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Research paper

Wind farms selection using geospatial technologies and energy generation capacity in Gwadar

Farrukh Zahid [a], Ali Tahir [a], Habib Ullah Khan [b,*], M. Asif Naeem [d,c]

[a] Institute of Geographical Information System (IGIS), NUST, H-12, Islamabad, Pakistan
[b] Department of Accounting & Information Systems College of Business Economics, Qatar University, P.O. Box 2713, Doha, Qatar
[c] Department of Computer Science, National University of Computer and Emerging Sciences (NUCES), Islamabad, Pakistan
[d] School of Engineering, Computer & Mathematical Sciences, Auckland University of Technology, Auckland, New Zealand

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ABSTRACT

Pakistan has been a victim of energy crisis since last few decades. This energy crisis has adversely affected country's socio-economic development and continues to do so. The continuously increasing demand–supply gap has negatively impacted the economic stability of the country. With the recent awareness and development of alternate energy resources like wind and solar, the current energy crisis can be minimized. However, proper planning is essential for successful execution of these renewable energy projects. This study aims to identify the suitable sites for wind farms in District Gwadar, Balochistan using Geographical Information Systems (GIS) and Web-based Spatial Decision Support System (SDSS). In this study, multi-criteria decision making is applied which assists breaking down the site selection complexity. Multi-Criteria evaluation methods provides different set of procedures that facilitate decision making by analyzing different alternatives. The underlying geospatial and ICT technologies used in this analysis form the core component of the planning process. Gwadar is currently drawing investor's attention due to its geographical location, deep seaport, and proposed China–Pakistan Economic Corridor (CPEC). This research is useful for stakeholders of Wind Energy to explore the wind potentials using GIS as an interactive decision-making tool during the pre-feasibility stage.

Furthermore, this research has considered the environmental, social and economic aspects during the decision-making process of wind farm development. This is the strength of multi-criteria evaluation as differently weighted scenarios provide different output, depending on the factors considered of highest importance. A detailed analysis of the sites in terms of their wind potential and energy generation capacity has also been reported in this study. This long coastline of Balochistan with huge wind energy potential has not been explored yet and therefore this study will assist researchers to further explore this area and can have a positive impact on CPEC.

1. Introduction

Energy demand is increasing with the increase of population across the world. It is estimated that the world energy demand is gaining momentum with the annual growth of about 2% (Grob, 2010). This growth in population affect standard of life directly that causes the increase in consumption of fossil fuels. The consumption of these fossil fuels has a negative impact on the environment as they are a major cause of global warming (Aydin et al., 2010). The utilization of fossil fuels in large amount increases greenhouse gases concentration. This concentration has been rising over the last 250 years (Janke, 2010). Increasing population growth rate, limited economic opportunities and the burden of high energy demand are creating pressure on Organization of the Petroleum Exporting Countries (OPEC) (BP, 2014). As a result, energy sector shifted towards renewable generation source due to the environmental concerns associated with both nuclear power and fossil fuels. The electricity from renewable sources is becoming popular as the largest alternate source. The increase in cost and environmental problems for large scale power generation has enforced the world to get electricity from alternate energy sources. Planners and economists are in search of cheap and eco-friendly sources. In this research, we have explored the wind potential in context of Pakistan.

Pakistan is an energy deficient country which is facing serious challenges. The price of energy is increasing by large which is producing negative impact on the development of the country. In addition to domestic problems, the industry has also assured

* Corresponding author.
E-mail address: habib.khan@qu.edu.qa (H.U. Khan).

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from lack of enough power. For example, textile industry contributes 57% to the country's exports and is the primary victim of power outages. While multiple sectors are badly affected by inadequate and expensive energy supply, the industrial sector is cross subsidizing the energy supplied to other sectors. In recent years, severe shortage of electricity for long hours in most of the country was really a test for citizens. One of the major reasons is technological advancement which brings critical change in the lifestyle of people.

Due to the limited hydro resources and conflicting water resource management, the importance of energy production from renewable sources become more critical in the developing country's context. Due to various reasons including high investment cost (for both electricity generation and transmission), socio-economic and socio-political issues (such as water allocation among the provinces and resettlement of people), full capacity potential has not been exploited yet. The country has a considerable potential of wind energy as highlighted in several studies. Different studies reveal that the overall estimated exploitable potential of wind power resources in Pakistan is 132,000 MW (Siddique and Wazir, 2016).

Energy sector must move towards renewable generation source, due to the environmental concerns associated with both nuclear power and fossil fuels. The environmental concerns associated with both nuclear power and fossil fuels are driving the energy sector to move towards renewable energy sources. Sustainable sources (including wind, solar, biomass, hydro-power and geothermal) have almost zero emission of greenhouse gases and pollutants.

The electricity from renewable sources became the largest alternate source before the 2015. The increase in cost and environmental problems for large scale power generation have enforced the world to get electricity from noncongenitally sources. This is a good opportunity for the planners and economist to search out the cheap eco-friendly sources of power generation. Out of wind and solar, wind power has added the most shares in renewable technologies over a time period. According to Brower et al. (2014), Asia is leading in wind energy shares with 52%, followed by EU 32% and North America 8% (Brower et al., 2014). Furthermore, in Asia, China is contributing 39% of its shares from wind turbines. Increase in wind energy installation has grown about average rate of 24% per year, since 2000. About 45 GW power capacity wind farms were installed in more than 50 countries, in 2010.

The location of the country itself is highly crucial in terms of political and strategic importance. While the country neighbors are China, India, Iran, and Afghanistan, at its south lies the Arabian sea, which has a great wind potential. Currently in Pakistan different wind power plants are producing wind energies and they are mostly located in Sindh province close to the Arabian sea. This research highlights the suitable site selection for wind farms in south western area of the country district Gwadar, which has a huge wind potential (Ilyas and Kakac, 2006). The Gwadar location is the most significant aspect of CPEC. The CPEC is $ 46 billion project which intends to upgrade the country's Transportation network and will provide a link from Gwadar Port to Xinjiang region of China (Saeed, 2015). The CPEC is much associated with the Pakistan's development in years to come. Therefore, this is the right time to report the development projects such as energy (e.g., wind, solar etc.) in Gwadar area.

For long term alternate energy projects such as wind farms require careful planning. Several tools exist which can facilitate planning including GIS and multi-criteria decision process. The planning of a wind farm is essentially related to spatial multi-criteria decision-making process. There are number of factors which can influence the decision outcome such as social, cultural, political, environmental and economical etc. Spatial planning can be a challenging task for the decision makers. Often planners are not aware of the full range of the factors that are involved in the planning process (Juieta Schallenberg-Rodriguez, 2014). This research will provide best appropriate way to find the suitable sites for wind farms. The assessment for site selection is an iterative process and will impact the design and arrangement of the wind farm. To solve complex problem of site selection, Analytical Hierarchy Process (AHP) is applied as a multi-criteria decision analysis technique.

The unique contribution of this research is the selection of highly strategic Gwadar area, which is an important aspect of CPEC. Secondly, the AHP is applied with GIS which will form an SDSS. This means that a system is available for extensive analysis on wind turbines site selection. There is an added Web dimension which is highlighted in this research. With Web as a shared platform for SDSS, multiple stakeholders can be taken on board on energy projects through this portal. Finally, the sites are not only proposed based on geographical criteria but also wind analysis has been reported. The final choice of site selection is being made after combining the GIS part and the Wind analysis which make the overall results fruitful for the planners.

The remainder of this article is as follows. The related literature review is presented in Section 2. Section 2 describes the methodology in detail while Section 4 highlights the result and discussion. Finally, conclusions are given in Section 5.

2. Related work

To the best of our knowledge, no wind farms site selection studies are conducted in Pakistan using GIS and SDSS approaches. The existing studies are mostly done on estimating wind potential in the country. According to Shami (Shami et al., 2016), Balochistan has the highest wind potential as compared to other three provinces of Pakistan while another study mainly focuses on Gwadar district in Balochistan. In the latter study, Gwadar is again found to be more stable in terms of wind patterns as shown by Weibull distribution which is a standard practice to measure wind speeds and wind power densities. Few studies such as (Rodrigues et al., 2015) provide the cost benefit analysis considering wind parameters in combination with GIS for the feasible site selection of wind farms.

Typical site selection using multi-criteria is a semi-structured problem which can be tackled through SDSS instead of GIS. GIS provides spatial data handling and management, storage, and retrieval functionality as well as the visualization of data that make it powerful for site suitability analysis (Malczewski, 2006), for instance wind farm site selection. Alone GIS does not constitute SDSS because GIS just tackles the data; it does not guide a systematic approach to making complex decisions. Similarly, SDSS needs GIS plus advanced modeling capabilities in order to perform complex calculations. Therefore, the combination of GIS and SDSS is important when seeking solution to multi-dimensional spatial problems. In this context, a framework for SDSS is also proposed by Malczewski (2006) by considering Multi-criteria Decision-Making approach both on spatial and non-spatial data.

