicated that the use of MCDM in offshore wind is rare as it is primarily used in onshore wind studies. Nevertheless, two different maps were created assuming all factors were of the same weight. A Decision Support System, which is an MCDM programme based on GIS tools was used [17].

Constraints were only used in the study of an offshore wind farms (OWF) in Petalioi Gulf in Greece [18]. The work excluded all unsuitable areas in the Gulf using the classical simple Boolean Mask, and then estimated the total capacity as being around 250 MW using the available wind speed data. It was apparent that the old Boolean Mask technique was used due to the limited area of the authors' study area (70 km^2), which makes the application of many criteria to locate one OWF difficult. Another study was conducted to measure offshore wind power around the Gulf of Thailand, using only four factors with no constraints [19]. The authors used their own judgment to weight the factors, and then used ArcGIS to select the suitable location for their study area. The work is detailed with appropriate charts. However, using only factors without considering constraints is likely to affect the accuracy of results. Further research to produce a suitability map for offshore wind areas around the UK was also undertaken but was biased

Table 1
Comparison between the different onshore and offshore wind siting studies and this study.

Location, year	Constraints	Factors	Method	Aggregate Method
Greece [11], 2015	• Buffer exclusion zones (between 0.15 and 3 km) for: Protected areas, historical sites, airports, urban areas, tourism sites, roads, farms, other sites • wind < 4.5 m/s and Slope >25%	• Slope • Wind speed • land uses • Distance from roads, national parks, tourism facilities, and historical	Pairwise Comparison	WLC
Western Turkey [12], 2010	• Buffer exclusion zones (between 0.25 and 2.5 km) for: Natural Parks, town centres, airports, bird habitats, and noise	• The same criteria as constraints but calculating the distance after the end of the buffer zone, and Wind Speed	RIM	OWA
Northern Jutland, Denmark [13], 2005	• Protected nature • Bird protection • Protected wetlands	• Wind speed • Proximity to: Coast, forests, population areas, water streams, lakes, roads, grid lines, and airports	fuzzy membership	WLC
Northern California, USA [14], 2006	N/A	• Wind speed, Environment, Human impact	Abundance rank	Classic aggregation
Lancashire, UK [15], 2001	• More than 10 km to roads and national grid • Wind < 5 m/s - Slope > 10% • Buffer exclusion zones (between 0.4 and 2.0 km) for: population, Forests, Water streams, and national parks	• Land use • Distance to roads • Population zones • Distance to importance sites • Distance to natural parks • Slope	Pairwise Comparison	WLC
The UK [16], 2012	Shipping Routes, Ports, Military zones, Natural Parks, Cables and pipe lines, Fishing areas, Oil and gas extraction Areas, Existing or planned farms, Sand Mining, protected wrecks, tunnels, and seascape	• Bathymetry, soil properties, wind intensity, distance to shore, and distance to Grid	Not defined	Not defined
The North Sea [17], 2012	Shipping Routes, Ports, Military zones, Natural Park, Cables and pipe lines, Fishing areas, Oil and gas extraction Areas, Existing or planned farms, Sand Mining, Storm surge, Wave height, and tidal range,	• Bathymetry, soil properties, wind intensity, distance to shore, distance to grid, and cost limit	Not defined	Not defined
Petalioi Gulf [18], 2013	Shipping Routes, Ports, Military zones, Natural Park, Cables and pipe lines, Fishing areas, Oil and gas extraction Areas	N/A	Boolean Mask	Boolean Mask
Gulf of Thailand [19], 2015	Wind speed, water depth, distance from shore, and distance to grid.	N/A	Not defined	Not defined
Black Sea, Turkey [20], 2017	• Wind speed	• territorial waters, military areas, civil aviation, shipping routes, pipelines and underground cables	–	–
The UK [21], 2016	• Bathymetry, wind speed, distance to shore.	• Exclusion areas identified by the Crown State	Cost modelling	LCOE
Egypt [This paper]	• Shipping Routes, Ports, Military zones, Natural Park, Cables and pipe lines, Fishing areas, and Oil and gas extraction Areas	• Bathymetry, soil properties, wind Intensity, Distance to shore, and distance to Grid	Pairwise Comparison	WLC

towards cost modelling [21]. The analysis was mainly based on data obtained from the UK Crown Estate using specific Crown Estate restrictions, weights and scores. The difference between this study and other offshore wind sitting studies is that authors used the overall Levelised Cost of Energy (LCOE) equation to aggregate factors. They produce two maps, one for restrictions (energy available map) and another for factors (cost map/MWh).

3. Approach utilised in siting of wind farms

Offshore and onshore wind spatial planning can be based on similar techniques, particularly when considering the wind speed factor. However, these techniques differ in terms of definitions of factors and constraints. For example, the main factors in onshore wind considerations are distance to roads and the proximity of farms to built-up areas, whereas for offshore wind, the factors are water depth and wind speed where the wind speed cube is proportional to power production. In most of the studies reviewed here as well as others not included, the approach taken for determining wind farm spatial planning can be summarised as follows:

1. Identify wind farm spatial characteristics and related criteria using APH or similar techniques.
2. Standardise different factors using fuzzy membership or some own-derived judgment.
3. Weight the relative importance of the various factors using pairwise comparison or similar methods.
4. Aggregate the different layers of factors and constraints using different GIS tools and WLC aggregation method.

As mentioned earlier, AHP is a technique used to organise and create weighted criteria to solve complex problems. The first step of AHP is to define the problem and the branch of science it relates to, and then specify the different criteria involved. All the criteria should be specific, measurable, and accepted by stakeholder/researcher or previously used successfully in the solution of similar problems. The next step in the analysis is to find the different relative importance of the factors. The final step is to evaluate all the potential solutions for the problem, and arrive at a solution by selecting the one with highest score. In Fig. 1, we illustrate the whole AHP process used in this study.

Two efficient ways to solve a multi criteria problem were suggested by Ref. [9]. The first is to study the problem and its characteristics, then arrive at specific conclusions through the different observations undertaken by the study. The second is to compare a specific problem with similar ones that have been solved previously. In this work, we have selected the second approach to define the criteria required and this could be a factor or a constraint.

Due to its dominant applicability in spatial decision-making problems, the pairwise comparison method was chosen to find the relative importance. Furthermore, factors have different "measuring" and "objecting" units, so there is a need to unify all factors to the same scale. In order to standardise the processes, a continuous scale suggested by Ref. [22] from 0 to 1 with 0 for the least suitable measure and 1 for the most suitable factor, which is named as the "Non-Boolean Standardisation". The scale should be used with different fuzzy functions because not all the factors act linearly.

