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GIS-based site suitability analysis for wind farm development in Saudi Arabia

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Abstract:

The harmful effects of traditional methods of power generation on the environment has created a need to strategically plan and develop renewable and sustainable energy generation systems. This paper presents the wind farm site suitability analysis using multi-criteria decision making (MCDM) approach based on geographic information system (GIS) modeling. This analysis is based on different climatic, economic, aesthetic and environmental criteria like wind resource, accessibility by roads, proximity to the electrical grid, and optimum/safe distance from various settlements and airports. Using information from published literature, criteria constraints like buffer zones, exclusion zones and suitability scores for each criteria is developed. An analytical hierarchy process, AHP is employed to assign appropriate weights to the criteria according to their relative importance. The developed model is then applied to the entire Kingdom of Saudi Arabia. The most suitable sites are found to be (i) near Ras Tanura on the coast in the Eastern Province; (ii) Turaif in Al-Jawf region at northern borders and (iii) Al-Wajh on the coast in the western region. The central and southeastern region is found to be unsuitable mainly due to scarce wind resource, few settlements and less connectivity by roads and electrical grid.

Keywords:

GIS; multi-criteria decision analysis; analytical hierarchy process; site suitability analysis; wind energy.

Highlights:

- GIS-based multi criteria wind farm site suitability analysis is proposed.
- Long term historical wind data from twenty nine weather stations are used.
- Different climatic, economic, aesthetic and environmental criteria are considered.
- An analytical hierarchy process, AHP is used to assign weights to the criteria.
- The most suitable sites for wind farms are Ras Tanura, Turaif and Al-Wajh.

1. Introduction

Concerns related to environmental degradation and energy security have invited global endorsement in the use of renewable and sustainable sources of energy. Wind energy is a very promising renewable energy source and is gaining universal acceptance due to its low production, operation and maintenance cost, besides the easy accessibility to efficient multi-megawatt wind turbines (Kaplan, 2015).

In 2016, an addition of 55 GW of wind power installations were made in 90 countries worldwide, resulting in an increase of cumulative wind power capacity by 12.6%, reaching a total of 486.8 GW. Wind power penetration rate is increasing continuously, Denmark leads by 40%, followed by Uruguay, Portugal and Ireland with well over 20%, Spain and Cyprus around 20%, Germany at 16%; and China, the US and Canada get 4, 5.5, and 6% of their power from wind, respectively (Global wind report, 2016). Saudi Arabia vision 2030, a government initiative to reduce Saudi Arabia's dependence on oil and diversify its economy, sets an initial target of producing 9.5 GW/year of renewable energy by 2023 (Saudi Vision 2030, 2017). As one of the first steps towards achieving this target, a wind turbine of 2.75 MW rated power was installed in January 2017 (Saudi Aramco, 2017). With a vast amount of vacant plain land, mostly encouraging wind resource in Saudi Arabia, development of wind farms can be a smart option to achieve greater wind power penetration.

The first challenge in designing and developing a wind farm is to identify suitable sites for wind farm installation. The potential sites should not only cater to wind energy requirements, but also satisfy several environmental and socio-economic factors. GIS is a popular site suitability analysis tool, involving the assimilation of spatially referenced data in a problem solving environment. On the other hand, multi-criteria decision making, MCDM analysis along with the analytical hierarchy process, AHP provides a tool for structuring, designing, evaluating and prioritising alternative decisions. The exactitude of this wind farm planning is largely dependent on the availability of accurate wind and geographic data.

GIS-based MCDM studies for identifying suitable locations for renewable energy resources, in general, are reviewed in this study. Omitaomu et al., 2012, presented an approach which takes factors such as water bodies, population, environmental indicators and tectonic and geological hazards to provide an in-depth analysis for power generation siting options in the United States. The siting model developed in this study, effectively provides feedback on land suitability based on technology specific inputs. However, the tool does not replace the required detailed evaluation of candidate sites. Schallenberg-Rodríguez and Notario-del Pino, 2014, presented a GIS-based methodology to assess solar and wind energy potentials of various sites. This methodology takes into account territorial constraints as natural protected area, urban areas or even an isolated house, and techno-economic constraints as minimum wind speed or maximum slope. This methodology is applied to a practical case, the Canary Islands, a Spanish archipelago located just off the southern coast of Morocco.

In particular, the use of GIS-based MCDM analysis for planning of wind farms gained significance in early 2000s and hence, being utilised in several countries like Turkey (Aydin et al., 2010), Greece (Latinopoulos and Kechagia, 2015), Denmark (Hansen, 2005), USA (Haaren and Fthenakis, 2011), UK (Baban and Parry, 2001), Germany (Krewitt and Nitsch, 2003), Poland (Sliz-Szkliniarz and Vogt, 2011), Vietnam (Nguyen, 2007) and Sweden (Siyal et al., 2015) some of which will be discussed later.

The most important part of MCDM analysis is the selection of various economic, planning and ecological criteria, followed by using them as either restriction and/or evaluation factors in order to identify potential wind farm sites. The selection of criteria and its application used in the aforementioned studies are reviewed in detail and presented in Table 1. Aydin et al., 2010 and Hansen, 2005 represented the economic, planning and ecological criteria as fuzzy sets by first defining the maximum and minimum restriction ranges and then giving a tolerance limit from 0 to 1 between these ranges. Latinopoulos and Kechagia, 2015 developed a tool for wind-farm planning at the regional level. The tool is also applicable to other study areas and particularly in the main land of Greece where most of the selected criteria are virtually similar. A constraint range is set for distance of potential wind farm sites from roads, however, the criteria of proximity to electricity grid is not considered. The results indicate that more than 12% of the study area in Greece is suitable for wind farm development. Haaren and Fthenakis, 2011 built an algorithm in ESRI ArcGIS software for New York State which consisted of three stages. The first stage excludes infeasible wind farm sites, based on land use and geological constraints. The second stage identifies the best feasible sites based on the expected net present value from four major cost and revenue categories: revenue from generated electricity, costs from access roads, power lines and land clearing. The third stage assesses the ecological impacts on bird and their habitats. The proposed methodology is then implemented in New York State and the results are compared with the locations of existing wind turbine farms. The selected restriction criteria of spatially dependent costs (grid connection, road access and land clearing) to be less than 20% of total cost. Sliz et al., 2011, calculated energy output throughout the region from three reference turbines of 0.6, 1.65 and 2.5 MW. Various spatial and ecological restrictions are applied on three energy potential maps obtained using three reference turbines. Almost 7500 km^2 of the study area is found to be feasible for wind farm siting. Nguyen, 2007, calculated energy output throughout the region from a reference turbine of 1.8 MW rated power and then applied social and technical restraints to eliminate unsuitable areas. Siyal et al., 2015, eliminated areas (grid cells) with Plant capacity factor less than 20% achieved using a reference turbine of 3 MW rated power. Baban and Parry, 2001 applied criteria restrictions using two different methods. In the first method, all the criteria are considered as equally important and in the second, the criteria are grouped and graded according to perceived importance. The first grade factors, roads and urban centers are assigned a combined weight of around 55% in the model. The second grade factors, rivers, water bodies, ecological sites, and railways are assigned a combined weight of around 25%. The third grade factors, historical sites and national trust properties are assigned a combined weight of around 12%. Finally, the fourth grade factors, paths, are assigned a weight of around 8%. Although Baban and Parry, 2001 employed the pairwise comparison method for assigning weights to factors, they did not mention the use of any systematic method such as the AHP for this purpose, and so are unable to evaluate the consistency of their judgments. Consistency is essential to MCDM analysis because of the intricacy of the criteria weighting process and the possibility of bias on the part of the different decision-makers (Chen, Yu and Khan, 2010).