Diaz and Soares suggest the most suitable site for floating wind farms in the Atlantic continental European coastline. They used GIS approach for suitable site selection. In this research authors divide their goal into 3 stages. In the first stage they collect all the data and analyzes the information of the different regulatory bodies, maritime concessions, marine spatial planning, and other sources. In the next stage they exclude all the nit feasible sites which are less important for floating wind farms. In 3rd final stage authors characterizes the available locations based on five major categories that are spatially dependent: met ocean data, viability data, logistics, facilities, marine environment, and techno-economic data. The proposed methodology is implemented at the European Atlantic coast, with specific reference to Portugal, Spain, and France. Authors highlights the effective use of GIS based tool for suitable site selection for wind farms (offshore). The usefulness of GIS-based tool and model for the task of planning for sustainable offshore wind has been highlighted. The introduction of novel concepts to the GIS-based assessments of floating wind suitability in the form of layers representing high wind potential regions and long-term shore-normal components assisted the identification of productive and sustainable offshore wind farm locations. The method represents a simple support tool for decision-makers. The stakeholders can prioritize their activities with specific technical, environmental, and social constraints. Moreover, the technique permits the quick implementation of new scenarios (Diaz and Soares, 2020).

A multi-criteria GIS-based model for wind farm site selection using interval type-2 fuzzy analytic hierarchy process for Nigeria done by Ayodele et al. (2018). In this research to determine the best suitable site for wind farms in Nigeria, they develop GIS model type-2 fuzzy analytic hierarchy process. The main contribution in this paper is to show that Interval Type-2 Fuzzy Analytic Hierarchy Process can be combined with Geographic Information Systems to evaluate the best site for wind farm development using the case study of Nigeria. For economic and technical evaluation, authors used five criteria namely grid lines proximity, wind speed, near to town, closest to road and slope. Along with these criteria authors also focus on protected areas, water bodies, birds' hotpots, airports, and rivers as environmental and social factors. These constraint criteria were used to prepare constraint maps. This model highlights the use of fuzzy sets to represent expert's linguistic judgment with the aim of addressing the issues of uncertainty, vagueness and inconsistency in wind farm site selection decision making. The results of the study revealed that the best sites for wind farm development are basically located in the Northern part of Nigeria.

To find the suitable site for wind farms in Greece Vavatsikos et al. used GIS suitability analysis and simulation procedures. According to author now a day's energy from renewable sources is at the peak of policy action in reducing the fossil fuels. In this study authors develop a model with GIS and Multi-criteria Decision analysis (MCDA) for best decision making. Thus, decision-making frameworks that combine GIS-based suitability analysis with traditional financial evaluation techniques can significantly enrich the planning phase to achieve efficient installations in terms of required area reduction, power generation maximization and local characteristics examination. With respect to the realization of wind energy exploitation projects, the paper at hand proposes a framework capable of expanding the use of the traditional GIS-based derived suitability index to establishing portfolios. Moreover, the proposed framework is enriched by robust analysis using Monte Carlo Simulation (MCS), which provides significant insights regarding the stability of the derived portfolios and the projects that they comprise. The proposed framework is illustrated through a case study in the Thrace region in northeastern Greece (Vavatsikos et al., 2019).

Xu et al. use GIS and multi-criteria decision making approach for suitable site selection of wind farms. In this research author used GIS, IAHP and stochastic VIKO for best suitable site of wind farms in the Wafangdian region, China. They focus on two major factors one is productive safety and biodiversity conservation for feasible wind farm site. After getting results from IHAP and VIKO, author compares the results with actual locations. They found that this approach is much ideological for site selection of wind farms. According to authors this approach can be utilize for geothermal, solar, hydroelectric and biomass site selection (Xu et al., 2020).

A GIS-based multi-criteria model for offshore wind energy power plants site selection in both sides of the Aegean Sea by Tercan et al. (2020). In this research they find suitable site for wind farms for offshore location with the help of Multi-criteria model and Geographical Information System (Tercan et al., 2020).

Mekonnen and Gorsevski (2015) mentioned the studies in the context of different countries which used GIS in their wind farms site selection, as shown in Table 1.

The existing literature as highlighted in the table is mostly based on multi-criteria SDSS. They include techniques such as collaborative planning, internet-based SDSS, spatial-group choice and stand-alone systems. Few of the studies also mention the thresholds used in Individual GIS criteria map such as while considering population; what should be the ideal distance of locating a wind farm away from population. Similarly, the threshold values of movements of birds, land use, ports, airports etc. have been followed based on existing successful implementations worldwide. Section 3 details specific criteria and their thresholds.

In terms of modeling, AHP is a very widely used technique which helps in streamlining the decision maker's preferences. The approach is tested on several site selection studies and yielded good results (Javaheri et al., 2006; Uyan, 2014; Tsoutsos et al., 2015). On the other hand, few authors have utilized fuzzy logic which provides more preciseness to the decision outcome (Akbari et al., 2008; Chang et al., 2008; Liu et al., 2014; Ayodele et al., 2018; Li et al., 2020).

The shared SDSS portals are also common with the advent of Web 2.0 (O'reilly, 2007), which allows more interactivity and computations on-the-fly. In this regard, a Web-based GIS application for collaborative planning and public participation for wind farm site selection is proposed by Simão et al. (2009). There are number of studies which highlight the overall collaborative SDSS such as involvement of Participatory Geographic Information System (PGIS) (Mekonnen and Gorsevski, 2015; Boroushaki and Malczewski, 2010). PGIS is the concept where public participation is encouraged for decision making through a Web portal. According to the authors, spatial planning is a complex task in which decision makers (planners) are not completely aware of the factors ranges which are involved during the implementation phase. Due to this reason, they add public participation for site selection of wind farm. In order to design such portals, there are number of Web GIS technologies (both closed source and open source) exist McArdle, (McArdle et al., 2010). Recently there has been a trend of using open-source geospatial technologies in order to avoid expensive licensing options and also due to more geospatial awareness among the common users (Ballatore et al., 2011).

Given the current scenario of CPEC, the geo-political location of Gwadar district in Balochistan, and the wind potential in the said area, this study can be very useful from both investors and researcher's viewpoint. This research can be used as a guide for the stake holders such as energy department to choose the sites which are best for wind turbines. This investigation will be useful to validate wind energy potential in the coastal region of Pakistan.

3. Methodology

This section is divided into five parts. The SDSS section is described as intelligence, design, and choice phases. Here the study area is described followed by the evaluation criterion maps explanation in the context of framework of multi-criteria decision analysis. The evaluation criterion maps are discussed both as constraints and attribute maps. A decision matrix has been created according to decision rules and decision makers preferences followed by sensitivity analysis. The wind analysis is discussed on the selected sites by using wind resource assessment and

Table 1
GIS-based Wind Site Selection.

Country	Authors	Country	Authors
China	Byrne et al. (2007) and Xu et al. (2020)	England	Baban and TP (2000) and Simão et al. (2009)
Vietnam	Nguyen (2007)	Brazil	Dutra and Szklo (2008)
Spain	Ramirez-Rosado et al. (2008) and Hurtado et al. (2004)	Australia	Bishop and Stock (2010) and Bishop and Stock (2010)
India	Ramachandra and Shruthi (2005)	United States	Hansen (2005), Janke (2010) and Gorsevski et al. (2013)
Turkey	Aydin et al. (2010)	Iran	Azizi et al. (2014) and Noorollahi et al. (2016)
Greece	Vagiona and Karanikolas (2012), Tegou et al. (2010) and Vavatsikos et al. (2019)	Indonesia	Pambudi and Nananukul (2019)
Taiwan	Yue and Yang (2009)	Thailand	Bennui et al. (2007)
Bangladesh	Anwar Khan (2014)	Nigeria	Ayodele et al. (2018)

wind power cost calculations. Finally, a web architecture based on open-source geospatial technologies is discussed towards the end of this section. Area wise district Gwadar is the 9th largest district of province Balochistan. The study area is shown in Fig. 1. Gwadar lies between 25 01^{prime} 58^{Prime}–25 49^{prime} 3^{Prime} North latitude and 61 36^{prime} 38^{Prime}–65 14^{prime} 19^{Prime} East Longitude.

