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WIND ENERGY POTENTIAL IN YOBE, NORTHEASTERN NIGERIA: AN AIDED TECHNIQUE THROUGH GEOGRAPHIC INFORMATION SYSTEM AND REMOTE SENSING

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ABSTRACT

The role of wind energy and other renewable energy sources in combating climate change cannot be overemphasized. Many countries including Nigeria have so far implemented policy measures to promote renewable energy. Moreover, the most important step to be taken in order to effectively harness renewable energy is to estimate their potentials in terms of viability and sustainability. This study was focused on evaluate the wind energy potential zones in Yobe State, northeast Nigeria, using integrated multiple criteria decision-making analysis (MCDA), Geographical Information System and Remote Sensing (GIS-RS), and Analytic Hierarchy Process (AHP) methods. Weibull distribution statistical method was applied to validate the GIS-RS based analysis. The study revealed a wind speed variation ranged from 1.48 to 7.15 m/s and an average annual wind power density of about 80 W/m^2. About 90 % of study area has about 90 % wind power density of about 85 W/m^2 and below while the remaining 10 % is covered by wind power density ranged between 85 and 616.89 W/m^2. The results of the study showed that the area is viable for wind power generation and distribution. Furthermore, the wind energy resource will yield favorable economic gain for the study area. Thus the study concluded that Yobe is a suitable area for wind power generation both at medium scale generation, and standalone connection system.

Keywords: Wind energy, Renewables, Geographic information system, Yobe, Remote sensing

INTRODUCTION

Wind energy is a renewable and sustainable energy source for generating electricity through the application of wind turbines. The energy source has a much smaller impact on environment when compared to burning fossil fuels. Wind energy generation entails the production of electrical energy by converting wind kinetic energy into rotational energy of turbines' blades and subsequently converting the energy into electricity using aerodynamic force from the rotor blades. Nigeria is endowed with sufficient energy resources that include reserves of crude oil and gas, coal, and renewable energy sources. Bioenergy, hydropower, solar, and wind are some of the abundant renewable energy sources in the country. Although Nigeria has implemented policy measures to promote renewable energy, only few of the renewables contribute to power generation in the country. Hydropower, for instance, is the major contributory renewable source that accounts for about 21 percent of the country's power generation. The resource ranked second after natural gas which accounts for about 77 percent of the entire power generation, while bioenergy and solar contribute 0.1 percent each. About 55 percent of the population have access to electricity (CTHN 2015). The rural populace, especially in northern part of the country, depend mostly on traditional sources of energy (fuelwood and charcoal) for basic energy needs, despite the attendant consequences on climate change and its devastating effect. Accordingly, the need to harness all the viable renewables for optimal energy mix that can ensure sustainable and environmentally friendly energy practices cannot be overemphasized. Being that energy policy and environmental policy go hand in hand, wind energy remains a viable option to ensure environmental sustainability and security of energy supply. Although wind is free, clean, and boundless, evaluation of environmental imminence and impact of power plant location are necessary to unravel the environmental trade off that are involved. Wind energy assessment of many possible sites is a necessity for appropriate wind classification (Ajayi *et al*. 2013; Oyedepo et al. 2012), to achieve sustainability and security of generation and supply.

Wind energy is a perceptible phenomenon associated with movement of air masses. The movement of the air (wind flow speed) is caused primarily by differential solar heating of the earth's surface. Wind flow speed is a fundamental atmospheric quantity that defines movement of air masses from region of high pressure to the region of low pressure. In Nigeria, the annual mean wind flow speed at the standard 10 meter heights above the ground varies from 2 to about 4 m/s from south (coastal) to far northern regions (CTHN 2015).

