Geographical information system based assessment of various renewable energy potentials in Nigeria

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Research Paper

Geographical information system based assessment of various renewable energy potentials in Nigeria

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ABSTRACT

Nigeria's energy transition plan is hinged on increasing the energy mix from renewable energy sources. An understanding of where the potentials of these renewable energy sources lie is very crucial to enhance quality and timely policy formulations, interventions and proper decision making. This paper aims at providing a holistic assessment of the potentials of key renewable energy resources; solar, wind, biomass and small hydro in Nigeria using ArcGIS; a geospatial analytical platform that provide data and visualizations of these potentials across the country. This paper focuses on the Inverse Distance weighting methodology which overlays various map shapefiles and spreadsheets containing relevant data such as; waterlines and water areas, road and rail networks, crop production, longitude and latitude, wind speeds, solar irradiation, elevation and other relevant map data, shape files for all the Nigerian states and local governments. These data are geo-processed to align the results to the exact locations as provided by their geographical positions stem coordinates. These interpolation results are further reclassed within standard limits for the various output parameters such as crops, forest areas, built-up areas, water bodies, shrubs/grasslands, barren lands and waterbodies to reveal suitability areas for siting the various renewable energy power generating plants.

1. Introduction

Nigeria is one of the West African countries with vast renewable energy resources that have the ability to significantly contribute to the country's energy demands while also promoting long-term development. Solar, wind, hydropower, biomass, geothermal, and biofuels are some of Nigeria's significant renewable energy potentials (Okedu et al., 2015). Other untapped potential energy sources that could contribute to the country's energy mix include waste-to-energy and ocean energy (Akinbami, 2001).

Nigeria has significant levels of solar irradiation all year, making solar energy one of the most promising renewable resources. Solar photovoltaic (PV) systems can be used in rural regions for off-grid electrification and distributed generation. Large-scale solar farms can also be built to supply power to the national grid.

According to (Ndaceko et al., 2014), a conservative estimate of Nigeria's technical potential for solar energy with a 5% device conversion efficiency is 15.0×10^{14} kilojoules (kJ) of usable energy per year. Nigeria receives an average solar radiation of roughly 7.0kWh/m^2 (25.2MJ/m^2 per-day). When compared to the nation's current yearly fossil fuel production, this translates to about 258.62 million barrels of oil equivalent per year (Akinbami, 2001).

Wind speeds are high in Nigeria's northern and coastal regions, providing a good opportunity for wind energy generation. Wind farms can be built in these areas to harness the kinetic energy of the wind and create power. A significant amount of study has been conducted to investigate the features and patterns of wind speed across Nigeria in

Abbreviations: CUF, Capacity Utilization Factor; DHI, Diffuse horizontal irradiation; ECN, Energy Commission of Nigeria; ESRI, Environmental Systems Research Institute; GEF, Global Electrification Fund; GHI, Global Horizontal Irradiation; GIS, Geographical Information System; GWh, Giga-Watt-hours; IDW, Inverse Distance Weighting; NC, North Central; NE, North East; NDVI, Normalized Difference Vegetation Index; NG, Nigeria; NGA_adm 0, Map shaped file for Nigeria; NGA_adm 1, Map shape file for States in Nigeria; NGA_adm 2, Map shape file for Local Government Areas in Nigeria; NW, North West; PVOUT, Specific photovoltaic power output; REA, Rural Electrification Agency; SE, South East; SS, South South; SW, South West; UN-FAO, United Nations Food and Agricultural Organization; UNIDO, United Nations Industrial Development Organization; WtE, Waste-to-energy.

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Nomenclature

E_{out}	annual output energy of the system in GWh
P_{out}	rated power of the system in GW
CUF	Capacity Utilization Factor
Wscore	overall weighted overlay score;
Ci	criteria score of i;
Wi	weight value of criteria i
V_{mean}	mean or average velocity
η_{max}	maximum turbine efficiency

order to find regions best suited for wind power generation (Agwu, 2013).

Nigeria also has numerous rivers and bodies of water that offer various opportunities for small and medium-scale hydropower plants. Hydropower is now used for grid-connected electricity generation, but it can also be used for decentralized rural electrification to bridge Nigeria's energy access gaps. The agricultural sector in Nigeria creates a significant amount of biomass resources, such as crop waste, animal waste, and forest products. These materials can be used to generate biogas, power plants, and cooking and heating systems based on biomass (Ukoba et al., 2023).

In the literature, several report on the use of ArcGIS in assessing solar energy has been reported. Boban and Milica, (2019), use ArcGIS to assess the potential of solar energy in the urban area of Vranje in southern Serbia. The authors of the paper reported a maximum irradiation in the area of study as 1,373kWh/m^2 annually, with average of 1227 kWh/m^2, annually. The paper further suggested that the input from the work could help in technical and economic analysis of solar energy utilization in a cost-effective way. In another study carried out by Bitigren and Filik (2017), a model was used to predict the solar energy potentials in Anadolu University, Eylul campus, in Turkey. The authors employed a digital surface model and high resolution orthoimage along with ArcGIS to evaluate the potential of solar energy resource in the study area. Ndukwe et al. (2021), evaluated the potential of solar energy generation in Eastern Nigeria, considering technologies of geospatial. In that study, a multi-criteria decision analysis was employed with GIS, based on images of Landsat satellite. The study reflected that the development of solar energy in the Eastern region, of Nigeria could help improve the energy mix of the country.

ArcGIS has also been employed in wind energy. In the literature, optimal solutions for renewable energy implementation in Romania, was reported by (Cristea and Jocea, 2016), based on GIS technology. The authors showed that GIS could replace other programs used for wind energy assessment. Ekeh, (2012), carried out a GIS based wind energy accessibility in Nigeria. A Nigerian map with wind energy distribution was presented to help policy makers kick-start the wind energy industry, and make investors know the possible locations of harnessing wind potential. The strength of wind energy in the Niger Delta region was exploited by (Kenu et al., 2023), where the use of wind energy as an alternative source was proposed to replace the conventional fossil and gas power plants in the region. Furthermore, Ndukwe E., et al., 2019, carried out the geospatial evaluation of the potential of wind energy in the south east and south south of Nigeria. The study considered wind energy generation potential map were wind speed ≥ 3 m/s, 2000 m were

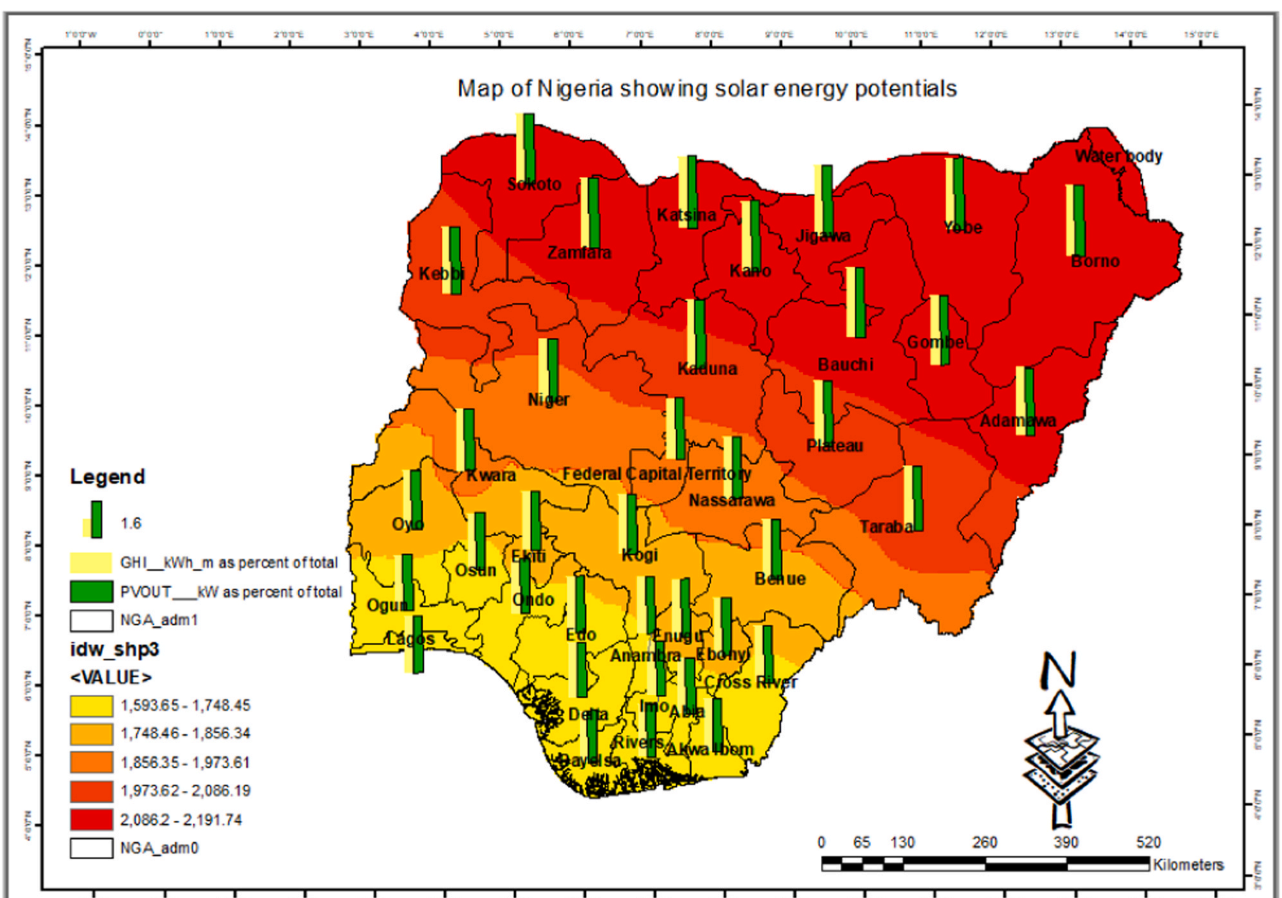

Fig. 1. Map showing idw_shp3 interpolation results for GHI data for Nigeria.

