# OFFSHORE WIND ENERGY POTENTIAL AROUND THE EAST COAST OF THE RED SEA, KSA

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**Abstract**

Under its Vision 2030, the Kingdom of Saudi Arabia (KSA) announced an ambitious strategy to diversify their economy from oil dependency. One of the goals of the vision is an initial target to produce 9.5 GW of electricity from renewable energy sources. Offshore wind energy conversion is considered to be mature technology with more than 12 GW of installed capacity globally. Offshore wind has advantages when compared with onshore wind, such as, higher wind speed, reduced turbulence, minimal visual and noise impacts. KSA has two shorelines, one is laying on the Arabian Gulf and the other is on the Red Sea. The work presented here evaluates offshore wind potentials in in the East Coast of the Red Sea in KSA which was chosen due minimum restrictions and has no close oil extraction facilities. The evaluation was based on a Boolean Mask model linked coupled analysis undertaken in Geographical Information System developed for the Red Sea area.

Using the UK's London Array wind farm as a minimum required area for offshore wind farms, the work identifies ten different locations as possible areas for the first offshore wind farms in KSA. The analysis considered the deployment of two types of turbine of capacities 3.6MW and 5MW. The results for the higher capacity turbine indicate that over 12.3 GW of offshore wind power can be generated from the identified sites. These results and the produced location maps could be used to help stakeholders in KSA in planning for the exploitation of offshore wind energy in KSA. Thus providing a pathway to contribute to achieving the 9.5 GW national target.

*Keywords: Wind energy, offshore wind, GIS, Boolean Mask, Red Sea, KSA*

## 1. Introduction

Offshore wind energy is considered mature technology with over 12 GW of installed capacity globally. The recent contract for difference (CfD) announcement in the UK showed halving the cost per MWh to £57.5 compared to the previous round (CB, 2017). Onshore wind on the other hand is further ahead in terms of economics, however, it has some disadvantages, such as the value of the land areas, noise, high vibrations, visual impacts, bird paths hazards, and shadow flicker effect. Shadow flicker effect that is an infrequent event, which could happen, when the sun's light is at horizon. Shadow flicker could be responsible for photo-induced seizures or photosensitive epilepsy and other disturbance to humans near the turbines (Knopper & Ollson, 2011). Offshore wind on the whole does not suffer from these disadvantages, and has two extra advantages: the average wind speed is larger than over onshore areas and the turbulence wind effect is minimized when compared to installation over land. The latter is important as fatigue stress encountered is smaller enhancing offshore wind turbines life.

The Kingdom of Saudi Arabia (KSA) has a total area of 2.2 million km$^2$, and a population of more than 30 million. KSA lies between latitude of 17.5 °N and 31 °N and longitude of 36.6 °E and 50 °E (Bahakeem, 2015). The west coastline of KSA is more than 1800 km in length and is situated around the Red Sea and the Gulf of Aqaba with a boundary between Haql to the north and Jazan to the south (Fig.1).

The energy consumption of KSA has been on rapid rise to cope with the growing demand of the industrial, water


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and building sectors. Most of this energy is derived from fossil fuels leading to high carbon emissions. This dependence is as a result of the vast oil resources in KSA estimated to be more than 250 billion barrels of oil reserves or one-fifth of total known global reserves (Bahakeem, 2015). Hence there is an urgent need for KSA to move towards low carbon renewable energy production.

In order to decrease its reliance on fossil fuels and balance its economy, KSA has developed the Vision 2030 programme under which it plans to generate 9.5 gigawatts of electricity from renewable energy sources (Gazette, 2016). This is more likely to be derived from solar energy and wind energy. Hence, this work is directed towards the latter, but concentrated on offshore wind around the Sea Area of KSA where we will identify suitable locations for offshore wind farms (OWF) and evaluate their potential. To our knowledge, only one article was found that considers the offshore wind resources in KSA but the study was focused on the east coast of the country (Rehman, 2005).

In summary, the aims of this work is to identify the suitable areas in KSA for offshore wind focusing on the the Red Sea regions, estimate the electrical power potential form the identified sites and provide suitability maps for these locations.

