S. Rehman

Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran-31261, Saudi Arabia

M. A. Baseer

Department of Mechanical & Manufacturing Engineering Technology, Jubail Industrial College, Jubail, Saudi Arabia

L. M. Alhems

Center for Engineering Research, Research Institute, King Fahd University of Petroleum and Minerals, Dhahran-31261, Saudi Arabia

GIS-Based Multi-Criteria Wind Farm Site Selection Methodology

It is prevalent that by 2050, the global energy demand would increase by 50% to the current demand. The projected demand for electricity in Saudi Arabia is expected to exceed 120 GW/year by 2032. The Saudi government has set a goal of generating 9.5 GW of wind energy by 2023. In this study, firstly, a spatial interpolation technique is used to build a first accurate wind map of the entire country, then a GIS-based multi-criteria decision-making model is developed to select suitable wind farm sites considering various ecological, environmental and socio-economic criteria. All the identified criteria are given equal weightage in the model. Therefore, with noncompliance with even a single criterion, the associated complete area is considered unsuitable. As a case study, this model is independently applied to four regions covering the entire of Saudi Arabia. In the northern region, three wind farm sites are identified. The central area has a more suitable area compared to other regions mainly due to good wind resources and road and grid connectivity. The suitable sites in the eastern region are located between Dammam and Hafr AlBatin city. The southern region has a scarcest suitable area for wind power exploitation located near the province of Madinah.

Keywords: GIS; Wind map; Multi-criteria decision making; Wind energy; Wind Farm; Site suitability analysis.

1. INTRODUCTION

Energy is vital for the growth of any country. Most of the energy is utilized by the industrial sector followed by the transportation, commercial, and residential sectors. It is stated that by 2050, the global energy demand would increase by 50% to the current demand [1]. Almost all of the energy consumption is provided by the burning of fossil fuels in the last century. This persistent burning of fossil fuels is the cause of growing environmental concerns and resulting in the depletion of fossil fuels. These concerns are the cause of exploring various alternative clean, renewable, and environmentally friendly resources of energy [2-4. Currently, wind energy is one of the most emerging renewable, sustainable, and commercially accepted sources of energy. The cost of electricity generated from modern commercial wind turbines is currently at par with energy generated by fossil fuel plants [5]. In the year 2018, 51.3 GW of new wind energy was installed globally [6]. To fulfill the government's initiative, Saudi Vision 2030 of generating 9.5 GW of wind energy by 2023, a 400 MW wind farm is planned in Dumat al-Jandal, Sakaka [7]. This wind farm is expected to be operational by the end of 2020 and would produce energy at a cost of $ 21.3 per MWh. Compared to European countries, wind energy penetration in the Middle East and Saudi Arabia is in an early stage. Saudi Arabia has huge empty plain land and good wind resource,

suitable for the realization of wind farms to attain greater wind power penetration locally and globally.

Precise wind farm siting is the first and major challenge in profitable wind turbines installations. The site location should satisfy all ecological, environmental, and socioeconomic constraints and policies in addition to wind energy resources. The geographic information system, GIS is an effective tool for site suitability analysis when integrated with long-term accurate data of various criteria involved in decision making. The multi-criteria decision making (MCDM) analysis provides a tool for structuring, designing, evaluating, and prioritizing alternative decisions [8]. The use of GIS-based MCDM analysis for the planning of wind farms gained importance in the early 2000s [9]. The GIS-based, Multi-criteria-decision making approach was applied to wind farm siting in Lancashire, UK in 2001 [10]. Two methods were used for the analysis. The first method used equal weightage or equal importance to all the criteria or layers identified for the region. The second method used weightage based on the importance of each layer or criteria pertaining to expert advice and prevalent in the literature [10].

Krewitt and Nitsch (2003), addressed the effects of wind farms on the local ecosystem and natural scenery in coastal regions of Germany. Criteria like landscape conservation areas, special bird protection areas, or areas with high visual sensitivity were considered in identifying suitable locations for wind farms. The study suggested that even under strict nature's conservation constraints there is still a large potential for on-shore wind energy development in Germany [11]. In Denmark, near the Baltic Sea region, a spatial planning tool was developed for efficient wind energy planning. This tool used multi-criteria evaluations for analyzing the

complex trade-offs between alternatives with different environmental and socioeconomic impacts [12].

The availability of long-term historical data of the criteria parameters in conjugation with efficient latest GIS tools has made it possible to make precise MCDM wind farm siting analysis. Therefore, the following state-of-the-art studies are supposed to be more accurate. In Turkey, 55 coastal regions were analyzed by the multi-criteria site selection process. Wind Atlas Analysis and Application Program (WAsP) was used to conduct statistical analysis to identify the most promising offshore wind farm deployment locations. According to the pre-processing step of the framework, only five coastlines were found to be the most suitable locations for offshore wind farm development [13]. In China, ecological, socioeconomic, and social environment criteria were selected and an ordered weighted average was applied to evaluate the suitability of the development of wind energy resources [14]. The study found that suitable sites were distributed in the Huludao, Jinzhou and Yingkou beach areas and shoreline of the Bohai Sea, Fuxin and Chaoyang in the Northwest Area, Dandong alpine region in the eastern Shenyang, Tieling, and Anshan in central plain areas.

Azad et al. (2019) studied three sites, Hamilton Island, Proserpine, and South Johnstone to identify the most suitable one for wind turbine installation. The wind energy potential was determined by using Weibull parameters obtained by the method of moments, empirical method, and power density method. The accuracy of the results was analyzed using a statistical test tool. Finally, Hamilton Island site was selected as the best for the proposed wind turbine specification [15]. A wind farm planning tool was developed in Greece at the regional level. All the criteria discussed earlier were addressed but the criteria of proximity to the electricity grid were not considered. It was found that 12% of the study area is suitable for wind farms installations [16].

The single most important task in GIS-based, multi-criteria analysis is the proper and comprehensive selection of economic, planning, and ecological criteria applicable to the study area based on the national policies. In this study, a comprehensive set of ecological, environmental, and socioeconomic constraints and policies are identified without reservations, and accurate data is procured for the entire country. The novelty and the uniqueness of the present work is development of a first accurate wind map was based on long-term historical wind data for 39 years from 46 weather stations country-wide and this study does not ignore any input criteria to identify the best area for wind farms development. To our understanding, based on the literature review, the earlier authors have ignored a few relevant criteria, mainly due to the unavailability of accurate long-term data of that criterion, as shown in Table 1. Moreover, no study has considered the criteria of minimum suitable continuous area for ease of wind farm layout planning. The wind resource assessment is conducted at all of these locations and mean wind speed is determined by Weibull analysis and the novel wind speed map is constructed using spatial interpolation method, Inverse distance weighted (IDW). All the identified criteria are given equal weightage, therefore,

with noncompliance of even a single criterion condition the complete associated area is considered unsuitable. An innovative wind farm site suitability map is developed for four areas covering the entire country. This study will assist in achieving the initial goal of the government to produce 9.5 GW of wind energy and will also help in developing comprehensive national wind energy-related policies that are currently not specifically defined for the region.

2. DESCRIPTION OF THE STUDY AREA

2.1 Study area

In this analysis, entire Saudi Arabia is considered a study area. Saudi Arabia is located in the southwestern corner of Asia. It is bordered by Kuwait, Iraq, and Jordan in the north; Oman and Yemen in the South; United Arab Emirates, Qatar, and Arabian Gulf in the East; and the Red Sea in the West. The total area of Saudi Arabia, (the thirteenth largest country in the world and largest in the Middle East), is 2.15 million km^2 [17].