This district has 4 Tehsils and 13 Union Councils. According to 1998 census, its population was 185,498 and projected population for year 2010 was 264,168. The total number of housing units 33680 were recorded in census 1998. The climate of Gwadar is hot and humid while the highest rainfall of 227 millimeter (8.9 in.) in 24 h was recorded in June 2010. The annual rainfall is about 100 mm (3 in.) while Gwadar has a coastal boundary with Arabian sea.

To solve a complex spatial problem multiple stakeholder, play an important role for the solution. For a desirable outcome different stakeholder convey different levels of information about the modules of the problem and clear expectations, replicating their individual experience. The basic methodology for this research is explained in Fig. 2.

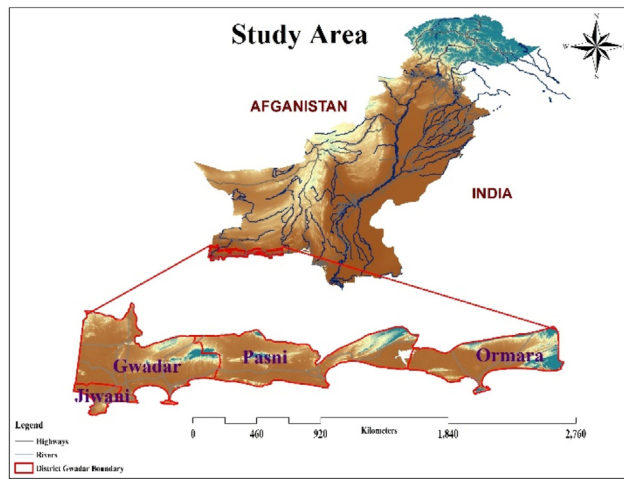

Fig. 1. Study area district Gwadar.

3.1. Intelligent phase- GIS

For wind farm site suitability multiple variables are used to represent the social, physical, human and environmental factors. The geographical model includes these variables. The criteria which are used are physical features, wind resources, obstacles, and terrain. The environmental factors include vegetation, wildlife, land use sensitive areas (wetlands or presence of endangered plants species). Finally, the human factors include proximity to development and public recreational facilities. All these datasets were obtained from various sources as described below.

Wind speed data were collected from Pakistan Meteorological Department (PMD), National Aeronautics & Space Administration (NASA) and Modern-Era Retrospective Analysis for Research & Applications (MERRA) project. The selected sites should be eco-friendly therefore only those sites which have no negative impact on environment are considered. The impact of birds on wind turbines is very serious matter due to bird's migratory routes as well as the physical presence of birds along the coast. For the Gwadar district area, birds' hot spots are collected from World Wildlife Federation (WWF) Pakistan. Population is also an important factor while choosing sites for wind farms. In this regard, residential areas were digitized. Additionally, for the transportation, ports are also digitized with the help of base map layer. The locations of existing grid stations in district Gwadar were obtained from National Electric Power Regulatory Authority (NEPRA). The wetlands and forest in the study area were extracted from Landsat 8 imagery acquired from U.S Geological Survey (USGS) website.

The tools (both geospatial and non-geospatial) employed in this study include the following. Starting from ArcMap, which provides a handy tool for the analysis and handling of geographical data in an efficient way. Several tools in ArcMap were used in this study for the purpose of site selection. For example, stacking was used for band combination of Landsat 8 imagery. Similarly, NDVI was used for the extraction of wetlands and forest zone. For digitization, editing tool was utilized. To generate constraint maps against each criterion, buffer was used. Vector to raster conversion tool was used for conversion of each vector layer into raster for overlaying analysis and for map making. The overlay tool was used to perform overlay for each layer. Retscreen was used for the calculation of wind profile curves and for the selection of wind turbines. This software also helped to estimate the cost of wind farms. Udig was used to symbolize the layers that are published through Geoserver in an efficient way. The other tools related to Web GIS implementation are described in Section 3.3. Almost all the maps were derived from the raw data (as mentioned previously) were in shape file vector format. To apply the suitability restrictions, the vector data were converted to raster data for processing. Each criterion is explained below.

Wind speed is an important factor for developing a wind farm in an area which is economically viable. Standard wind turbines require a minimum speed of 3–3.5 m/s to operate effectively (Grassi et al., 2012). This is almost a key consideration as better the resources of wind, the greater will be the power production and hence, more revenue.

Roads must fall within the wind farms construction sites. This is also very important from planning viewpoint. roads are costly to build, locations outside of this minimum distance, but near roads are preferred, order to reduce construction costs. For the

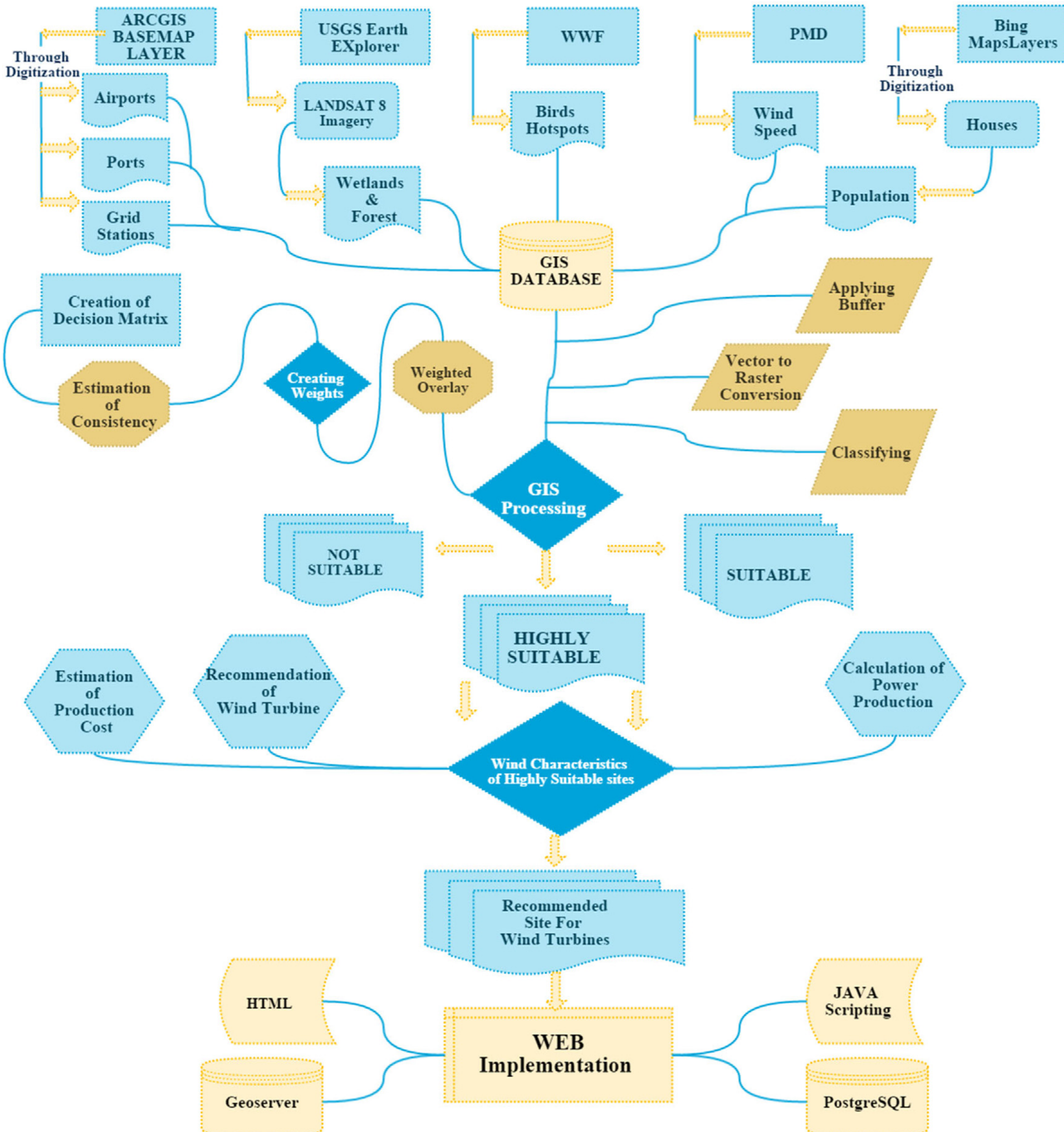

Fig. 2. Methodology.

Table 2
Ranging score for GIS layer-highway region.