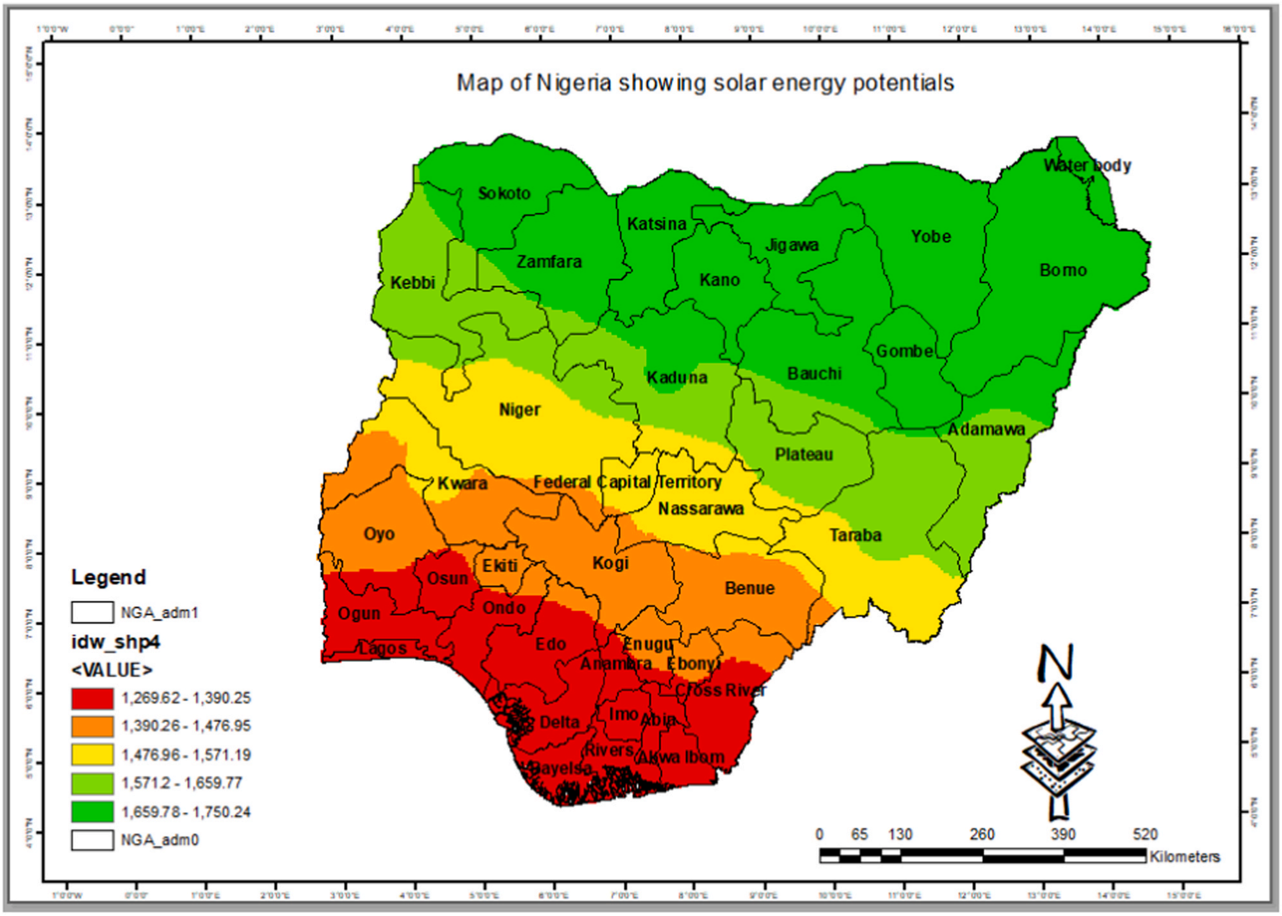

Fig. 2. Map showing idw_shp4 interpolation results for specific PV output potentials for Nigeria.

considered to buffer from built-up areas, 2500 m from airports and outside the forest reserve. The study showed the availability of wind energy potential, southernmost part of the region studied.

More so, in the literature, many studies on biomass energy assessment using GIS have been reported. The authors (Voivontas et al., 2001) reported the GIS scheme employed to trace the distribution of biomass energy for power generation based on the facilities of the biomass plant, sizing, locations, and distribution pattern of the biomass resources. In another study (Papadopoulos and Katsigiannis, 2002) a computer program GIS based system was used to determine optimal biomass plant site locations considering biomass resources that are available. A recent work was carried out by (Jusakulvijit et al., 2022) for a bioethanol manufacturing process potential from agro residues. The investigation was carried out using an integrated GIS assessment scheme considering logistics analysis in Thailand. The findings from the study revealed the suitability analysis in seventy-one locations for bioethanol plant installations to provide power generation in the studied area. In Nigeria, there is readily available and huge potential for biomass resources for clean energy production. Oyedepo et al. (2019), reported a pathway for the development of bioenergy technology in Nigeria for effective sustainable energy development, based on the United Nations development goals.

There are numerous rivers and dams in Nigeria, which are economically viable for hydroelectricity in the country and would make a good contribution to the entire energy mix (Odje et al., 2018). (Uhunmwangho et al., 2015) did assessment of small hydro power potential in River Benue located in the middle belt of Nigeria. In the same vein, (Uhunmwangho et al., 2018) and (Okedu et al., 2020), reported similar reports on the potential of hydropower in Bumaji stream in Cross River state and the Cross River state of southern Nigeria. The authors in these studies argued that the use of small hydropower technology in Nigeria is very limited, despite its abundance due to lack of government policy in tapping the abundant hydro resources in the country. The hydropower potential assessment of some feasible sites in Nigeria, considering its six geopolitical zones using ArcGIS techniques was investigated by (Oyinna B. et al., 2023). The studies reported the accurate mapping of the appropriateness for small hydropower sites in Nigeria considering the inland water bodies.

In light of the above, renewable energy sources can help Nigeria to diversify its energy supplies, cut greenhouse gas emissions, and enhance energy access and security for its expanding population (Olanipekun and Adelakun, 2020). Thus, this paper aims to drive at the effective harnessing and utilization of the various renewable energy sources in Nigeria, considering their locations using GIS-based spatial data analysis. ArcGIS platform was used to assess the potential of these renewable energy resources across the country by overlaying the various shapefiles and XY data on the map to show the spread across the country for better decision making. This paper would help in the optimal mapping of solar, wind, biomass, and hydropower energy resources and location of its facilities in Nigeria, since this has not been widely reported in the literature. The existing works in the literature reported only one renewable energy source at a time. However, this paper tends to breach that research gap by considering these four major renewable energy sources at a time for better understanding of the renewable energy potentials in the country. Since there is huge abundant of these various renewable energy resources in Nigeria, with the capability of clean power generation to the national grid, energy policy makers, investors and stakeholders would be encouraged to de-centralised the various renewable energy plants in Nigeria. In this paper, the Inverse Distance Weighting methodology which overlays various map shapefiles and spreadsheets containing relevant

Table 1
Reclassed data and weighted scores.

Elevation h (m)	Wind speeds (m/s)	Value	Weighted overlay %
10 m	0.045326 - 1.620607	1	20%
	1.620607 - 2.262388	2	
	2.262388 - 2.845825	3	
	2.845825 - 3.312575	4	
	3.312575 - 3.662638	5	
	3.662638 - 4.071044	6	
	4.071044 - 4.829513	7	
	4.829513 - 6.463138	8	
	6.463138 - 14.981324	9	
50 m	0.378071 - 2.478876	1	20%
	2.478876 - 3.233012	2	
	3.233012 - 3.825546	3	
	3.825546 - 4.364215	4	
	4.364215 - 4.795149	5	
	4.795149 - 5.226083	6	
	5.226083 - 5.710885	7	
	5.710885 - 6.572754	8	
	6.572754 - 14.114106	9	
100 m	0.658337 - 2.973499	1	20%
	2.973499 - 3.815377	2	
	3.815377 - 4.499402	3	
	4.499402 - 5.13081	4	
	5.13081 - 5.709601	5	
	5.709601 - 6.183157	6	
	6.183157 - 6.656713	7	
	6.656713 - 7.393356	8	
	7.393356 - 14.128375	9	
150 m	0.766913 - 3.279491	1	20%
	3.279491 - 4.221707	2	
	4.221707 - 4.849851	3	
	4.849851 - 5.477996	4	
	5.477996 - 6.158485	5	
	6.158485 - 6.78663	6	
	6.78663 - 7.310083	7	
	7.310083 - 7.833537	8	
	7.833537 - 14.167325	9	
200 m	0.80793 - 3.436958	1	20%
	3.436958 - 4.498681	2	
	4.498681 - 5.206497	3	
	5.206497 - 5.914312	4	
	5.914312 - 6.622128	5	
	6.622128 - 7.279385	6	
	7.279385 - 7.886083	7	
	7.886083 - 8.442224	8	
	8.442224 - 13.750839	9	

data such waterlines and water areas, road and rail networks, crop production, longitude, latitude, wind speeds, solar irradiation, elevation and other relevant data, on the NGA_adm 0, 1 and 2 shape files containing map data for Nigerian states and local governments were the main focus in the methodology employed. These data are geo-processed within the limits of the NGA_0 and 2 to align the results to the exact locations as provided by their Geographical Positioning System (GPS) coordinates. These interpolation results are further reclassed within standard limits for the various output parameters such as crop and forest areas, built-up areas, water bodies, shrubs/grasslands, barren lands and waterbodies to reveal suitability areas for siting various renewable energy power generating plants. Consequently, Nigeria must pass enabling legislation, offer investment incentives, upgrade its infrastructure, and increase renewable energy research and development in order to fully fulfill these renewable energy potentials.

2. The state of renewable energy sources in Nigeria

2.1. Solar energy

Nigeria has made strides in harvesting solar energy as part of its renewable energy development, owing to its proximity to the equator and ample sunlight. Throughout the year, the country receives significant amounts of sun irradiation, making it a suitable location for solar energy projects (Bamisile et al., 2017).