In 1991, Saudi Arabia was divided into (13) administrative provinces as shown in Figure 1, each with various governorates. The settlements are linked administratively to these governorates [17]. In this study, four areas are selected as shown in Figure 2 to find suitable sites for wind farms development in each. The southern area consists of Madinah, Makkah, Bahah, Asir, Jizan, and Najran provinces. The northern area consists of Tabuk, Al Jawf, and Al hudud ash Shamaliyah provinces. The central area consists of Hail, Al Quassim, and Riyad provinces. Finally, the eastern area consists of only one province, Ash Sharqiyah. This province also includes the Empty Quarter composed of the world's largest unpopulated sand dunes and lava fields and occupies an estimated area of 640,000 km^2 [18].
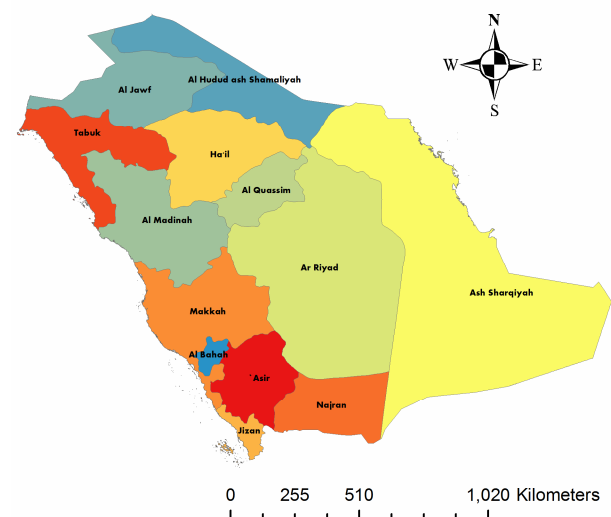

Figure 1. The thirteen provinces of Saudi Arabia

Saudi Arabia has huge geographically diverse land with varying climatic conditions. Most of the regions, like in the eastern province, are generally hot in summer and cold in winter with moderate rainfall. In general, the climate in the western and southern regions is moderate. [17].

Table 1. Selection of restriction criteria for wind farm site selection studies worldwide.

Study area/ Study Criteria	Economic		Planning			Ecological			Geographical	
	Wind speed /density	Proximity to the electricity grid, m	Safe distance from aerodromes, m	Distance from roads/highways, m	Distance from settlements, m	Distance from birding locations and flying paths, m	Distance from parks, forests and public places, m	Distance from lakes, rivers and springs, m	Terrain slope, %	
Denmark	250–650 W/m²	×	5000–7500	×	500–1500	×	300–800	150–650	×	[12]
Germany	> 4 m/s (at 10 m AGL)	×	×	>500	>500	×	> 500	×	×	[11]
Greece	5-7.5 m/s	×	3000	5000-200	1500	×	1000	1000	>25%	[16]
Spain	<4.5 m/s	>100	2500	>100	>550	×	> 200	<50 m	>30%	[47]
Sweden	Turbine output	>200	2500	>200	>500	×	×	> 100	>15⁰	[23]
Turkey	200–400 W/m²	×	3000-6000	×	1000-2000	> 500	3000-6000	2500-5000	×	[29]
UK	> 5 m/s	< 10000	×	< 10000	> 2000	×	> 500	> 400	>10%	[10]
USA	×	Cost analysis	×	< 5000	> 2000	Away from selected IBA's	×	> 3000	>10%	[21]
Vietnam	Turbine output	×	2500	>100	> 2000	×	> 500	> 400	×	[30]

Table 2. The wind station names, location (latitude and longitude), altitude, and hourly average wind speed.

S.No	Wind station	Latitude (N)	Longitude (E)	Altitude (m)	Av. WS at 50 m AGL (m/s)
1	Abha	18.2	42.7	2093	3.74
2	Ad-Dawadimi	24.5	44.4	900	6.47
3	Afif	24	43.125	984	6.5
4	Al Ahsa	25.5	49.375	178	5.81
5	Al Baha	20	41.25	1652	4
6	Al Hawiyah	29	38.75	888	5.57
7	Al Jawf	29.8	39.9	753	5.68
8	Al Jubail	27	49.375	3	5.77
9	Al Khafji	28.5	48.125	31	6.18
10	Al Kharj	24	47.5	512	5.59
11	Al Lith	20	40.625	-	3.67
12	Al Qunfudah	19	41.25	-	3.85
13	Ar Rass	26	43.75	779	5.82
14	Arar	31	41.25	549	5.43
15	Az Zulfi	26.5	45	623	6.1
16	Bisha	20	42.5	1162	5.8
17	Damat Al Jamdal4	30	40	-	5.59
18	Damat Al Jandal1	29.5	39.375	-	5.6
19	Damat Al Jandal2	29	40	-	5.59
20	Damat Al Jandal3	29.5	38.75	-	5.5
21	Dariyah	24.5	43.125	949	6.48
22	Dhahran	26.5	50	17	5.82
23	Gassim	26.5	43.75	648	5.76
24	Guriat	31.5	37.5	504	5.73
25	Hafr AlBatin	28.5	46.25	358	6.15
26	Hail	27.5	41.875	1002	5.85
27	Jeddah	21.5	39.375	17	5.24

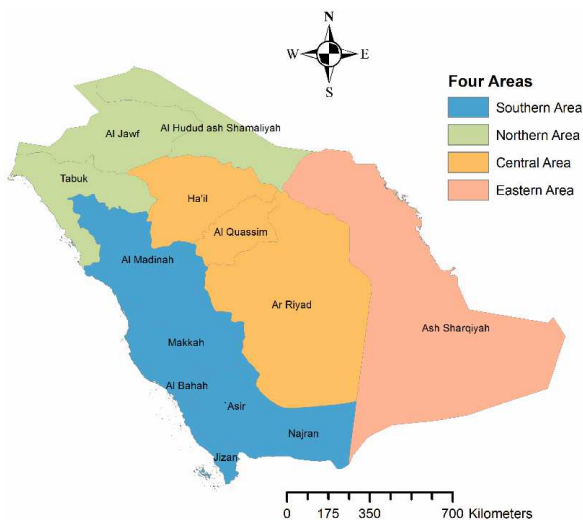| S.No	Wind station	Latitude (N)	Longitude (E)	Altitude (m)	Av. WS at 50 m AGL (m/s)
28	Khamis Mushait	18.5	43.125	2056	5.39
29	Madinah	24.5	39.75	636	5.55
30	Makkah	21.5	40	240	4.99
31	Mudaylif	19.5	41.25	53	3.73
32	Nejran	17.5	44.375	1212	4.95
33	Rabigh	23	39.375	382	4.64
34	Rafha	29.5	43.75	444	5.78
35	Riyadh	24.5	46.875	620	5.72
36	Sabya	17	42.5	295	3.78
37	Safwah	26.5	50	53	5.82
38	Sharourah	17.5	46.875	725	5.82
39	Sulayel	20.5	45.625	614	5.89
40	Tabuk	28.5	36.875	768	5.45
41	Taif	21.5	46.875	453	5.45
42	Turaif	31.5	38.75	852	6.08
43	Ummluj	25	37.5	411	5.22
44	Unayzah	26	43.75	724	5.82
45	Wejh	26.5	36.25	24	5.99
46	Yanbo	24	38.125	10	5.08

Figure 2. The four selected areas of Saudi Arabia

The demand for energy and desalinated water in Saudi Arabia in increasing rapidly due to growth in population and fast industrialization. The population increased by more than 500% in the last four and a half decades [17], during the same period, the number of industries increased by around 35 times [19]. By 2030, the projected demand for energy is expected to exceed 120 GW/year [20].

3. DESCRIPTION OF THE IDENTIFIED WIND FARM SITE SELECTION CRITERIA

All the criteria that have any impact on the site selection were carefully identified from the literature. The identified criteria and description are presented below.

3.1 Wind Speed

The wind resource is the foremost criterion in all wind farm site selection studies reviewed [21-23]. In this study, the long-term historical hourly time step wind data from 1980 to 2019 was obtained for 46 stations throughout the country [24] as shown in Figure 3. The location of the stations, average wind speed at a height of 50 m, and the altitude of stations are presented in Table 2 below.