In our AHP analysis, we used the Pairwise Comparison method to weight the different factors developed in Refs. [9,23]. The intensity of importance definitions and scales used to indicate pairwise comparisons between factors are the same as those used in Ref. [9]. That is starting with a score of 1 for a pair where both factors are of equal importance and ending with 9 to score a pair wherein the first factor is of extreme importance compared to the other. The intensity of importance can be chosen using personal judgment, experience, or knowledge. The process is accomplished by building the pairwise comparison matrix (see e.g. Table 5), which has equal rows and columns, the number of rows (columns) equal to the number of the factors. If the factor in the left side of the matrix has higher importance compared to the top side factor, the matrix relevant cell will assume the value assigned in the scale of intensity of importance. In the opposite case, the cell will equal the inverse of the scale value. A new normalised matrix can be created by taking the sum of every column and then dividing each matrix cell by its total column value. Finally, the weight of each factor is equal to the average of its row in the new matrix. The aggregation of all factor weights equals to one (see Tables 5 and 6 below).

Consistency Ratio (CR) was suggested by Ref. [23] to validate the pairwise comparison assumptions: any matrix with CR greater than 0.1 should be rectified. CR is given by: CR = CI/RI; where RI is the Random Consistency Index, and its value depends on the factor number n, RI values adopted from Ref. [23]. CI is the Consistency Index given by: CI = (λ_{max} - n)/(n - 1); where λ_{max} is the Principal Eigen value, equals to the product of factor weight and the summation of its column in the pairwise matrix.

WLC is the last step in AHP to find the optimal solution. The WLC method combines the standardised factors after multiplying each factor by its weight and finally multiplying the result map with a Boolean mask produced by multiplying all the constraints together. The resultant map is called the Suitability Map. The WLC equation [10], used to calculate the suitability map is given by:

$$\textit{Suitability} = \left(\sum_{i=1}^{n} W_i X_i\right) \times \left(\prod_{j=1}^{l} C_j\right) \quad (1)$$

where W_i = weight assigned to factor i, X_i = criterion score of factor i, n = number of factors, C_j = constraint j (Boolean Mask j), Π = product of constraints, and ℓ = no. of constraints.

WLC used in parallel with Boolean overlay, in which Boolean relationships such as ("And", "OR", or "Not") are applied to achieve a specific decision with "0 or 1" as a result value. In this work, a combination of the approaches discussed above such as (AHP, pairwise comparison, standardised scale, WLC, and Boolean overlay) were used. These provided the basis to develop the models into two software packages - Microsoft® EXCEL, (used to complete pairwise process), and ArcGIS, (used to configure, design, input, manage, display, manipulate, digitise, and for analysis of the spatial data).

After reviewing the information in the literature contained in Refs. [11–20], the identified and appropriate constraints for our methodology are as follows: Shipping Routes, Ports, Military Zones, Natural Park, Cables and Pipe Lines, Fishing Areas, and Oil and Gas Extraction Areas. The factors are: Bathymetry, Soil Properties, Wind Intensity, Distance to Shore, and Distance to Grid. These are listed in Table 2 where more detailed definitions and limitations of the different factors and constraints used in this methodology are given. The analytical methods are Pairwise Comparison and WLC.

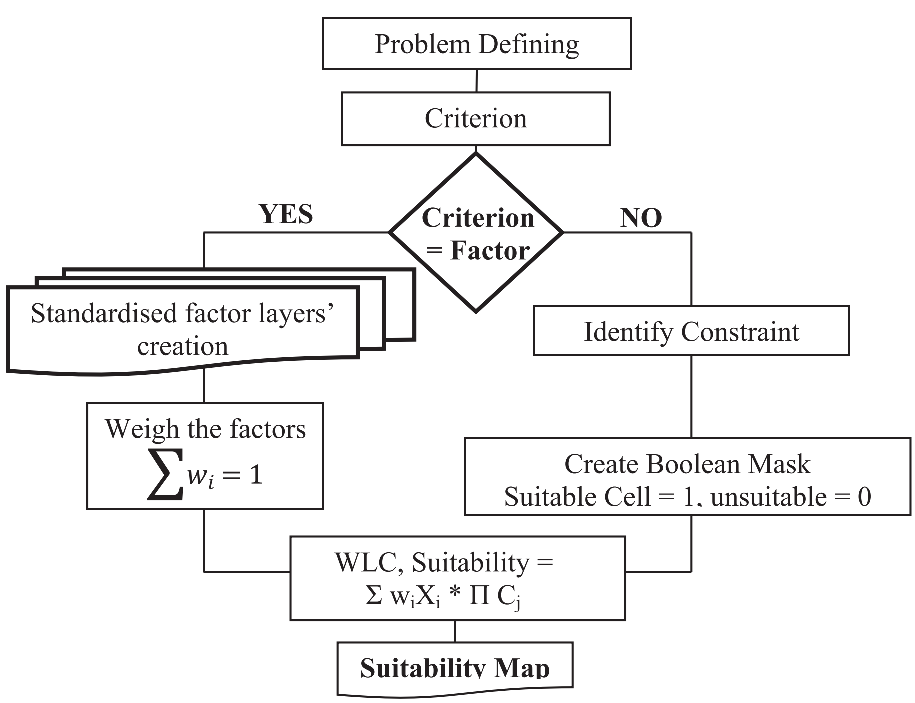

Fig. 1. Diagrammatic representation of the AHP process.

Table 2
Criteria definitions and optimisation needed for locating offshore wind farms. Where F is a factor and C is a constraint.

Criteria	Description	Unit	Optimisation	Type (F/C)
Wind	Energy of the wind	W/m^2	Identify areas with wind resource, between 45 and 850 W/m^2	F
Water depth	Water depth in selected area of the sea	m	Identify areas with depth between 5 and 60 m	F
Cables	Submerged cable paths.	–	Avoid	C
Oil	–	–	Avoid	C
Parks	Legally protected areas to preserve endangered marine ecosystem	–	Avoid	C
Shipping Routes	Ships/vessels movement routes	–	Avoid	C
National Grid	Length between the cell and national grid.	m	Choose places closer to the grid	F
Military Areas	Identified by military defence authorities.	–	Avoid	C
Soil	Determined by borehole tests - status, type and depth of soil	m	Choose sites with sandy sediment layer closer to the seabed.	F
Distance to shore	Distance to shoreline	m	1.5–200 km to shore, to reduce cable cost	F
Fishing areas	Areas determine by the authorities for fishing.	–	Avoid	C

4. Case study: Egypt energy and offshore wind

In order to apply the above approach for offshore wind farm sitting, we have identified Egypt as an appropriate case study. This is due to its unique location between two inner seas, its huge need for renewable energy, and wind data availability (Egypt is the only country in the Middle East that has a detailed wind atlas).