Over recent years, many studies have been conducted using a number of techniques, mostly the statistical Weibull distribution, to explore wind energy potential for power generation in different parts of Nigeria. For instance, Ngala *et al*. (2007) employed the Weibull distribution and conducted a statistical analysis of wind energy potential in Maiduguri, Borno state northeastern Nigeria. The statistical analysis was able to characterized the economic feasibility of wind energy for electricity generation and supply in Maiduguri. Ajayi *et al.* (2013) applied wind flow speed data to different statistical tests in comparison to Weibull probability density function to analyzed the electricity generation potential from wind at Kano, northwestern Nigeria. Oyedepo *et al.* (2012) studied the wind speed characteristics and energy potential in selected locations in the southeastern part of Nigeria. A review of wind energy potential and the possibility of wind energy grid integration in Nigeria was as well conducted (Alabi and Olulope 2018). Essentially, the energy crisis in Nigeria has stirred up interest in scientific studies of various energy sources for power generation and distribution (Adedayo et al. 2021; Adewuyi *et al*. 2020). Fagbenle et al. (2010) attempted to evaluate wind energy potential of Potiskum and Maiduguri of Yobe and Borno states respectively, using the Weibull distribution method. The Weibull distribution method has been employed in many studies for evaluation of wind energy potential (Ojosu *et al*. 1990; Owebor *et al*. 2021; Ilbahar *et al.* 2019; Mosfequr *et al*. 2013).

While most of the studies above stuck around the statistical Weibull distribution method for evaluation of wind potential, very few, or none of the studies (especially around the study area), integrated multiple dimensional approach using robust data processing tools such as ArcGIS to develop stronger wind potential model. For instance, Pilar (2018) and Shirgholami *et al*. (2016) have deployed Geographic Information System (GIS)-based technique, using the ArcGIS processing tool for wind power site selection in Andalusia (Spain). Gagliano et al. (2013) used the GIS-based approach and assessed the performance of micro wind turbine. evaluate wind power potential zones across the study area. The GIS-based technique is essentially a multi-dimensional tool used in solving multi-dimensional problems that involve spatial factors. The aim of this study was to integrate multiple criteria decision-making analysis (MCDA) within Geographical Information System and Remote Sensing (GIS-RS) environment, using Analytic Hierarchy Process (AHP) method to evaluate wind energy potential zones in Yobe, Northeast Nigeria, while a statistical method, the Weibull distribution was applied to validate the GIS-RS based analysis. The AHP technique is a multiple criteria analysis tool which simplifies complex problems in a hierarchic way. The GIS-RS based analysis was conducted using ArcGIS 10.3.1. software. The ArcGIS is a geographical information system (GIS) software with the capacity to handle and analyze multiple dimension datasets such as climatic data and lots more. ArcGIS is a vast-reaching software for multi-dimensional analysis.

MATERIALS AND METHODS

Study area

The study area lies within latitude $10^0$05’00’’N to $13^0$03’00’’N and longitude $9^0$06’00’’E to $12^0$05’00’’E, with total land area of about 47,153 square kilometers. The area is located at an elevation of about 350 meters above sea level, with annual mean temperature of about 32 centigrade, and an average sea level pressure of about 4.0 millibar (mb). The annual high temperature in the area explains why there is high demand for power (electricity) supply. Electricity demand is tied to a number of climatic variables, especially the atmospheric temperature (Ali *et al*. 2013). The area has a demography of about 4 million people with 3 percent annual increase rate (PHC). Most of the populace are however, rural dwellers with little or no access to electricity (Babagana and Kolo 2021). The annual mean wind flow speed in Yobe is about 4.04 meter per second. The area is subdivided into seventeen administrative boundaries (Figure 1).

Software validation

Complex analysis involving spatial factors are conducted time and again using the ArcGIS software, some of which are included here. The ArcGIS is a powerful data processing tool for more reliable spatial analysis (Lawal *et al.* 2021). In order to calculate wind turbine index, ArcGIS software has been proved as an essential tool to carry out a number of spatial analysis to that effect (Al-Shabeeb *et al*. 2016). The study was **to** identify potential sites for wind turbine in the North West of Jordan, were in, GIS with Analytic Hierarchy Process was used. Digitization, conversion and analysis operations have been carried out to design a regional spatial planning guide and to assess location selection decisions of landfill sites embedded in the Antalya–Burdur–Isparta Environmental Plan using the ArcGIS software (Tercan *et al*. 2020). Datasets including solar irradiance, slope, aspect, proximity to transmission lines, land use/land cover, distance from major roads, distance from settlements and water bodies were executed, processed and calculated in the ArcGIS (Iqbal *et al*. 2020).