The mean wind speed data in this study is interpolated to 50 m from the anemometer height of 10 m AGL by using one-seventh power law also known as Hellmann's power law [25,26].

$$V_2 = V_1 \left(\frac{Z_2}{Z_1} \right)^n \tag{1}$$

where V_2 is the average wind speed to be found at height Z_2, when the average wind speed, V_1 at height Z_1 is available, and 'n' is the wind shear coefficient, dependent on the geographic features of the site terrain. This value is assumed to be 1/7 for open land with fewer trees and bushes. [27, 28].

1.	Abha	17.	Damat Al Jamdal4	33.	Rabigh
2.	Ad-Dawadimi	18.	Damat Al Jandal1	34.	Rafha
3.	Afif	19.	Damat Al Jandal2	35.	Riyadh
4.	Al Ahsa	20.	Damat Al Jandal3	36.	Sabya
5.	Al Baha	21.	Dariyah	37.	Safwah
6.	Al Hawiyah	22.	Dhahran	38.	Sharourah
7.	Al Jawf	23.	Gassim	39.	Sulayel
8.	Al Jubail	24.	Guriat	40.	Tabuk
9.	Al Khafji	25.	Hafr AlBatin	41.	Taif
10.	Al Kharj	26.	Hail	42.	Turaif
11.	Al Lith	27.	Jeddah	43.	Ummluj
12.	Al Qunfudah	28.	Khamis Mushait	44.	Unayzah
13.	Ar Rass	29.	Madinah	45.	Wejh
14.	Arar	30.	Makkah	46.	Yanbo
15.	Az Zulfi	31.	Mudaylif		
16.	Bisha	32.	Nejran		

Figure 3. Locations of meteorological stations.

3.2 Distance from the electricity grid

A wind farm should be planned in proximity to the electricity grid to avoid transmission losses and cabling costs. Some studies have neglected this important criterion in their model [12,16,29,30]. For the current analysis, the map of the national electrical grid (Figure 4) and power stations was acquired from the Saudi Electrical Company, [31]. The existing, planned, and ongoing electrical grid lines are considered in this study.

Figure 4. The electricity grid map of Saudi Arabia. (Saudi Electricity Company, 2019)

3.3 Distance from settlements

The minimum distance from major settlements to a prospective wind farm is a vital criterion for ecological reasons and to avoid noise and other hazards. Almost all the studies reviewed have considered this criterion. However, the prohibited buffer distances vary as shown in Table 1 [10,16,21-23,29]. This distance should also be reasonably within a specific range to serve the immediate community in an optimum manner without transmission losses [29, 12].

3.4 Distance from roads/highways

A prospective wind farm should be within close vicinity to a suitable approach road for heavy vehicles that carry huge commercial wind turbines and also used for maintenance

work after installation. Some studies also recommend prohibitory distance [16,23] which is generally not considered very important. The reviewed studies considered different distances from the road, Latinopoulos and Kechagia, 2015 [16] and Van Haaren and Fthenakis, 2011 [21] used a maximum distance of 5000 m, Baban, and Parry, 2001 [10] used 10000 m and Sliz-Szkliniarz and Vogt, 2011 [22] used the buffer distance of 100 and 200 m only.

The GIS shapefiles of national highways (Figure 5) and roads (Figure 6) are procured from online libraries of Stanford University [32] and are compared with data from the ministry of transport, Saudi Arabia.
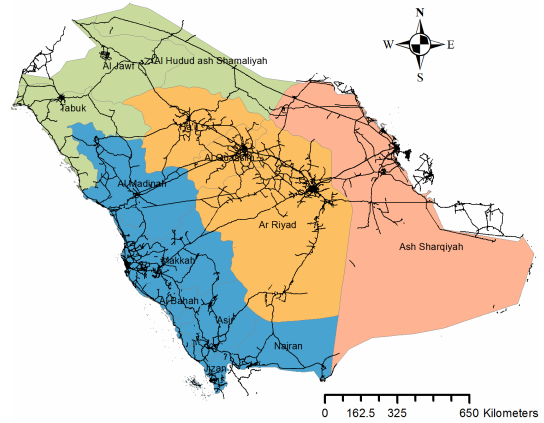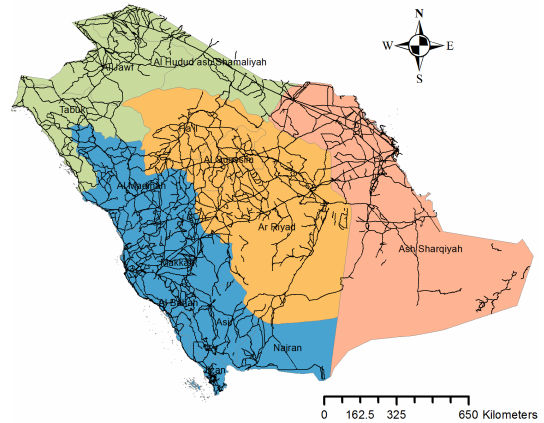

Figure 5. The Saudi Arabian highways.

Figure 6. The Saudi Arabian roads.
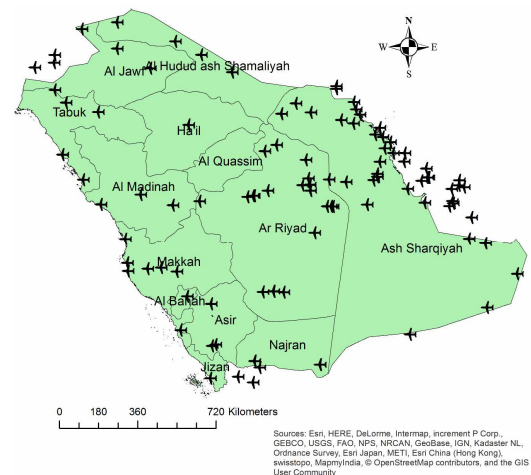
3.5 Safe distance from aerodromes

Figure 7. Aerodromes (International, domestic, cargo, and military) of Saudi Arabia.

Wind turbines may interfere with the radar signal used by aerodromes and aircraft. Therefore, a prospective wind farm should have a safe distance from the airports (Figure 7) and communication towers. The reviewed literature presents a buffer distance of 3000 to 6000 m around airports [16,29].

3.6 Distance from parks, forests, and places of tourism

The aesthetic aspects of wind farms may conflict with public places like parks, forests, and places of tourism. The criterion of suitable distance from these places is an essential aesthetic criterion. Some studies have ignored this criterion [21,23]. The studies that have considered this criterion have applied different restrictions based on the local energy policies [10,16,21,20].

3.7 Impact on birds

The migrating birds may collide with the rotating wind turbine blades, so it is recommended to plan a wind farm away from the migrating path of the birds or even away from important bird areas, IBA. Only a few studies have considered this relevant criterion [21], [29] as shown in Table 1. In the fall season, from August to October, the birds migrate to Europe from Asia and Africa and return between March and May. Saudi Arabia is a transit point for these migrating birds [33].

Out of the fifteen IBA's in the Arabian Peninsula [34] as shown in Figure 8, none are located inside Saudi Boundary and five are near national boundary. Saudi Arabia, in general, is dry land, and birds fly over mountain ranges, water bodies and natural habitats for survival. In this study, the popular birding locations are also considered (Figure 9).