The main shortcoming of the studies reviewed are exclusion of certain significant criteria, insufficient application of MCDM methods, particularly of the AHP approach, and subjective assignment of criteria weights.

In this study, firstly, a general MCDM tool for wind farm site selection is developed and then applied to the entire Kingdom of Saudi Arabia. The AHP approach has been employed to determine the weights of siting criteria. The method developed by Saaty, 1977 is one of the multi-criteria methods for hierarchical analysis of decision problems. To the best of authors' knowledge, this wind farm site suitability analysis is the first of its kind in the region and till date, national policies pertaining to wind energy has not been published.

2. Description of study area, data and methodology.

2.1 Study area

Saudi Arabia is a largest country in the Middle East. Desert covers more than half the total area of Saudi Arabia. Temperatures can vary considerably from a midsummer maximum of 51°C in the shade to winter lows close to -8°C in the mountainous areas and, sometimes, at night in the desert (KACARE, 2016; Ministry of foreign affairs, 2016). The Kingdom is experiencing rapid population, industrial and agricultural growth, subsequently resulting in an ever-increasing demand on power and water supplies. The total population increased by almost five and half times within the last four and a half decades, from 5,772,000 in 1970 to 31,742,308 in 2017 (General Authority for Statistics, 2017). The number of operating industries has increased by around 35 times within the last four decades, from 198 in 1974 to 7,007 in 2015 (Saudi Industrial Development Fund, 2017). The growth rate of the manufacturing industries increased at an average of 6% per annum, which is considered to be one of the highest among the other economic sectors (Saudi Industrial Development Fund, 2017).

A more important aspect in the development of the manufacturing industries in the Kingdom is indicated by the change that occurred in the sectoral composition of Saudi manufacturing over the past period, as the share of the manufacturing industries (other than oil refining) in manufacturing Gross Domestic Product increased from 57% in 1975 to 87% by the end of 2013. This trend reflects the dynamism of the Saudi manufacturing industries sector (other than oil refining). In this regard, we refer in particular to the substantial progress and expansion experienced by the petrochemical industries in the Kingdom over the last two decades (Saudi Industrial Development Fund, 2017).

The total energy consumption in Saudi Arabia from 2000 to 2014 increased from 126,191 to 311,807 GWh, an increase by 2.5 times in the last one and a half decades (Saudi Electricity Company, 2016).

In Saudi Arabia, the per capita energy consumption has reached 9,000 kWh in 2014, compared to 5,500 kWh in 2000 (Saudi Electricity Company, 2016), an increase of around 65% in one and a half decades. Saudi Arabia requires investments worth $150 billion to meet growing electricity requirements in the next 10 years. The housing sector consumes about half of the electricity supply, followed by industries that consume 21% the trade sector 15% and government facilities 12%. Currently, the government provides subsidised fuel worth $40 billion to the Saudi Electricity Co. for power generation [17].

With the country's high growth in population and rapid industrialisation, the demand for energy is also increasing rapidly. According to government estimates, the projected demand for electricity in Saudi Arabia is expected to exceed 120 GW/year by 2032 (KACARE, 2016). The overall demand of fuel for industry, transportation and desalination is estimated to grow from 3.4 million barrels of oil equivalent per day in 2010 to 8.3 million barrels of oil equivalent per day by 2028 (KACARE, 2016). Therefore, Saudi Arabia is exploring alternative energy sources for generating power. The power of the wind can be utilised to partially supplement the existing national grid. Moreover, since Saudi Arabian land is mostly plain with minimal mountain ranges and without any perennial lakes or rivers, it is generally very suitable for development of wind farms.

2.2 Data description of wind farm siting criteria

2.2.1 Wind speed

The average interpolated wind speed is the main and highest weighted criterion in siting a wind farm in almost all reviewed studies (Haaren and Fthenakis, 2011; Krewitt and Nitsch, 2003; Sliz-Szkliniarz and Vogt, 2011; Nguyen, 2007; Siyal et al., 2015; Janke, 2010). In this study, the wind data from 29 meteorological data measurement stations spread over the entire Kingdom is obtained from the Presidency of Meteorology and Environment (PME, 2016). This governmental organisation is responsible for the maintenance, calibration and collection of meteorological data in Saudi Arabia. The mean wind speed and data collection duration at all the stations at 10 m above ground level (AGL) are given in Table 2. For all 29 stations, the hourly (data frequency) values of wind speed is recorded manually and then daily (time interval) average, maximum and minimum values are saved on the computer. The location maps of 29 PME weather stations spread all over the country are shown in Figure 1.

The wind speed used in the criterion is interpolated to 100 m from 10 m AGL by using traditional one-seventh power law also known as Hellmann's power law (Rehman et al., 2015; Peros et al., 2009; Bansal et al., 2002; Masters, 2004; Patel, 2006).

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

Where V_1 and V_2 are the wind speeds at heights Z_1 and Z_2 respectively and n is the value of wind shear coefficient. This coefficient is a function of the topography at a specific site and frequently assumed as a value of 1/7 for open land (Bansal et al., 2002; Masters, 2004; Patel, 2006).

All the twenty nine weather stations are distributed quite evenly in the entire kingdom. A spatial interpolation technique is used to predict the wind speed between the weather stations, where directly measured data is not available. In this analysis, the method used to convert the point data into raster format is the inverse distance weighted, IDW. It determines cell values 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 location. The IDW interpolation technique is applied as it is found to be more accurate. Ali et al. (2012) tested five wind speed interpolation methods (i.e. IDW, global polynomial interpolation, local polynomial interpolation, spline with 3 sub-types, and kriging with 4 sub-types) in Iraq. Based on the root mean square error values, the predicted values are compared with actual values for the period between 1971 and 2010. The results demonstrated that the IDW yielded the best results, while the ordinary Kriging method occupied the second rank (Ali et al., 2012).

2.2.2 Distance from electricity grid

Long transmission lines between wind farms and the electricity grid are associated with costs related to cabling and electricity losses. Wind farms should be sited in the close vicinity of the electricity grid. Many studies have neglected this criterion in their analysis (Aydin et al., 2010; Latinopoulos and Kechagia, 2015; Hansen, 2005; Krewitt and Nitsch, 2003; Nguyen, 2007).

For the current analysis, maps of the national electrical grid and power station are obtained from the electrical data book of the Saudi Electrical Company, SEC (2016). SEC is a national electric utility company responsible for generation, transmission and distribution of electric power.

2.2.3 Distance from settlements

The buffer (preventive) distances from residential areas for avoiding noise, nuisance and natural surroundings must be defined. This is a very important criterion in wind farm siting. In all similar studies, these distances are well defined. However, these buffer distances are different in different studies (Aydin et al., 2010; Latinopoulos and Kechagia, 2015; Hansen, 2005; Haaren and Fthenakis, 2011; Baban and Parry, 2001; Krewitt and Nitsch, 2003; Sliz-Szkliniarz and Vogt, 2011; Nguyen, 2007; Siyal et al., 2015) and their selection has to be justified case-by-case by the national planning authority (e.g. the municipal administration). On the other hand, it is important that wind farm locations should be within a reasonable close distance from settlements to minimise transmission losses. Many studies present a range of distances from the settlements where wind farm siting analysis is done, distances on either side of this range are completely infeasible (Aydin et al., 2010; Hansen, 2005).

The national demographic data of Saudi Arabia are obtained from Central Department of Statistics and Information (CDSI, 2014). The CDSI falls under the authority of the Ministry of Economy and Planning and is the principal agency in the Kingdom for the collection, analysis and distribution of statistical information.