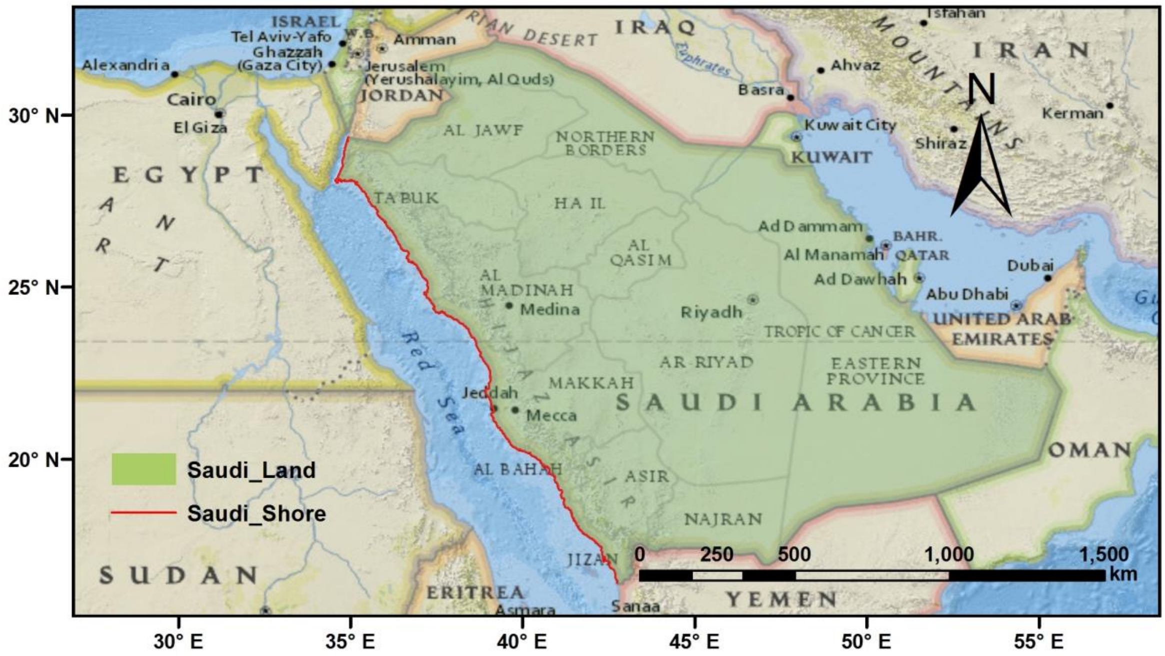


**Fig.1: Study area map, KSA is shaded with light green, the Red Sea east shoreline is the red line, adopted from (esri, 2012).**

## 2. Methodology

In this work the required outcome is a spatial siting of the wind farms. Such a problem comprises a large number of suitable alternatives and multiple constraints to choose the alternative with zero constraint. Both the constraints and alternatives can be determined or evaluated and weighted by stockholders, or scholars based on their knowledge and experience (Estoque, 2011).

The map of the study region is divided to grid as an equal size, the smallest part of such grid is called a cell, which corresponds to one of the feasible alternative. For instant, to decide the suitable cell for offshore wind energy in the Red sea, wind speed, water depth, distance to shore, distance to the electricity grid, shipping routes, military areas, cables paths, and reserved natural parks, are the constraints to be considered in the analysis and before taking a final decision. Fig.2 provides a flow chart summarising the whole assessment process, under the Boolean Mask technique utilised in this study to solve the problem.

Boolean Mask (overlay), is used to locate sites with no restrictions (constrains). Boolean relations [and, or, and not] are used, from which the name has been derived.The created map layer has two colours (boundaries), one represents areas that has a value of 1 (the unrestricted areas) and the other represents areas of value 0 value (restricted areas). Boolean mask is a powerful tool for simple and quick spatial decisions (Jiang & Eastman, 2000).

In this work, we need to create a primary map for suitable offshore wind farms in the Red Sea, around the KSA coast, and evaluate the potential electrcila power from these farms. The **Constraints** can be explained as a tool to eliminate alternatives (cells). The limitations or restrictions of the constraints are defined as a (true/false) relationship. For example, if the commercial wind power development becomes feasible around wind speed greater than 3 m/s, so all areas with wind speed less than this threshold (3 m/s) will be given 0 value, while other areas will take the value of 1.

The equation used to calculate the Boolean Map is adopted from (Eastman, Jiang, & Toledano, 1998), and is given by:

$$Boolean\ Mask = \left(\prod_{j=1}^{l} C_j\right) \qquad \text{(eq. 1)}$$

Where:

$C_j$ is the constraint j (Boolean Mask j),

Π is the product of constraints, and

ℓ is the number of constraints.

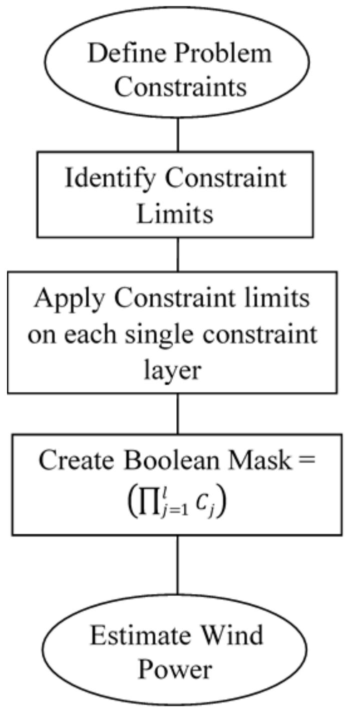


**Fig.2: Flow chart summarising the whole assessment process, under the Boolean Mask technique utilised in this work.**

## 3. Analysis

To satisfy the conditions of the sites around the Red Seas in KSA coasts, nine constraints were considered, and are summarised in Table 1. In addition, the table also provides the two limits for each constraint, where only two values are identified; zero value, which is the undesirable areas (cells) according to the constraint definitions, while the value of one is assigned the other areas (cell).

### *3.1 Relevant Data*

A map layer in ArcGIS was created for each constraint, using the available and relevant spatial data. The bathymetry data for the Red Sea around the shores of KSA was adopted from (The British Oceanographic Data Centre, 2014), the source file of water depth data was in raster form, with a sell size of 800 x 800 m, and the file "GCS_WGS_1984" is the Geographic Coordinate System used. Due to the source file cell size and the coordinating system type, all constraints layers were confined to same cell size and GCS_WGS_1984 coordinate system. Fig.3, shows the water depth map for the Red Sea, which has a range from 0 to -3000 m. The areas with the required depth for offshore wind farm are concentrated in the South West part of the KSA. Wind speed data was adopted from the "Wind Atlas for Egypt" (Mortensen et al., 2006) and from the Global Atlas for Renewable Energy (Kieffer & Couture, 2015). The map layer in Fig.4 shows the average wind speed in [m/s] at a height of 10 m over a flat and uniform sea, which has a range between 3 and 7 m/s. Locations with desirable wind speed are centred in the North West part of the KSA.