Nigeria has invested in solar power plants in order to diversify its energy mix and lessen its reliance on fossil fuels. Several solar farms and installations have been developed in various parts of the country; nevertheless, this is woefully inadequate because many rural and urban populations lack access to power. Off-grid solar solutions have grown in popularity as a result of the difficulties in expanding the national power system to rural and remote places. Solar household systems and mini-grids, which provide electricity to towns that are not connected to the main grid, are examples of these (Adaramola, Paul and Oyewola, 2014).

The Nigerian government has demonstrated its commitment to solar energy development by introducing a variety of projects and policies. The Nigerian Rural Electrification Agency (REA), for example, has been leading efforts to promote off-grid solar alternatives (Ndaceko et al., 2014). To stimulate the use of solar energy, the government has provided tax rebates and tariff reductions to solar power producers and investors (Kapadia, 2004). Despite the potential, the rise of solar energy in Nigeria has been fraught with difficulties. Inadequate infrastructure, restricted access to financing, bureaucratic impediments, and inconsistent regulations are among them. The private sector has been active in solar energy projects, working with the government to create and implement solar initiatives (Akinyele et al., 2020).

Solar energy has helped to increase access to electricity in Nigeria's rural and neglected communities. Off-grid solar systems have brought electricity to previously unserved populations. Solar energy projects have the potential to provide jobs, boost economic growth, and reduce reliance on expensive fossil fuel imports (Mbinkar et al., 2021).

2.2. Wind energy

Nigeria also has significant wind energy potential, especially in specific regions of the country. Here are some key points regarding wind energy potentials in Nigeria. Nigeria's northern regions, particularly the northeast and northwest, have excellent wind resources especially the states of Kano, Sokoto, Katsina, Jigawa, and Kaduna. These areas experience consistent and strong winds, making them ideal for wind energy projects (Olanipekun and Adelakun, 2020). Other areas like the coastal areas of Lagos, Ondo, Delta, and Cross River states, also offer significant wind energy resources. The coastal regions experience relatively higher wind speeds due to the proximity to the Atlantic Ocean (Agwu, 2013). The country had started exploring wind energy through the establishment of wind farms. Some notable wind farms include the 10 MW Katsina wind farm in Katsina state and the 37 MW Rimi wind farm in Sokoto State (Aika et al., 2020).

The Nigerian government has recognized the potential of wind energy and has shown interest in supporting its development. Various policies and incentives have been introduced to encourage private sector investment in wind energy projects. Despite the potential, the growth of wind energy in Nigeria has faced challenges similar to other renewable energy sources (Aika et al., 2020). These include financial constraints, regulatory uncertainties, and infrastructure limitations. Integrating wind energy into the national power grid requires careful planning and investment in grid infrastructure. This aspect has been a focus of attention for the successful deployment of wind energy projects (Ozim et al., 2021).

Jobs and local development might be generated by wind energy installations in the areas where they are located. This may promote social and economic advancement as well as community empowerment. Wind power is a clean, renewable energy source that can help fight climate change by lowering greenhouse gas emissions. Its adoption aligns with Nigeria's commitment to sustainable development and meeting international climate targets (NdukweE et al., 2019; N.E. Chiemelu et al., 2019). Since wind energy is now more efficient and economical, thanks to advancements in wind turbine technology, it is a viable alternative for supplying Nigeria's expanding energy needs.

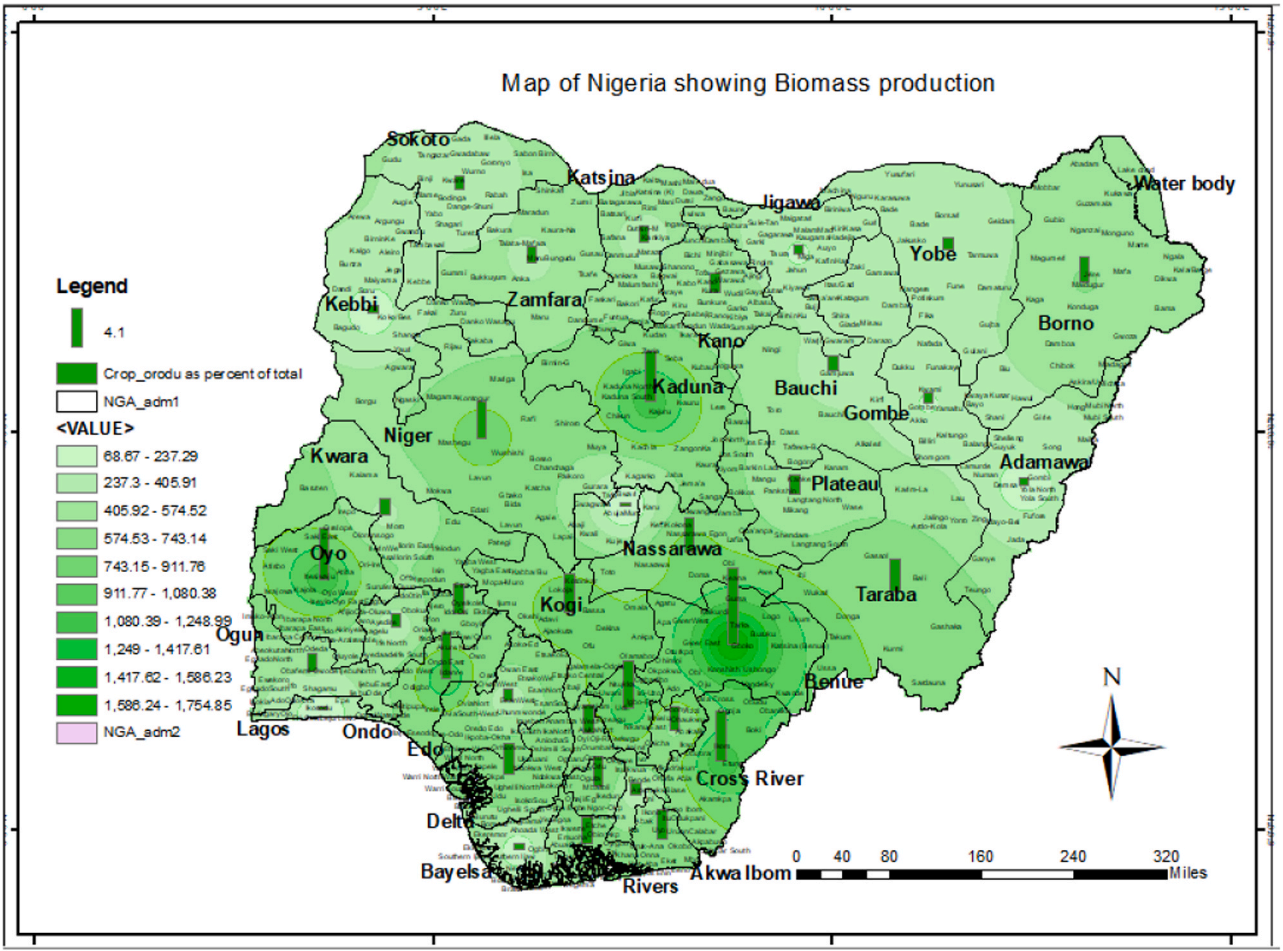

Fig 3. Map of Nigeria showing biomass production across the 36 states and FCT.

2.3. Biomass

Nigerians are becoming more aware of biomass energy production as a viable source of renewable energy. Organic resources like agricultural waste, animal waste, forest products, and municipal solid waste are the source of biomass energy. These resources are plentiful in Nigeria and can be used for cooking, heating, and electricity production (Küçük and Demirbaş, 1997). Nigeria's high population and extensive agricultural economy produce enormous biomass resources. Animal waste and agricultural waste can both be used as biomass feedstock for energy generation, including crop residues and husks (Mokraoui, 2015).

Electricity can be generated from biomass in a number of ways (Wang and Jia, 2006). In biomass power plants, organic materials are burned to produce steam, which powers turbines attached to electrical generators. In order to reduce reliance on conventional wood and charcoal, which contribute to deforestation and indoor air pollution, biomass can also be utilized for cooking and heating in homes and businesses (Ukoba et al., 2023). Despite its potential, Nigeria has a number of obstacles in its adoption of biomass energy, including a lack of financial incentives, insufficient technical know-how, and restricted infrastructure for biomass energy projects. Concerns about the sustainable procurement of biomass to prevent adverse environmental effects may also exist. The Nigerian government has expressed interest in increasing biomass and other forms of renewable energy, however strong policies are needed for effective implementation.

2.4. Small hydro

Nigeria's abundant rivers and other bodies of water give it a significant modest hydroelectric potential. The term "small hydroelectric power plants" refers to those with a 10 MW or less capacity. These smaller-scale hydropower initiatives can support the development of sustainable energy sources and rural electricity in many parts of the nation (Ohunakin et al., 2011).

Numerous rivers and other bodies of water in Nigeria could be used as locations for small hydroelectric generating facilities. The Niger River, Benue River, Kaduna River, and Cross River are just a few of the prominent rivers with great hydropower potential. The potential for minor hydropower development in Nigeria's northern and central areas, where rivers like the Kaduna and Niger flow, is particularly high (UNIDO, 2019).

Small hydropower projects can be extremely important in bringing electricity to isolated and rural areas with poor grid access. These initiatives can raise living standards and promote regional economic growth. Small hydroelectric facilities typically have a smaller environmental impact than large hydropower projects because they require less land and are less likely to create substantial ecological disruptions (Akinbami, 2001).