Almost all the birding locations are in the eastern province and one in Al Qassim region. Some studies have not considered in their analysis, the acceptance criteria in terms of bird habitat may be due to non-interference with IBAs [10,30].
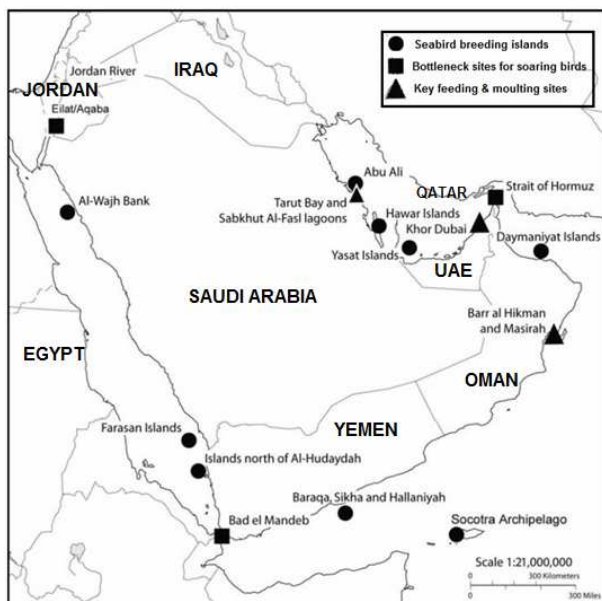

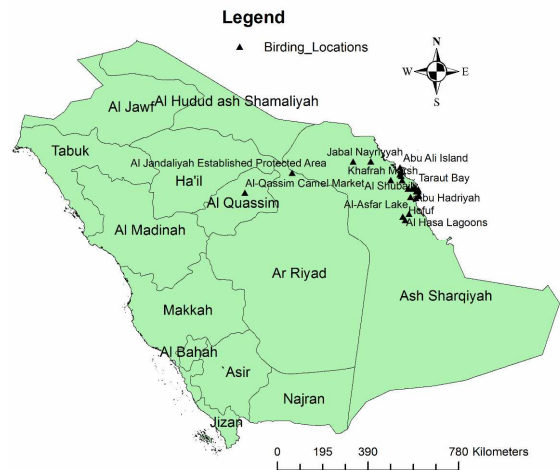**Figure 8. The Important bird areas, IBA near Saudi Arabia (Pavokovic and Mandusik, 2006).**

Figure 9. The birding locations in Saudi Arabia

3.8 Distance from lakes, rivers, and springs

Almost all the reviewed studies have considered the criteria of unsuitable buffer distance from water bodies and waterways [10,16,29]. In Saudi Arabia, there are very few perennial rivers. However, there are few springs, water bodies, and non-perennial rivers as shown in Figure 10.
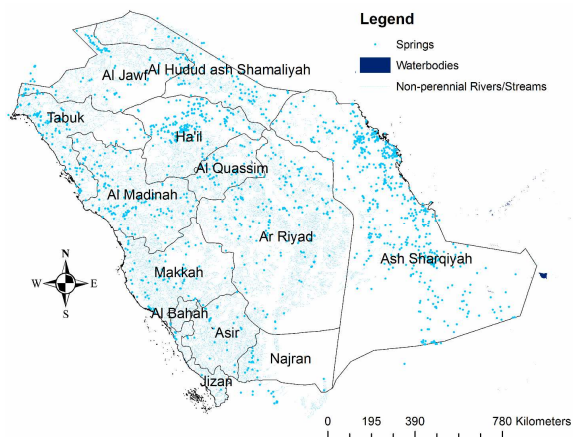

Figure 10. The waterbodies of Saudi Arabia.

3.9 Slope of terrain
The wind farm site and the surrounding region should be plain to provide accessibility for installation and maintenance of wind turbines.
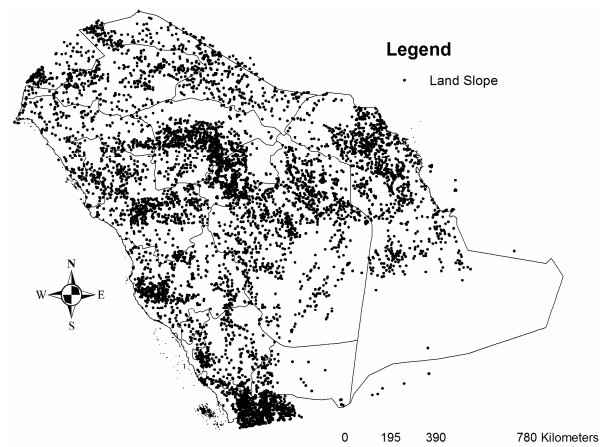

Figure 11. The areas with a slope greater than 15%.

Moreover, the wind may also be blocked by the terrain from the high altitude directions. In reviewed studies, the allowed maximum slope threshold range is considered from 10% [10] to 30% [35]. In a few studies, [12,29,36] the criterion of the slope is completely neglected. The terrain slope map used in the present study is shown in Figure 11.

4. THE METHODOLOGY OF SITE SELECTION

All the criteria identified and discussed in the previous section are assessed simultaneously by MCDM analysis using ArcMap 10.7, 2019, the main component of ESRI's GIS software.

4.1 Multi-criteria decision making (MCDM) of terrain

MCDM is a method of making intricate decisions by considering the assessment of numerous variables as input criteria [21]. The identification of relevant criteria that effects site suitability is a critical step in this process. The criteria are sometimes assigned by suitable weighted classes or categories, which are then symbolized on the map layer showing the suitable areas for those criteria.
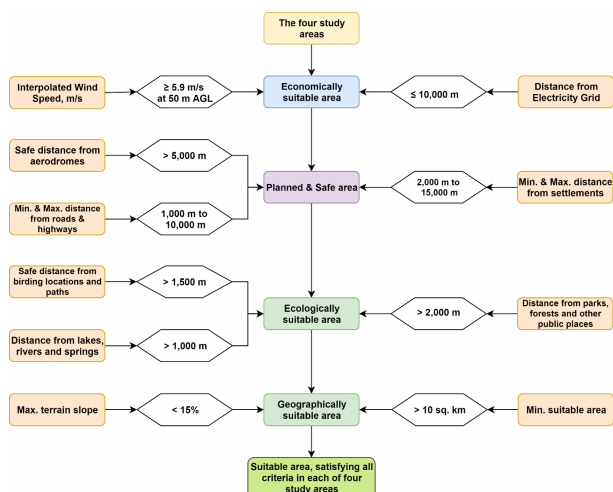
Figure 12. The conceptual model of the site suitability analysis.

The several layers, each representing identified classed criteria are superimposed over each other to create a suitability map from which the user can identify ideal areas and continue with a more detailed investigation of those sites. The selected criteria with the applied restrictions are detailed in the methodological framework illustrated in Figure 12.

4.2 Restrictions on the selected wind farm siting criteria

All the identified criteria correspond to several constraint factors like economic, safety, planning, ecologic, and geographical as summarized in Table 3. A suitable wind farm site should satisfy all the criteria restrictions without any exceptions and must only include areas with the high wind resource corresponding to the wind speed greater than 5.8 m/s at 50 m AGL, the distance from national electrical grid less than 10 000 m, at least 5 000 m away from all aerodromes, more

than 1 000 m and less than 10 000 m from the roads and highways, more than 2 000 m and less than 15 000 m from the major settlements, at least 1 500 m from birding locations and flying paths, at least 1 000 m from all types of water bodies and waterways, at least 2 000 m from parks, forests, and other public places, with a terrain less than 15% slope, and finally should have at least 10 km^2 of area. As shown in the conceptual model of the site suitability analysis (Figure 12), after the application of restrictions on economical, planned, safe, ecological, and geographical criteria the suitability map is generated.

Table 3. Criteria restrictions for the location of the wind farm.

Criteria	Restriction	Consideration
High mean wind speed	> 5.8 m/s	Economic
Proximity to national grid	< 10 000 m	Economic
Safe distance away from aerodromes	> 5 000 m	Safety/Planning
Distance from roads/highways	1 000 to 10 000 m	Planning
Distance from settlements	2 000 to 15 000 m	Planning
Safe distance from birding locations and flying paths	> 1 500 m	Safety/Ecologic
Distance from lakes, rivers, and springs	> 1 000 m	Ecologic
Distance from parks, forests and public places	> 2 000 m	Ecologic
Terrain slope	< 15%	Geographic
Minimum suitable continuous area	> 10 km^2	Geographic/planning

5. RESULTS AND DISCUSSION

Understandably, the foremost criterion in this site selection analysis is the wind resource in the region. An accurate wind map is very essential for planning a wind farm.