4.1. Energy needs in Egypt

Egypt has approximately 3000 km of coastal zones situated on the Mediterranean Sea and the Red Sea (Fig. 2). Approximately 1150 km of the coast is located on the Mediterranean Sea, whilst 1200 km is bordered by the Red Sea with 650 km of coast located on the Gulf of Suez and Aqaba [24]. According to the 2014 census, the population of Egypt was estimated to be around 90 million, 97% of which live permanently in 5.3% of the land mass area of Egypt [25]. Egypt's electricity consumption is increasing by around 6% annually [26]. Within a five-year period, the consumption has increased by 33.7%, which was delivered by a 27% increase in capacity for a population increase of only 12% during this period (Table 3). Until 1990, Egypt had the ability to produce all its electricity needs from its own fossil fuel and hydropower (High Aswan Dam) plants. However, in recent years, due to a combination of population increase and industrial growth, the gap between production and consumption has widened greatly [27].

The Egyptian New and Renewable Energy Authority (NREA) estimates that energy consumption will be double by 2022 due to population increase and development [29]. The Egyptian government is currently subsidising the energy supply system to make electricity affordable to the mostly poor population [27]. Such subsidies create an additional burden on the over-stretched Egyptian economy. The budget deficit in 2014/2015 was 10% of GDP accompanied by a “high unemployment rate, a high poverty rate, and a low standard of living” [30]. The projected increase in energy consumption will undoubtedly lead to more pollution such as CO_2 emissions, as increased capacity will be derived from greater consumption of fossil fuels.

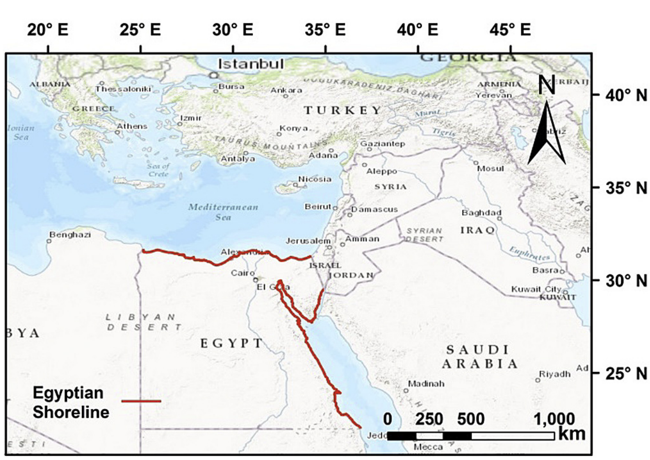

Fig. 2. Study area map, Egypt is shaded in red, the map adopted from Ref. [28].

Wind and solar resources are the main and most plentiful types of renewable energy in Egypt. In 2006, and in order to persuade both the public and the public sectors to invest in renewable energy, NREA conducted a study which emphasised that Egypt is a suitable place for wind, solar, and biomass energy projects [29]. The study urged the Egyptian government to start building wind farms, and the private sector to develop smaller projects to generate solar and biomass energy [29]. Egypt aims to produce 20% of its electricity needs from renewable energy by 2020 with approximately 12% derived from wind energy. Onshore wind currently supplies only 1.8% of the Egyptian electrical power and there are no offshore wind farms. Without more and urgent investments in wind energy, there is an increased possibility that the 2020 target will be pushed back to 2027 [26].

The first action taken by the Egyptian government towards generating electricity from wind was the creation of the Egyptian Wind Atlas [31]. This was followed by installation of the Za'afarana onshore wind farm, which has 700 turbines and a total capacity of 545 MW. The monthly average wind speed at this farm is in the range 5–9 m/s. The government is now planning to develop three more wind farms at different sites in Egypt [32]. As indicated earlier, all wind energy in Egypt is currently generated onshore, and the emphasis now is to scale up capacity from the current 1 GW–7.5 GW by 2027 [33], by going offshore where the wind resource is much higher.

Due to its geographical location, Egypt (for its size) has one of the largest offshore wind potentials in the world [34]. The Red Sea region has the best wind resource, with a mean power density, at 50 m height, in the range 300–800 W/m^2, at mean wind speed of 6–10 m/s. Egypt's offshore wind potential in the Mediterranean Sea is estimate to be around 13 GW. For a relatively small land footprint, this resource is large when compared with, for example, the estimated total offshore wind resource for much larger countries such as the USA with 54 GW potential [35].

As previously indicated, Egypt is currently experiencing serious electricity shortages due to ever-increasing consumption and the lack of available generation capacity to cope with demand [29]. In many instances, power blackouts occur many times a day [30]. In order to cope with the demand and provide sustainable energy, the Egyptian government embarked on a programme to produce electrical power from onshore wind. To date, however, only a small number of wind farms are in production with a total capacity of

Table 3
Egypt Yearly Peak Load (YPL) [26], population [25], and electricity consumption [26].

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016
YPL (GW)	19.74	21.33	22.75	23.47	25.71	27.00	26.14	28.02	29.2
Population (millions)	77.4	79.1	81.7	83.3	85.9	88.1	92.8	96.3	99.8
Consumption (TWh)	106.6	111.7	118.9	125.2	134.1	140.3	143.6	146.7	149.2

around 1 GW, which is not sufficient to support the ever-increasing demand [29]. In order to alleviate power shortages, offshore wind can play a major part in this respect as the resource is vast and its exploitation will increase capacity thereby alleviating shortages. Investment in offshore wind will also benefit economic development of the country and will reduce pressure on land areas where wind speeds are high but are of greater commercial importance for recreation and tourism [34].