2.2.4 Distance from roads/highways

To minimise the construction and maintenance costs of wind farms, it is necessary that the distance between the proposed wind farm location and road network should be as less as possible. However, many studies recommend a buffer distance as well (Latinopoulos and Kechagia, 2015; Krewitt and Nitsch, 2003; Sliz-Szkliniarz and Vogt, 2011; Nguyen, 2007; Siyal et al., 2015). This buffer or preventive distance is decided by regional planning authorities. In most wind farm siting assessments, the areas further away from roads are considered less suitable than those closer to roads (Latinopoulos and Kechagia, 2015; Haaren and Fthenakis, 2011; Baban and Parry, 2001; Janke, 2010; Gorsevski et al., 2013; Ramírez-Rosado et al., 2008; Tegou, Polatidis and Haralambopoulos, 2010). However, there is no generally valid definition of a maximum distance from the wind turbines to the road network. Different studies considered different distance from road criterion, Latinopoulos and Kechagia, 2015 and Haaren and

Fthenakis, 2011 used a maximum distance of 5000 m, Baban and Parry, 2001 used 10000 m and Krewitt and Nitsch, 2003 and Sliz-Szkliniarz and Vogt, 2011 used buffer distance of 100 and 200 m only. The access roads to wind farm must comply with following minimum requirements (Latinopoulos and Kechagia, 2015; Krey, 2006):

i) minimum width of 4 m
ii) minimum subsoil load bearing capacity of 45 MPa
iii) a solid pavement,
iv) maximum radius of curve, external 28 m
v) maximum incline with solid surface (paved) 12%

The GIS shape files of national highways and roads are downloaded from GIS data websites (Diva-gis.org, 2016) and are compared with maps provided by the ministry of transport, Saudi Arabia (Mot.gov.sa, 2016).

2.2.5 Safe distance from airports

Wind turbines can interfere with aviation radar signal and would require a significant buffer around airports. Most of the similar studies present a buffer distance around airports (Aydin et al., 2010; Latinopoulos and Kechagia, 2015; Hansen, 2005; Sliz-Szkliniarz and Vogt, 2011; Nguyen, 2007; Siyal et al., 2015).

2.2.6 Slope of terrain

The accessibility for installation and maintenance of wind turbines is hindered by steep slope of a terrain. In literature, the allowed maximum slope threshold range from 10% (Baban and Parry, 2001) to 30% (Tegou et al., 2010). Rodman and Meentemeyer, 2006 even prefer ridge crests and set the threshold for slope to 40°, which corresponds to approximately 84%. In few studies, (Aydin et al., 2010; Hansen, 2005; Rahman et al., 2012; Gorsevski et al., 2013) the slope is not at all considered as a criteria.

2.2.7 Impact on birds

There are some minor impacts on migrating birds reported by few researchers (Aydin et al., 2010; Haaren and Fthenakis, 2011), mainly due to their collision with turbine rotor. Studies also show that climate changes have much more significant threat to wildlife than wind farms (Pavokovic and Mandusik, 2006). The Arabian Peninsula, which comprises of Kuwait, Bahrain, Qatar, United Arab Emirates, Oman, Yemen and Saudi Arabia is a transit point for birds migrating between Asia, Africa and Europe, particularly during the fall from August to October and returning between March and May heading toward the north, covering 70,000 km every year (Arab news, 2016).

Although, there are fifteen important bird areas, IBA in the Arabian Peninsula (Shobrak 2011) including bottleneck areas for soaring birds, sites for feeding and moulting and seabird breeding islands as shown in Figure 2, only five IBA's are located near the Saudi Arabian national boundary and none completely inside Saudi Arabia as birds fly over mountain ranges, waterbodies and natural habitats for survival. Therefore, this study is assumed not to have any impact on birds.

The important bird areas, IBA i.e. breeding grounds, non-breeding areas, including intermediate resting and feeding places should fall at least 300 m away from a prospective wind farm (Aydin et al., 2010; Haaren and Fthenakis, 2011). In few similar studies, [Baban and Parry, 2001; Nguyen, 2007; Miller and Li, 2014; Hossain et al. 2011] the acceptance criteria in terms of bird habitat is not considered as a criterion maybe due to non-interference with IBAs.

2.3 Methodology and GIS-based Modeling:

The methodological framework of the wind farm siting procedure applied in this study is structured in different steps that are summarised and illustrated in Figure 3.

2.3.1 Multi-criteria decision making (MCDM)

MCDM is a method for assessing the comparative importance of several variables as input criteria for making complex decisions (Hansen, 2005; Haaren and Fthenakis, 2011). The essential idea being that a number of relevant criteria must be identified and assessed in terms of weight, with respect to the influence the criteria have on the final decision. In spatial analysis, this is often accomplished by creating a suitability map that is composed of several layers, each layer representing one of the criteria. The criteria are given a weighted suitability score, and these scores are represented as different classes or categories, which are then symbolised on the map layer showing the suitable areas for that criteria. The layers are then overlaid on the map to present a final site suitability map, from which the user can then identify optimal areas and continue with a more detailed investigation of those sites.

2.3.2 Selected wind farm siting criteria

In this site suitability analysis, several wind farm siting criteria are developed as shown in Table 3. These criteria corresponds to a number of constraint factors like wind resource, accessibility, safety, aesthetics, noise and optimum utilisation. Areas where wind farm installation is not feasible includes sites that are less windy (wind speed is less than 5 m/s at 100 m AGL), more than 10 000 m away from roads and highways, more than 10 000 m away from the national electricity grid, less than 500 m from settlements, less than 2 500 m from airports. The criteria of distance from water bodies and slope of terrain are not considered in this study as there are no perennial lakes and rivers in Saudi Arabia and even though few mountains exist in the north-western region, the slope is not that steep to be included as a criterion.

2.3.3 Reclassification of selected criteria

All of the criteria, listed in Table 3, are first converted into the raster data structure by reclassifying into six classes/suitability scores, with six corresponding to excellent and one to lowest suitability score for wind farm development, as shown in Table 4.

According to the wind planners, an average wind speed of more than 6 m/s at hub height is considered to have tremendous suitability, and less than 5 m/s is not suitable, even though it may still generate power (Sunak et al., 2015). Based on this notion, in reclassification of wind speed criteria, areas with wind speeds above 6 m/s are considered to have excellent suitability, as shown in Table 4. The suitability score decreased uniformly until it reached a lowest suitability score for areas where wind speed range is 5.2 – 5 m/s. Areas with wind speeds less than 5 m/s are ignored. Suitability scores increased with proximity to the electrical grid, major roads and highways. Same rating scheme is selected for all these three criteria. Distance less than 2000 m is considered to have excellent suitability, the suitability score decreased gradually until it reached a lowest suitability score of 1 for the distance range of 8,500 – 10,000 m (Rodman and Meentemeyer, 2006). A distance between 2000 – 4000 m from settlements is considered to have excellent suitability. Suitability scores decreased gradually until a score of 2 is reached for distance range of 8,500 – 10,000 m. Since a prospective site should not be too close to settlements, due to noise, nuisance and disturbance to natural surroundings, lowest suitability score of 1 is given to a distance less than 2000 m.

For each criteria, the maximum and minimum range of values are obtained from literature, corresponding to excellent and lowest suitability respectively (Malczewski, 2006; Olufemi et al., 2012; Julieta, 2014; Aydin, Kentel and Duzgun, 2010; Latinopoulos and Kechagia, 2015; Hansen, 2005; Haaren and Fthenakis, 2011; Baban and Parry, 2001; Krewitt and Nitsch, 2003; Sliz-Szkliniarz and Vogt, 2011; Nguyen, 2007; Siyal et al., 2015; Gorsevski et al., 2013; Tegou, Polatidis and Haralambopoulos, 2010; Rodman and Meentemeyer, 2006; Ma et al., 2005). Then the values falling in between are divided into six equal intervals, and given suitability scores as shown in Table 4.