Category	Ranging Score (km)	Score	Class
1	10>	0	Less Suitable
2	1–10	0.5	Suitable
3	>1	1	Highly Suitable

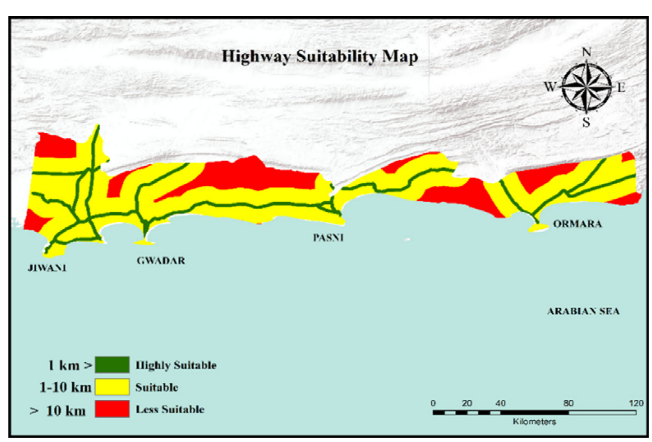

Fig. 3. Highway suitability zone.

transportation of wind equipment, it is important to consider nearest highway access while selecting suitable sites for wind farm (Tegou et al., 2010). Suitability classes of highways used in this study are shown in Table 2 while the map of highway is illustrated in Fig. 3.

Typically, there exist both risks and cost for building electricity infrastructure in order to connect wind farms to the id. In general, the distance must be kept minimum. The location of existing grid station in District Gwadar was obtained from NEPRA. Closer locations will be considered more suitable, as existing infrastructure will help cut down on construction costs (Tegou et al., 2010).

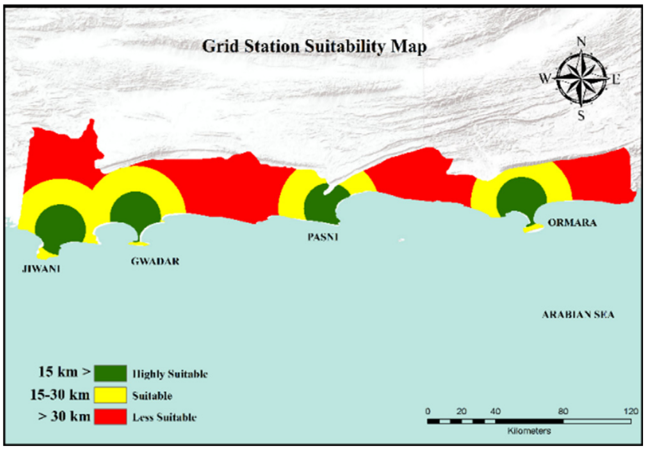

Fig. 4. Grid station suitability.

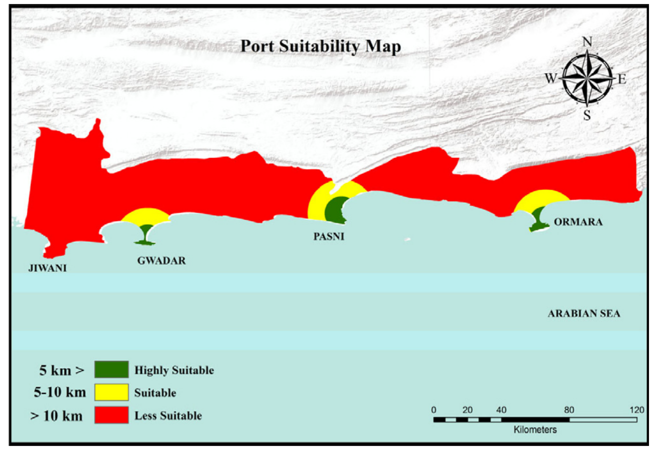

Fig. 5. Port suitability zones.

Table 3
Ranging score for GIS layer-grid station classes.

Category	Ranging Score (km)	Score	Class
1	>30	0	Less Suitable
2	15–30	0.5	Suitable
3	10>	1	Highly Suitable

Table 4
Ranging score for GIS port region.

Category	Ranging Score (km)	Score	Class
1	>10	0	Less Suitable
2	5–10	0.5	Suitable
3	>5	1	Highly Suitable

Table 5
Ranging score for GIS layer—airport region.

Category	Ranging Score (km)	Score	Class
1	>5	0	Not Suitable
2	5>	1	Suitable

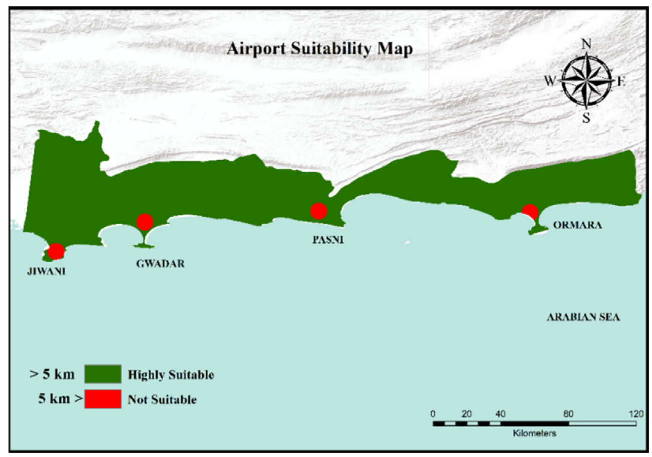

Fig. 6. Airport suitability zone.

Table 6
Ranging score for GIS layer—residential classes.

Category	Ranging Score (km)	Score	Class
1	1>	0	Not Suitable
2	>1	1	Highly Suitable

Table 7
Ranging score for GIS layer—birds hotspot classes.

Category	Ranging Score (km)	Score	Class
1	1>	0	Not Suitable
2	>1	1	Highly Suitable

Suitability classes of grid are highlighted in Table 3 while the map of grid station is shown in Fig. 4.

Commercial wind turbines have huge structure which is made of different large size components. Their logistics is an easy task. These components are normally preferred to transport through ships to the nearest port of proposed site. Therefore, the location of port is very important. District Gwadar has a deep seaport. Suitability classes of port are highlighted in Table 4 while the map of port is illustrated in Fig. 5.

Wind farms can be hazardous to aviation, as their height can conflict with low flying aircraft, particularly given their visibility. These gigantic structures can also affect the performance of navigation and communication of control tower (NASAG, 2012). According to Nguyen (2007), while selecting wind farms one important consideration is the aviation areas which impact safety and visibility. Nguyen mentioned that wind turbines should be at least 2500 meters away from the airport region (Nguyen, 2007). In this study areas less than 5 kilometers from the airport are considered as not suitable for wind farms. On the other hand, areas more than 5 kilometers from the airport are considered as highly suitable for wind farms. Suitability classes of an airport are highlighted in Table 5 while map of airport zone is shown in Fig. 6.

Air passing through the blades of wind turbines in order to rotate the blades produces noise. This noise has negative pact on population (Helga and Moiloa, 2009). Turbine noise increases as the wind speed increases and decrease in case slow speed. Although new technology in turbines manufacturing have reduced the noise emission, wind turbines must be located away from the residential areas. Suitability classes of residential areas are highlighted in Table 6 while the map of residential areas is illustrated in Fig. 7.

Birds are also the soft targets and may collide with wind turbines (Drewitt and Langston, 2006). Therefore, it is vital give due importance to designing and installation of wind turbines in order to minimize the collision. In this study, bird's movement and presence in the area are given due importance. Suitability classes of bird's hotspot are highlighted in Table 7 while the map of bird's safety zone is shown in Fig. 8.

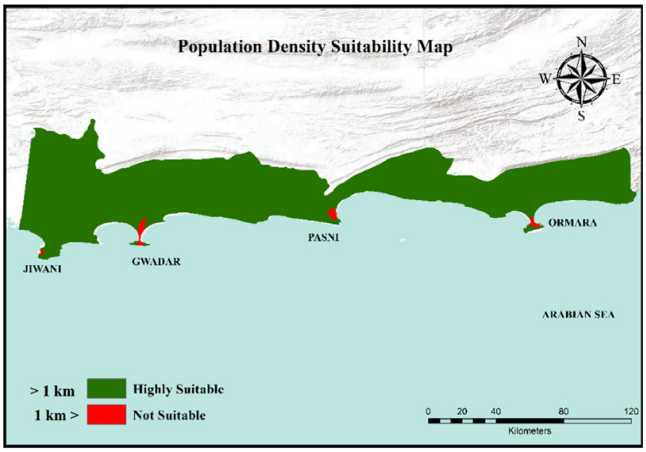

Fig. 7. Population density suitability.