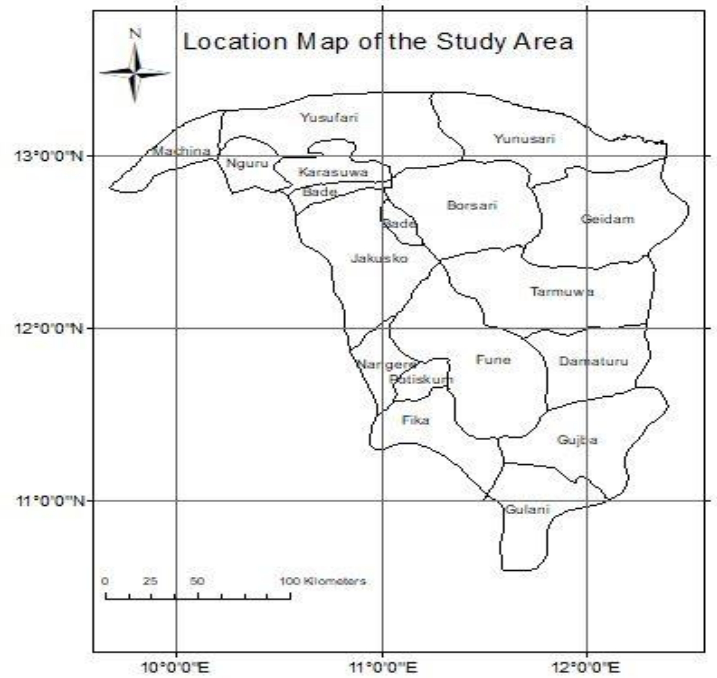

Figure 1: The location map of the study area showing administrative boundaries across the area, obtained from geospatial analysis

Table 1: The selected criteria and their respective ranking, based on the peculiarity of the study area

Criterion	Ranking
Wind power density (WPD)	5
Topography & Geology (TG)	4
Slope (SL)	3
Land Use (LU)	2
Waterways (WW)	1

Material and sources

The datasets required for wind potential zone mapping in this study were acquired from different sources. Ten years' mean wind speed GIS data (2008 – 2017) were obtained from Global Wind Atlas on the web: https://www.globalwindatlas.info/. Topography and geologic (geomorphology) data were obtained from Landsat 8 courtesy of the United State Geological Survey (USGS). Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) was equally obtained from the USGS on the web: https://earthexplorer.usgs.gov/. Ten years' conventional meteorological wind speed data (2011 – 2020) were form Nigeria's Meteorological Department of Federal Ministry of Aviation.

Multiple criteria decision-making analysis (MCDA) was applied within GIS environment using Analytic Hierarchy Process (AHP) method. A statistical method, the Weibull distribution was used and wind power potential of a portion (Damaturu) of the study area was estimated to validate the GIS-RS analysis in this study.

GIS-RS based analytic hierarchy process

Pairwise Comparison technique was employed to compute relative priorities of various criteria namely; technical, socio-economical, and environmental criteria within the study area, and suitable Pairwise Comparison Matrices (PCMs) were holistically developed for mapping of wind power potential zone based on the peculiarity of the area. A priority scale for the PCMs' elements was adopted from 1 to 5 as per Table 1 while Tables 2 and 3 show the PCMs adopted for the purpose of this study. The scale values 1, 2, 3, 4, and 5, represent equal importance, intermediate, moderate importance, strong importance, and extreme importance respectively. The selected criteria (in order of importance) are wind power density, Slope, Topography and Geology, Land use, and waterways. The criteria selection was such that existing environment remains unchanged and conflict over land use prevented. The selection was designed involve the economic efficiency of wind energy utilization while catering for as many needs as possible. Ranking and weightage of the criteria were applied based on peculiarity vis-à-vis viability of wind power generation in the study area. The overall weightages of all categories and subcategories were calculated and processed as per the Tables 2 and 3. In the process, environmental protection has been taken into account to determine the inclusion or exclusion of a criterion.