2.3.4 Criteria weights by Analytic hierarchy process, AHP

All assessment criteria are not equally important in influencing the selection of potential wind farm sites. Therefore, the AHP method is used to assign appropriate weights to the criteria according to their relative importance. The AHP is based on pairwise comparisons, which are used to determine the relative importance of each criterion. The first step of this method is to structure the decision problem in a hierarchy. The goal of the decision is on the top level of the hierarchy; the next level consists of the criteria relevant to the decision problem; at the third level are the alternatives to be evaluated (Ma et al., 2005). The second step is the comparison of criteria in order to rank the alternatives. By comparing a pair of criteria at a time using a verbal scale, decision makers can quantify their opinions about the criteria magnitude (Kontos, Komilis and Halvadakis, 2005). As shown in Table 5, it uses a fundamental nine point's scale measurement to express individual preferences or judgments, creating a reciprocal ratio matrix. Specifically, the weights are determined by normalizing the eigenvector associated with the maximum eigenvalue of the reciprocal ratio matrix (Malczewski, 1999).

The AHP also provides mathematical measures to determine inconsistency of judgments. Based on the properties of reciprocal matrixes, a consistency ratio, CR can be calculated. In a reciprocal matrix, the largest eigenvalue, λ_{max} is always greater than or equal to the number of rows or columns, n. If a pairwise comparison does not include any inconsistencies, $\lambda_{max} = n$. The more consistent the comparisons are, the closer the value of computed λ_{max} to n. A consistency index, CI that measures the inconsistencies of pairwise comparisons can be written as (Saaty, 1980):

$$CI = \left(\frac{\lambda_{max} - n}{n-1}\right) \qquad (2)$$

A measure of coherence of the pairwise comparisons can be calculated in the form of consistency ratio (CR)

$$CR = \frac{CI}{RI} \qquad (3)$$

Where RI is random consistency index, the average CI of the randomly generated comparisons (Saaty, 1980). As a rule of thumb, a CR value of 10% or less is considered as acceptable. Otherwise a re-voting of comparison matrix has to be performed (Ma et al., 2005).

The pairwise comparison values have been assigned based on information depicted from literature (Latinopoulos and Kechagia, 2015; Baban and Parry, 2001; Gorsevski et al., 2013; Effat, 2014; Höfer et al., 2016; Atici et al., 2015; Miller and Li, 2014). To assign weight to each criterion, the five selected criteria are compared against each other in pairs. The relative importance of each criterion over the other is determined by comparing weights assigned to that pair, individually in all seven reviewed studies. Finally, the average criteria weight is assigned using the fundamental scale according to Saaty, 1977. The normalised matrix of the analysed criteria and the resulting weights of each criteria is given in Table 6. The values of λ_{max}, CI and CR are found to be 5.21, 0.053 and 0.047 respectively which shows that the assigned weights are very consistent.

3. Results and discussion

Different criteria layers used in this suitability analysis are shown schematically by Figure 4 to 8. The study is performed on ArcMap 10.3.1, 2015, the main component of ESRI's ArcGIS suite of geospatial processing programs.

The shapefiles of roads and highways of Saudi Arabia are combined in one using the merge function in ArcMap 10.3.1, 2015 as the constraints, rating scheme applied to both are same.

The site suitability model with the criteria restrictions and its reclassification is shown in Figure 9. All data layers are combined using the weighted overlay method as shown by the flowchart model. The final suitability indices for the entire country are determined by reclassifying the scores derived from the weighted overlay into six classes. This is a generalised model and can be applied for any region worldwide where wind data and all related shape files are available.

The final wind farm suitability map is shown in Figure 10. This map is distributed into six classes, where class 6 is the most suitable area for wind farm development and class 1 is the least suitable area.

In the suitability map, 1.86% of the total classed area fall under the most suitable category, whereas next best area is 14.65% of the total area. From this suitability map, three most suitable locations for development of wind farms are identified as follows:

(i) In the Eastern Province, near Ras Tanura close to Dammam city along the coast,

(ii) In northern- region, Turaif in Al-Jawf

(iii) In the north western borders region, near Al-Wajh.

Ras Tanura is a port city located in east of Saudi Arabia, has a population of around 80,000 (General Authority for Statistics, 2017). It is situated close to the modern industrial port city of Jubail. It is the main oil operations center for Saudi Aramco, the largest oil company in the world. Although it is located on a small peninsula, due to modern oil tankers' need for deeper water, numerous artificial islands are built for easier docking. In addition, offshore oil rigs and production facilities have been constructed in the waters nearby, mostly by Saudi Aramco and other oilfield service companies. It will be stimulating to build a wind farm near the port and on these artificial islands and will be interesting to look into the possibility of running some of the oil refining operation by wind power.

Turaif is a town in the northern borders province, close to the border with Jordan. It has a population of around 95,000 (General Authority for Statistics, 2017). The city of Turaif is established mainly due to presence of international oil pipeline. Saudi Arabia’s first wind turbine of 2.75 MW rated power is installed at Turaif in January 2017 (Saudi Aramco, 2017).

Al Wajh is a coastal town in the north-western Saudi Arabia, located on the coast of the Red Sea. It is one of the largest cities in Tabuk province, with a current population of around 55,000 (General Authority for Statistics, 2017). Fishing is a primary activity of the town's residents. The port at Al Wajh used to be one of the main shipping centers in the region 50 years ago. Al Wajh is one of the best places for people looking for nice, clean and beautiful beach.

The entire route connecting the three main cities of Saudi Arabia; Dammam in the eastern province, Riyadh in the central province and Jeddah in the western province has reasonable suitability, as shown in Figure 10. A wind farm en route these three major cities may serve power needs of large number of population. Settlement pockets, denoted by the least suitable red dots in the map, are comparatively denser in the central province, near Riyadh, hence not suitable for a wind farm site due to safety and aesthetics. The region near Jeddah, coastal city of the western province is unsuitable for wind farm development as it is less windy with dense settlements. Some central areas and entire southeastern area are found to be completely unsuitable for wind farm development mainly due to low mean wind speeds, few settlements, and less connectivity by roads and the national electrical grid. Since this study is done for the entire country of Saudi Arabia, in which three regions are identified as most suitable, a lot of alternatives in these regions still remain. Detailed and pertinent siting of wind farm locations for these regions individually can be considered as significant and interesting future work. Also, since a lot of studies on wind farm siting and wind energy policies are reviewed and a first of its kind study performed in Saudi Arabia, this paper provides an insight in national wind energy policy making.

4 Conclusions

In this study, a GIS-based model is developed for suitable wind farm site selection considering various climatic, economic, aesthetic and environmental parameters and applied to Saudi Arabia. The energy consumption in Saudi Arabia is projected to increase threefold by 2030. At present, renewable energy sector is in the developing phase in Saudi Arabia. The government has set an initial target of installing 9.5 GW of renewable energy by 2023 (Saudi Arabia vision 2030). This target accounts for about 15% of the total energy consumption. This study will help in achieving this target explicitly from the point of view of proper site selection and optimum harnessing of wind energy.

A spatial interpolation technique is used to estimate the wind speed in locations where data are not available. The results could be a guide for large scale wind energy installations even in those geographical areas where physical meteorological stations do not exist.