Fig.5 shows all constraints in the study area, KSA has only two maritime reserved parks in the Red Sea named "Umm al-Qamari Islands" and "Farasan Islands". Locations and shape dimensions of these parks were taken from the official web site of the Saudi Wildlife Authority (SWA, 2017). Shipping Routes in the Red Sea adjacent to the KSA coast line were identified using the data available from ship density maps of Marine Traffic website (The MarineTraffic, 2015). Submerged undersea cable locations and paths were extracted from the submarine cable map of (TeleGeography Company, 2015). Marine military restricted areas was assessed from Royal Saudi Navy Forces official website (RSNF, 2017). According to Saudi Aramco (Aramco, 2017), all petrol oil extraction areas are located on the Arabian Gulf, so the oil extraction constraint was excluded.

**Table 1: Constraints 0, and 1 definitions and data source data.**

| Constraint | Symbol | 0 description and data source | 1 |
|---|---|---|---|
| Wind Speed (m/s) | $W_B$ | Areas with wind speed less than 3.0 m/s **or** more than 25.0 m/s at a height of 10 m over a flat and uniform sea (Archer & Jacobson, 2005), wind speed data were adopted from (Mortensen, Said, & Badger, 2006) and (Kieffer & Couture, 2015). | Else |
| Water Depth (m) | $D_B$ | Depths less than 5.0 m **or** more than 60.0 m, the bathymetry data was adopted from British Oceanographic Data Centre (BODC) (The British Oceanographic Data Centre, 2014). | Else |
| Distance to the shore (km) | $S_B$ | Distance less than 1.5 km or more than 200.0 km, the distances data was adopted and processed using ArcGIS Program (esri, 2012). | Else |
| Distance to the Grid (km) | $G_B$ | Distance more than 250.0 km, the distances data was adopted and processed using ArcGIS Program (esri, 2012). | |
| Military Practice & Exercise Areas | $M_B$ | Locations were adopted from (RSNF, 2017).. | Else |
| Shipping Routes | $R_B$ | Shipping areas adopted from (The MarineTraffic, 2015) | Else |
| Maritime Boundaries | $B_B$ | Boundaries were adopted and processed using ArcGIS Program (esri, 2012).. | Else |
| Nature Reserves | $N_B$ | Places in the sea area protected by the power of law to reserve the endangered marine ecosystem species, marine parks were adopted from (SWA, 2017). | Else |
| Under Sea Cables | $U_B$ | Locations of the submerged sea cables (TeleGeography Company, 2015). | Else |

Fig.6 shows the map layer of the National Electricity Transmission Grid of KSA (the grid is drawn as a line network in a black colour), which was adopted from the Global Energy Network Institute (GENI, 2017). The Euclidean Distance Tool was deployed to calculate the distance between nearest electricity line to each cell, (Fig.6). Fig.7 shows the coastline of the Red Sea of KSA in km and was drawn using data from (esri, 2012). Euclidean Distance Tool within the ArcGIS programme was applied to create a map shown in Fig.7, which illustrates the distance from each cell to the coastline of KSA.

### *3.2 Boolean Mask*

A Boolean mask was created to eliminate restricted cells, constraint cell value = 0, and unrestricted cell value = 1, see Fig.5. The Raster Calculator tool was used to produce the final Boolean Mask, and is shown in Fig.8. The below equation was used:

$$\text{Boolean Mask} = W_B \times D_B \times S_B \times G_B \times M_B \times R_B \times B_B \times N_B \times U_B \quad \text{(eq. 2)}$$

Where: $W_B$, $D_B$, $S_B$, $G_B$, $M_B$, $R_B$, $B_B$, $N_B$, and $U_B$ are defined in Table 1 above.