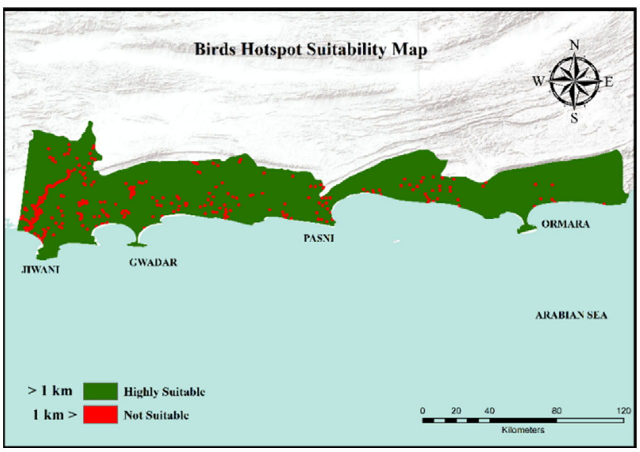

Fig. 8. Birds suitability zone.

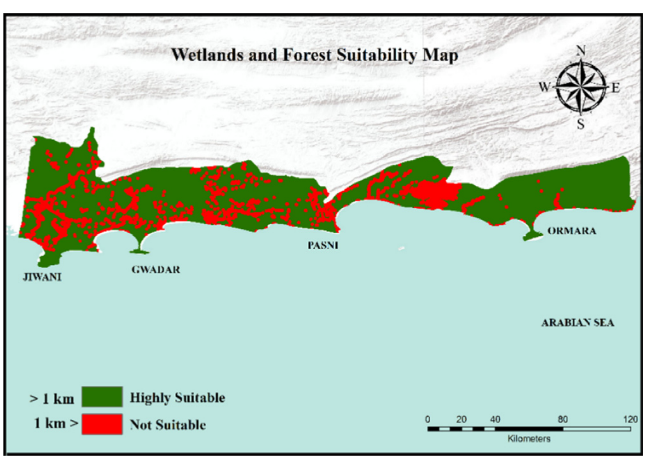

Fig. 9. Wetlands and forest suitability zone.

Wetlands are also considered in the proposed study. Generally, there is a lack of development infrastructure in the wetland areas due to environment related issues. Similarly, areas of existing tree cover are not considered ideal for the installation of wind related equipment. Suitability classes of wetlands and forest are highlighted in Table 8 while the map is shown in Fig. 9.

Data for each of these parameters were mapped in ArcMap. All these layers were converted to raster format, resampled to thirty meters by thirty meters which was the highest available resolution data set.

Table 8
Ranging score for GIS layer—wetlands and forest region.

Category	Ranging Score (km)	Score	Class
1	1>	0	Not Suitable
2	>1	1	Highly Suitable

3.2. Design Phase-Multi-Criteria Decision Analysis

The development and analysis of possible solutions are proposed with the help of a model in the design phase. This section focuses on weights assignments to each criterion using AHP. The steps are as follows:

First, the unstructured problem is defined with the objectives and desired outcomes in hand followed by breakdown of the complicated problem. Then pairwise comparisons are performed, and eigenvalue method is used to find out the relative weights. Finally, the consistency is calculated and aggregates. A pairwise consistency comparison is used to determine the weights of each criterion. With this approach, factors are then compared to determine their relative importance and weighting for each scenario.

As per the above steps, first the weighted scenarios were created, with factors compared against each other. The highest weighted factors that influence construction and maintenance costs of wind turbines and the industrial facility were selected. These factors were proximity to grid station and proximity to roads followed by port. Socio-environmental scenario considered factors relating to social acceptance and ecological concerns to be of greatest importance while choosing suitable sites. In this category, most important criteria were proximity to residential area, distance from airports, distance from the bird's hotspot and wetlands and forest in decreasing order of importance. The values for each factor were multiplied by a value of 100 as a standardization process.

According to Saaty (1988), AHP procedure generally involves six steps. With the help of Saaty's scale for pairwise comparison, scores were given to each criterion when comparing one to other. This scale ranges from 1 to 9. 1 denotes equal importance; 2 equals to moderate importance; 3 moderate importance; 4 moderates to strong importance; 5 strong importance; 6 strong to very strong importance; 7 very strong importance; 8 very to extremely strong importance; 9 extreme importance. Decision matrix was formed by the comparison of each criterion. The value of diagonal matrix is assigned 1, when comparing criterion with itself, while the other values are placed as per the decision rules highlighted above using Saaty's scale for pairwise comparisons. The decision matrix of criteria is shown in Table 9.

After assigning scores in decision matrix, the sum of each column was calculated. Each value of decision matrix as divided by its column sum. Next the sum of each row was calculated. This sum is the actual weight of each criterion. The total sum of all criterion must be equal to 1. These weights were multiplied by 100. In the next step sum of each column divides the value of each score assigned in the pairwise comparison matrix. The average of each row generates the weights of each criterion.

3.3. Choice Phase-Multi-Criteria Decision Analysis/GIS

After obtaining the weights as described in previous section, it is necessary to verify the consistency. Normalized matrix will be used for the value of Eigen value λ of the comparison matrix.

Table 9
Pairwise comparison of criteria: decision matrix A.

	Population	Port	Grid Station	Highway	Airports	Birds Hotspot	Wetlands and Forest
Population Density	1	6	7	5	4	3	5
Port	0.16	1	2	3	0.33	4	5
Grid Station	0.14	0.5	1	6	0.33	3	3
Highways	0.2	0.33	0.16	1	0.33	5	5
Airports	0.25	3	3	3	1	5	7
BirdsHotspots	0.33	0.25	0.33	0.2	0.2	1	5
Wetlands and Forest	0.2	0.2	0.33	0.2	0.14	0.2	1
Total	**2.29**	**11.28**	**13.83**	**18.40**	**6.34**	**21.20**	**31.00**

Table 10
Normalized matrix.

	Population	Port	Grid Station	Highways	Airports	Birds Hotspots	Wetlands and Forest	Sum	Weights
Population	0.383	0.747	0.796	0.452	0.785	0.190	0.146	3.50	9.141
Port	0.064	0.124	0.227	0.271	0.065	0.253	0.146	1.15	9.255
Grid Station	0.055	0.062	0.114	0.542	0.065	0.190	0.087	1.12	8.331
Highways	0.077	0.041	0.019	0.090	0.065	0.316	0.146	0.75	7.043
Airports	0.096	0.373	0.341	0.271	0.196	0.316	0.204	1.80	7.521
BirdsHotspots	0.128	0.031	0.038	0.018	0.039	0.063	0.146	0.46	6.147
Wetlands and Forest	0.077	0.025	0.038	0.018	0.028	0.013	0.029	0.23	5.591
								Total	53.029

This normalized matrix is generated by dividing each column of Decision Matrix by the weight obtained from the pairwise comparison. The normalized matrix is shown in Table 10. The value of 1 must be greater than or equal to the number of criteria (in our case it must be greater than or equal to 7 since the number of criteria used are 7).

$$\lambda = \frac{53.03}{7}$$

$$\lambda = 7.57$$

In our case total number of criteria are 7 and the obtained value of is 7.57. This shows that the condition is true our case. The next step is to estimate the Consistency Index (CI), which is shown in Eq. (1) while the formula or computation of Consistency Ratio (CR) is shown in Eq. (2).

$$CI = \frac{\lambda - n}{n - 1}$$
$$CI = \frac{7.57 - 7}{7 - 1} = 0.095 \tag{1}$$

$$CR = \frac{CI}{RI} = \frac{0.095}{1.32}$$
$$CR = 0.07267 \tag{2}$$

RI is random index provided by Saaty and it depends on the number of criteria.

RI is random index provided by Saaty and it depends on the number of criteria. In our case the value obtained from the pre-defined values will be 1.32 as proposed by Saaty. If CR $<$ 0.10 the ratio indicates a reasonable level of consistency. If CR $> =$ 0.10 the ratio indicates an inconsistent judgment and the relative criterion pair wise comparison matrix needs re-consideration and the whole process must be repeated. In order to get to this step, sensitivity analysis was performed and after number of attempts in readjusting the criteria values, 0.072 value was obtained which indicates that the consistency is reasonable.

In this study initially 13 different criteria were selected for the site selection procedure. Ignoring the importance of criteria which had not significant impact on the site selection were removed. There were a few criteria which were decomposed while others were made non-redundant. As a result, only 7 criteria were selected in the final process which has significant impact on site selection for wind farms. Necessity and sensitivity tests were performed to check the consistency of weights. It is very important to check the consistency of weights. The normalized matrix helps to check consistency of weights. From normalized matrix Eigen value, 1, CI and CR were calculated. This validates that the mathematical calculations performed are within the reasonable limits.