The developed wind speed maps, identification and annexation of local criteria listed in Tables 3 and 4 for the entire country will be of great help in defining the further line of action and policy-building towards wind power development and utilization in the Kingdom.

As future work, pertinent wind farm site suitability analysis can be conducted discretely for three identified regions, Ras Tanura, Turaif, and Al-Wajh. Additional explicit analysis for these sites may include (i) applying buffer distances around single dwellings for noise emission control and to avoid visual and scenic intrusion of the wind turbines, (ii) placing restrictions on certain areas due to negative effects of flora and fauna, (iii) applying buffer distances around certain regions restricted by planning authority like the municipal administration, (iv) checking soil conditions for suitability of mounting wind turbine towers and so on. Also, one of the suitable sites, Ras Tanura is close to the biggest thermal desalination plant in the world, operated by Saline Water Conversion Corporation (SWCC). Thermal desalination process is an energy intensive process and supply of this energy can be provided by wind energy.

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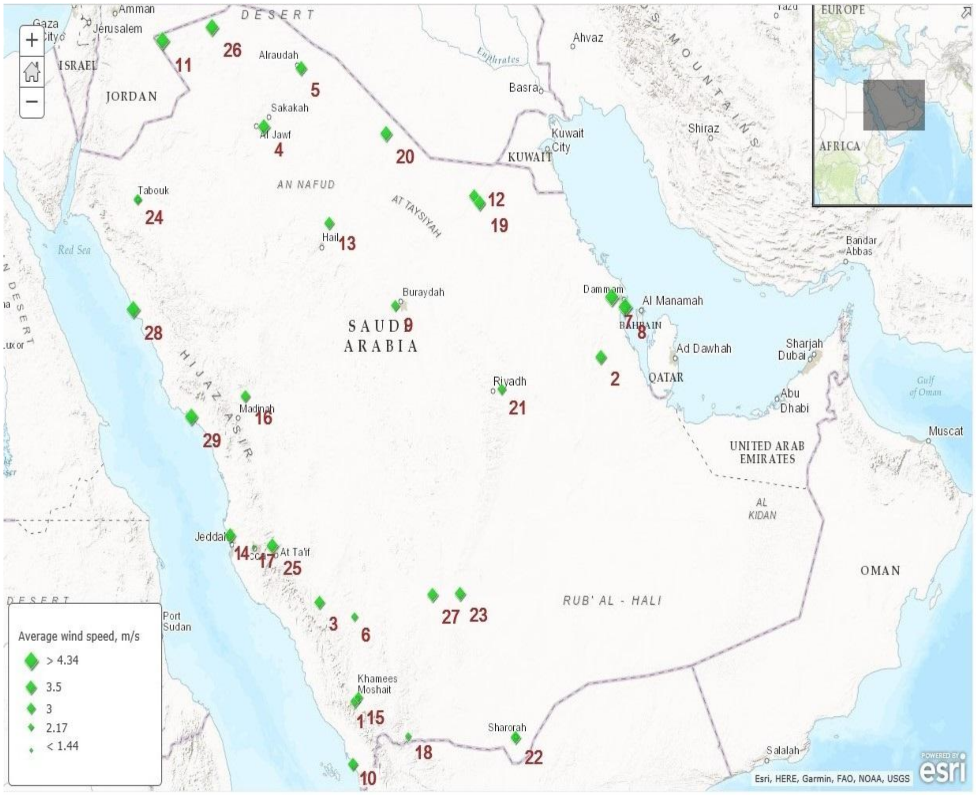

1.	Abha	7.	Dammam	13.	Hail	19.	Qaisumah	25.	Taif
2.	Al-Ahsa	8.	Dhahran	14.	Jeddah	20.	Rafha	26.	Turaif
3	Al-Baha	9.	Gassim	15.	Khamis-Mushait	21.	Riyadh-New	27.	Wadi-Al-Dawasser
4.	Al-Jouf	10.	Gizan	16.	Madinah	22.	Sharorah	28.	Wejh
5.	Arar	11.	Gurait	17.	Makkah	23.	Sulayel	29.	Yanbo
6.	Bisha	12.	Hafr-Al-Batin	18.	Najran	24.	Tabuk		

Fig. 1. Locations of meteorological stations countrywide with station names.

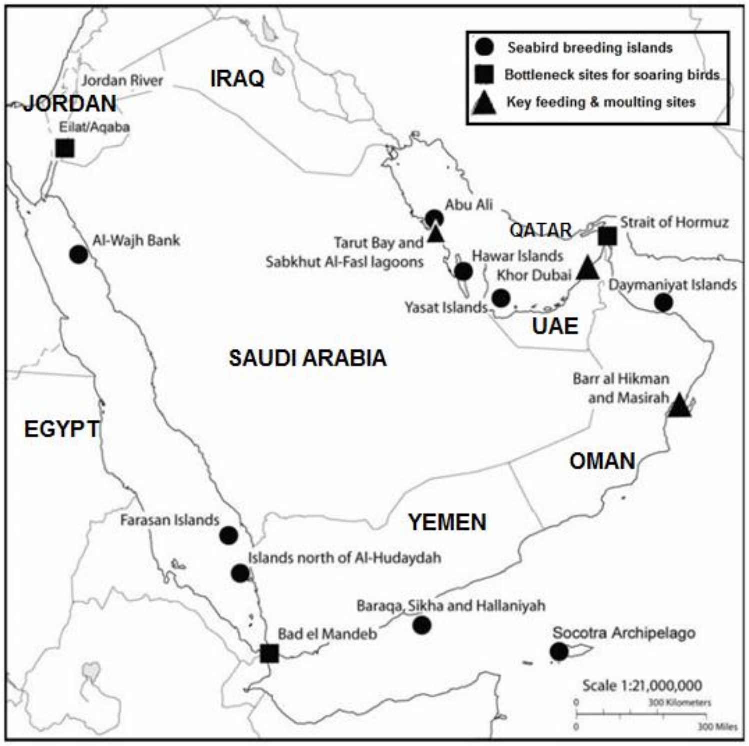

Fig. 2. Important bird areas, IBA in Arabian Peninsula (Pavokovic and Mandusik, 2006)