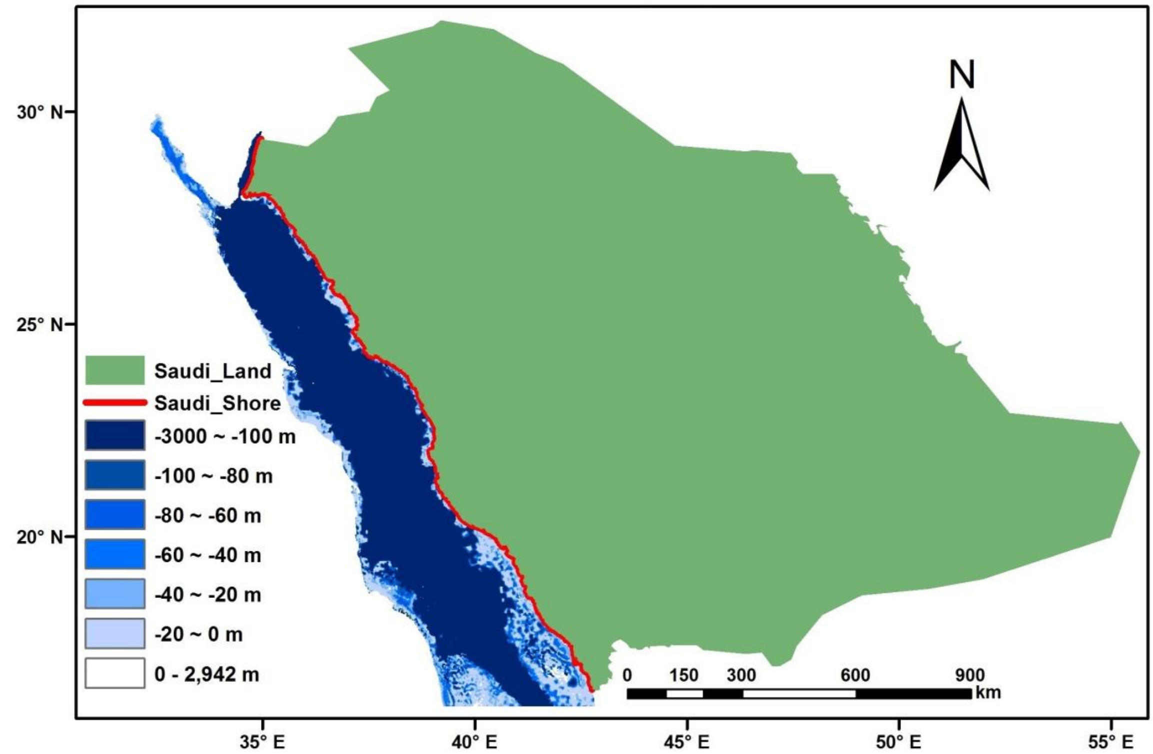


**Fig.3: Bathometry map of the Red Sea.**

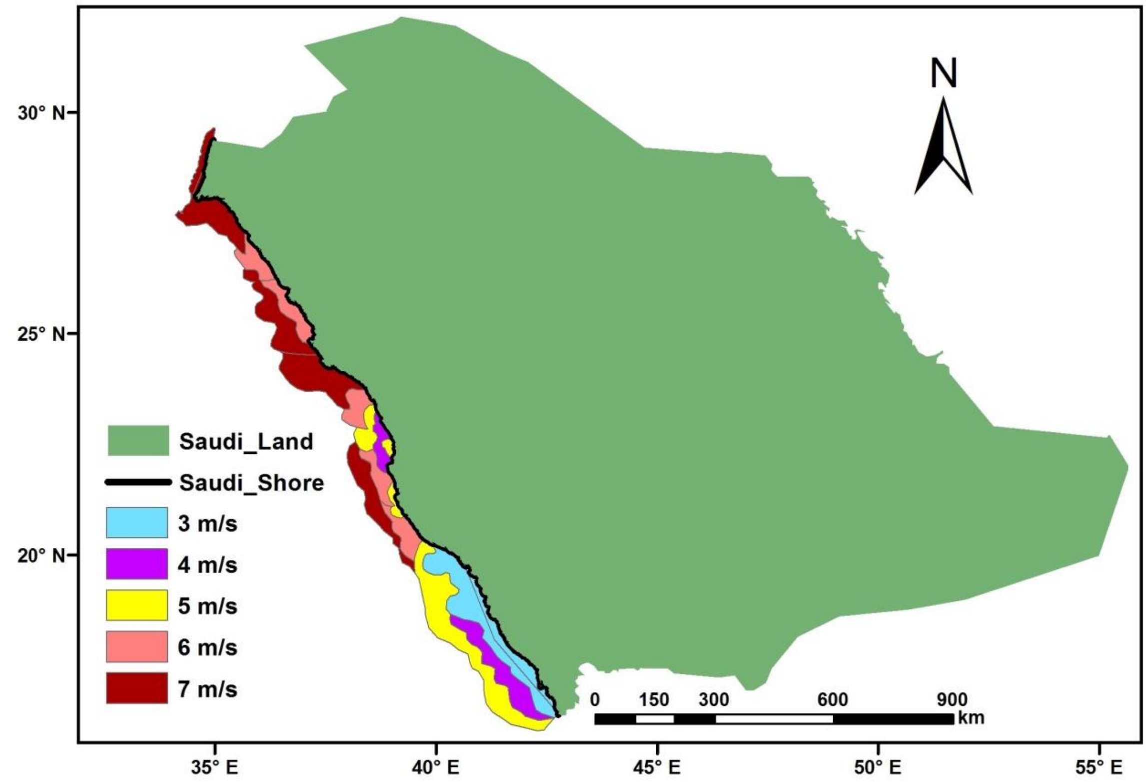


**Fig. 4: Wind Speed [m/s] map around the Red Sea coastline of KSA.**

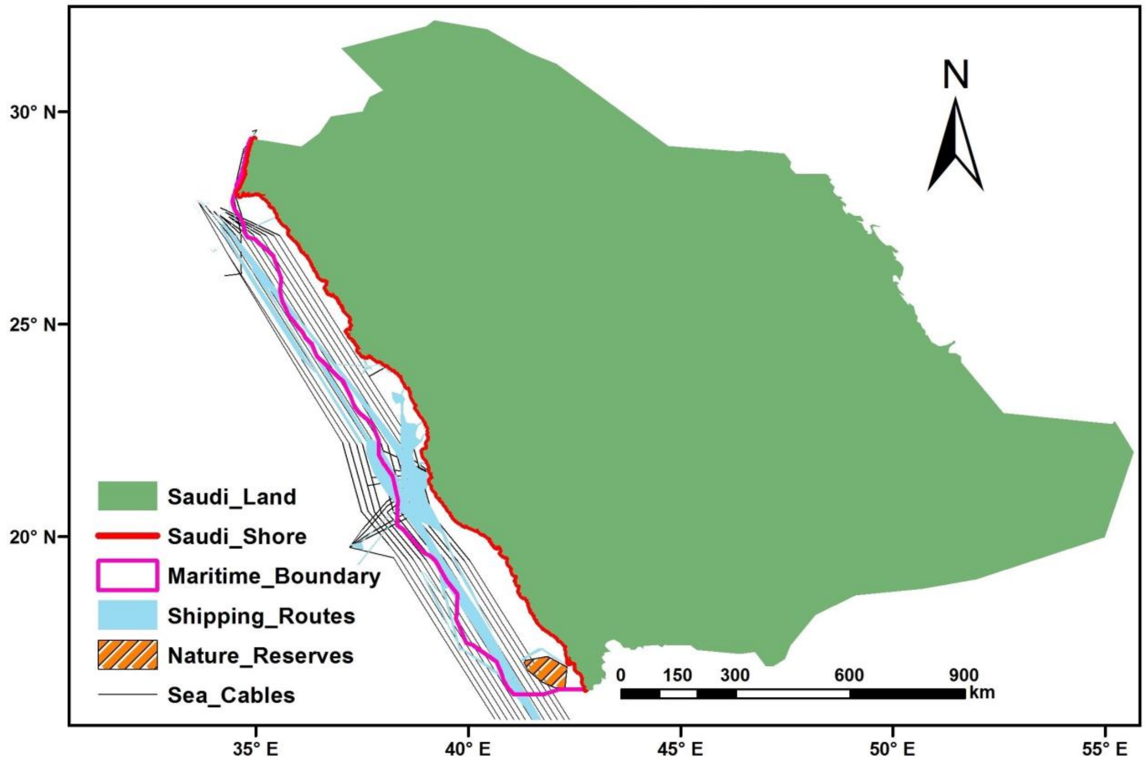


**Fig. 5: Raster layer for the all restricted areas around the Red Sea region of KSA.**

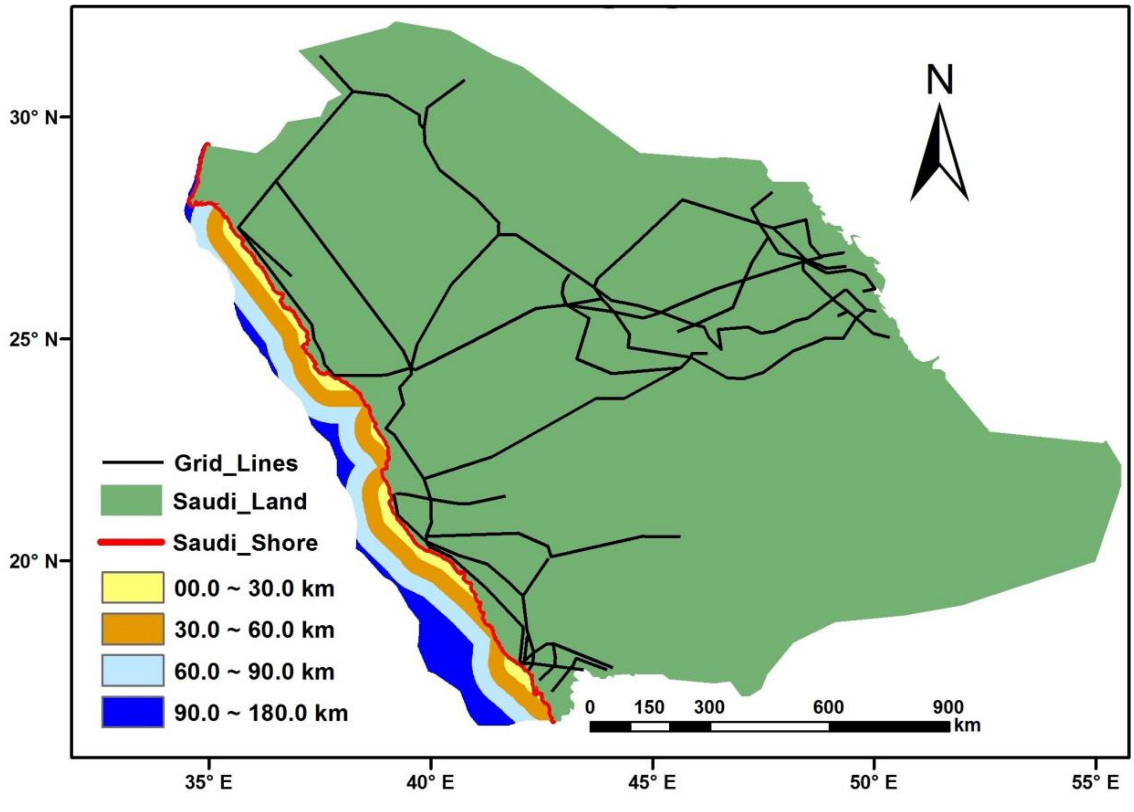


**Fig. 6: KSA electricity grid lines for and the distance between cells and the grid near the Red Sea region of KSA.**

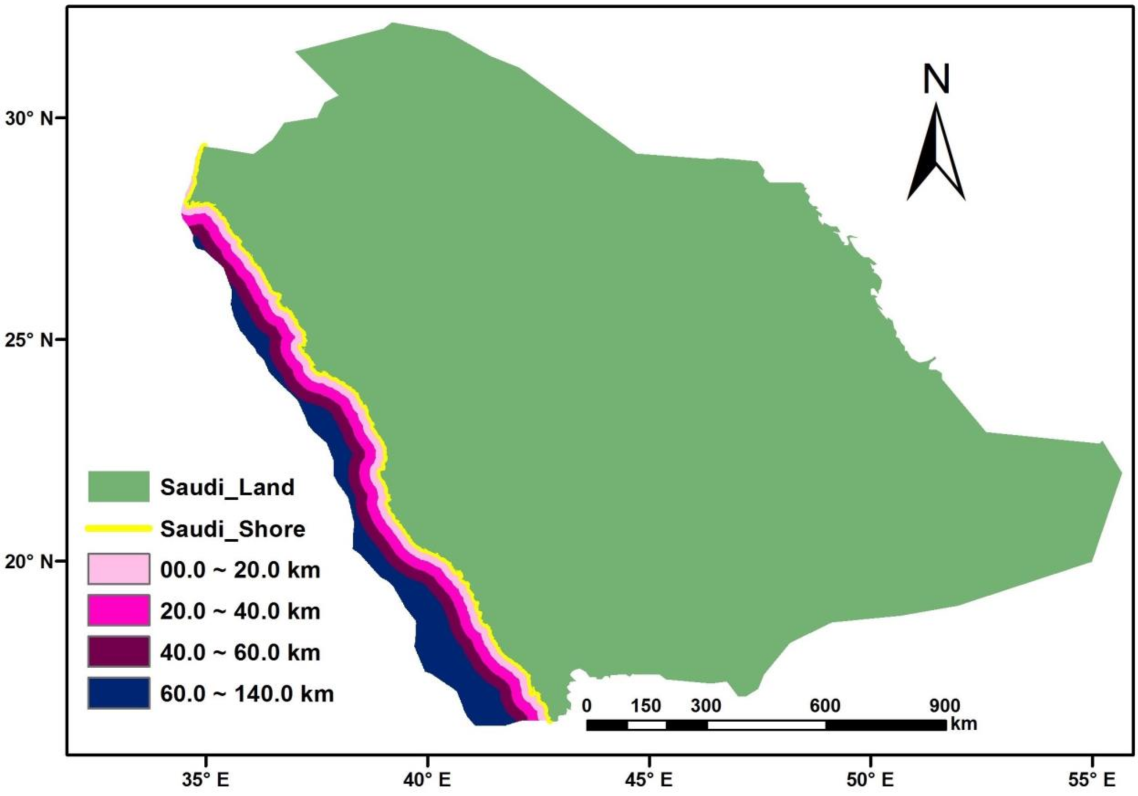


**Fig. 7: Layer map of the distance between cells and shoreline around the Red Sea region of KSA.**

## 4. Results, Discussion and Conclusions

The results shown here were based on analysis undertaken for the wind energy potential for the offshore Red Sea region of KSA. The analysis is based on a the development of a Geographical Information System (GIS) encompassing Boolean Mask technique through which a model was developed to create