Small hydro project development in Nigeria confronts difficulties because of lack of funds, regulatory restrictions, and technical know-how. Furthermore, project implementation may face logistical difficulties due to the remoteness of feasible sites. The government of Nigeria has expressed interest in increasing renewable energy sources, such as small hydroelectric power and have collaborated with local and

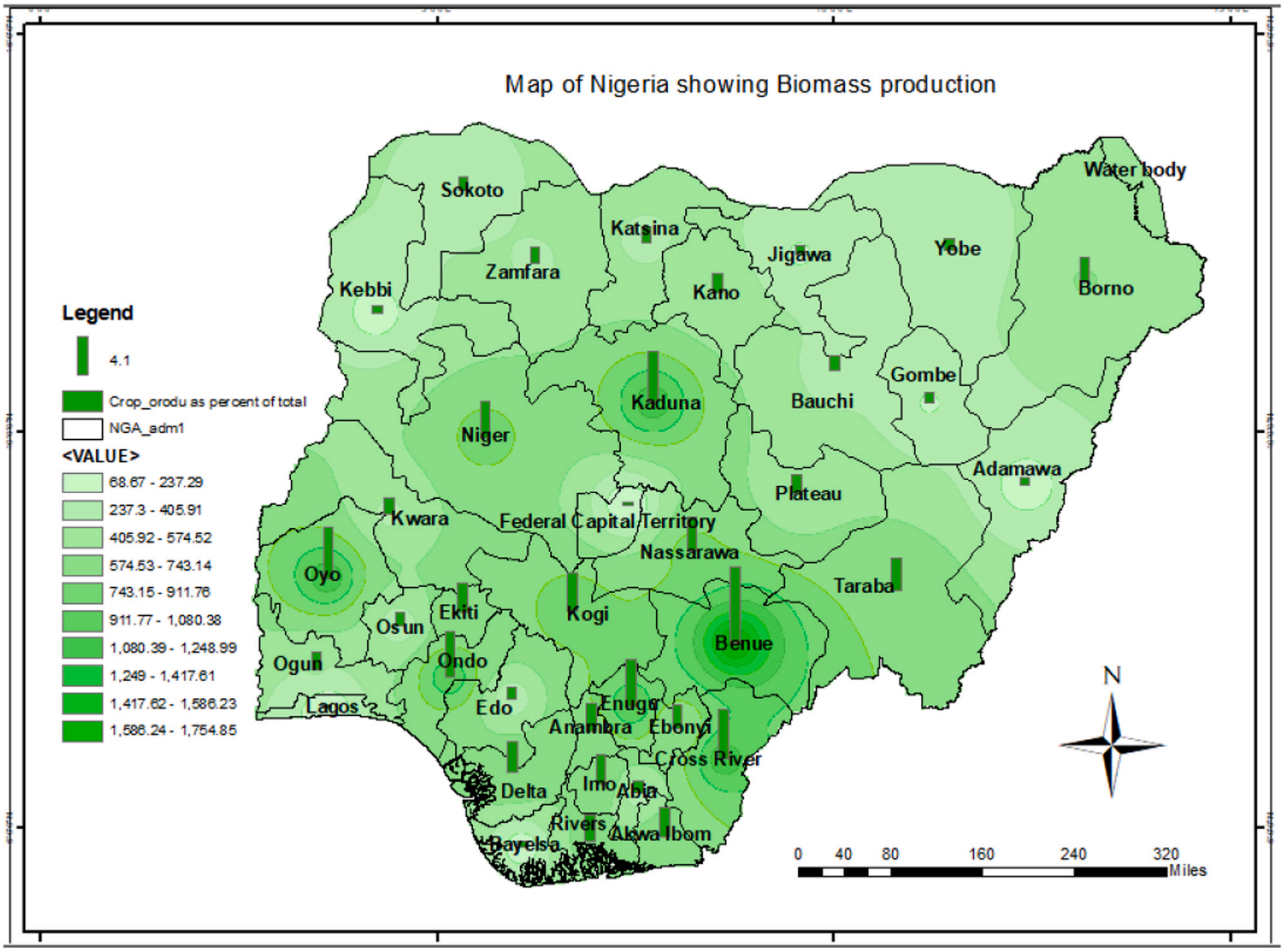

Fig. 4. Map of Nigeria showing locations within states with the highest biomass production.

International agencies like UNIDO through the Global Electrification Fund (GEF) Project to incentivise small hydro projects across the various river basins in the country (UNIDO, 2019).

2.5. Geothermal energy

Geothermal energy uses heat from the Earth's interior to provide direct warmth and power. Geothermal areas with high, moderate, and low temperatures can be used to generate electricity and directly consume heat under the right circumstances (Tester et al., 2005). According to the accepted geology of geothermal energy, heat from the earth's molten core is transported to nearby rocks and finally transferred by convection to subterranean water reservoirs. Using diverse technology, the steam or hot water generated by geothermal heat may be extracted and directed towards different purposes. The chemical and thermodynamic properties of geothermal fluid are critical to its use. The geothermal system that produced the fluid controls these variables.

Nigerian sedimentary basins have been investigated for hydrocarbons for many years; as a result, the oil corporations have access to a vast array of subsurface temperature data. According to data sets from water and oil wells, the Niger Delta's geothermal gradient varies from 1.3 to 4.7 °C/100 m (Shaaban and Petinrin, 2014). There may be potential geothermal resources in this area given the abundance of warm/hot springs and seepages in Nigeria, the majority of which are found in the sedimentary basin of the Benue Trough. These features are geological phenomena that appear as visible manifestations of geothermal energy within the subsurface.

Nigeria's southwest is home to the Ikogosi warm spring. This thermal spring is situated in the Nigerian basement complex's quartzite-schist structure. The temperature of the spring water is 37 °C (Kurowska and Schoeneich, 2010). Even now, it functions as a local tourist hub and has a swimming pool. In Nigeria right now, this is most likely the sole direct application of geothermal energy. Rafin Ruwa, close to Lere, is home to another warm spring northwest of the Jos Plateau (central shield). The spring produce 42 °C spring water that seeps from gneissic and magmatic rock formations. Jos Plateau is home to a number of springs that are now known to exist. The local people frequently use the cool, pure water that these springs supply. According to Kurowska and Schoeneich (2010), the finding of the Ikogosi warm spring and its existence indicate that local anomalies may cause a diversification of the distribution of geothermal heat within Precambrian basement strata in Nigeria.

The Nigerian government has initiated programs to encourage and assist the development of geothermal energy through various institutions, including the Federal Ministry of Power and the Energy Commission of Nigeria (ECN) (Eyinla et al., 2016). The high initial expenses of research and drilling, the necessity for technical know-how, and the demand for funding to expand geothermal operations are some of the obstacles to using this energy source in Nigeria (Ayuba and Lawal, 2019).

2.6. Waste-to-Energy

Nigeria has a lot of opportunity for waste-to-energy (WtE) projects because of its vast population and the garbage that comes with it. Waste-to-energy is the process of using different technologies to turn solid waste into heat or power (Oando, 2021). Nigeria's per capita trash creation has been estimated through a number of investigations. A range of 0.3 to 1.1

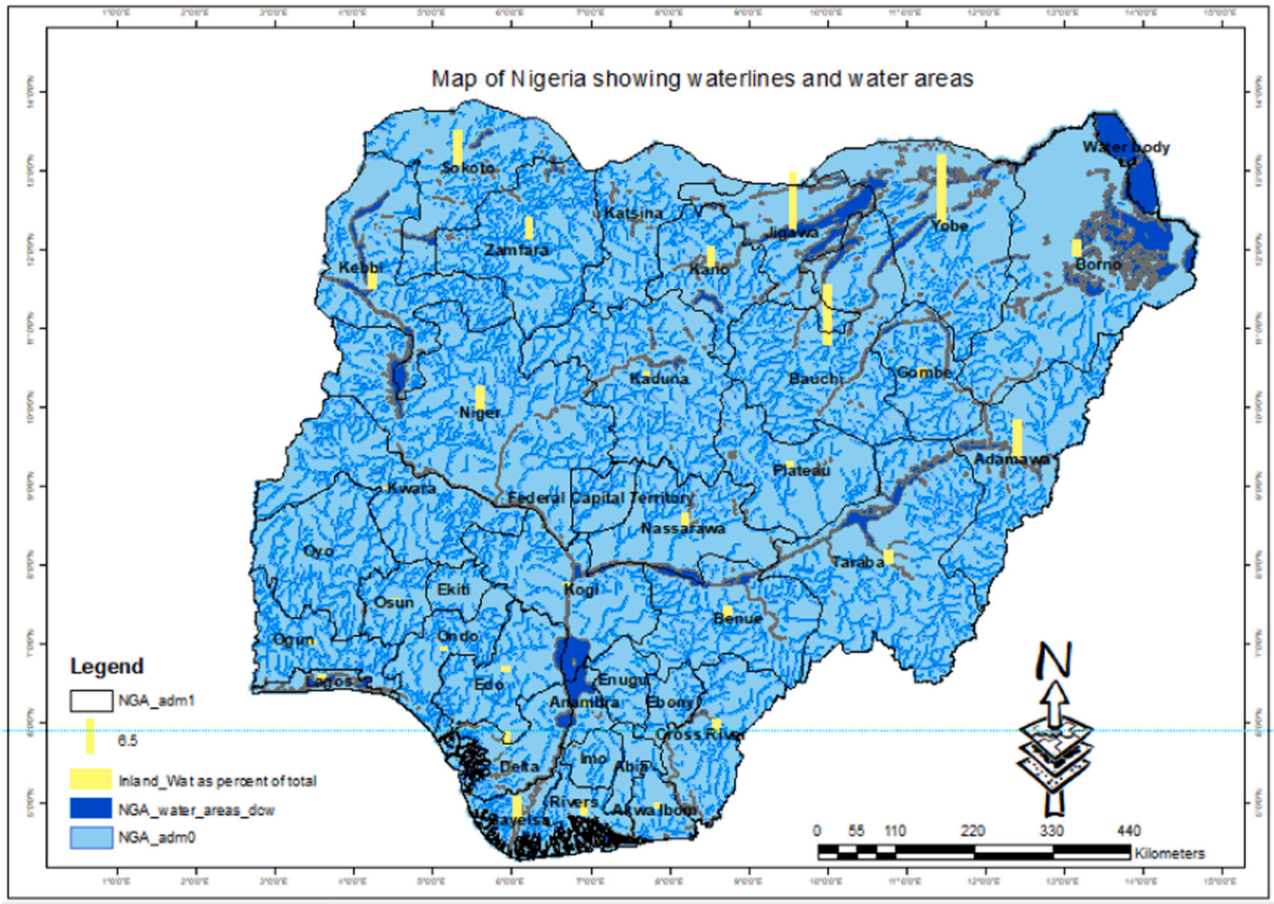

Fig. 5. Map of Nigeria showing waterbodies and waterlines multiple ring buffer.

kg/person/day have been observed in different national cities. The average national amount, according to several experts, is between 0.45 and 0.55 kg/person/day. These amounts appear to match the estimates provided by certain credible international organizations using relative income level as a criterion as well as the weighted average of the individual cities (Atta *et al.*, 2016). The country's waste burden was projected to reach around 29 million tons in 2021 (Oando, 2021), with a population of over 200 million and an average waste generation rate of 0.5 kg/person/day. Financial limitations, public opinion, and technological acceptance are obstacles to the implementation of waste-to-energy projects in Nigeria (Christian, 2010). It would take an all-encompassing strategy including community awareness, commercial sector involvement, and government backing to overcome these obstacles.