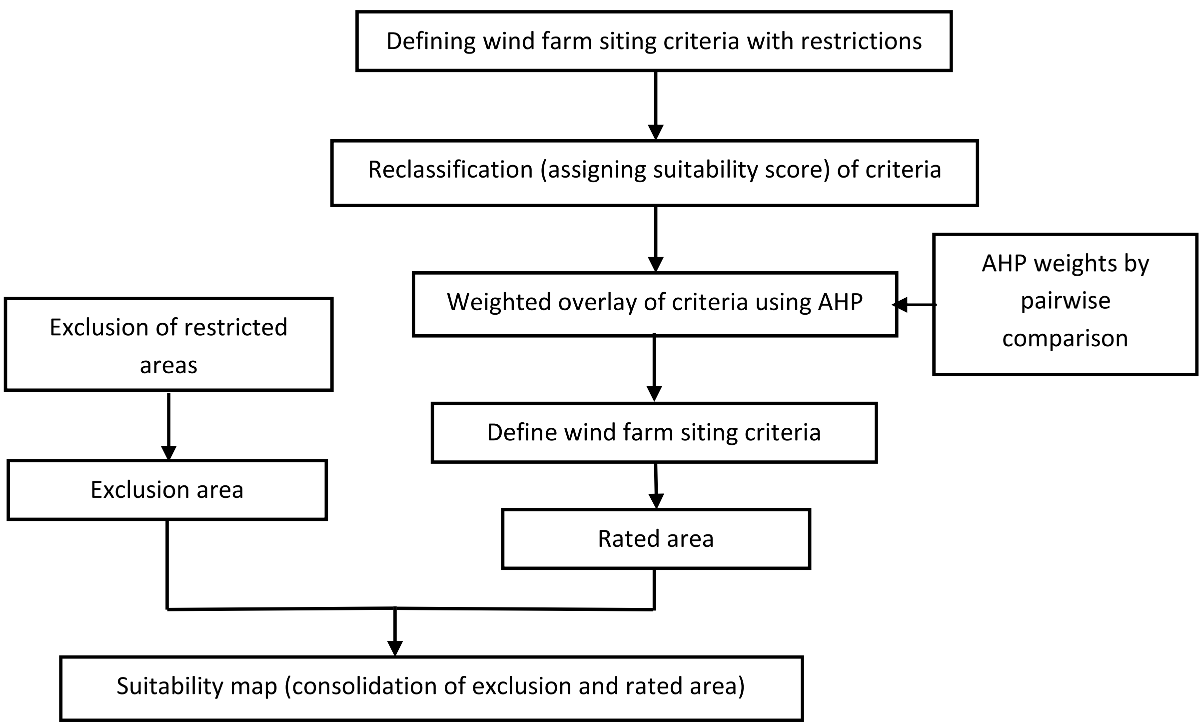

Fig. 3. The methodological framework of wind turbine siting.

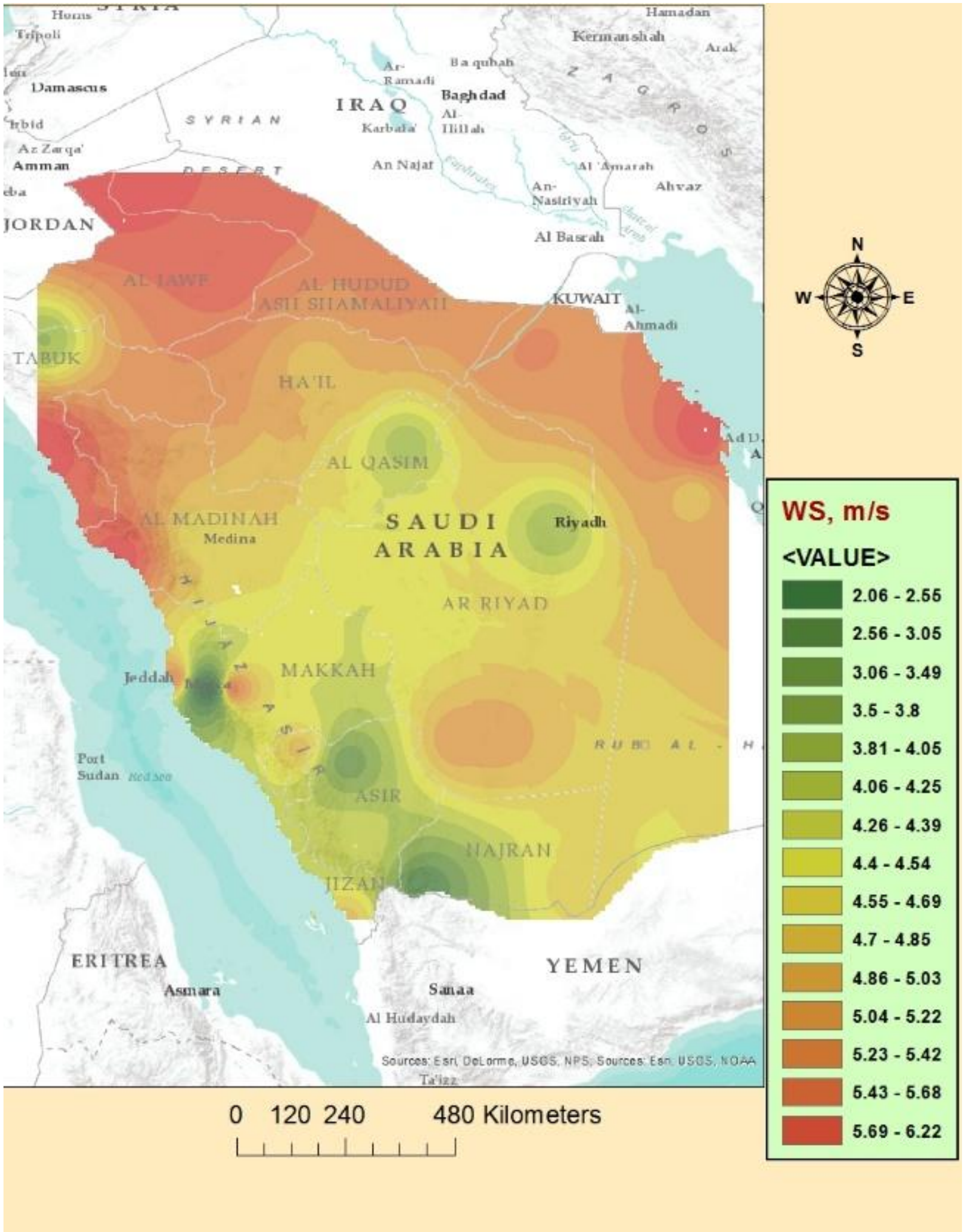

Fig. 4. Interpolated wind speed at 100 m AGL.

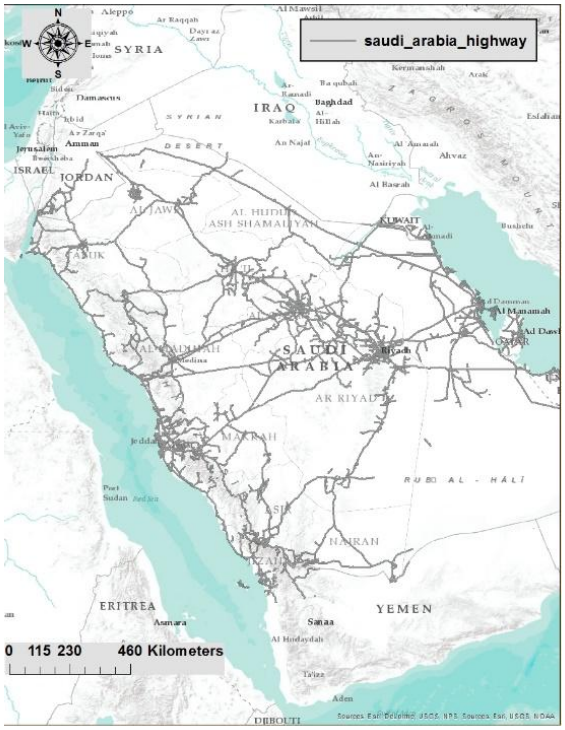

Fig. 5. Highways of Saudi Arabia.

Fig. 6. Roads of Saudi Arabia.

Fig. 7. International, domestic and military airports of Saudi Arabia.