Digital elevation model (DEM)

DEM square mesh was applied using Kriging interpolation method the for three-dimensional models in this study. The Kriging method has the capacity to use limited set of sampled data points to evaluate the value of a variable over a continuous spatial field. A total of thirteen DEM tiles of 30 m resolution were acquired to cover the entire study area. The tiles were mosaicked such that a single tile (raster) for the study area was developed. The raster layer was projected from EPSG: 4326 Geographic Coordinate System (GCS) to Coordinate Reference System (CRS). The projected raster was then clipped to fit in area extent of the study. The DEM raster was also interpolated and voids (pixels with on data) were filled.

Topography and geologic data

The geospatial data acquired was used and an interpretive geologic map developed. The geologic map provided some guides on roughness or otherwise for land topography vis-a-vis soil stability requirement for wind power plant site suitability. The data was processed, and specifically classified using Symbology tool wherein, a number of colorants were applied for smooth analysis (Fig. 2). Land use and waterways were spatially analyzed as in Figures 3 and 4.

Wind data

Air density, mean wind speed, and mean wind power density data were processed as per Figures 5, 6, and 7 respectively. The wind data were ab initio in Raster format (without Attribute Table). Hence the Raster Datasets were copied and converted from 32-bit floating point raster to 32-bit signed integer raster. Attribute Table was then built on the 32-bit signed integer raster, using the Build Raster Attribute Table tool. The processed data were further categorized into different colors for clear analysis. The categorization was performed using the Symbology tool as well. Slope variation in the area was assessed to ascertain the roughness of the terrain (Fig. 8).

Based on the overall weightages calculated, thematic maps for wind power density, slope variation, topography and geology, land use, and waterways were integrated to map out the wind power potential zones (Fig. 9).

Weibull distribution function

The Weibull two parameter Probability Density Function (PDF) was used to analyze wind power density using the conventional wind data. The Weibull analysis was performed on wind dataset of 10 years (2011 – 2020) for Damaturu (a portion of the study area). The analysis was purposely for comparison and validation of the GIS-RS based analysis. Equation 1 to 3 were used for the analysis.

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (1)$$

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (2)$$

$$v_m = c\mathcal{T}\left(1 - \frac{1}{k}\right) \quad (3)$$

Where k and c are Weibull shape and scale parameters respectively. $f(v)$ is probability of observing wind speed, and $F(v)$ is the cumulative distribution function of observing wind speed. v_m is the mean value of wind speed, and $\mathcal{T}()$ is the gamma function of ().

Economic costs and trends

Estimating and understanding the project costs and benefits are essential elements of planning any energy development project. Wind energy project provide many economic benefit that include direct and indirect employment, lower electricity rates in wind-rich regions, and local tax revenue. The cost of wind energy largely depends on turbine and project sizes, and location (land lease payments). The major economic impact derived from wind energy development is the energy's ability to offset energy costs. As financial incentive, wind turbine typically pays for itself after some years, even though it will have high upfront costs. In essence, evaluation and understanding of developments and trends in wind power market is key to effective planning and management of wind energy project.

According EERE (2022), domestic wind-related job in the U.S grew to a record number in 2021, with more than 120,000 Americans now working in the wind industry. The over 13,000 megawatts (MW) of new utility-scale wind capacity driving the job growth in 2021 is largely attributed to significant improvement in the cost and performance of wind power technologies vis-à-vis supportive government policies. With the addition of 13,413 MW, the US got a cumulative capacity total of 135,886 MW, enough to power 39 million American homes annually. As wind turbines continue to grow in size and power, the average nameplate capacity of newly installed wind turbines is at 3 MW-up 9% from 2020. In 2011, no turbines used blades that were up to 115 m in diameter, but in 2021, about 90% of newly installed turbines feature such rotors (115 m and above).

Lower wind turbine pricing has significantly pushed down installed project costs over the last decade. The average wind turbine prices in 2021 ranged between \$800 and \$950 per kilowatt (kW), while the average installed cost of wind projects was \$1,500/kW. This suggested a down more than 40% since the peak in 2010. Lower installation costs lead to energy produced at lower cost, with the average cost of energy for utility-scale wind power down to \$32/MW-hours in 2021.