3.3.1. Wind resource assessment

This section explains the wind characteristic for district Gwadar. Wind resource assessment can be defined as the "assessment of wind speed with the increasing height". In other words, with the increase in height wind speed also increases. The wind is a vector quantity that has magnitude, speed, and direction. It is noted that the height may affect the wind velocity. In the context of wind power, the outstanding feature of wind resources is its changeability. This changeability describes the reason of different climatic regions on Earth's surface.

To set up wind farm two factors are very important i.e., shape of wind profile and the position of the terrain at the building site. The unevenness of terrains can seriously affect the three-dimensional wind flow. In rising terrain with ridge, there may be an overshoot of the wind profile curves. For installing wind farm, it is necessary to observe the terrain to ensure maximum output. Therefore, the aerodynamic nature of wind has a strong impact on the wind Profile. The lower portion of this atmosphere is called Planetary Boundary Layer (PBL). The PBL is subject to face the earth's surface friction. Within PBL, layer properties depend on Coriolis Effect and the roughness of surface. The roughness of surface is described by the roughness length z_0. The common values of are shown in Table 11.

The wind speed at different heights in Gwadar district are calculated with the help of Eq. (3). The reference wind speed U (z) is measured at height z, where U (z_2) is the wind speed at height z_1.

$$U_{z2} = U_{z1}\left(\frac{z_2}{z_1}\right)^{\alpha} \tag{3}$$

Table 11
Typical values of roughness factor.

Roughness Class	Roughness Length Z0	Land cover types
0	0.0002 m	Water surfaces: seas and lakes
0.5	0.0024 m	Open terrain with smooth surface, e.g., concrete, airport runways, mown grass etc.
1	0.03 m	Open agricultural land without fences and hedges; maybe some far apart buildings and very gentle hills
1.5	0.055 m	Agricultural land with a few buildings and 8 m high hedges separated by more than 1 km
2	0.1 m	Agricultural land with a few buildings and 8 m high hedges separated by approx. 500 m
2.5	0.2 m	Agricultural land with many trees, bushes, and plants, or 8 m high hedges separated by approx. 250 m
3	0.4 m	Towns, villages, agricultural land with many or high hedges, forests, and very rough and uneven terrain
3.5	0.6 m	Large towns with high buildings
4	1.6 m	Large cities with high buildings and skyscrapers

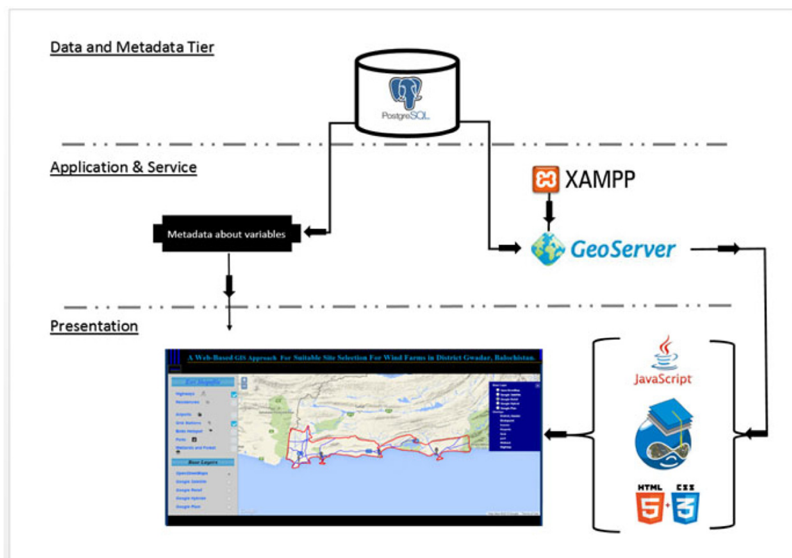

Fig. 10. Web-based SDSS architecture.

The wind power cost can be measured in several ways including financing cost, equipment cost, total installation cost variable and fixed operating and maintenance (O&M). The wind projects require heavy investments as comparing with other renewable technologies but has no fuel cost. The economic key parameters for cheap wind energy are investment cost, O&M cost, capacity factor, economic lifetime and cost of capital.

3.3.2. Web-based SDSS architecture

For web architecture, open-source geospatial technologies are preferred. There has been a lot of awareness in recent years as far as the volunteered contribution towards open-source development is concerned. Typical web architecture is a three-tier model. The first tier is called the presentation tier. The JavaScript, CSS and HTML work at the presentation layer while Open-Layers is used as a geospatial web mapping library to display interactive maps onto the web interface.

The technologies which work at the presentation tier are also called client-side technologies. Dreamweaver is also used for web development. The next layer is called the application layer. This layer is responsible for publishing GIS layers from database to application server. All criteria maps are published through Geoserver on to a Web map. XAMPP is free open-source software by Apache, which has been used to publish maps and relevant data to the Web. It provides a platform for web server solutions and Interprets scripts written in PHP and other programming languages. Finally, the data tier is responsible for all tasks related to Database Management System (DBMS). PostgreSQL has been configured along with PostGIS, as a spatial extension, which supports vector and raster data. PostgreSQL also provides data security and it allows other software to retrieve data on request. The web architecture is shown in Fig. 10.

4. Results and discussion

This section presents the results and discussion of the findings. Based on the approach outlined in Section 3, wind sites are proposed. After this, each site is further analyzed for wind power production using RET Screen software and results are discussed in terms of turbine type and financial analysis on given sites. Finally, the Web interface designed for proposed SDSS is discussed. All the factors with their limitations and restrictions were buffered in ArcMap and then converted into maps. These maps were overlayed with the help of overlay tool in ArcMap. While overlaying process weight of each criterion was also applied on each factor. By processing all these steps, a final suitability map for wind farm

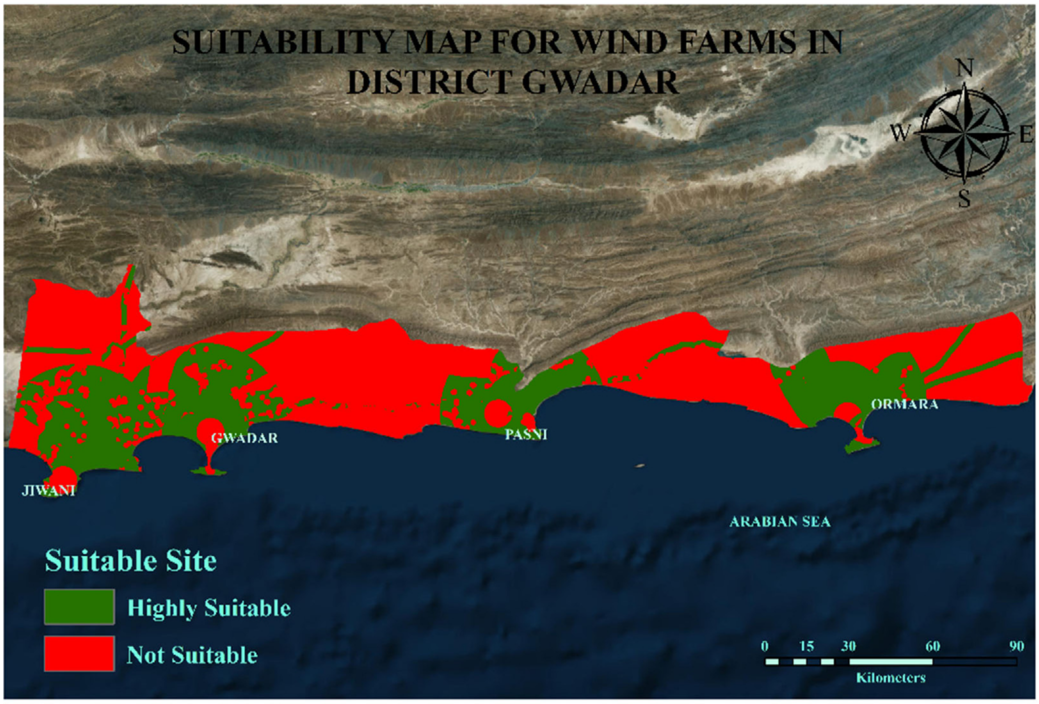

Fig. 11. Suitability map for wind farms in district Gwadar.

was obtained. This map depicts the suitable sites for wind farms (see Fig. 11). All the green areas as shown in the final map are highly suitable while red color shows all those areas which are not suitable.

Each tehsil (a local word used to denote the administrative area) of district Gwadar has some suitable areas for wind farms. However, the best site needs to be selected which should be economical as per the objective of this research. In order to perform economic analysis, wind speed data were analyzed on each obtained site.