5.1 The wind map of Saudi Arabia

To identify areas with high wind resource, the hourly averaged wind data of 46 weather stations from 1980 to 2019 is used to construct a recent and accurate wind map of Saudi Arabia. Firstly, the inverse distance weighted, IDW is used to predict the wind speed between the weather stations and construct the wind map. This spatial interpolation technique converts the point wind data into a raster area format. This technique determines the cell values of missing data using a linear weighted combination of a set of sample points. The weight is a function of inverse distance. The surface being interpolated should be a variable dependent on the location. This interpolated wind data is then reclassified into 9 classes as shown in the wind map in Figure 13. This interpolated wind speed at 50 m AGL, is found to be ranging from 3.7 to 6.4 m/s. The last two classes ranging from 5.8 to 6.4 m/s are considered to be excellent and are considered suitable for the wind farm site. It can be observed that the eastern and the central region is abundant in wind resources and a few small areas in the northern border and southern-north coastal region. In general, the southern coastal area is lacking in

good wind resources and corresponds to wind classes 1 to 5 (wind speed less than 5 m/s at 50 m AGL). The reclassified wind map (Figure 13) is the first of its kind as it is based on long term (39 years of historical, accurate, and latest wind speed data) obtained from 46 stations, spread over the entire country. Different layers of suitable and unsuitable criteria used in this study are shown schematically in Figs. 14 to 21. The study is performed using ArcMap 10.7, 2019, the main component of ESRI's ArcGIS suite of geospatial processing programs.
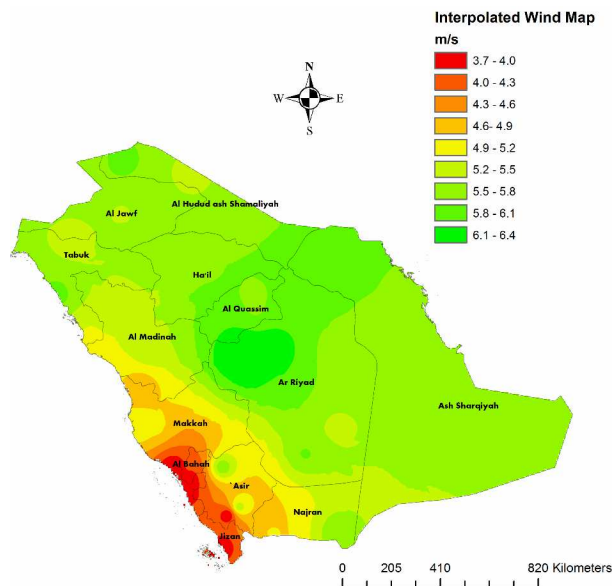

Figure 13. The wind map of Saudi Arabia.

5.2 The maps with criteria restrictions

The areas with wind resources corresponding to classes 8 and 9 (wind speed > 5.8 m/s at 50 m AGL) are depicted on the density map in Figure 14. All the areas with wind speed less than 5.8 m/s are removed using the 'erase' function of the program from the wind map. It can be observed that the eastern and central regions are most suitable along with few small areas in the north, west, and southern regions. All the areas which are 10 000 m or farther from the national electric grid are considered unsuitable and removed from the map of existing, ongoing, and planned national electricity grid (Figure 15). It is observed that the regions with the dense desert in the eastern province are not connected to the grid and are thinly populated and therefore not considered for wind farm development. The area within 5 000 m of aerodromes, military, passenger, and cargo airports is considered unsuitable and erased from the map shown in Figure 16. The shapefiles of roads and highways are combined in one map using the merge function in ArcMap (Figure 17). Additionally, all the areas which are away (> 10 000 m and < 1 000 m) from highways and roads are not included in the analysis and excluded from the map shown in Figure 17. It is observed that the areas in the central and the south-western regions are well connected with roads and highways and seem to be more suitable under this criterion. A prospective wind farm should be closer to the population to efficiently serve the community, whe-

reas it should be not too close for ecological reasons. In this study, the areas more than 15 000 m and less than 2 000 m away from major settlements are considered unsuitable and depicted in the map (Figure 18).

In general, the land of Saudi Arabia is arid and scarce in water, therefore, the migrating birds mostly fly along the Arabian Gulf in the east. Most of the important bird areas are located along this coast. In this analysis, bird breeding, feeding, and resting locations which are less than 1500 m away from these locations are considered to be dangerous for birds and hence unsuitable (Figure 19). The areas nearby waterbodies are also considered unsuitable ecologically. Additionally, a buffer distance of 1 000 m from springs, perennial, and non-perennial rivers and lakes is considered unsuitable and hence excluded from the map (Figure 20). Also, all the areas nearby; around 2 000 m; of forests, parks, and other public places are unsuitable ecologically and hence are removed from the map (Figure 21). Finally, the areas with a slope of more than 15% are not included in the suitability map because the construction of wind farms is not possible on steep slopes and it also blocks wind from the high altitude directions. The areas which are found suitable for wind farm construction but have area <10 km^2 are also excluded from the suitability map.

5.3 The final suitability maps of the four regions

The site suitability analysis is performed separately for the four identified regions, as shown earlier in Figure 2. The names and areas of the thirteen provinces in each of the four selected regions and the suitable area for wind farm development within the province and selected region are presented in Table 4. The percentages of suitable land areas are also shown in column 8 of Table 4. The wind farm site suitability maps for these regions are shown in Figs. 22 to 25.
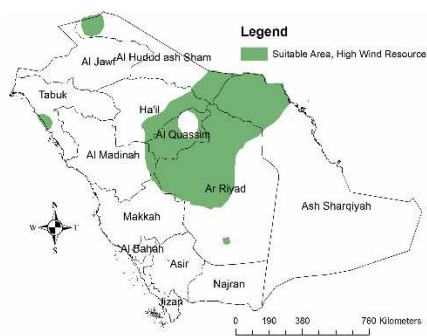

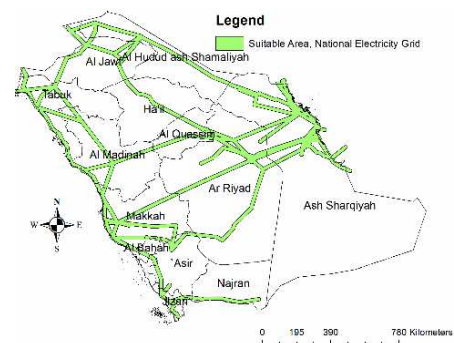**Figure 14. The suitable area based on wind resources**

Figure 15. The suitable area based on Proximity to the National Electricity Grid

Table 4. Area suitable for wind farm development

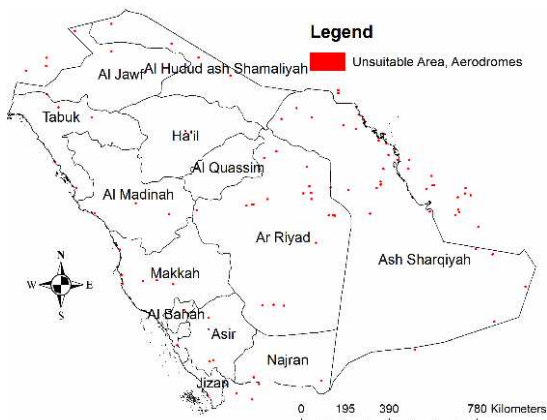| S. No	The selected regions		Provinces	Area, km²	Total area km²	Suitable area km²	Total suitable area km²	Percentage of suitable area, %
1.	The Northern Area	1.	Al Hudud ash Shamaliyah	117687	336191	1385.37	1452.4	0.43
		2.	Al Jawf	117979		-		
		3.	Tabuk	100525		67.03		
2.	The Central Area	1.	Ar Riyad	377605	553575	5664.21	8576.41	1.54
		2.	Al Quassim	54449		2582.24		
		3.	Hail	121521		329.95		
3.	The Eastern Area	1.	Ash Sharqiyah	553109	553109	3290.99	3290.99	0.59
4.	The Southern Area	1.	Al Madinah	145199	475271	201.80	201.80	0.04
		2.	Makkah	138410		-		
		3.	Al Bahah	10344		-		
		4.	Asir	77239		-		
		5.	Najran	88266		-		
		6.	Jizan	15813		-		