a map for offshore wind farm locations in the Red Sea, KSA. The developed model to solve the spatial sitting for offshore wind farms is efficient and was successful to deal with the conflicting constraints.

Using the UK's London Array wind farm which has an area of 122 $km^2$ (The Crown Estate, 2012) as a minimum required area (threshold) for offshore wind farms, the analysis was set to identify different locations as possible areas for offshore wind farms in KSA. Ten different locations which conform to the London array threshold were identified using the Boolean Mask map as shown in Fig.8.As can be seen from the figure, the largest locations can be found in the middle part of the coastline stretch, which is due to the main two constraints (wind speed and water depth), which are centred in two different directions of the map, see Fig.3, 4, and also the results in Fig.9.

To estimate the offshore wind power potential for the identified sites, we use the analysis to estimate the array spacing between offshore wind turbines developed by (Sheridan, Baker, Pearre, Firestone, & Kempton, 2012) given by Equation 3 below.

$$S = R_d^2 \times L_d \times L_c \qquad \text{(eq. 3)}$$

Where:

$S$ is the array spacing between offshore wind turbines

$R_d$ is rotor diameter

$L_d$ is the downwind spacing factor

$L_c$ is the crosswind spacing factor

Furthermore, and according to E.ON data (E.ON, 2012), to reduce turbulence interaction between turbines, the ideal turbine spacing is 5 to 8 times rotor diameter. In our analysis we confine the turbine capacities to a 5 MW and 3.6MW turbines to estimate offshore wind power for the identified sites. The 5 MW turbine has a 126m rotor diameter and the characteristics of the turbine were adapted from (Jonkman, Butterfield, Musial, & Scott, 2009). The 3.6 MW turbine has a 107m rotor diameter and the characteristics of the turbine were adapted from (Ajayi, Fagbenle, & Katende, 2011).