Wind profile curves of all four tehsils with different ground conditions such as terrains are depicted in Fig. 12a while Figs. 12b–12e show individual tehsils along with their maps. Each tehsil shows different behavior of wind speed according to the height. Each site with different wind speed varies different output with different capacity factor. Ormara tehsil shows the best profile curves indicating that this site is the best among all.

Various wind turbines of multiple manufacturers with different power ratings and hub heights were tested for all sites to select the most suitable one using RET Screen software. Maximum capacity factor and maximum annual energy generation were considered as selection criteria. Capacity factor is the ratio of maximum energy generated by wind turbine to its rated power. A high-power rating turbine with greater capacity factor indicates the maximum usage of wind turbine capacity. Following figures show the plot of capacity factor and energy generated in Giga watt hours w.r.t 28 different wind turbines. The results show that two wind turbines showed the maximum energy generation and capacity factor i.e. FL3000 manufactured by Furhlaender and W2E120/3000 manufactured by Wind to Energy. For the case below, we have considered FL3000 turbine.

Fig. 13 shows the power curve of the aforementioned wind turbines.

Capacity factor calculated for Site 1 is 31.8% and energy generated is 142.155 GWh. This indicates a promising wind potential for installation of wind farm (see Fig. 13a).

For site 2 Energy generated is ranging from 118.48 GWh to 151.50 GWh with maximum capacity factor of 33.9% (see Fig. 13b).

For site 3, minimum capacity factor is 27.4% while maximum capacity factor is 34.3%. Annual energy generation using FL3000 is 153.29 GWh (see Fig. 13c).

Capacity factor calculated for site 4 is 34.7% with total energy generation of 155.144 GWh showing that wind speed can be effectively utilized in the proposed location (see Fig. 13d).

Energy generation for Site 5 is in the range of 122.565 GWh to 155.863 GWh and capacity factors are ranging from 28% to 34.9% (see Fig. 13e).

5. Conclusion

Given the strategic and geo-political importance of Gwadar, a study was conducted on wind site selection. The wind analysis was performed along with GIS and multi-criteria decision analysis techniques. 7 evaluation criteria (highway, grid station, port, airport, residential areas, birds' hotspots and wetlands) were investigated with the help of AHP and their overall impact on the wind farms site selection was determined. GIS techniques such as reclassification and buffering were applied on each constraint map layer. The use of the overlay function to combine all the layers produced final potential sites. It was concluded that Tehsil Ormara is the best site for the installation of wind farms. The capacity factor of Tehsil Ormara lies between 30 to 36% for each wind turbine which is acceptable for wind farm installation. The Ormara site is found to be eco-friendly as the site does not produce negative impact on wildlife and human life. Similarly, the site also is safe for aviation services. The Makran coastal highway is also going through the Ormara that can facilitate the transportation. Also, there is a good deep seaport in Tehsil Ormara that will be beneficial for the transportation of wind turbines equipment. Overall, Installation of wind farms in Tehsil Ormara will yield good amount of electricity as the detailed analysis on energy generation capacity is performed. This approach can be positively utilized for the installation of small wind farms for industrial purposes. This study can easily be replicated for the suitable site selection of solar installation for power generation or other suitability purposes by replacing solar characteristics with

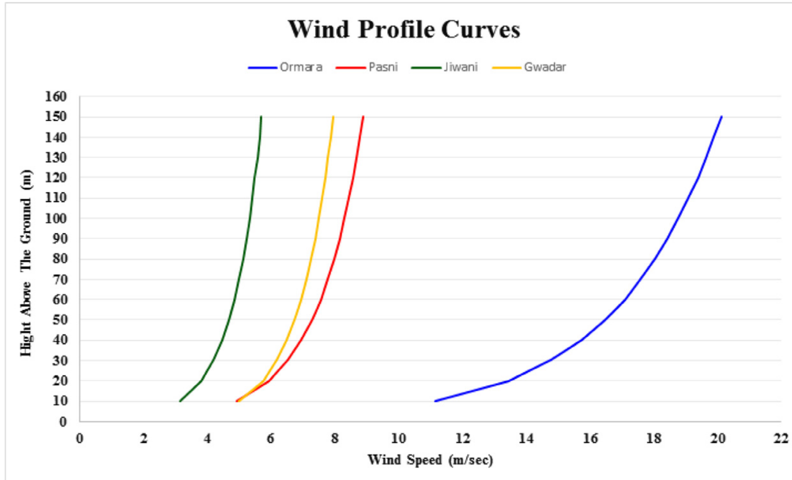

Fig. 12a. Wind profile curves.

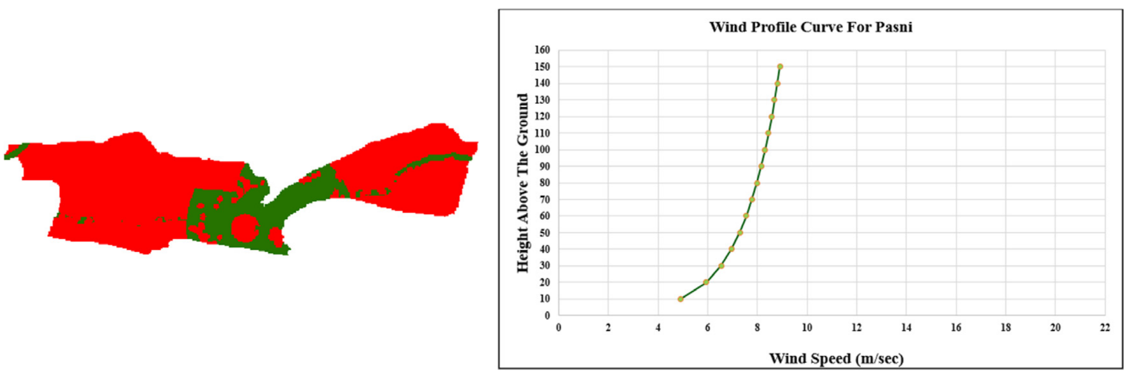

Fig. 12b. Wind profile curve for Pasni.

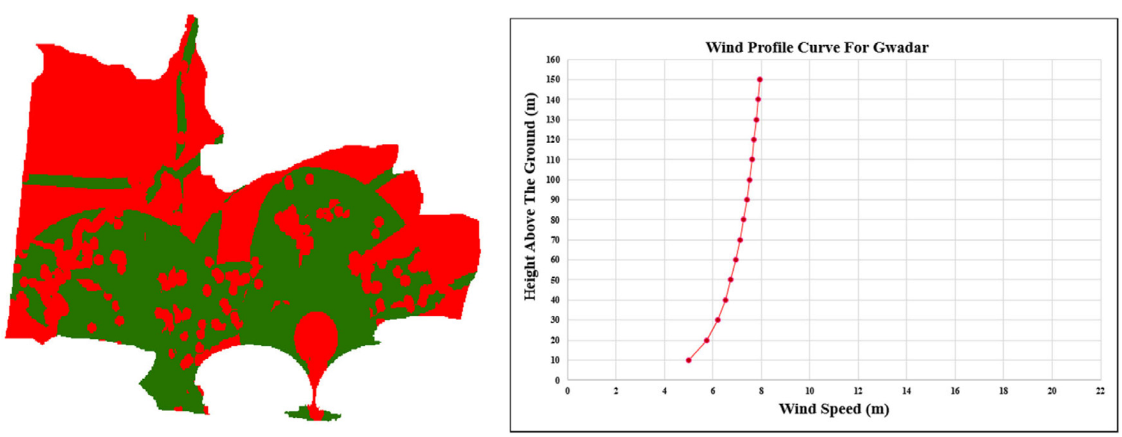

Fig. 12c. Wind profile curve for Gwadar.

that of wind. for wind farm installation. The Ormara site is found to be eco-friendly as the site does not produce negative impact on wildlife and human life. Similarly, the site also is safe for aviation services. The Makran coastal highway is also going through the Ormara that can facilitate the transportation. Also, there is a good deep seaport in Tehsil Ormara that will be beneficial for the transportation of wind turbines equipment. Overall, Installation of wind farms in Tehsil Ormara will yield good amount of electricity as the detailed analysis on energy generation capacity is performed. This approach can be used for the installation of small wind farms for industrial purposes. This study can easily be replicated for the suitable site selection of solar installation for power generation or other suitability purposes by replacing solar characteristics with that of wind.

While there are strengths of the developed approach, there are some improvements which are left for future work. For example, GIS can be used for the strategic Environmental Impacts Assessment (EIA). The stake holders can be enforced to choose the best suitable sites which should not violate any EIA issues. Similarly, there are other criteria which can be incorporated in order to further strengthen the approach. In order to take multiple stake holders on board, a collaborative web SDSS can be developed.