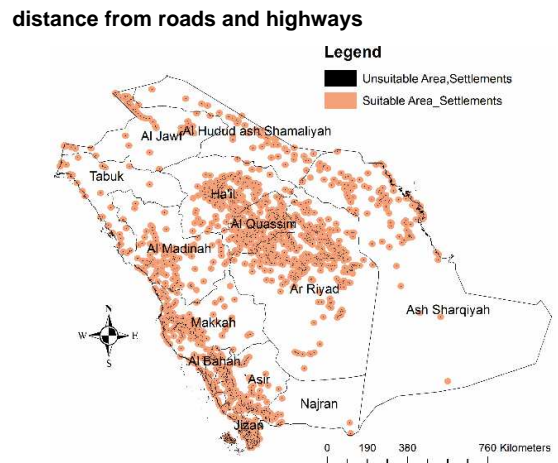**Figure 16. The suitable area based on the safe distance from all aerodromes**

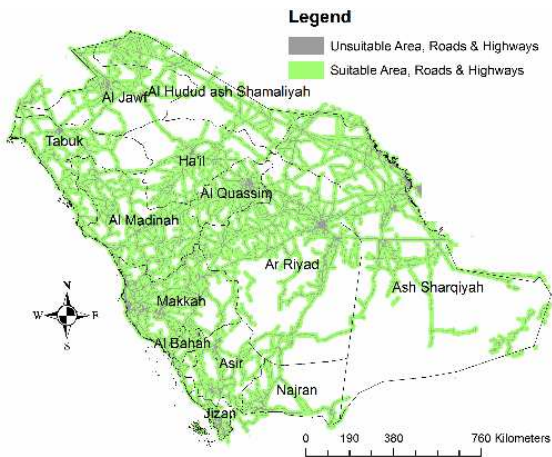**Figure 17. The suitable and unsuitable area based on distance from roads and highways**

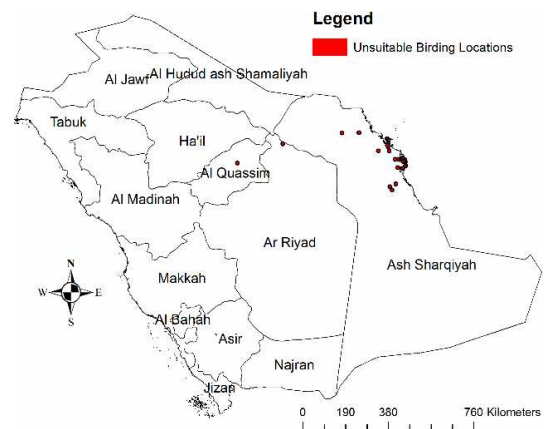**Figure 18. The suitable and unsuitable area based on distance from major settlements**

Figure 19. The unsuitable area based on distance from birding locations.
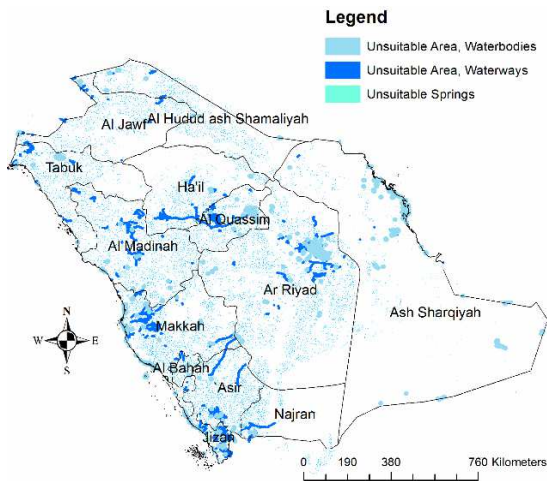
Figure 20. The unsuitable area based on distance from waterbodies, waterways, and springs.
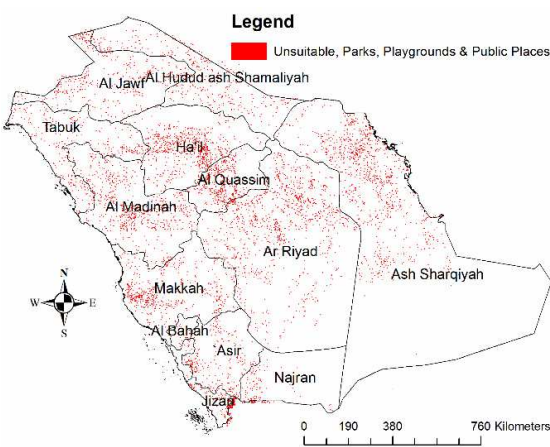

Figure 21. The unsuitable area based on distance from parks, playgrounds, and other public places.

5.3.1 The Northern Area

In the northern region, three wind farm sites are identified that satisfy all the criteria listed in Table 4. Site 1 is located in Turaif, near the Jordanian border, and site 2 in the middle of the northern Iraqi border near Hafr Al Batin, Al Hudud ash Shamaliyah province. Site 3 is located in Tabuk province, on the Red Sea coast (Figure 22). There is no suitable wind farm site in Al Jawf province, as shown in Table 4. A total of 1452 km² of the area is suitable, about 0.43% of the total selected area in the Northern Province.
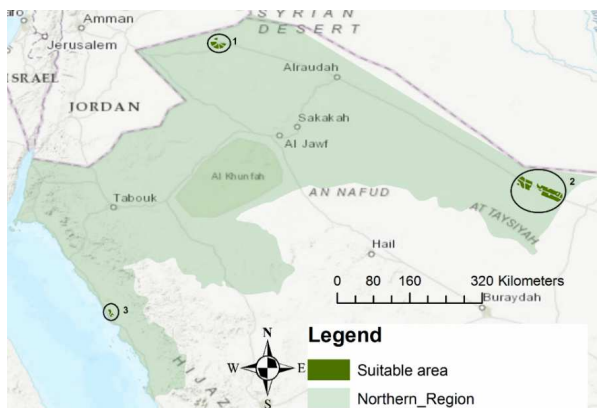

Figure 22. The windfarm site suitability map of the northern region

5.3.2 The Central Area

In Central Province, the more suitable area is found compared to other regions due to good wind resources and required proximity of roads for ease of equipment transport and grid for wind power dispatch from the wind farms. Most of the suitable sites are seen in Riyadh and Hail province and a few in Al Quassim as well. A total of 8576.41 km² of the area is found to be suitable for wind farm development which accounts for about 1.54% of the total regional area (Figure 23). This percentage is highest compared to the other three regions.
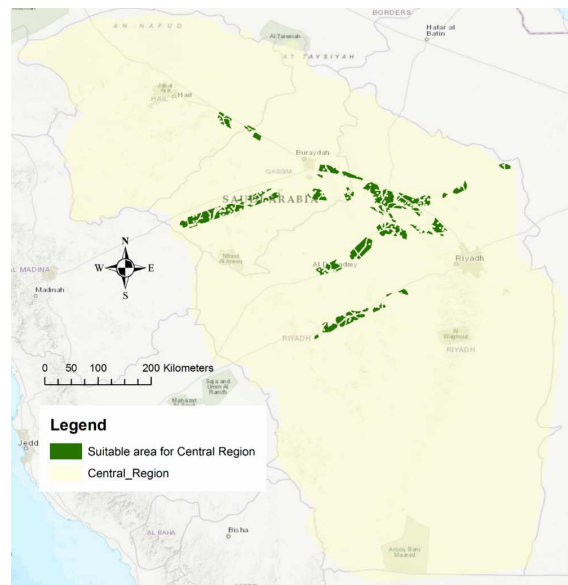

Figure 23. The windfarm site suitability map of the central region.