Table 2 shows the area for each possible location for offshore wind farm. The two dimensions a, and b are length and width of the rectangular of the locations measured in ArcGIS. The power in GW represent the full power captured by the turbines and was calculated for both 5MW, and 3.6MW using Equation 3. While the last two columns of the table show the estimated actual power assuming a capacity factor, $C_f$, of equal 0.4 and 0.5. The Capacity Factor which also known as the Load Factor ranges from 0.32 to 0.43 for 80m – 107m rotor diameter, and from 0.40 to 0.50 for turbines with rotor diameter more than 120m (Estate, 2017).

**Table 2: Estimate offshore wind power for the chosen sites, where a, and b are the length and width of the rectangles of the location shown in Fig.9.**

| Location, see Fig. 10 | a [km] | b [km] | Area [km²] | Power (GW) | | Estimated Power for | |
|---|---|---|---|---|---|---|---|
| | | | | | | $C_f$ = 0.40 | $C_f$ = 0.50 |
| | | | | 3.6MW turbine | 5.0MW turbine | 3.6MW turbine | 5.0MW turbine |
| Location 1 | 11.8 | 27.8 | 328.0 | 1.7 | 2.6 | 0.7 | 1.3 |
| Location 2 | 7.2 | 33.0 | 237.6 | 1.2 | 1.9 | 0.5 | 0.9 |
| Location 3 | 7.2 | 24.6 | 177.1 | 0.9 | 1.4 | 0.4 | 0.7 |
| Location 4 | 9.2 | 18.5 | 170.2 | 0.9 | 1.3 | 0.4 | 0.7 |
| Location 5 | 5.3 | 26.9 | 142.6 | 0.7 | 1.1 | 0.3 | 0.6 |
| Location 6 | 14.3 | 24.1 | 334.6 | 1.8 | 2.7 | 0.7 | 1.4 |
| Location 7 | 11.8 | 33.2 | 391.8 | 2.0 | 3.1 | 0.8 | 1.5 |
| Location 8 | 18.6 | 47.6 | 885.4 | 4.6 | 7.0 | 1.8 | 3.5 |
| Location 9 | 7.3 | 38.0 | 277.4 | 1.4 | 2.2 | 0.6 | 1.1 |
| Location 10 | 7.7 | 21.8 | 167.9 | 0.9 | 1.3 | 0.3 | 0.7 |
| Total | | | 3122.5 | 16.1 | 24.6 | 6.4 | 12.3 |

As can be seen form Table 2, the total estimated wind power for the identified sites is around 6.4 GW and 12.3 GW for the 3.6MW and 5MW turbines, respectively. These results confirm that offshore wind energy conversion can play a major role in the short and long term plan for the renewable energy expansion in KSA. For instant, utilising the 5MW turbine route would more than satisfy the 9.5 GW target stipulated in the KSA Vision 2030. Hence this work can be used to plan for offshore wind expansion in KSA and provide a knowledge platform for stakeholders interested in wind energy deployment.