RESULTS AND DISCUSSION

All the relevant thematic maps were prepared from GIS-RS based AHP analysis of DEM and wind datasets covering a period of ten years (2008 – 2017), while conventional meteorological wind data covering the period from 2011 to 2020 was applied for the Weibull statistical as presented in Table 4. The analysis of geologic dataset was also captured with different geologic formations, namely; Cretaceous (K), Lower Cretaceous (KL), Mesozoic (Mi), Quaternary (Q) and Tertiary (T). others area Tertiary and Cretaceous (TK), Triassic (Ti) and Precambrian (pCm) as per Fig 2. The air density in Yobe revealed a variation ranged between 1.08 to 1.13 kg/m^3 (Fig. 5). High air density of 1.12 kg/m^3 and above prevails in the northeast and southern part of the area. About 60% of the entire area revealed a region of high air density ranged between 1.11 and 1.13 kg/m^3, while low air density region stretches across southeast and southwest, with air density value of 1.11 kg/m^3 and below. The variation in air density is consequent upon the change in altitude from north to south. The area is a near-flat terrain at 325 m elevation, although with slim between 350 and 360 m in the south. This however accounted for the slope variation ranged from 0 to about 67 % Fig 8). About 50% of Yobe exhibits a slope variation of less than 20 %, which suitable for wind power plants.

Table 2: The calculated weights for the selected factors using the Analytic Hierarchy Process (AHP)

Factors	WPD	SL	TG	LU	WW	Weight
WPD	5	4	3	2	1	0.45
SL	5/2	4/2	3/2	2/2	1/2	0.21
TG	5/3	4/3	3/3	2/3	1/3	0.15
LU	5/4	4/4	3/4	2/4	1/4	0.10
WW	5/5	4/5	3/5	2/5	1/5	0.90

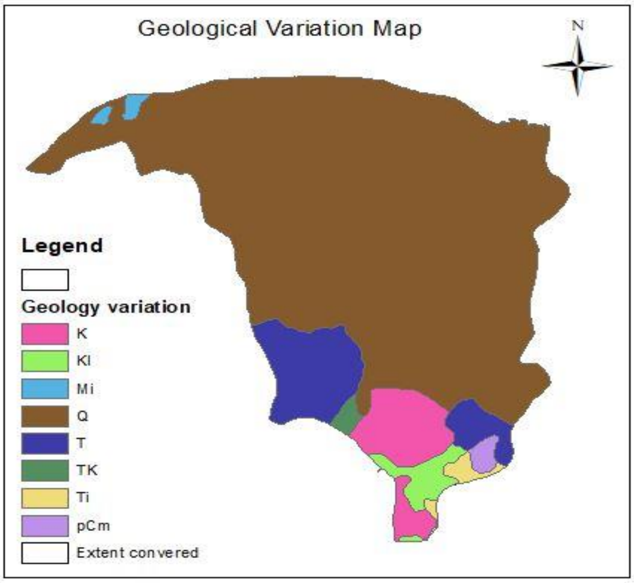

Figure 2: The geologic map of the study area, obtained from the Geographic Information System and Remote Sensing (GIS-RS) based analysis

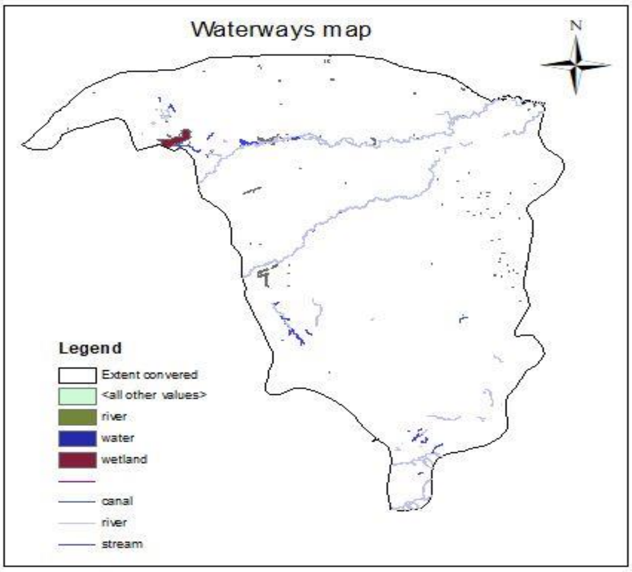

Figure 3: The waterways map showing water bodies across the study area, as obtained from the GIS-RS based analysis