5.3.3 The Eastern Area

The eastern region is comprised of one large province, Ash Sharqiyah. Most of the eastern region is found unsuitable for wind farm development as shown in Figure 24.
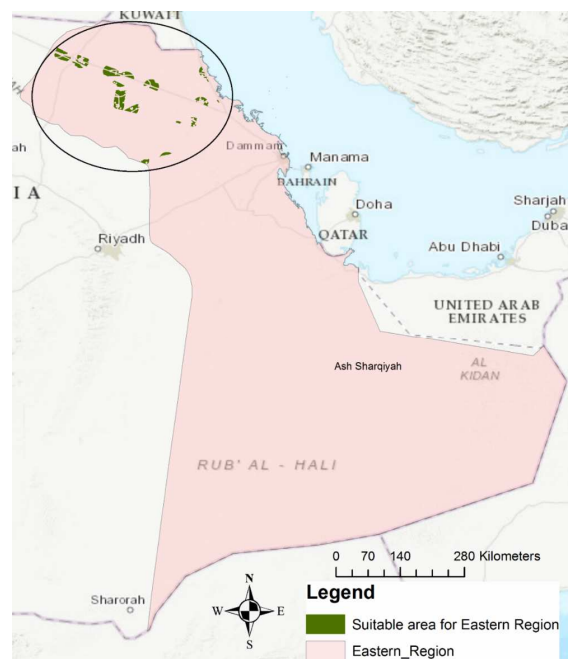

Figure 24. The windfarm site suitability map of the eastern region.

This province holds the largest unpopulated desert in the world, Rub Al Khali. There is no electric grid and has limited road connectivity. In this region, suitable sites for wind farm development are observed between Dammam and Hafr Al Batin city. A total of 3291 km^2 of the area is found to be suitable for wind farm development i.e. about 0.59% of the total area of the Eastern Province.

5.3.4 The Southern Area

The southern area holds six provinces and has limited suitable areas for wind farm development. These suitable sites are concentrated around the Madinah region while other provinces do not have any potential windy areas (Figure 25). A total of 201.8 km^2 of the area is found to be suitable for wind farm development which accounts for only 0.04% of the total regional area. This area percentage share is the lowest compared to the other three regions.

Figure 25. The windfarm site suitability map of the southern region.

6. CONCLUSION

In this study, a GIS-based multi-criteria decision-making model is developed for suitable wind farm site selection considering various ecological, environmental, and socioeconomic criteria and applied to Saudi Arabia. Ministry of Energy has set an initial target of installing 9.5 GW of renewable energy by 2023 [37]. This target accounts for about 15% of the total energy consumption. This study will help in identifying the profitable potential sites for wind power deployment to partially achieve this target explicitly from the point of view of proper site selection and maximum harnessing of wind energy.

For this purpose, long-term historical hourly mean wind speed data were obtained for 46 stations throughout the country for 40 years between 1980 and 2019. A spatial interpolation technique is used to estimate the wind speed at some locations where direct data was not available to build an accurate wind map of the country. This wind map is used as a reference for large scale wind energy installations as it gives an estimate of the wind speed where physical meteorological stations do not exist.

A list of all criteria that may have a direct or indirect impact on the siting of the wind farm is identified from the literature. All the criteria are given equal weightage in the analysis. However, with noncompliance with even a single criterion condition, the associated complete area is considered unsuitable.

The site suitability analysis is performed separately for the four identified regions, the northern, the eastern, the central and the southern. In the northern region, three wind farm sites are identified at Turaif, near the Jordanian border, in the middle of the northern Iraqi border near Hafr Al Batin, and in the Tabuk province, on the Red Sea coast. A total of 1452 km^2 of the area is suitable which is about 0.43% of the total selected northern area. The central area is found to have a more suitable area compared to other regions mainly due to good wind resources, roads, and grid connectivity. Most of the suitable sites are found in Riyadh and Hail province and a few in Al Quassim too. A total of 8576.41 km^2 of the area is found to be suitable for wind farm development, pertaining to about 1.54% of the total regional area. In the eastern region, suitable sites are located between Dammam and Hafr Al Batin city. A total of 3291 km^2 of the area is found to be suitable for wind farm realization, i.e. about 0.59% of the total eastern area. The southern region has the least potential area for wind power plant development. A total of 201.8 km^2 of the area is found to be suitable for wind farm development which is around 0.04% of the total regional area. In a similar study for Saudi Arabia, the entire region was ranked using criteria weighted overlay method but with wind data from 29 weather stations only. A few relevant criteria like safe distance from birding locations and flying paths, buffer distance from lakes, rivers, springs, parks, forests and public places and terrain slope were neglected [9].

The selection of the optimum wind turbines and the design layout for the suitable wind farm sites identified in this study can be considered as future work. The selection of an optimum wind turbine is a challenging task [38] and requires consideration of various factors in the decision-making process [9, 39-46].

REFERENCES

[1] U. S. E. I. Administration, "International Energy Outlook 2019," 2019.

[2] T. E. Amin, G. Roghayeh, R. Fatemeh, and P. Fatollah, "Evaluation of nanoparticle shape effect on a nanofluid based flat-plate solar collector efficiency," *Energy Explor. Exploit.*, 2015.

[3] J. T. Dellosa, "Potential effect and analysis of high residential solar photovoltaic (PV) systems penetration to an electric distribution utility (DU)," *Int. J. Renew. Energy Dev.*, 2016.

[4] Rehman, S. & Natarajan, N. & Mohandes, Mohd & Alam, Mahbub. (2020). Latitudinal wind power resource assessment along coastal areas of Tamil Nadu, India. FME Transactions. 48. 566-575. 10.5937/fme2003566R.

[5] Y. Noorollahi, H. Yousefi, and M. Mohammadi, "Multi-criteria decision support system for wind farm site selection using GIS," *Sustain. ENERGY Technol. ASSESSMENTS*, vol. 13, pp. 38–50, 2016.

[6] G. Wind and E. Council, "NAME HERE REPORT 2018 GWEC | GLOBAL WIND REPORT 2018," no. April, 2019.

[7] P. Technology, "Dumat Al Jandal Wind Farm." [Online]. Available: https://www.power-technology.com/projects/dumat-al-jandal-wind-farm. [Accessed: 17-Feb-2020].

[8] Ž. Stevi, "SS symmetry Application of MCDM Methods in Sustainability Engineering : A Literature Review 2008 – 2018," 2018.

[9] M. A. Baseer, S. Rehman, J. P. Meyer, and M. M. Alam, "GIS-based site suitability analysis for wind farm development in Saudi Arabia," *Energy*, 2017.

[10] S. M. J. Baban and T. Parry, "Developing and applying a GIS-assisted approach to locating wind farms in the UK," *Renew. Energy*, 2001.

[11] W. Krewitt and J. Nitsch, "The potential for electricity generation from on-shore wind energy under the constraints of nature conservation: A case study for two regions in Germany," *Renew. Energy*, 2003.

[12] H. S. Hansen, "GIS-based multi-criteria analysis of wind farm development," in *ScanGIS 2005 - Proceedings of the 10th Scandinavian Research Conference on Geographical Information Sciences*, 2005.

[13] M. Argin, V. Yerci, N. Erdogan, S. Kucuksari, and U. Cali, "Exploring the offshore wind energy potential of Turkey based on multi-criteria site selection," *Energy Strateg. Rev.*, vol. 23, no. March 2018, pp. 33–46, 2019.

[14] Z. Li, "Study of site suitability assessment of regional wind resources development based on multi-criteria decision," *Clean Technol. Environ. Policy*, vol. 20, no. 6, pp. 1147–1166, 2018.