3. Renewable energy policy in Nigeria

In order to diversify its energy mix, lower greenhouse gas emissions, and increase energy accessibility, Nigeria adopted a number of laws and programs that supported renewable energy. The following are a few of Nigeria's most important renewable energy policies:

National Renewable Energy and Energy Efficiency Policy (NREEEP): This policy in Nigeria outlines a framework for renewable energy growth and energy efficiency, outlining production goals and rules for investment, research, and development (Kamran, 2023).

National Energy Policy: Renewable energy is acknowledged as being essential in Nigeria's National Energy Policy in order to achieve sustainable development and energy security (Olanipekun and Adelakun, 2020). The goal of the strategy is to increase the share of renewable energy sources in the energy mix while promoting the usage of clean energy technology.

Rural Electrification Strategy and Implementation Plan (RESIP): With the help of renewable energy sources including solar, small hydro, and biomass, the RESIP aims to increase access to electricity in rural and underserved areas (Akpan, Essien and Isihak, 2013).

Feed-in Tariff (FiT) Scheme: The FiT program was established by the Nigerian Electricity Regulatory Commission (NERC) to encourage the production of renewable energy by offering fixed prices to renewable energy providers (Akinyele et al., 2020). The program seeks to advance energy diversity and investment in renewable energy initiatives.

Mini-Grid Regulations: In order to encourage the installation of mini-grids powered by renewable energy sources, the Nigerian government enacted legislations. With the help of these regulations, the private sector will be able to supply electricity to remote and underserved communities (Van Hove et al., 2022).

National Biofuel Policy and Incentives: A national biofuel policy is also in place in Nigeria with the aim of promoting the development and use of biofuels as an alternative to traditional fossil fuels (Wang and Jia, 2006). The policy provides incentives to promote investment in and production of biofuels.

Renewable Energy Master Plan (REMP): The REMP gives a development roadmap and describes the potential of several renewable energy sources in Nigeria. It establishes precise goals for various renewable energy sources and evaluates the financial commitment necessary to meet these goals (Akinyele et al., 2020).

Sustainable Energy for All (SE4ALL) Action Agenda: Nigeria is a member of the global Sustainable Energy for All program, which aims to ensure widespread access to contemporary energy services, double the rate of improvement in energy efficiency, and double the proportion of renewable energy in the world's energy mix by 2030 (Facts, 2016).

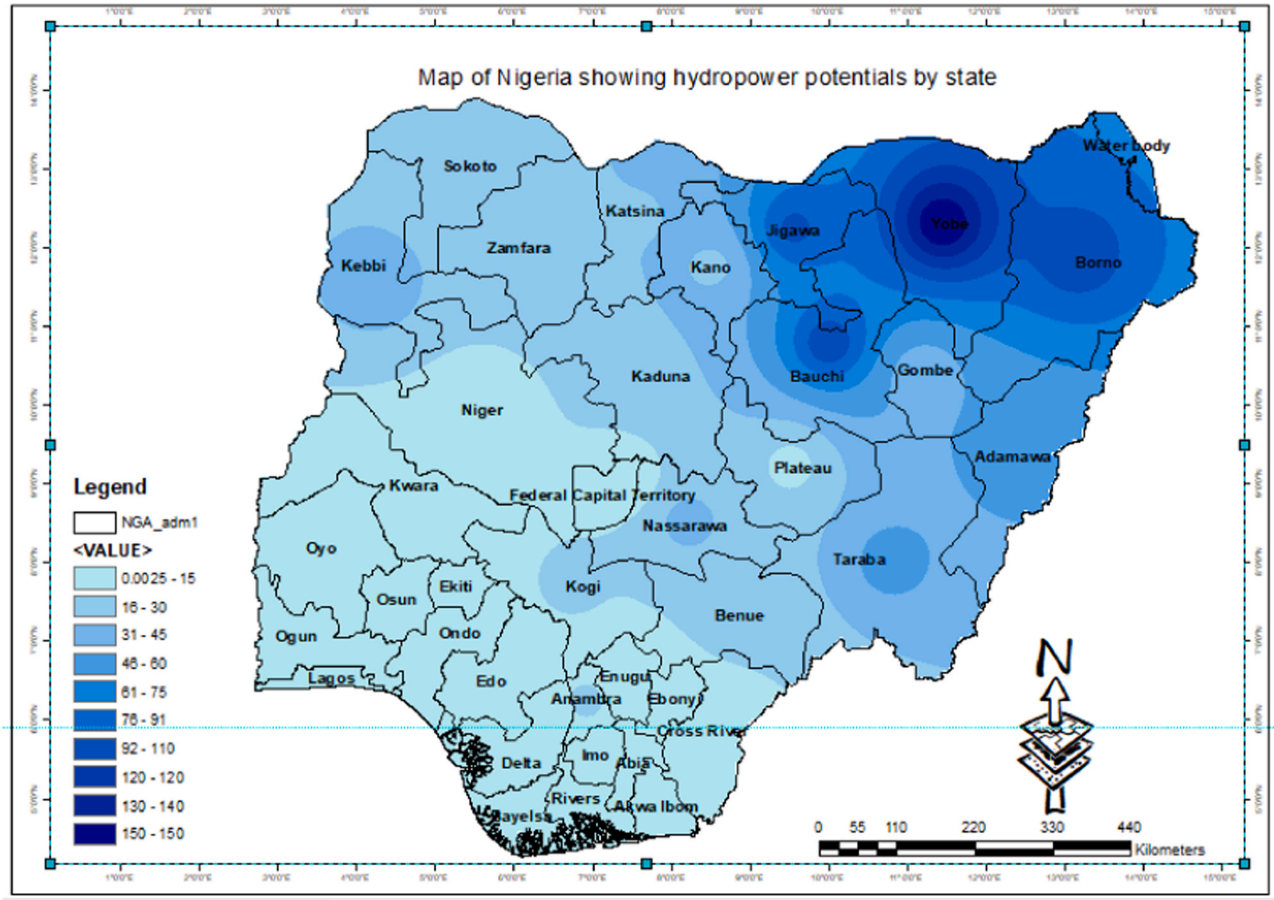

Fig. 6. Hydropower potentials in Nigeria.

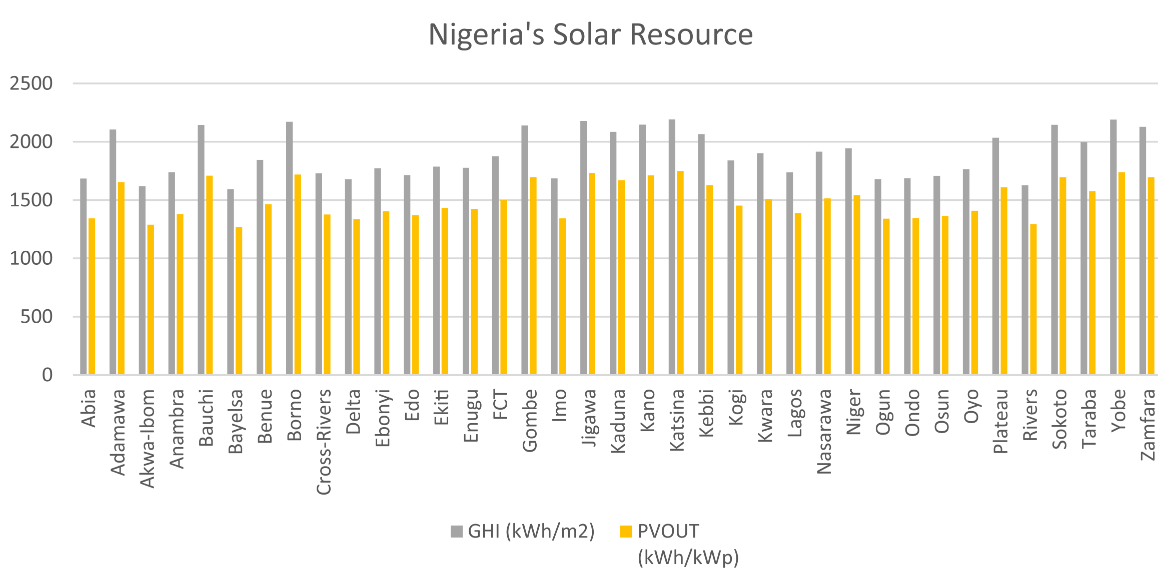

Fig. 7. Global Horizontal Irradiation and Specific PV output of Nigerian states.

4. The ArcGIS software

The Environmental Systems Research Institute (ESRI) is the company that developed the Geographic Information System (GIS) software called ArcGIS. Owing to its vast array of tools and capabilities, it enables users to organize, examine, and present geographic data for a variety of applications (Oyinna et al., 2023).

ArcGIS provides a framework for creating and managing geographic datasets, which enhances the organization of data and efficient administration. It also handles various geographic analytic problems and provides useful data which can be employed for planning and decision making processes (Lyu and Yin, 2023).