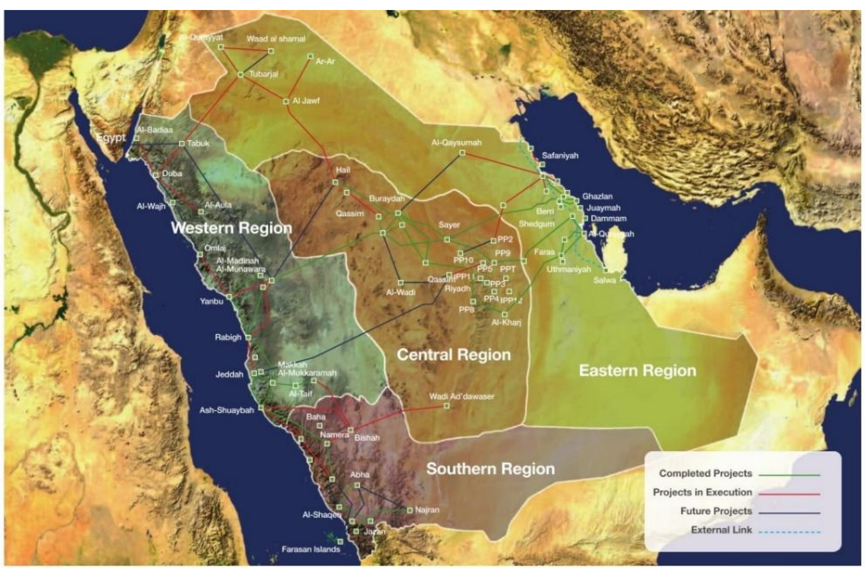

Fig. 8. National electricity grid of Saudi Arabia. (Saudi Electricity Company, 2016)

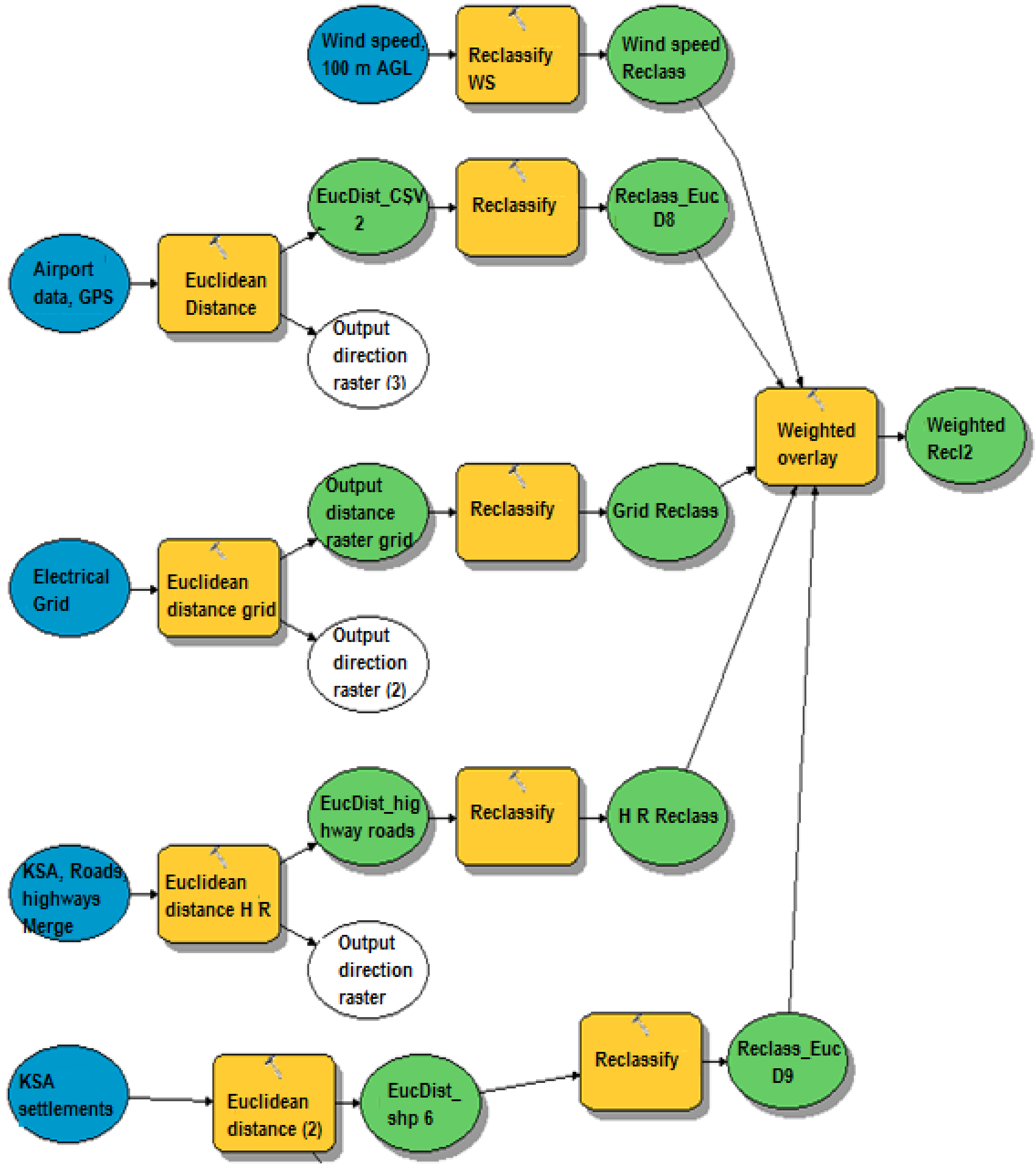

Fig. 9. Wind farm site suitability model.