Distance from residential area and alternative land use options area quite encouraging in the study area (Fig. 4). The topographical characteristics for the area reveal such features as river, canal, stream, and wetland, with adequate flat areas where wind flow will not be interrupted (Fig. 3). Fig. 6 and Table 4 respectively provide the GIS-RS based and the Weibull statistical annual wind speed available at the standard height of 10 m above ground level. The viability of wind energy generation of an area, to a large extent, depends on sufficient wind speed at the height at which turbines are to be installed. Choice of wind turbine design must be based on the average wind velocity at the area. Wind energy potential for a given area can be formulated with wind power density which represents the effect of wind speed distribution and wind speed (Suvire, 2011). For the GIS-RS based analysis in this study, the wind speed variation ranged from 1.48 to 7.15 m/s. Most of the area however, revealed a variation of 3.68 m/s and below. The Weibull statistical analysis reveals wind speed variation ranged from 0.08 to 2.45 m/s for Damaturu, which is in agreement with the GIS-RS based analysis (Fig. 6). The statistical analysis therefore validates the GIS-RS based analysis and suggests the viability of the later in wind energy potential delineation and mapping.

Table 3: The overall weightages of subcategories of the selected criteria, calculated using allocated ranking

Subcategories	Ranking	Overall weightages
	WPD in W/m^2 (specific weight is 45)	
0 – 40	1	45
40 – 60	2	90
60 – 80	5	225
80 – 160	3	135
160 – 600	3	135
	SL in %(specific weight is 21)	
10 – 20	5	105
20 – 50	3	63
50 – 100	1	21
	TG (Topography and Geology) specific weight 15	
Q	5	75
Ti & pCm	3	45
Kl & K	2	30
Others	1	15
	Land Use (specific weight is 10)	
Crop land	2	20
Built up land	1	10
Water bodies	1	10
Land without shrub	5	50
Land with shrub	2	20
Fallow land	3	30

Table 4: The results of monthly wind power density variation across the study area using the Weibull distribution function analysis (Weibull parameter K and C also obtained from the statistical analysis) in the statistical period of 2011 – 2020

Period	Wind speed (m/s)	K	C	WPD (W/m^2)
January	1.16	3.76	4.87	106.18
February	2.41	1.50	6.78	207.10
March	1.46	3.37	5.67	154.01
April	1.12	3.47	4.81	94.15
May	1.37	3.17	4.49	76.40
June	1.35	2.86	4.39	70.10
July	1.24	3.36	4.21	60.42
August	1.03	4.51	3.96	57.04
September	0.86	3.91	3.41	34.20
October	1.31	1.36	4.79	61.64
November	1.06	4.02	4.81	97.31
December	0.89	4.90	4.63	90.36
Wet season	1.06	4.02	4.81	97.31
Dry season	1.21	3.76	4.97	106.20

Wind speed and direction can vary depending on the characteristics of topography (Brower 1992). Topography and prevailing wind conditions determine turbine placement and spacing within wind power plant. In flat areas where there is nothing to interfere wind flow, at least 2600 – 6000 m^2/MW may be required (Kikuchi 2008). More land may be needed in areas with more rugged or complex topography and wind flow interference. Wind turbines are usually sited on power plant that have slope smaller than 10 – 20 % (Baban and Parry 2001). Garrique or maquis, for instance are more advantageous than forests as land cover for wind power plant sitting (Tegou et al. 2010).