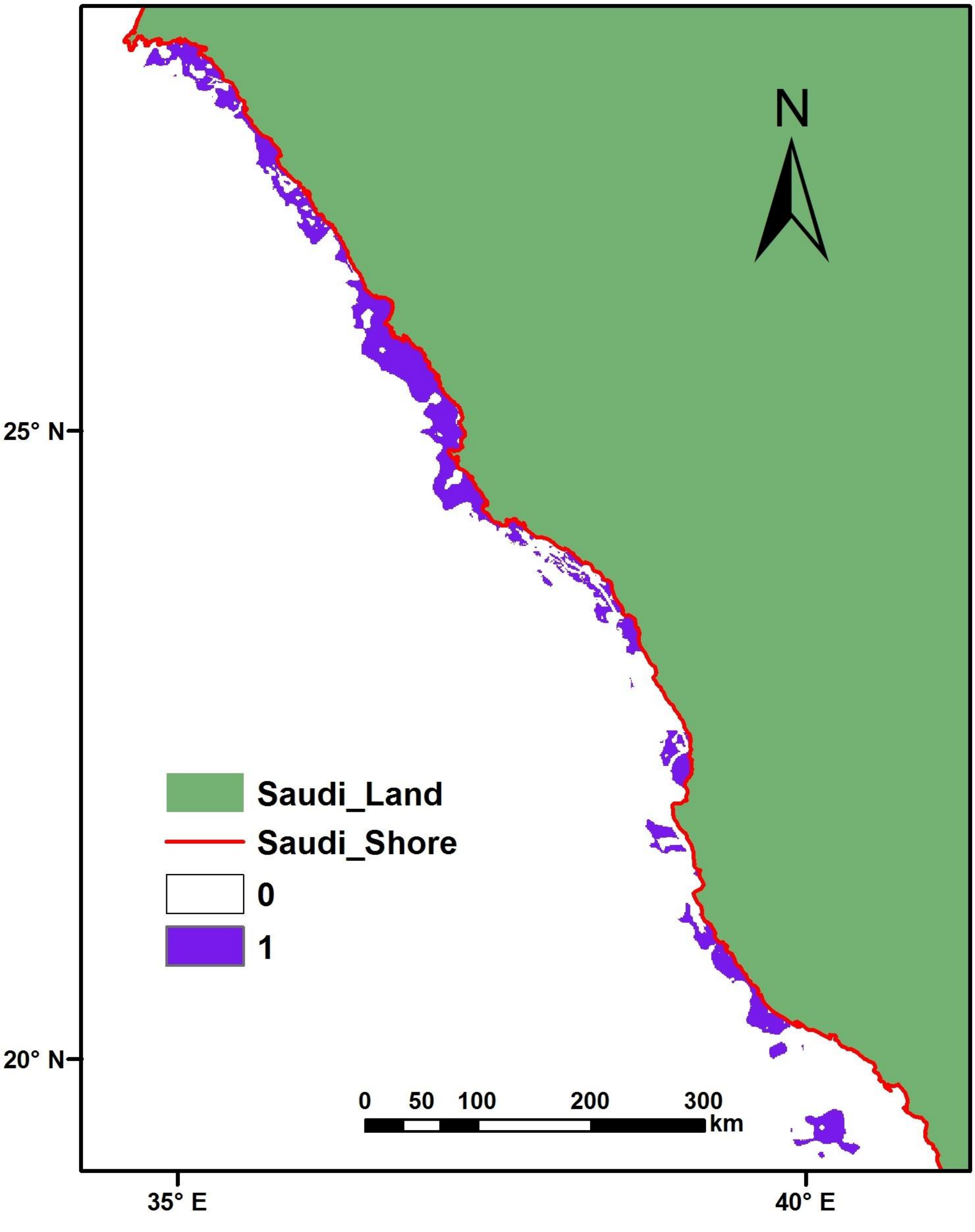


**Fig. 8: Final Boolean Mask for offshore wind areas around the Red Sea, KSA.**

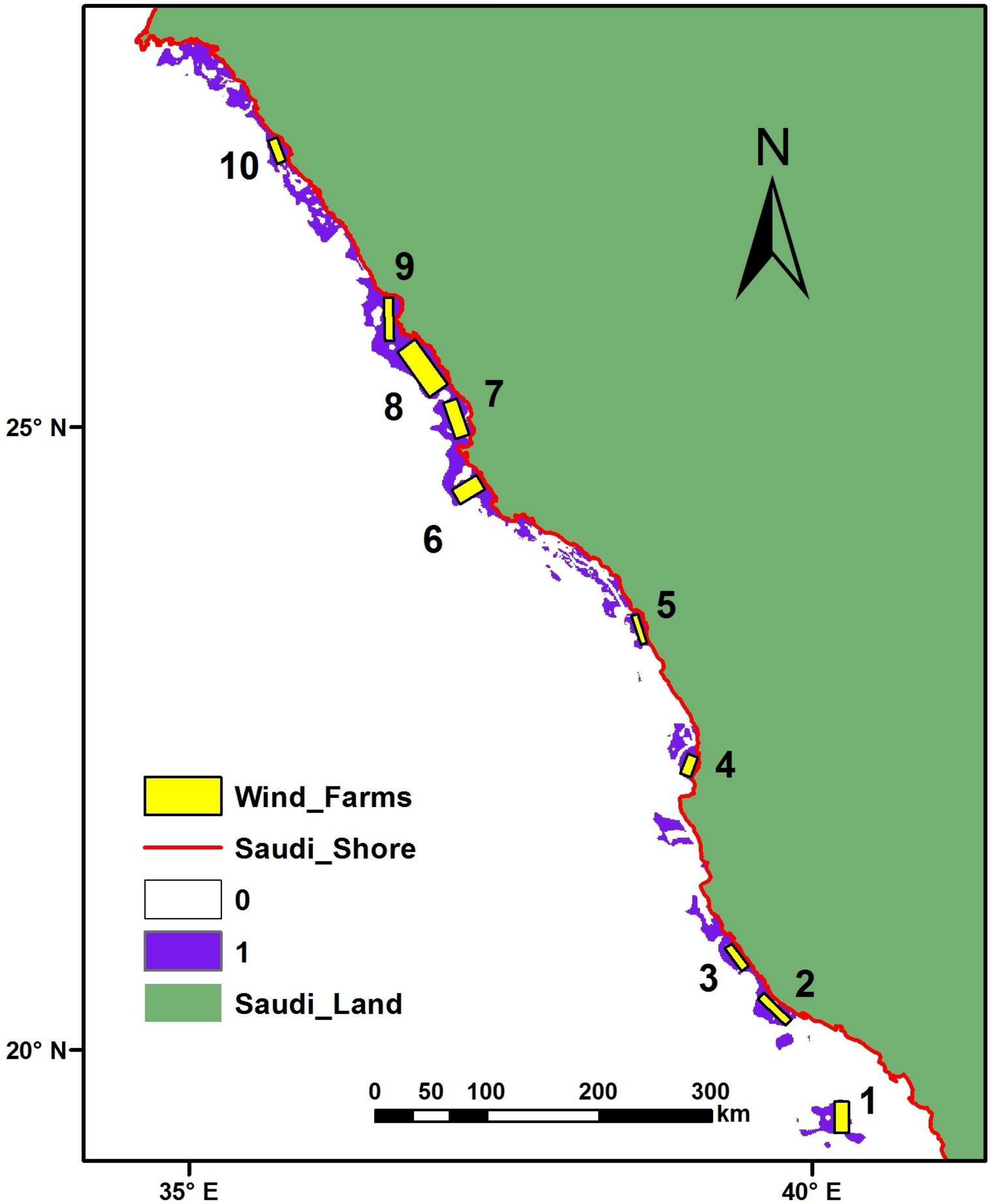


**Fig. 9: Locations of the proposed offshore wind farms around the Red Sea region of KSA.**

## 5. Acknowledgment

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