ArcGIS excels in data visualization and cartographic output. Thanks to its mapping and visualization features. Configurable symbology and

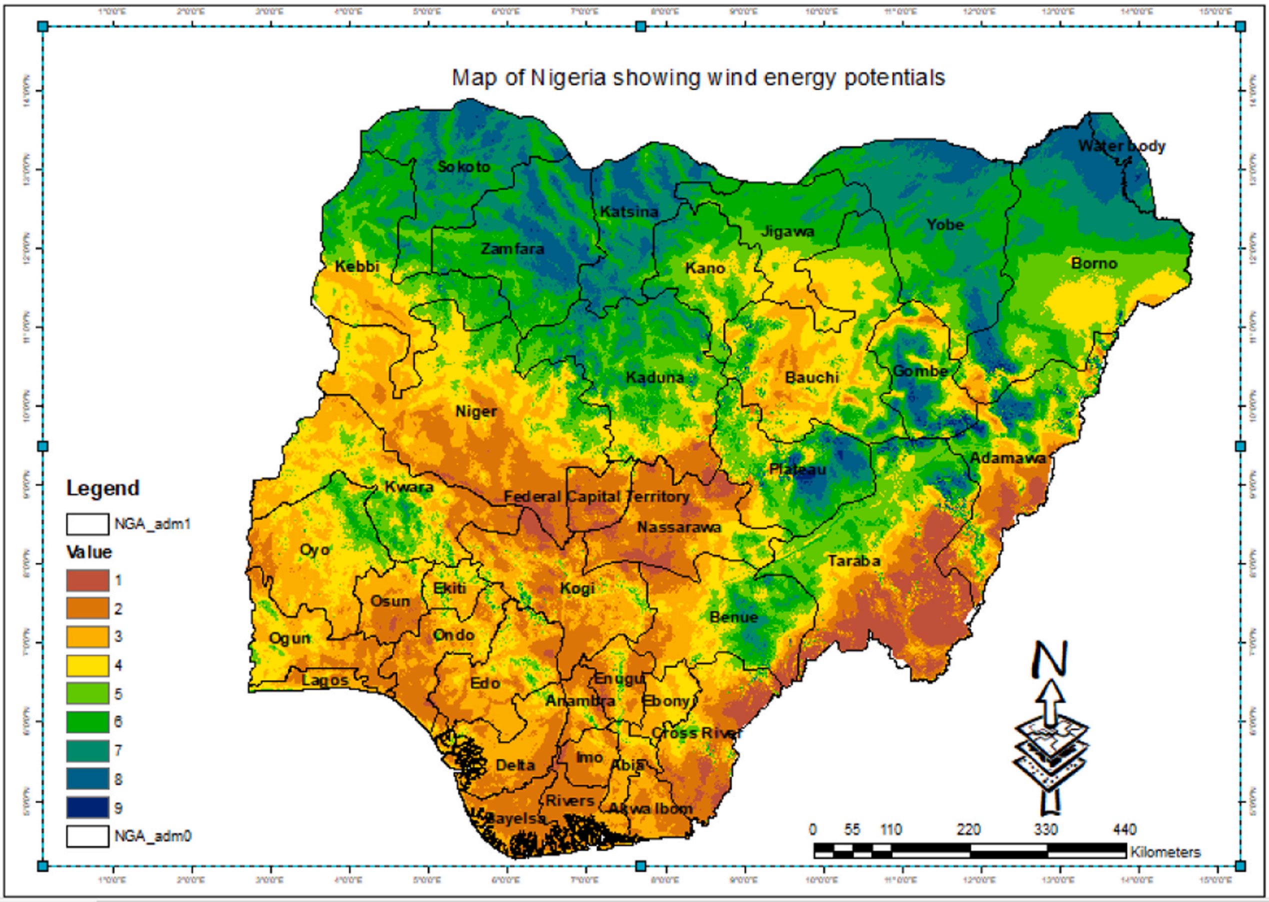

Fig. 8. Wind energy potentials in Nigeria with elevation between 10–200 m (overlayed 20% and reclassified).

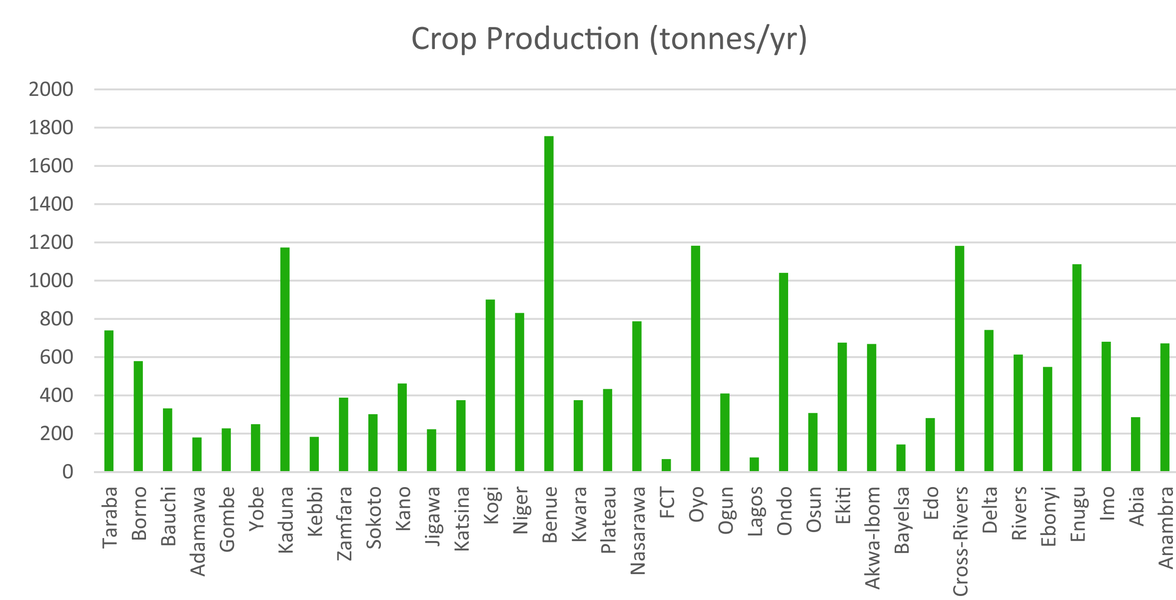

Fig. 9. Biomass energy potentials in Nigeria.

thematic representations enable users to produce aesthetically pleasing maps that clearly convey geographic patterns and relationships. The 3D visualization tools in ArcGIS allow users to create three-dimensional representations of geographical features and terrains (Asadi, Pourhossein and Mohammadi-Ivatloo, 2023).

5. Methodology

ArcGIS utilizes a combination of tools for spatial analysis. These includes Inverse Distance Weighting, Normalized Difference Vegetation Index (NDVI) calculations, Weighted Overlay analysis, etc. This paper focuses on the Inverse Distance Weighting (IDW) methodology which

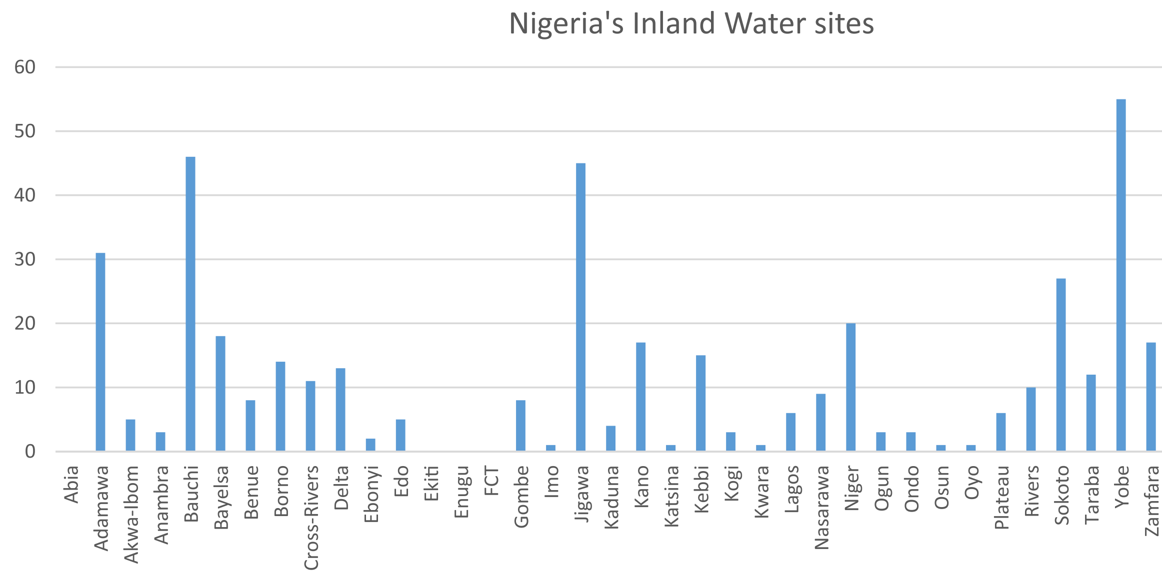

Fig. 10. Hydropower potentials in Nigeria.