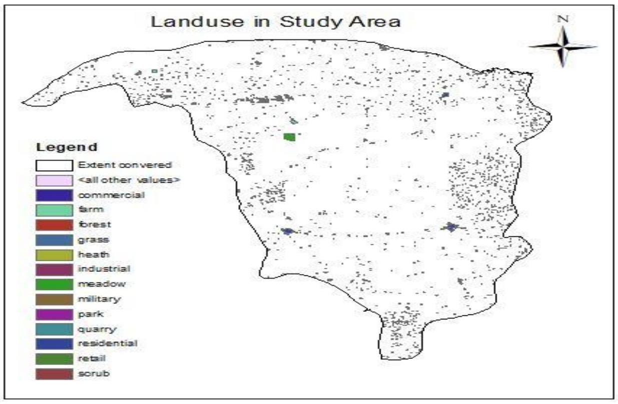

Figure 4: The results of Land Use distribution across the study area, obtained from the GIS-RS based analysis

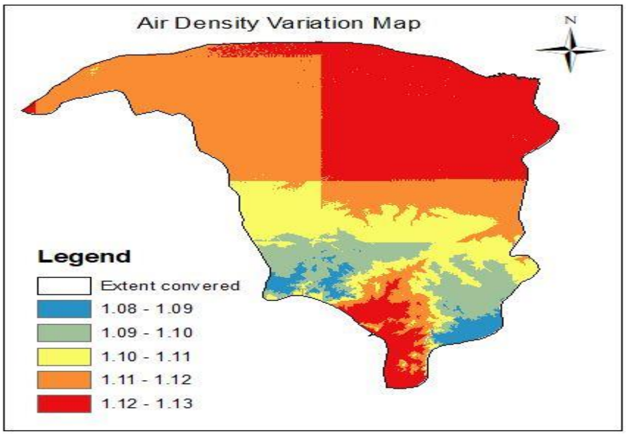

Figure 5: The air density distribution across the study area, obtained from the GIS-RS based analysis

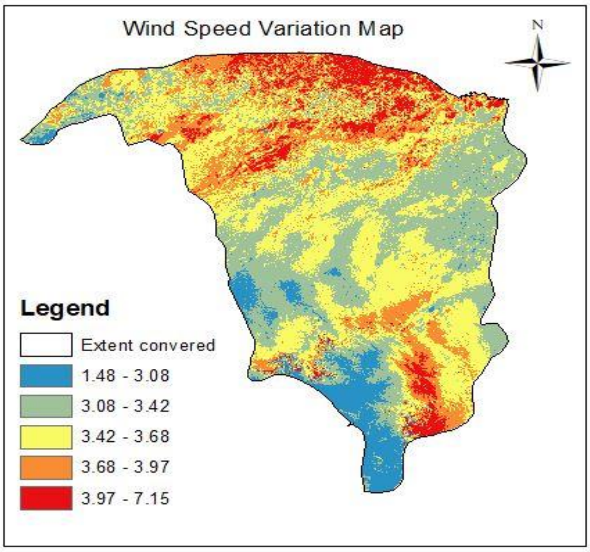

Figure 6: The results of wind speed variation across the study area, obtained from the GIS-RS based analysis

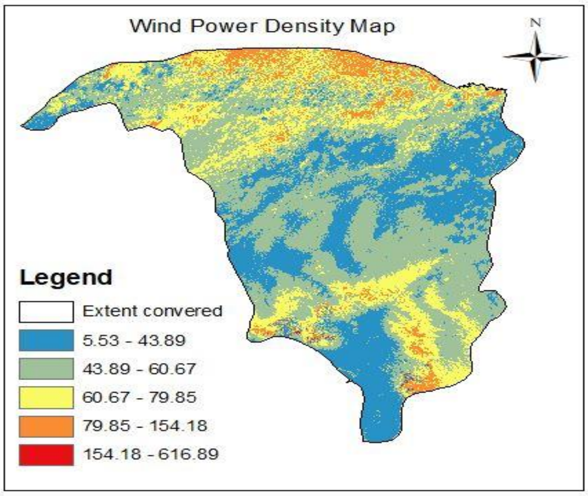

Figure 7: The results of wind power density distribution across the study, obtained from the GIS-RS based analysis