4.2. *Previous wind energy studies in Egypt*

To date and to the authors' knowledge, there have been no detailed studies conducted to explore offshore wind energy potential in Egypt. The only available literature consists of few studies on onshore wind. For example, the economic and the environmental impact of wind farms was assessed by Ref. [36] using a Cost-Benefits Ratio. It concluded that Za'afarana along the Red Sea coast was the most suitable site in Egypt for onshore wind farms. A "road map for renewable energy research and development in Egypt" was produced by Ref. [37], which emphasised that wind energy is the most suitable renewable energy source for Egypt particularly for technology positioning and market attractiveness. The first survey to assess the wind energy potential in Egypt used 20-year old data from 15 different locations to estimate the wind energy density at 25 m height and the mean wind power density [38]. It estimated the magnitude of the wind energy density to be in the range 31–500 kWh/m^2/year and the power density in the range of 30–467 W/m^2. The study concluded that the Red Sea and the Mediterranean Sea, plus some interior locations (Cairo, Aswan, El-Dabah, and El-Kharga) were the most suitable locations for onshore wind farms.

Many studies presented a set of analyses that covered the land areas adjacent to the Red Sea and the Mediterranean Sea coasts [33,39–43], as well as some interior locations around Cairo and Upper Egypt [44,45]. Small size (100–200 kW capacity) wind farms are a suitable solution for the isolated communities in the Red Sea coast and 1 MW capacity farms are appropriate for the northern Red Sea coast area which could be linked to the Egyptian Unified Power Network [46]. The "Wind Atlas of Egypt", which took nearly 8 years to complete, was the only institutional effort [31].

As can be seen from the above, there is a gap in addressing the wind renewable energy resource in Egypt, and especially offshore wind. Our additional aim is to address this gap through systematic analysis based on well-understood approaches developed for other global sites.

5. Analysis

In order to establish a pathway for exploiting the offshore wind resource, systematic analysis for such exploitation is needed and this is one of the reasons Egypt was used as the case study for the methodology. Additionally, the work will also address the paucity of knowledge on offshore wind energy in Egypt. In order to test our proposed methodology outlined above, the analysis for the case study will investigate the wind energy potential, specify appropriate locations of high resources with no imposed restrictions and generate suitability maps for offshore wind energy exploitation. It will also identify the needed criteria that govern offshore wind farms spatial siting.

5.1. *Criteria identifying*

In accordance with Egyptian conditions, all criteria that affect the cost will be considered, in addition to two added environmental restrictions. All criteria in Table 2 are included except for fishing areas constraints. According to Egyptian law 124 (1983) the allowed depth for large fishing vessels is more than 70 m [47]. In addition, fishing using simple techniques noted unlikely to interfere with offshore-submerged cables [48]. Hence fishing activities around Egypt will have no effect on OWF locations which will operate at maximum depths of 60 m.

5.2. *Spatial data accumulation and processing*

A map layer in ArcGIS was created for each the criterion using the available and relevant spatial data. Wind power data was derived from the "Wind Atlas for Egypt" [31]. A shape file of the land cover of Egypt was created and was used as a base map. To represent the wind power map as a layer in the ArcGIS, the Georeferencing Tool using geographical control points was used to produce a map image. The power density areas contours were then entered as a shape features. Finally, the shape feature was converted to a raster file with cell size (x, y) = (0.8, 0.8) km, the Geographic Coordinate System used was "GCS_WGS_1984", (Fig. 3).

The bathymetry data (in raster form) for both the Red and Mediterranean Seas was adopted from the British Oceanographic Data Centre [49]. Fig. 4 shows the topography of Egypt raster map in meters. Later on, we will apply a Boolean mask to eliminate levels above −5 m. In Egypt, tunnels exist only in Cairo, and beneath the Suez Canal, according to the National Authority for Tunnels [50]. Therefore there is no need to account for tunnel data in the sea. Undersea cables locations were extracted from the Submarine Cable Map web [51]. Fig. 5 shows the raster map for these cables and additionally depicts other parameter determined by the analysis.

In Egypt, Law number 20 (1976) [52], permits the establishment of offshore structures in areas preserved for future excavation or mining but for safety reasons, a restricted buffer zone of 1 km was created around present and future offshore oil and gas wells. Data for these areas and restrictions adopted from Ref. [53] are shown in Fig. 5. Under Law number 102 (1983) [48], 30% of the Egyptian footprint, encompassing 30 regions, were declared as Nature Reserves. The Sea Marine Nature Reserves represent nine such areas with seven located in the Red Sea, and the others located in the Mediterranean Sea. The locations and dimensions of the reserves were established from the official web site of the Egyptian Environmental Affairs Agency [48]. The data processing was conducted in the same way as the wind power density layer and the resultant raster map is shown in Fig. 5.

The shipping routes around Egypt were determined from the ship density maps of marine traffic for the period 2013-14 [54]. Ports and approach channels areas were identified from the Marine Traffic and Maritime Transport Authority of Egypt [55]. The GIS

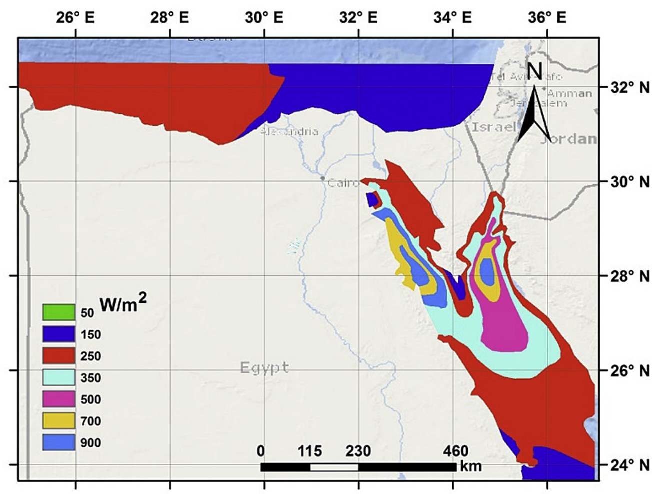

Fig. 3. Digitized map layer of the wind power density over the sea 'areas only, the wind power density was calculated over a 50 m height.

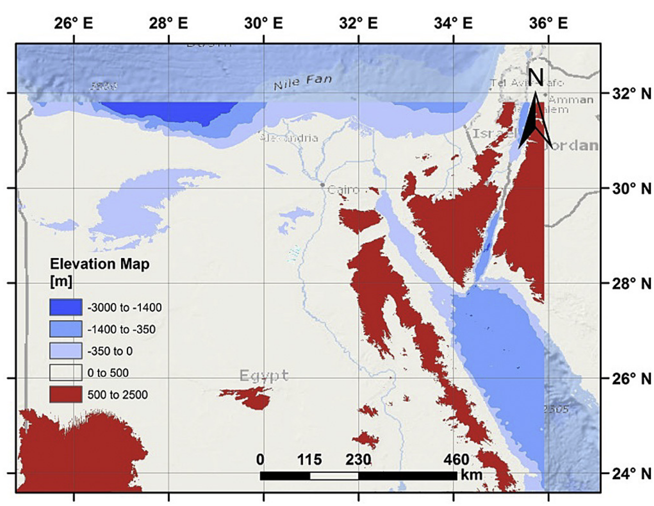

Fig. 4. Topography and bathymetry raster map of Egypt.