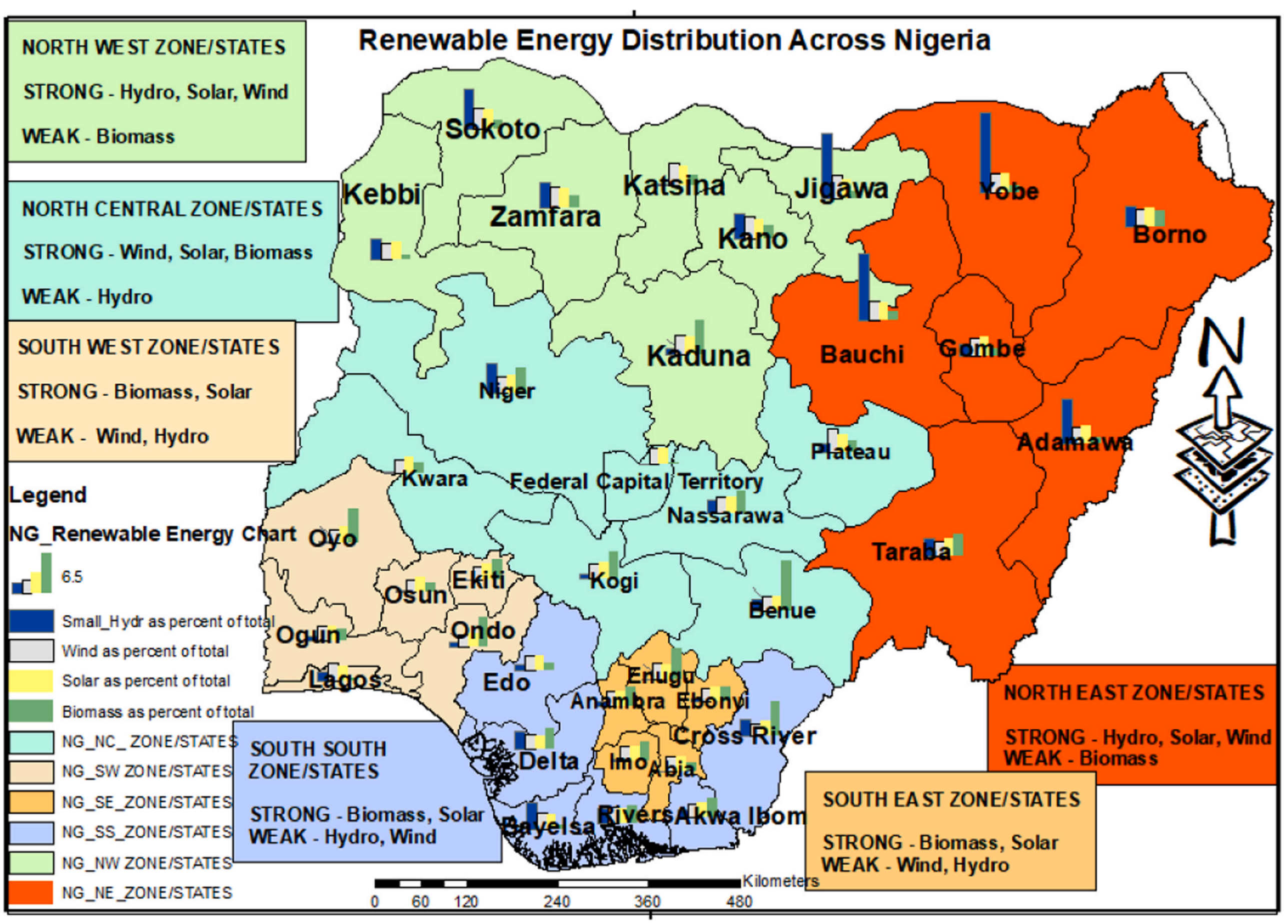

Fig. 11. Distribution of Renewable Energy Resources in Nigeria.

overlays various map shapefiles and spreadsheets that contains relevant data such waterlines and water areas, road and rail networks, crop production, longitude and latitude, wind speeds, solar irradiation, elevation and other relevant data, on the NGA_adm 0, 1 and 2 (Nigerian shape files containing map data for Nigeria, Nigerian states and Nigerian local governments). These data are geo-processed within the limits of the NGA_0 and 2 to align the results to the exact locations as provided by their GPS coordinates.

These interpolation results are further reclassed within standard limits for the various output parameters such as crop and forest areas, built-up areas, water bodies, shrubs/grasslands, barren lands and waterbodies to reveal suitability areas for siting various renewable energy power generating plants. The following are the mathematical formulations employed in the course of the study.

5.1. Inverse distance weighting

The inverse Distance Weighting Interpolation method is calculated using the Shepard's method (Thacker et al., 2010) and expressed as

$$f(x,y) = \sum\nolimits_{i=2}^{n} W_i f_i \tag{1}$$

where n is the number of scatter points in the set ($n > 1$), f_i are the prescribed function values at the scatter points (e.g. the dataset values), and w_i are the weight functions assigned to each scatter point.

5.2. Weighted overlay analysis

ArcGIS weighted overlay analysis tool is used to display low – high potential areas on a scale of 1–9 (Asadi et al., 2023). The raster files are reclassified and added as input raster to the weighted overlay domain with percentage assigned to make up 100% to signify the weights of the different criterion on the output raster.

The weighted overall score is calculated as shown below;

$$W_{score} = \sum_{m}^{n} C_i * W_i \tag{2}$$

Where;i = (windspeed at different heights, waterlines, water_area, distances from road etc);W_{score} is overall weighted overlay score;C_i is criteria score of i;W_i is weight value of criteria i.

The subsequent sections of this paper would discuss the evaluation of the various renewable energy source in Nigeria, using ArcGIS technique.

5.2.1. Assessment of solar energy potentials in Nigeria

Assessment of solar resources at a location is vital for knowing the potential for utilization. The Sun emits 3.846×10^{26} W energy in one year with an annual solar flux on earth varying from 800 to 2450 kWh/m^2. Photovoltaic (PV) solar energy generation requires at least solar flux of at least 1750 kWh/m^2 (4.5 kW/m^2 in a day) (Renné, 2016).

$$\text{Peak sun Hours} = \text{GHI}/1000 \tag{3}$$

$$\text{Global Horizontal Irradiation(GHI)in kWh/m}^2 = \text{DNI} * \cos\theta + \text{DHI}\left(\text{W/m}^2\right) \tag{4}$$

Where; DNI is the Diffuse horizontal irradiation in kWh/m^2 measured by a pyranometer.

ϴ is the angle of tilt.

The potentials to utilize this energy varies from one location to another due to the difference in solar irradiation and available peak sun hours. The data for Global Horizontal Irradiation (GHI) in kWh/m^2 and Specific photovoltaic power output (PVOUT) in kWh/kWp for all states across Nigeria was obtained from Global Solar Atlas and converted to shapefile using conversion tool on ArcGIS. This map data is subsequently overlaid 100% on the NGA_adm0 shapefile to visualize the spread across Nigeria. Inverse distance weighting calculations were done to show the weighted score of solar irradiations across the various states of Nigeria and compared against the Irradiation at Standard Testing Conditions (1000 W/m^2) to determine the peak sun hours and available solar power potentials. Symbology was used to visualize color ramp of yellow to red for GHI results in ascending order in Fig. 1, and red to green for PVOUT in Fig. 2.

5.2.2. Assessment of wind energy potentials in Nigeria

The power available in the wind per unit area P_w is dependent on wind velocity V and can be represented by the equation below (Ozim et al., 2021);

$$P_w = \frac{1}{2}\rho V^3 \tag{5}$$

Where; ρ is the density of air.

The elevation or altitude z of a location affects wind velocity V as given in the equation below;

$$v_2 = v_1 * \left[\frac{z_2}{z_1}\right]^{\alpha} \tag{6}$$

Where v_1 is the known wind speed in m/s^2 at measurement height z_1, v_2 is the unknown wind speed in m/s^2 at height z_2, α is the wind share exponent (often assigned as 0.143).

This relationship justifies the variation in windspeeds from locations with different elevations, hence the need to obtain data for different elevation and analyse for suitability areas for various categories of wind energy capacities across the country.

Raster files for NGA_wind speed were obtained from Global wind atlas for a range of heights from 10 m, 50 m, 100 m, 150 m and 200 m. These raster data were extracted by mask within the boundaries of NGA_adm2, converted to polygons and overlayed on the NGA_adm0 map shapefile with weighted overlay calculation done assigning 20% each to find intersections in the suitability areas. The output raster is reclassed with weights and priority given a descending order of elevations showing areas with the highest windspeeds due to elevations.

Colour ramping was done using the symbology tool to show areas of high wind energy potentials with a blue colour and brown for areas with very low potentials. Table 1 shows the reclassed data for the analysis for all ranges of elevation and windspeeds.

5.2.3. Assessment of biomass potentials in Nigeria

Biomass potential is assessed by considering theoretical, technical, practical and economic potentials in a given geographical location (Ukoba et al., 2023). The total biomass production from crop, forestry and other sources can be expressed as follows;

$$Total \quad Biomass \quad Potential\left(\frac{Tonnes}{yr}\right) = \sum E_{theoretical} + E_{technical} + E_{economic} + E_{practical} \tag{7}$$

Where; $E_{thoeritcal}$ is the maximum amount of biomass that could potentially be harvested from a given area or region. $E_{technical}$ is the amount of biomass that can realistically be harvested and utilized using existing technologies and best practices, $E_{economic}$ is the amount of biomass that can be harvested and utilized for energy considering the costs and benefits of the entire supply chain. $E_{practical}$ is the amount of biomass that can realistically be harvested and utilized considering social, economic, and environmental factors.

Biomass energy conversion system design is key to harnessing the biomass potentials quantified by the relationship mentioned in Eq. (7). The annual Energy Output of a conversion system, E_{out}, is a function of the output power (P_{out}) and the Capacity Utilization Factor (CUF) and be calculated using Eq. (8) (Ejiofor *et al.*, 2020):

$$E_{out} = P_{out} * 8760 * CUF \tag{8}$$

Where: E_{out} is the annual output energy of the system in GWh. P_{out} is the rated power of the system in GWh.CUF is the Capacity Utilization Factor.

The power output (P_{out}) of the Biomass Plant in a given study area is calculated using Eq. (9) below as:

$$P_{out} = \frac{M_b * 1000 * CV_b * \eta_c}{365 * 3600 * t_c} \tag{9}$$

Where: M_b is the annual availability of biomass in the study area. η_c is the conversion efficiency of the biomass plant. t_c is the operating hour of the plant in a day. CV_b is the calorific value of the biomass.

Data for the total crop production in Nigeria was obtained from United Nations Food and Agricultural Organization (UN-FAO), converted to a map shape file and XY data and overlayed on the NGA_adm_0, 1 and 2 being shapefiles for Nigerian map. Inverse distance weighting interpolation (IDW), a tool for spatial analysis was used with NGA_adm_2 as raster for geoprocessing extent, enabling the analysis to indicate exact locations within the states where the various crop production units in tonnes/year applies. This was further classified into 10 categories for ease of visualization with a color ramp with light green showing the least and deep green, the highest crop production units. The XY data containing GPS data was overlayed 100% on the adm_2 map file percentage of total enabled in the symbology to show bar charts with heights showing exact production unit in the various locations. Fig. 3 shows the biomass production across the 36 states of Nigeria, including the Federal Capital Territory (FCT), while Fig. 4, shows the result of the IDW interpolation with attributes enabled for NGA_adm1 and 2 beings states and Local government areas respectively.