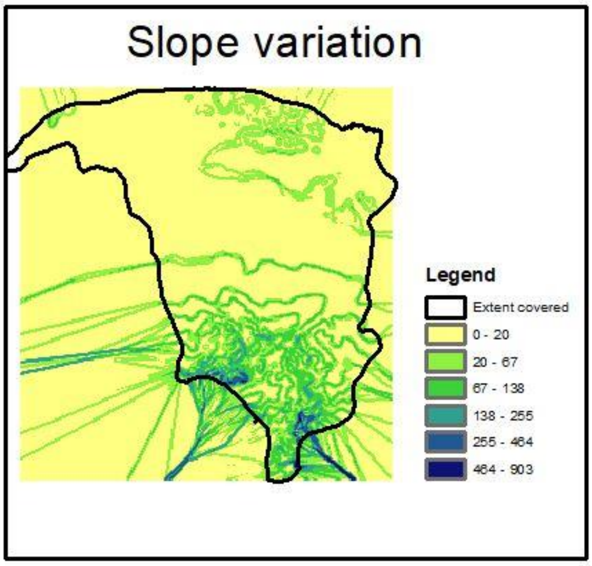

Figure 8: The slope variation across the study area, obtained from the GIS-RS based analysis

In this study, evaluation of wind energy potential was formulated with the wind power density, which represents the effect of wind speed distribution and wind speed. The study area reveals the distribution of wind power density ranged from 5.53 to 616.89 W/m^2 (Fig. 7). significant areas were covered by wind power density of about 80 W/m^2 and below, with higher concentration in the North. The Weibull analysis reveals a variation of the wind power density from 34.21 to 207.10 W/m^2 for Damaturu, which equally validates the GIS-RS based analysis.

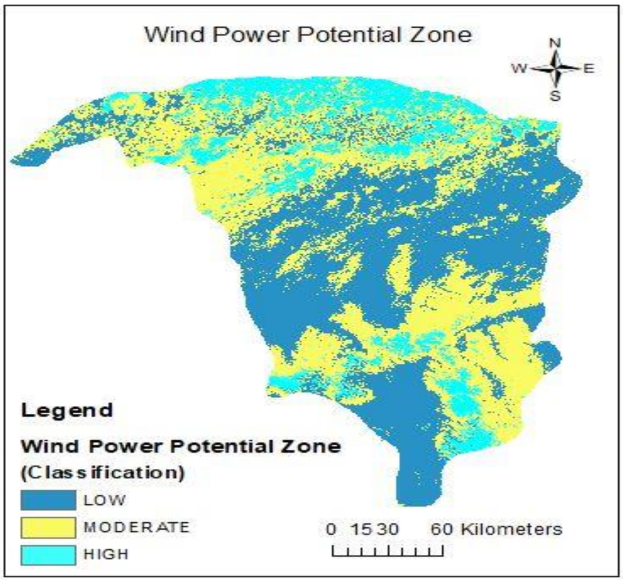

Figure 9: The results of wind energy potential zones across the study area, obtained from the GIS-RS based analysis

Tables 2 and 3 provide the pairwise comparison matrices for specific and overall weightages of the criteria adopted. Conventional implementation method of AHP was applied in this study. The wind energy potential map was evaluated based on the ranking and the weights of each thematic layer. Table 3 provides the overall weightages of the adopted criteria for wind energy potential mapping within the study area. All related thematic layers were integrated using the ArcGIS software to map the suitable areas for wind power generation in Yobe. Wind turbine index (Si) was computed through summation of the entire overall weightages. The WLC method was applied to generate the wind energy potential map of Yobe (Fig. 9). The area was categorized into three classes namely; low, moderate, and high regions of wind power potential.

CONCLUSION

GIS-RS based AHP analysis method has satisfactorily evaluated the wind energy potential in Yobe, and significant findings were gathered. The method estimated marginal distribution of wind power intensity and suggested the viability of wind energy utilization in Yobe. The study revealed a wind speed variation ranged from 1.48 to 7.15 m/s and an average annual wind power density of about 80 W/m^2, to established that the area is viable for wind power generation and distribution. The study also suggests that wind resource will yield favorable economic gain in Yobe. About 90 % of Yobe is covered by wind power density of about 85 W/m^2 and below while the remaining 10 % is covered by wind power density ranged between 85 and 616.89 W/m^2. This study concluded that Yobe is a suitable area for wind power generation both at medium scale generation, and standalone connection system.

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