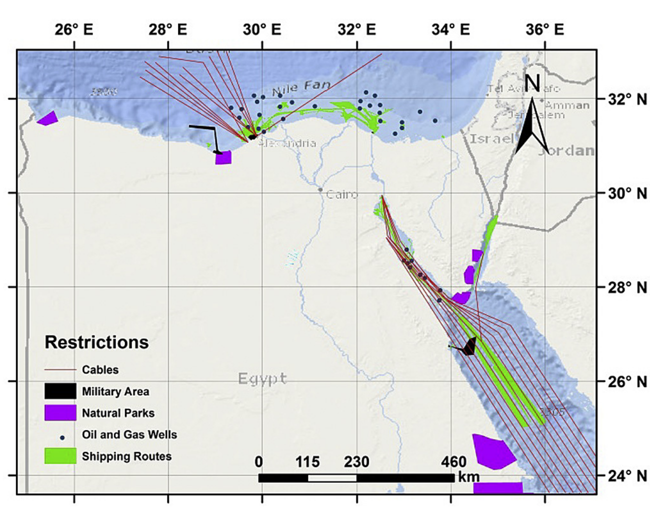

Fig. 5. All constrains layers of our study, coloured areas will take a value of 0, and other areas will take a value of 1.

representation of these areas is shown Fig. 5.

The Egyptian power network from which it is possible to identify appropriate grid connections to high wind resource sites [56]. The Euclidean Distance Tool in ArcGIS was used to estimate the distance from each electricity grid line to the sites and the raster layer results are in Fig. 6.

To ascertain and assess the proximity of military exercise areas to the high wind resource regions, data used was gathered from the official website of Ministry of Defence and Military Production [57] and these areas were excluded from our analysis as shown in the layers in Fig. 5. The coastline of Egypt was drawn to calculate the distance from the sea to the shoreline, applying the Euclidean Distance Tool, and the results are shown in Fig. 7. In terms of ground conditions, most of the seabed adjacent to the Egyptian coast has a medium to coarse sandy soil [58–60]. Hence, all cells in the modelling within the sea will have a score of 1.

6. Results and discussion

In our analysis, the factor spatial layer was ranked using the scale from Ref. [9], assuming that wind power density has the same importance as the total cost of the project and as such was given the same weight. The other factors comprise the major items for calculating the total cost. Data obtained from Ref. [21] was used to compare factors and to identify the different elements of costs of OWF. It should be noted that the cost values were estimated as an average from the cost of offshore wind projects in the UK spanning the period 2010 to 2015 [21]. Table 4 gives the cost of the various components for a wind farm including turbine foundation, cabling cost and their percentage of the total cost [21].

Table 5 takes into account the importance of the various scales assigned to "intensity of importance" to identify the impact between pairs. For example, wind power density factor was assigned a score of 3 compared to 1/3 assigned to the depth factor, as the latter represents about 1/3 of the project total cost (Table 4) and according to the pairwise comparison rules (see Section 3).

The comparison matrix of the calculated factors' weights is given in Table 6. This was determined by dividing each cell in Table 5 by the sum of its column. The values of the CI, RI, λ_{max} and CR were found to be 0.039, 1.12, 5.16 and 0.04 respectively; CR value is much less than 0.10, indicating that the assumptions and the calculations are valid.

Fuzzy function describes the relationship between the increases in a factor's magnitude as compared to overall cost appreciation/reduction. Such an assessment also depends on the experience and the knowledge about the factors. The data from Ref. [1] indicates that the relationships for the major factors (wind, distance to shore, and water depth) are linear.

The Fuzzy Membership tool in ArcGIS was applied to produce a new standardised layer for each factor. Table 7 shows the factor membership type and its limitations, which was adapted from Table 2. Some factors need another Boolean mask to conduct their limitations, these were, distance to shore and water depth for more than the maximum value limit.

Boolean mask was created to exclude the restricted cells by giving them value 0 or 1 (Table 8), which was adopted from the constraints shown in Table 2. Finally, all these constraints were gathered in one layer, using Raster Calculator tool, and shown in Fig. 8. All criteria were aggregated to create the suitability map of OWF in Egypt. The WLC equation was used to conduct the aggregation. The standardised layers were first multiplied by its weights, then summed together, using Weighted Sum tool in ArcGIS. Finally, the Weighted Sum layer was multiplied by the Boolean Mask layer, using the Raster Calculator tool. The final Suitability Map layer is shown in Fig. 9.