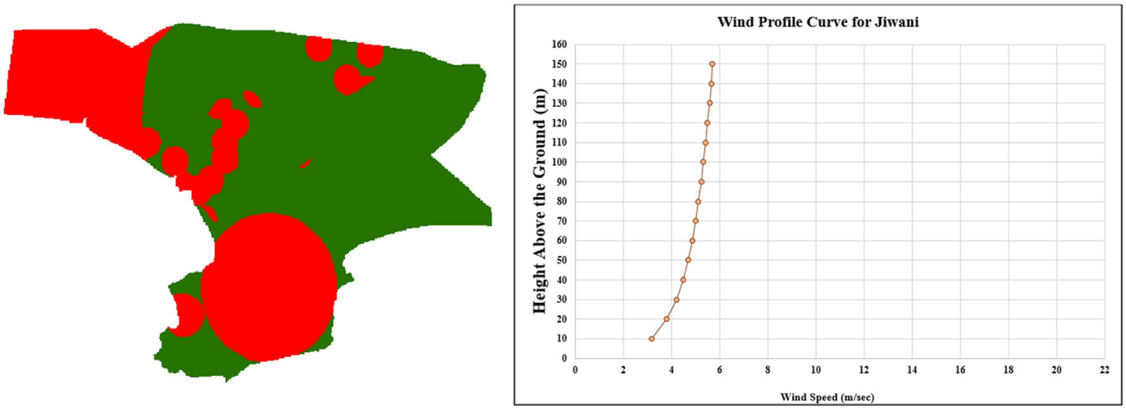

Fig. 12d. Wind profile curve for Jiwani.

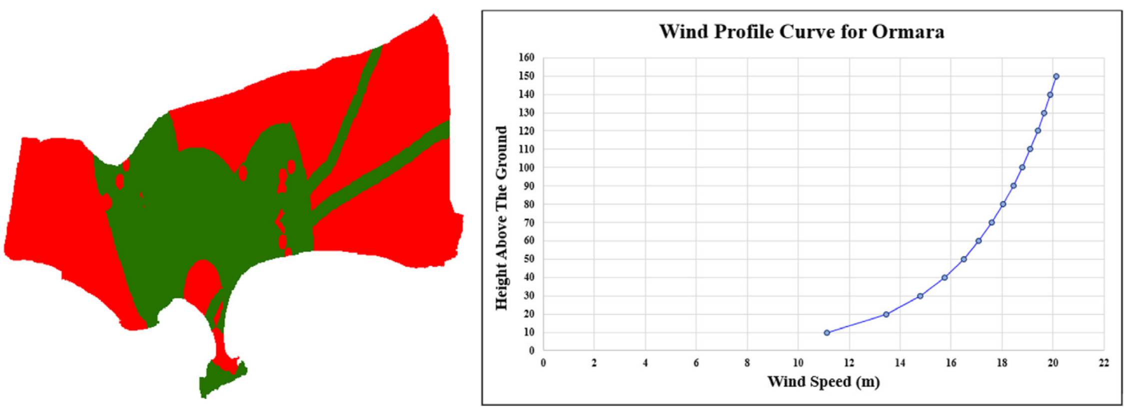

Fig. 12e. Wind profile curve for Ormara.

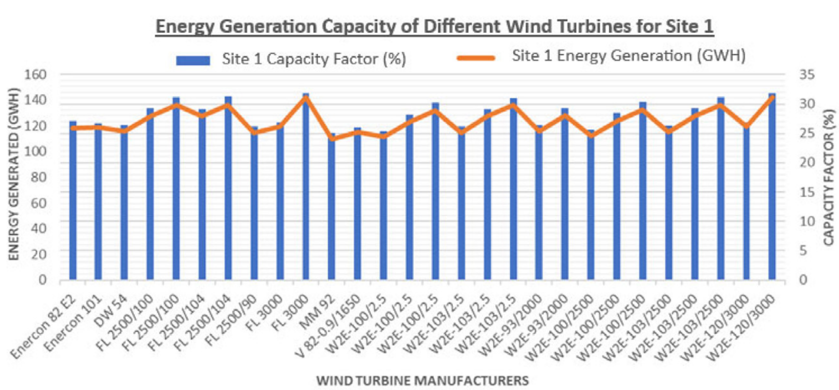

Fig. 13a. (a): Energy generation capacity of different wind turbines for site 1.

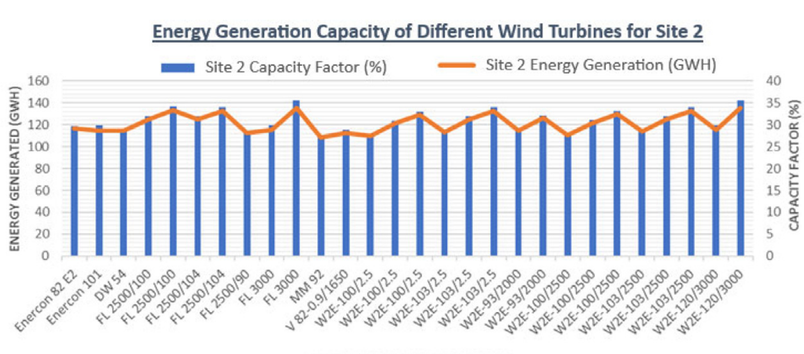

Fig. 13b. Energy generation capacity of different wind turbines for site 2.

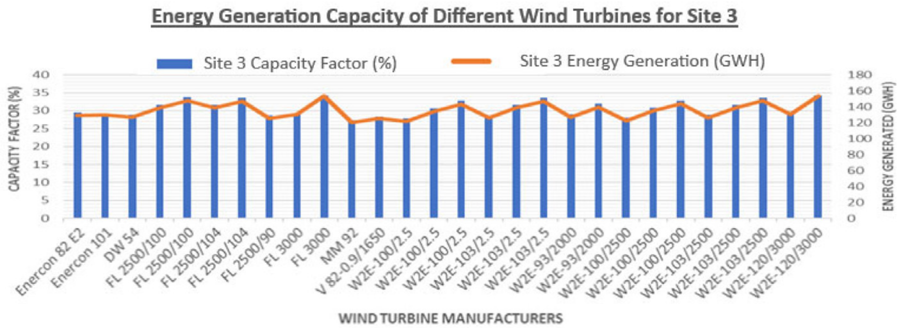

Fig. 13c. Energy generation capacity of different wind turbines for site 3.

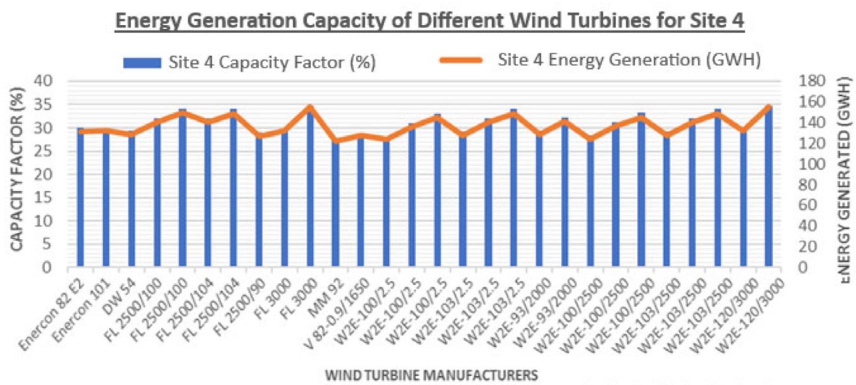

Fig. 13d. Energy generation capacity of different wind turbines for site 4.

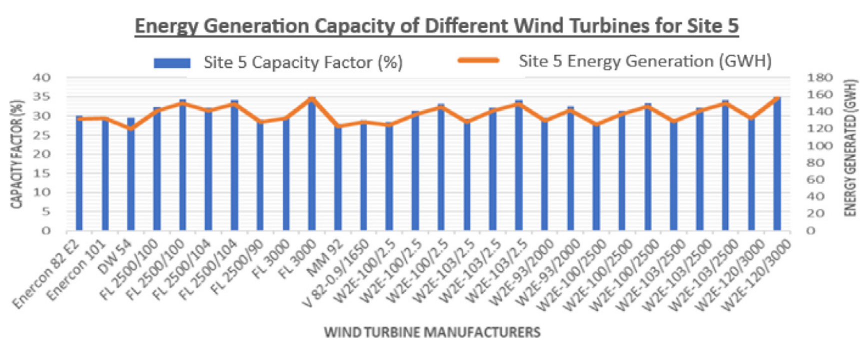

Fig. 13e. Energy generation capacity of different wind turbines for site 5.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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