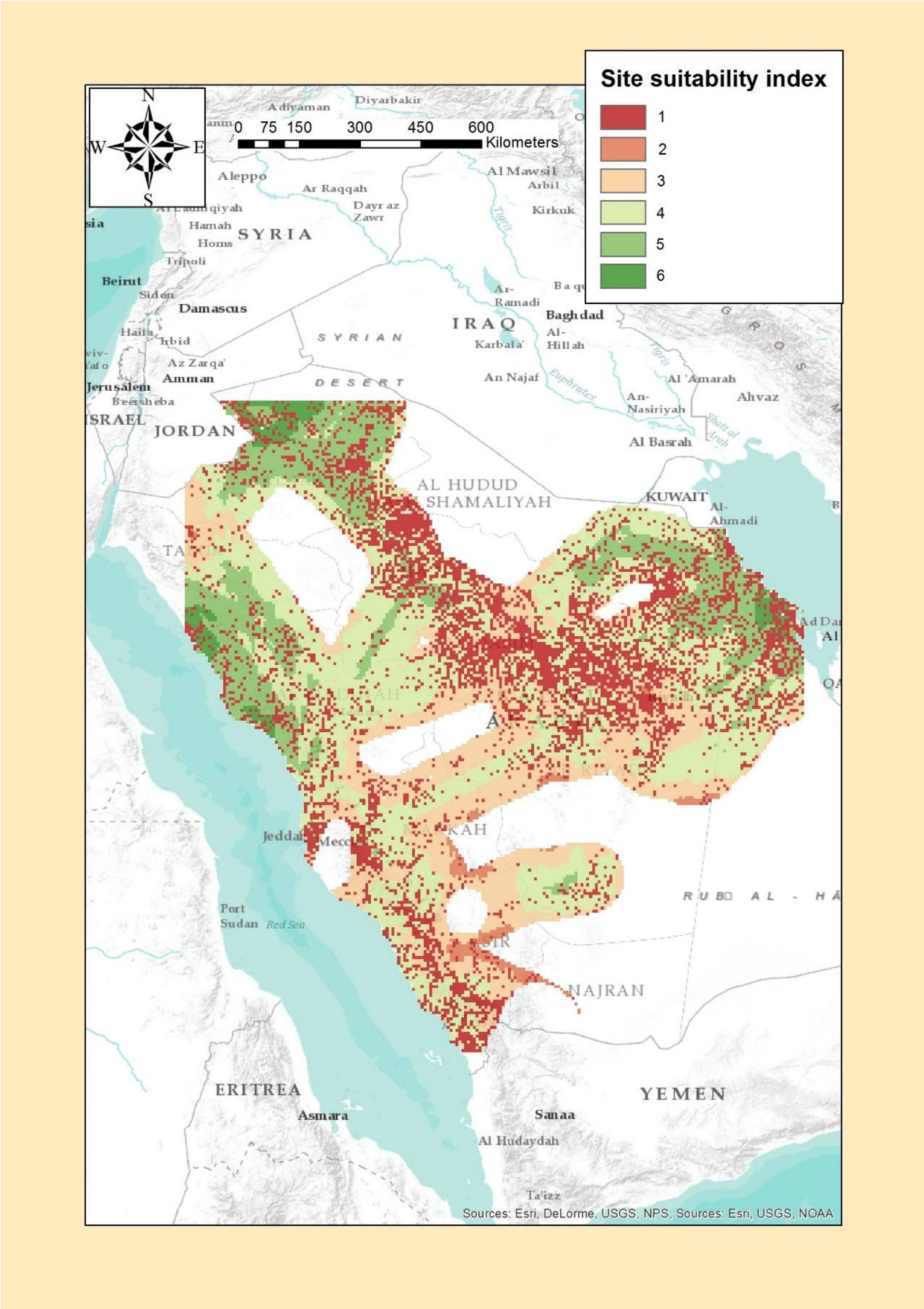

Fig. 10. Wind farm site suitability map.
1=least suitable 6=most suitable

Table 1

Restriction criteria from chosen wind farm site selection studies.

Study Criteria	Economic			Planning			Ecological	
	Wind speed /density potential	Buffer distance/ proximity from electricity grid, m	Proximity /buffer to roads & highways, m	Buffer distance from forests & parks, m	Buffer distance from airports, m	Buffer distance/ proximity from settlements, m	Buffer distance from lakes & rivers, m	
Turkey	200–400 W/m^2	×	×	3000-6000	3000-6000	1000-2000	2500-5000	Aydin, Kentel and Duzgun, 2010
Greece	5-7.5 m/s	×	5000-200	1000	3000	1500	1000	Latinopoulos and Kechagia, 2015
Denmark	250–650 W/m^2	×	×	300–800	5000–7500	500–1500	150–650	Hansen, 2005*
USA	×	Cost analysis	< 5000	×	×	> 2000	> 3000	Haaren and Fthenakis, 2011
UK	> 5 m/s	< 10000	< 10000	> 500	×	> 2000	> 400	Baban and Parry, 2001
Germany	> 4 m/s (at 10 m AGL)	×	>500	> 500	×	>500	×	Krewitt and Nitsch, 2003
Poland	Turbine output	> 200	>100	200-1000	3000	>500	> 200	Sliz-Szkliniarz and Vogt, 2011
Vietnam	Turbine output	×	>100	> 500	2500	> 2000	> 400	Nguyen, 2007
Sweden	Turbine output	>200	>200	×	2500	>500	> 100	Siyal et al., 2015

Table 2
Wind tower locations with hourly average wind speed, standard deviation, location, data duration and altitude.

Station #	Wind tower location	Av. WS, m/s at 10 m AGL	Standard Deviation	Data duration	Latitude	Longitude	Altitude (m)
1.	Abha	3.24	1.34	1978 – 2013	18.23	42.66	2084
2.	Al-Ahsa	3.59	1.89	1985 – 2013	25.29	49.49	172
3	Al-Baha	3.41	1.37	1985 – 2013	20.29	41.64	1021
4.	Al-Jouf	3.85	1.81	1974 – 2013	29.78	40.10	771
5.	Arar	3.61	1.72	1970 – 2013	30.91	41.14	552
6.	Bisha	2.50	1.15	1970 – 2013	19.99	42.62	1157
7.	Dammam	4.34	1.60	1999 – 2013	26.47	49.80	567
8.	Dhahran	4.35	1.65	1970 – 2013	26.27	50.15	17
9.	Gassim	2.96	1.39	1973 – 2013	26.30	43.77	650
10.	Gizan	3.27	0.96	1970 – 2013	16.90	42.59	3
11.	Gurait	4.25	2.17	1985 – 2013	31.41	37.28	499
12.	Hafr-Al-Batin	3.49	1.73	1990 – 2011	28.45	45.96	355
13.	Hail	3.24	1.32	1970 – 2013	27.92	41.91	1013
14.	Jeddah	3.63	1.32	1970 – 2011	21.67	39.15	12
15.	Khamis-Mushait	3.00	1.25	1970 – 2013	18.31	42.73	2054
16.	Madinah	3.18	1.14	1970 – 2013	24.48	39.60	631
17.	Makkah	1.45	0.76	1985 – 2013	21.43	39.81	310
18.	Najran	2.24	1.00	1974 – 2013	17.50	44.13	1203
19.	Qaisumah	3.71	1.89	1970 – 2013	28.31	46.13	355
20.	Rafha	3.82	1.76	1970 – 2013	29.64	43.50	447
21.	Riyadh-New	2.89	1.42	1984 – 2013	24.65	46.71	612
22.	Sharorah	3.32	1.31	1985 – 2013	17.49	47.12	722
23.	Sulayel	3.50	1.63	1970 – 1989	20.47	45.57	612
24.	Tabuk	2.79	1.31	1970 – 2013	28.39	36.58	770
25.	Taif	3.73	1.42	1970 – 2013	21.45	40.35	1449
26.	Turaif	4.13	1.87	1973 – 2013	31.68	38.65	813
27.	Wadi-Al-Dawasser	3.53	1.51	1978 – 2013	20.44	44.79	627
28.	Wejh	4.20	1.36	1970 – 2011	26.23	36.46	16
29.	Yanbo	4.11	1.73	1970 – 2011	24.08	38.08	14

Table 3
Constraints criteria for location of wind farm.

Criteria	Constraint factor	Considerations
High mean wind speed (>5 m/s)	Wind resource	Climatic
Proximity to roads (<10 000 m)	Access	Economic
Proximity to highways (<10 000 m)	Access	Economic
Proximity to national grid (<10 000 m)	Access	Economic
Buffer distance away from airports (>2 500 m)	Safe/aesthetic	Planning
Buffer distance from settlements (> 500 m)	Noise	Planning
Proximity to settlements (rating scheme)	Optimum utilisation	Economic

Table 4
Suitability score of selected criteria.

Criteria	Suitability score					
	Excellent-6	Very Good-5	Good-4	Mediocre-3	Low-2	Lowest-1
High mean wind speed, m/s	> 6	6 – 5.8	5.8 – 5.6	5.6 – 5.4	5.4 – 5.2	5.2 - 5
Proximity to roads/highways, m	< 2000	2000 - 4000	4000 - 5500	5500 - 7000	7000 - 8500	8500 - 10000
Proximity to national grid, m	< 2000	2000 - 4000	4000 - 5500	5500 - 7000	7000 - 8500	8500 - 10000
Proximity to settlements, m	2000 - 4000	4000 - 5500	5500 - 7000	7000 - 8500	8500 - 10000	< 2000

Table 5:
The fundamental scale according to Saaty, 1977.

Intensity of importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement slightly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is favored very strongly and its dominance is demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	When compromise is needed
Reciprocals	If one activity i has one of the above activities assigned to it when compared with activity j, then j has the reciprocal value when compared with i (i.e. 5 = 1/5 or .200)	

Table. 6.
The normalised pairwise comparison matrix and criteria weights

	Wind resource	Proximity to roads/highways	Proximity to national Electricity grid	Proximity to settlements	Buffer from airports	**Criteria weight %**
Wind resource	1	7	5	5	9	**60**
Proximity to roads/highways		1	1/3	1/3	2	**7.5**
Proximity to national electricity grid			1	1	4	**13.5**
Proximity to settlements				1	4	**13.5**
Buffer from airports					1	**5.5**

$\lambda_{max} = 5.21$ CI = 0.053 CR = 0.047