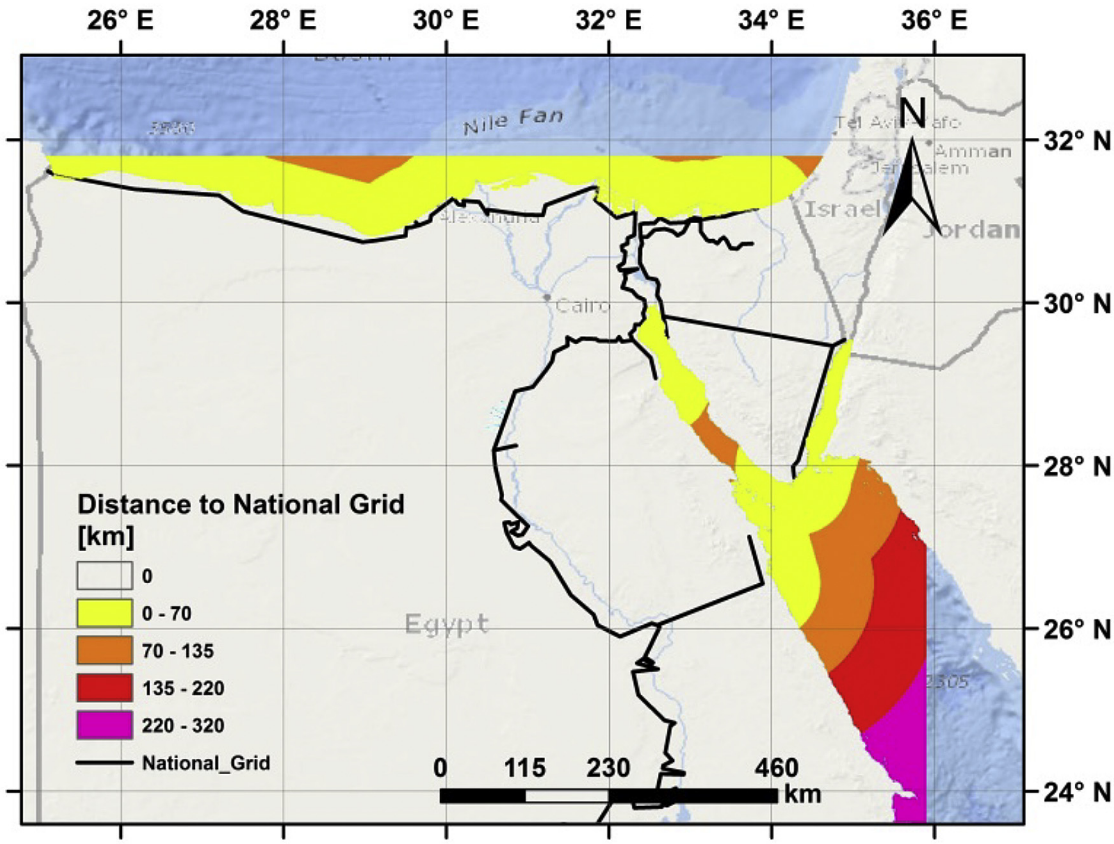

Fig. 6. Map showing distance from sites to national grid.

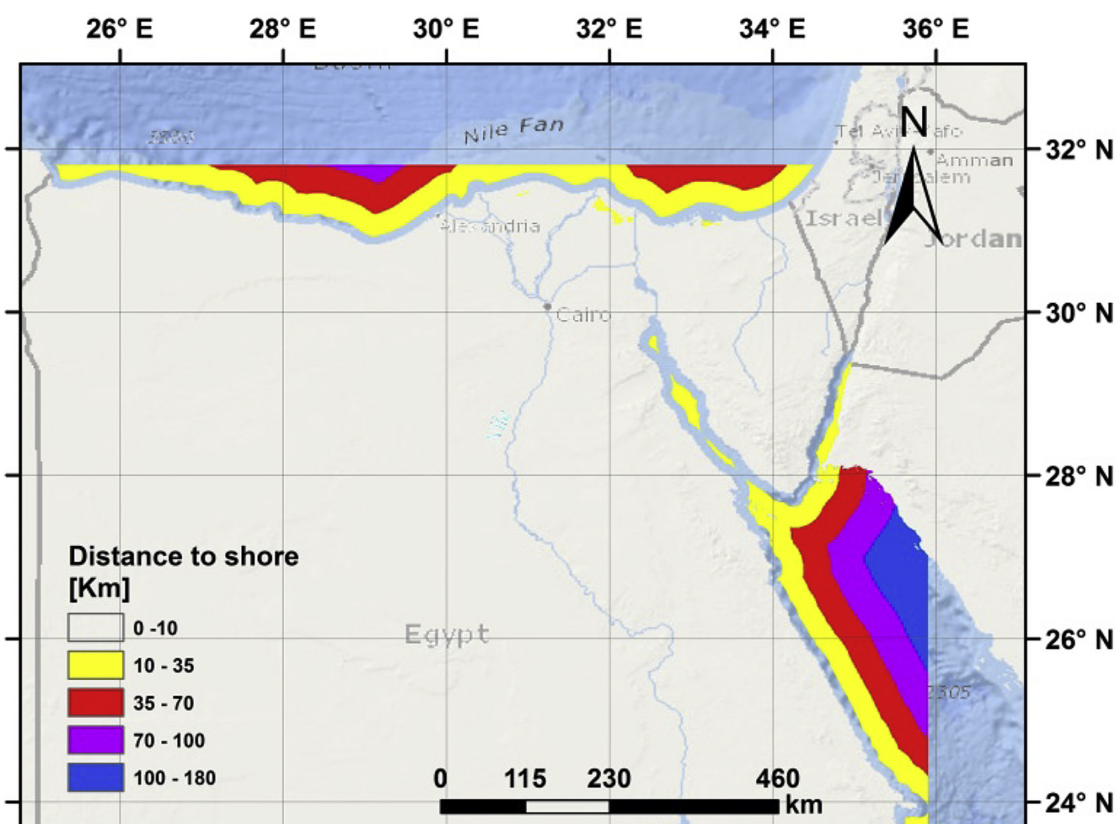

Fig. 7. Distance to the Egyptian's shore.

Table 4
Average cost and % to total cost estimated from UK OWF costs [21].

Factor		Cost £m/MW	%
Foundation	Depth	0.50	27
	Soil Properties	0.23	12
Connecting to the National Grid		0.16	5
Distance from shoreline (Under water cables)		0.29	9
Installation and substations		0.67	21
Total		1.85	100
Total including the turbine		3.2	–

Table 5
Pairwise Comparison matrix.

Factor	F1	F2	F3	F4	F5
Wind power density (F1)	1	3	8	9	6
Depth (F2)	1/3	1	4	5	3
Soil Properties (F3)	1/8	1/4	1	2	1/2
Distance to National Grid (F4)	1/9	1/5	1/2	1	1/3
Distance from shoreline (F5)	1/6	1/3	2	3	1
Sum	1.74	4.78	15.5	20.0	10.8

Table 6
Normalised matrix and weight determination.

Factor	F1	F2	F3	F4	F5	Weight	λ_{max}
F1	0.58	0.63	0.52	0.45	0.55	0.54	0.95
F2	0.19	0.21	0.26	0.25	0.28	0.24	1.13
F3	0.07	0.05	0.06	0.10	0.05	0.07	1.04
F4	0.06	0.04	0.03	0.05	0.03	0.04	0.88
F5	0.10	0.07	0.13	0.15	0.09	0.11	1.16
Sum	1.00	1.00	1.00	1.00	1.00	1.00	5.16

In our analysis, an area with a value of 1 was found inland in the Boolean mask layer, circled in red (Fig. 8). The reason for this confliction is that the area considered has an altitude less than −5 m below mean sea level and corresponds to the *Qattara Depression*, located in the north west of Egypt. This is "the largest and deepest of the undrained natural depressions in the Sahara Desert", with the lowest point of −134 m below mean sea level [61]. Identifying such areas gives further confidence in the robustness of the analysis and these points were excluded from the suitability map.