[15] K. Azad, M. Rasul, P. Halder, and J. Sutariya, "Assessment of wind energy prospect by weibull distribution for prospective wind sites in Australia," in *Energy Procedia*, 2019.

[16] D. Latinopoulos and K. Kechagia, "A GIS-based multi-criteria evaluation for wind farm site selection. A regional scale application in Greece," *Renew. Energy*, 2015.

[17] "General Authority of Statistics, Saudi Census," *Statistical Yearbook*, 2015. [Online]. Available: https://www.stats.gov.sa/en/4025. [Accessed: 17-Feb-2020].

[18] The Editors of Encyclopaedia Britannica, "Encyclopaedia Britannica," *Rubʿ al-Khali*. [Online]. Available: https://www.britannica.com/place/Rub-al-Khali.

[19] "Saudi Industrial Development Fund, SIDF," 2019. [Online]. Available: https://www.sidf.gov.sa/en/Pages/default.aspx. [Accessed: 17-Feb-2020].

[20] "KACARE," *2020*. [Online]. Available: https://www.kacare.gov.sa/ar/pages/default.aspx. [Accessed: 17-Feb-2020].

[21] R. Van Haaren and V. Fthenakis, "GIS-based wind farm site selection using spatial multi-criteria analysis (SMCA): Evaluating the case for New York State," *Renewable and Sustainable Energy Reviews*. 2011.

[22] B. Sliz-Szkliniarz and J. Vogt, "GIS-based approach for the evaluation of wind energy potential: A case study for the Kujawsko-Pomorskie Voivodeship," *Renewable and Sustainable Energy Reviews*. 2011.

[23] S. H. Siyal, U. Mörtberg, D. Mentis, M. Welsch, I. Babelon, and M. Howells, "Wind energy assessment considering geographic and environmental restrictions in Sweden: A GIS-based approach," *Energy*, 2015.

[24] "Global modeling & assimilation office," *National Aeronautics and Space Administration, NASA*, 2020. [Online]. Available: https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/. [Accessed: 17-Feb-2020].

[25] S. Rehman, M. Shoaib, I. Siddiqui, F. Ahmed, M. Tanveer, and S. Jilani, "Effect of Wind Shear Coefficient for the Vertical Extrapolation of Wind Speed Data and its Impact on the Viability of Wind Energy Project," *J. Basic Appl. Sci.*, 2015.

[26] B. Peros, I. Boko, and V. Divic, "Wind shear characteristics of local winds," in *7th Asia-Pacific Conference on Wind Engineering, APCWE-VII*, 2009.

[27] M. R. Patel, *Wind and Solar Power Systems*. 2005.

[28] M. S. Islam, M. Mohandes, and S. Rehman, "Vertical extrapolation of wind speed using artificial neural network hybrid system," *Neural Comput. Appl.*, 2017.

[29] N. Y. Aydin, E. Kentel, and S. Duzgun, "GIS-based environmental assessment of wind energy systems for spatial planning: A case study from Western Turkey," *Renewable and Sustainable Energy Reviews*. 2010.

[30] K. Q. Nguyen, "Wind energy in Vietnam: Resource assessment, development status and future implications," *Energy Policy*, 2007.

[31] SEC, "Saudi Electricity Co. Annual Report," 2019.

[32] EarthWorks, "Stanford Libraries," *ESRI*, 2020. .

[33] J. Babbington, "Birds of Saudi Arabia." [Online]. Available: https://www.birdsofsaudiarabia.com/p/birding-locations.html. [Accessed: 10-Feb-2020].

[34] M. Shobrak, "Bird flyways and stopover conservation sites in the arabian peninsula," *Zool. Middle East*, 2011.

[35] L. I. Tegou, H. Polatidis, D. A. Haralambopoulos, "Environmental management framework for wind farm siting: Methodology and case study," *J. Environ. Manage.*, 2010.

[36] F. Rahman, S. Rehman, and M. A. Abdul-Majeed, "Overview of energy storage systems for storing electricity from renewable energy sources in Saudi Arabia," *Renewable and Sustainable Energy Reviews*. 2012.

[37] "Vision 2030," 2019. .

[38] B. Rašuo, M. Dinulović, A. Veg, A. Grbović, A. Bengin, "Harmonization of new wind turbine rotor blades development process: A review," *Renew. Sustain. Energy Rev.*, vol. 39, pp. 874–882, 2014.

[39] S. Rehman, S. A. Khan, "Fuzzy logic based multi-criteria wind turbine selection strategy - A case study of Qassim, Saudi Arabia," *Energies*, 2016.

[40] M. M. Rafique, S. Rehman, M. M. Alam, L. M. Alhems, "Feasibility of a 100 MW installed capacity wind farm for different climatic conditions," *Energies*, 2018.

[41] S. Rehman and S. A., "Multi-Criteria Wind Turbine Selection using Weighted Sum Approach," *Int. J. Adv. Comput. Sci. Appl.*, 2017.

[42] S. Rehman, M. M. Rafique, M. M. Alam, and L. M. Alhems, "Vertical axis wind turbine types, efficiencies, and structural stability – A Review," *Wind and Structures, An International Journal*. 2019.

[43] M. A. Baseer, J. P. Meyer, S. Rehman, M. M. Alam, "Wind power characteristics of seven data collection sites in Jubail, Saudi Arabia using Weibull parameters," *Renew. Energy*, vol. 102, 2017.

[44] S. Rehman, S. S. Ali, and S. A. Khan, "Wind Farm Layout Design Using Cuckoo Search Algorithms," *Appl. Artif. Intell.*, 2018.

[45] B. P. Rašuo, A. Bengin, "Optimization of wind farm layout," *FME Trans.*, vol. 38, no. 3, pp. 107–114, 2010.

[46] B. Rašuo, A. Bengin, A. Veg, "On Aerodynamic Optimization of Wind Farm Layout," *Pamm*, vol. 10, no. 1, pp. 539–540, 2010.

[47] P. Díaz-Cuevas, "GIS-based methodology for evaluating the wind-energy potential of territories: A case study from Andalusia (Spain)," *Energies*, 2018.

NOMENCLATURE

GIS	Geographic Information System
MCDM	Multi-Criteria Decision Making
IDW	Inverse Distance Weighted
AGL	Above Ground Level
WS	Wind Speed
V_1	Average Wind Speed at Height 1

Superscripts

n	Wind Shear Coefficient

ВИШЕКРИТЕРИЈУМСКА МЕТОДОЛОГИЈА ИЗБОРА ЛОКАЦИЈЕ ВЕТРОПАРКА БАЗИРАНА НА ГЕОГРАФСКОМ ИНФОРМАЦИОНОМ СИСТЕМУ

С. Рехман, М.А. Басер, Л.М. Алхемс

Сматра се да ће глобална потражња за енергијом, у односу на тренутну ситуацију, порасти за 50% до 2050. године. Очекује се да ће пројектоване потребе за електричном енергијом у Саудијској Арабији бити веће од 120 гигавата годишње до 2032. Саудијска влада је поставила циљ да ветропаркови произведу 9,5 гивавата до 2023. У раду се користи техника просторне интерполације за израду прецизне мапе ветрова за целу земљу.

Развијен је вишекритеријумски модел одлучивања за избор погодних локација за изградњу ветропаркова, који укључује еколошке, безбедне по околину и социо-економске критеријуме. Сви кретиријуми имају подједнаку тежину код модела. Према томе, уколико није задовољен један од наведених критеријума таква локација се сматра непогодном. У студији случаја овај модел је примењен на четири региона који покривају целу Саудијску Арабију. У северном делу земље одређене су три локације. Централна зона има погодније локације у поређењу са осталим регионима, јер има добре ресурсе ветра, путну и координатну мрежу. У источном делу земље одговарајуће локације се налазе између Дамама и Хафр АлБатина. Јужни регион има најмање погодне локације за експлоатацију енергије ветра, једино у близини провинције Мадина.