The total number of high suitability areas for OWF is approximately 3200 cells which represent about 2050 km^2, while the moderate suitability area is approximately 21650 cells which represent about 13860 km^2. These numbers are promising when compared with, for example, the 122 km^2 of the world's largest OWF, the London Array, which has a capacity of 630 MW [16]. The areas that are unsuitable for OWF are equal to 16403 km^2. In our work, the cell dimensions are 800 m by 800 m, which represent an area of 0.64 km^2.

Zooming into specific areas to obtain a finer grain of suitable locations in the suitability map given in Fig. 10, we arrive at the most suitable locations for OWF in Egypt, which are shown circled (in red colour the figure). Locations 1 and 2 are in the Egyptian territorial waters, while location 3 is situated between Egypt and Saudi Arabia. Location 1, 2, and 3 contain 1092, 2137, 969 km^2 of high suitable areas for OWF, respectively.

In order to estimate the potential wind energy capacity of these areas, we use the method described in Refs. [62,63] which estimates the effective footprint per turbine (array spacing) using the expression: *Array Spacing* = *(rotor diameter)*^{2} × *downwind spacing factor* × *crosswind spacing factor.* However, we adopted the E. ON data for the turbine spacing of 5–8 times rotor diameter (to reduce turbulence between turbines) and used an average wind speed of 10 m/s [31]. Hence, for a 5 MW turbine of 126 m rotor diameter, a one square kilometre of the chosen areas would yield ~7.9 MW of installed capacity. Following these considerations, Table 9 gives our estimated power for the three locations shown in Fig. 10. The total wind power capacity of all these sites is around 33 GW.

From the final suitability map (Fig. 9), it is clear that most of the high suitability cells are concentrated in areas that have wind power density > 600 W/m^2, which reflects the strong influence of wind power criterion on the cells' ranks. This is reasonable because the wind power has a relative importance of more than 50%. The second factor is water depth which it has a 24% share of the total weight, and this explains the long, wide area with moderate suitability which can be seen adjacent to the northern coast of Egypt (shown as yellow areas within the black rectangle in Fig. 9). Despite an average mean power density of less than 200 W/m^2 in these areas, their slope is mild (shallow) approximately less than 1:800 for more than 50 km away from the sea [49].

7. Conclusions

A new methodology to model and identify suitable areas for offshore wind sites is introduced which addresses a gap in knowledge in the offshore wind energy field. The methodology can be easily utilised in other regions by applying the four steps summarised in Section 3 and the process depicted in Fig. 1. There are some assumptions, requirements, and limitations related to the proposed methodology. The model is limited to national or regional scales requiring a wide knowledge and data (wind speed and bathometry) when considering these scales. The model was built on the assumption that cost related criteria are higher in weight than those assigned to the environmental aspect of the site to be exploited.

Table 7
Fuzzy membership functions of the factors and its limitations.

Factor	Membership Type	Max Value = 1.0	Min Value = 0.0	More than Max	Less than Min
Wind	Linear	850 W/m^2	45 W/m^2	1.0	0.0
Depth	Linear	5.0 m	60.0 m	0.0	0.0
Sandy soil level	Linear	5.0 m	21.0 m	1.0	0.0
National Grid	Linear	1 km	450 km	1.0	0.0
Distance to shore	Linear	1.5 km	200 km	0.0	0.0

Table 8
Constraints definition and limitation.

Constraint	0	1
Depth	Depths <5.0 m or >60.0 m	Else
Distance from shore	Distance <1.5 km or >200.0 km	Else
Military Areas	Military areas as shown in Fig. 5	Else
Shipping Routes	Areas as shown in Fig. 5	Else
Oil & Gas Areas	Areas as shown in Fig. 5	Else
Cables and tunnels	Lines as shown in Fig. 5	Else
Nature Reserves	Marine parks as shown in Fig. 5	Else

Table 9
Estimate wind power capacity per considered area (Fig. 10).

Location in Fig. 10	Area (km^2)	Estimated power (GW)
Red Circle 1	1092	8.6
Red Circle 2	2137	16.8
Red Circle 3	969	7.6
Total (GW)		33.0

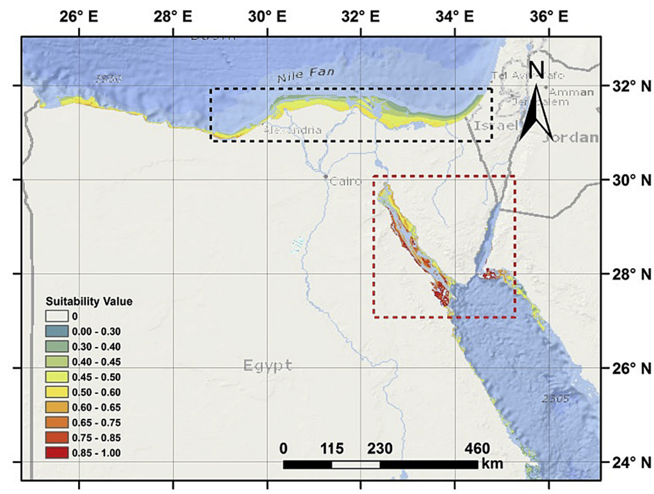

Fig. 9. Final Suitability Map for offshore wind in Egypt, where the legend indicates the weights of suitability where 0 = least suitable and 0.99 = most suitable. Black and red rectangles represent areas of moderate and high suitability respectively.

The approach presented was successful in providing a suitability map for offshore wind energy in Egypt. The applied model is capable of dealing with the conflicting criteria that govern the spatial planning for offshore wind farms. The spatial analysis was undertaken at a medium resolution (800 m by 800 m), which is confined to the cell size of the bathymetry map data availability.

Five factors and seven constraints were applied using MCDM and GIS models for Egypt as the case study area. The analysis was conducted at large scale covering the whole of Egypt and its surrounding waters and hence has implications for renewable energy policies in Egypt and, to some extent, Saudi Arabia. The study transcends different conditions present in two seas – the Red Sea and the Mediterranean Sea, and hence is of wider applicability in these regions. To our knowledge, no detailed studies have been conducted either onshore or offshore, that have considered such a footprint, provided spatial planning examination of appropriate sites.

The final results indicate that Egypt could potentially benefit from around 33 GW, achieved by only considering installations at the high suitability offshore wind sites available. This significant amount of green renewable energy could provide a solution to the electricity shortage in Egypt; furthermore, the offshore wind solution has no effect on important tourist resort lands around the chosen sites. This outcome confirms the huge offshore wind energy potential in Egypt. In addition, as the fuel from wind electrical power production is free, exploitation of offshore wind could positively contribute to the country's Gross domestic product (GDP) and budgets balances, reducing dependence on imported fuels

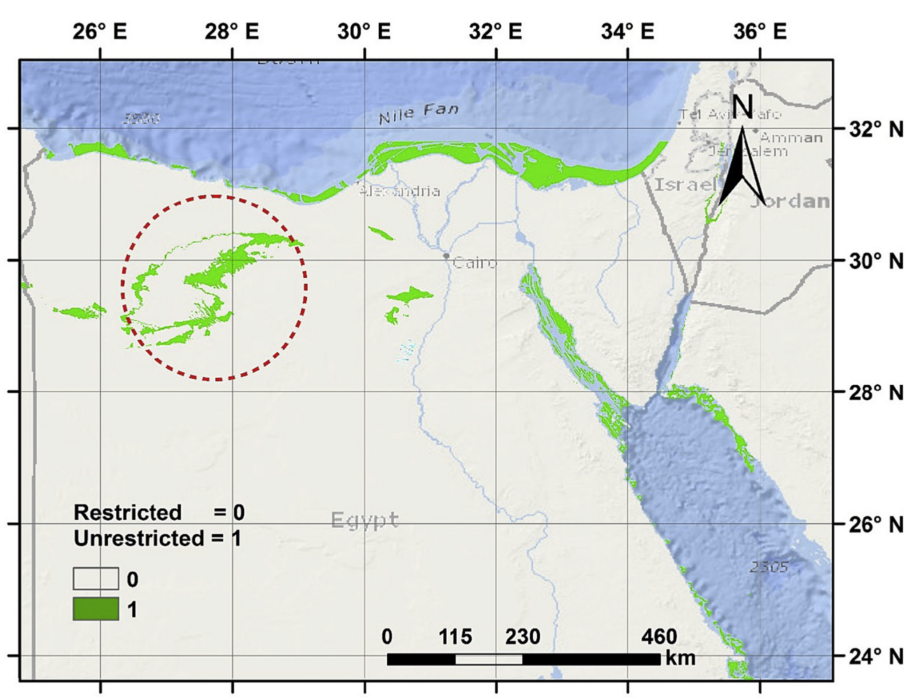

Fig. 8. Final Boolean mask layer – The red circle showing the Qattara Depression (see text under results).

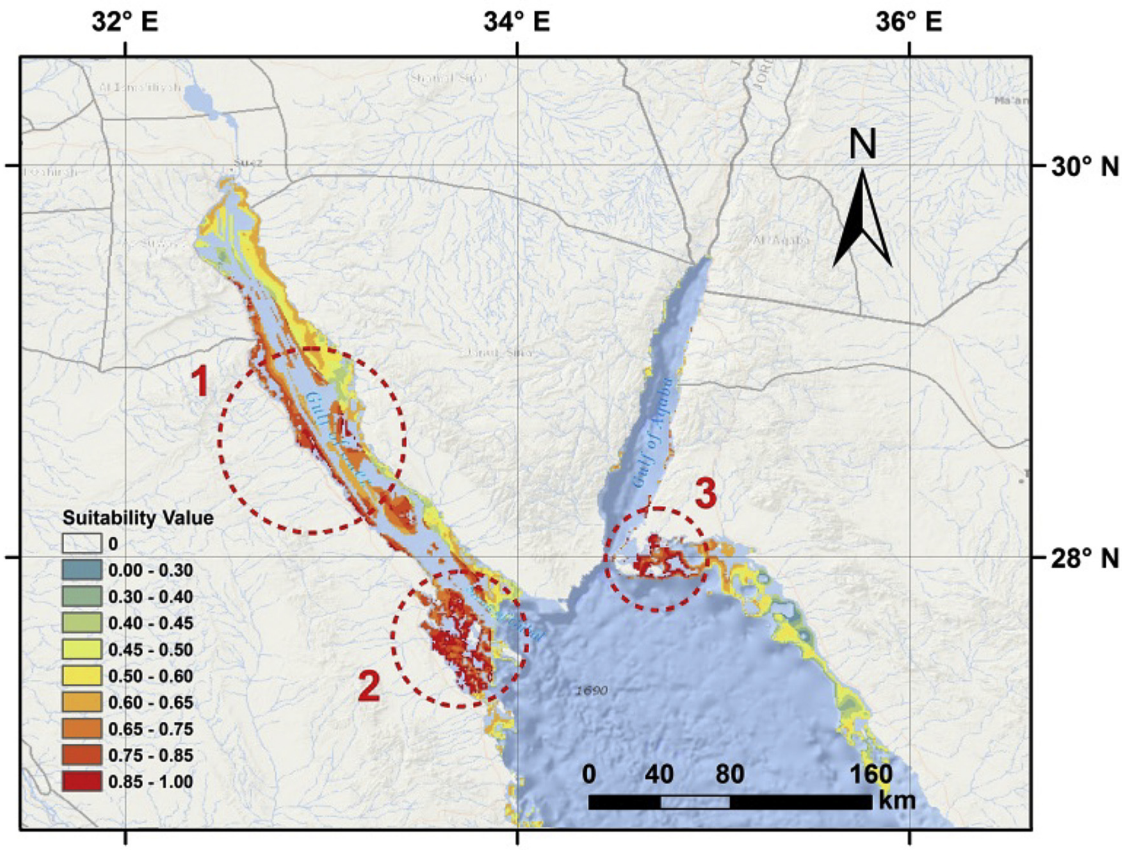

Fig. 10. The Suitability Map for offshore wind farms around the southern coast of Sinai Peninsula, Red Sea, Egypt. The encircled area areas show high wind energy potentials.

whilst providing a cleaner and more sustainable approach to electricity production in Egypt. Nevertheless, a coherent policy coupled with capacity building would be needed to allow such exploitation to occur.

This case study provides the needed evidence to establish an appropriate programme to exploit the offshore wind energy resource in Egypt and will contribute to the country energy mix so that it can cope with its ever-increasing energy demand. In essence, the work presented here not only plugs a knowledge gap but also provides realistic evaluation of the Egyptian offshore wind potential which can form the basis of the needed blueprint for developing the appropriate policies for its exploitation. The existence of vast commercial experience in offshore wind is more than likely to consider such a resource and can be marshalled to support it exploitation in Egypt.

Lastly, the scope and methodology of this study addressed a knowledge gap in the development of renewable energy systems, particularly that of offshore wind. The methodology used here provides a robust offshore spatial siting analysis that can be applied in different locations around the world.

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