5.2.4. Assessment of hydropower potentials in Nigeria

The capacity of hydropower that can be harnessed from a given location is dependent on the hydrology and hydraulics of such a location (Odiji et al., 2021). These include the available head in meters and the volumetric flow rate Q in m^3/sec. The power output from any hydropower scheme is given by the equation below;

$$P_{\max \quad output} = Q * H_{net} * g * \eta_{\max}(\text{kW}) \tag{10}$$

The volumetric flow rate Q is dependent on the Cross-sectional area of the river in m^2 and the mean velocity in m/s and can be represented by the equation below

$$Q = A * V_{mean}\left(\frac{m^3}{s}\right) \tag{11}$$

The Cross-sectional area of the river is directly proportional to the vertical depths, d(m) from the river's surface to its bed and can be represented by the equation below;

$$A = \frac{1}{n}\sum_{i-1}^{n} \frac{d_n.(b_k - b_{k-2})}{2} m^2 \tag{12}$$

Where,a = the area (m^2) of the trapezium formed with regard to the reference point and varied directly with numbers of vertical depths. n = number of vertical depth sub-division across the river cross-section width usually an integer, k = n + 1d = the vertical depths (m) from the river's surface to its bed, b = the horizontal distance (m) from the river bank at one end of its width to the vertical depth spot per time being considered. A = the river cross section area (m^2) given as the average areas of the smaller trapeziums formed. Q is the flow rate in m^3/s, V_{mean} is the mean or average velocity in m/s. η_{max} is the maximum turbine efficiency, g is the acceleration due to gravity in m/s^2.

Inland waters provide a reliable source of water with required depth, d and cross section area A for large dam schemes needed for large scale hydropower generation and these potentials reduce as availability of inland water sites declines across the nation.

Hydropower potentials were analyzed using datasets obtained from UN-FAO containing waterlines and water areas for Africa. These datasets in form of XY data were converted to shapefiles for water areas and waterlines respectively and overlaid 100% on NGA_adm 0, 1 & 2 shapefiles. The overlayed shapefile is clipped and extracted using spatial analyst tools within the boundaries of NGA_adm 2. IDW interpolations were done with NGA_adm_2 as geoprocessing extent and NGA_waterbodies as input features. Idw_shp output raster with 36 points were reclassed into 10 points. Color ramping was done using the symbology for the 10 reclassed points and charts were inserted by converting the waterbodies_shp file to XY data and exporting to a.csv file. These charts were displayed as percentages of total, signifying the various weights and quantities of inland waters available in various locations across Nigeria. A multiple ring buffer as shown in Fig. 5 with distances ranging from 500 m to 5 km was conducted using the NG_waterline_shp file to showcase suitability areas for hydropower projects. Fig. 6 shows the various locations of hydropower potentials in Nigeria.

6. Results and discussions

6.1. Solar energy potentials in Nigeria

Solar energy resource and potentials PV outputs were analyzed and the result shows the spread across Nigeria. Katsina state is showed with the highest solar energy potential with a GHI of 2191.8kWh/m^2 and specific PV output (PVOUT) of 1750.3kWh/kWp. Other states with high solar energy potentials include; Yobe, Jigawa, Borno, Kano and Sokoto states with GHI and PVOUT as (2191.88kWh/$m^{2,}$ 1750.3 kWh/kWp), (2190.38kWh/m^2, 1739 kWh/kWp), (2179.58kWh/$m^{2,}$ 1732.2 kWh/kWp), (21718kWh/$m^{2,}$ 1718.9 kWh/kWp), (2146.98kWh/m^2, 1712 kWh/kWp) and (2145.88kWh/$m^{2,}$ 1695.7 kWh/kWp) respectively. Bayelsa is seen to have the lowest Solar energy potentials with GHI and PVOUT of 1593.5 kWh/$m^{2,}$ and 1269.5 kWh/kWp as shown in Fig. 7.

6.2. Wind energy potentials in Nigeria

Fig. 8 shows result from the weighted overlay calculation showing a great potential of wind energy at various altitudes with the highest potentials within the states in Northern Nigeria. States like Yobe, Borno, Katsina, Zamfara and Sokoto with a rage windspeeds of between 8.4 m/s to 14.7 m/s. Other potentials are found in the states within the middle-belt such as Plateau, Benue, Gombe, Kaduna and Adamawa. These potentials however vary with the elevation of the geographical locations as established earlier in this paper.

6.3. Biomass potentials in Nigeria

From the Fig. 9, the analysis shows Benue state with the highest biomass potential with a crop production of 1755.71tonnes/yr contributed by crop productions in Gboko, Gwer-East and Tarka local government area. Kaduna, Oyo and Cross River states has the second highest biomass potentials with crop productions from southern Kaduna, Itse Iweju, Etung local government areas with 1171, 1182 and 1181tonnes/yr respectively. Lagos state and FCT were found to have the lowest potentials for Biomass production with annual crop production of 75 and 67 tonnes/yr, giving the stakeholders a hint to explore alternative means for power generation.

6.4. Hydropower potentials in Nigeria

The results from the analysis in Fig. 10 shows Yobe state with the highest potentials for large hydropower schemes owing the availability of 55 inland water sites. This is followed by Bauchi, Jigawa, Adamawa, Sokoto and Niger states with 46, 45, 31, 25, 20 inland water locations respectively. No inland water potentials were shown in Abia, Ekiti, Enugu and the FCT. The results show a progression of different hydropower schemes from large dams to run-of-the-river schemes as can be applicable based on availability of water and other hydraulic requirements for an efficient power production. Pumped hydro storage systems could also be developed for areas with little water to boost mini-grid operations.

Fig. 11 shows the distribution of renewable energy resources across the six geopolitical zones of Nigeria; North Central (Jade colour), North West (Tzavorite green), North East (Fire red), South West (Tan color), South East (Lt Orange) and South-South (Sugilite Sky Blue). The states in the North Central are Benue, Kogi, Kwara, Nasarawa, Niger, Plateau and the Federal Capital Territory. North Western states include; Kaduna, Kano, Katsina, Kebbi, Jigawa, Sokoto and Zamfara while the North East Zone has the following states: Adamawa, Bauchi, Borno, Gombe, Taraba and Yobe. Nigeria's South Western Zone states are: Ekiti, Lagos, Ogun, Ondo, Osun and Oyo, South Eastern states include: Abia, Anambra, Ebonyi, Enugu and Imo.

The analysis in Fig. 11 shows the distribution of small hydro, wind, solar and biomass resources across the various zones with their strengths and weaknesses in the Nigerian Renewable Chart with Blue colour showing small hydro, gray for wind, yellow for solar and green for biomass. The North West and North East zones were found to have strong hydro, solar and wind potentials with a weak availability of biomass potentials, while the North Central zone was found to have strong wind, solar and biomass potentials with weak hydro potentials. The South East, South West and South-South zones were found to have strong solar and biomass potentials with weak hydro and wind potentials. This analysis therefore provides clarity on the distribution of renewable energy potentials across the country for further feasibility studies and government decisions.

7. Conclusions and recommendations

Nigeria has great potentials to cater for its energy needs using various natural and renewable energy sources. This study evaluated the various renewable energy sources in Nigeria using ArcGIS assessment. The analysis presented in this paper reflects the abundance of renewable resources for power generation and where they are located to help decision making and policy formulations. The results of this paper show Katsina state with the highest solar energy potential with a Global Horizontal Index (GHI) of 2191.8kWh/m^2 and specific PV output (PVOUT) of 1750.3kWh/kWp. Other states with high solar energy potentials include; Yobe, Jigawa, Borno, Kano and Sokoto states with GHI and PVOUT as (2191.88kWh/m^2, 1750.3 kWh/kWp), (2190.38kWh/m^2, 1739 kWh/kWp), (2179.58kWh/m^2, 1732.2 kWh/kWp), (21718kWh/m^2, 1718.9kWh/kWp), (2146.98kWh/m^2, 1712 kWh/kWp) and (2145.88kWh/m^2, 1695.7 kWh/kWp) respectively. Bayelsa has the lowest Solar energy potentials with GHI and PVOUT of 1593.5 kWh/m^2, and 1269.5 kWh/kWp. A great potential of wind energy at various altitudes was seen within the states in Northern Nigeria like Yobe, Borno, Katsina, Zamfara and Sokoto with a range wind speeds of between 8.4 m/s to 14.7 m/s. Yobe state has the highest potentials for large hydropower schemes owing the availability of 55 inland water sites, followed by Bauchi, Jigawa, Adamawa, Sokoto and Niger states with 46, 45, 31, 25, 20 inland water locations respectively. No inland water potentials were shown in Abia, Ekiti, Enugu and the FCT. Benue state was also shown to have the highest biomass potentials from crop production of more than 1700 tonnes/yr followed by Kaduna, Oyo and Cross River states with 1171, 1182 and 1181tonnes/yr respectively.

This paper hereby recommends the following as the contributions of this study to the body of knowledge and to provide the much-needed background for policy implementations by the government in line with the Nigeria Energy Transition Plan which hinges on harnessing renewable energy resources for sustainable development and improving energy access to Nigerians. This analysis hereby provides the much-needed insights and mapping of renewable energy potentials across the six geopolitical zones of the country. The following recommendations are therefore imperative to help achieve the objectives of the Nigerian Energy Transition Plan;.

- Hybrid Power Projects consisting of Solar, Wind and Pumped Hydro storage plants should be sited in the North Eastern part of the country, particularly within states like Katsina, Yobe and Borno states to support the national grid
- Incentives should be provided to promote research into large scale development of biogas and biomass resources in Benue, Kaduna, Oyo and Cross-river states to provide alternative, cleaner and cheaper cooking gas for Nigerians
- Rural Electrification Agency and other renewable energy implementing agencies should provide frameworks and capacity building for developers to explore pumped hydro storage in areas with good elevations and little hydropower resources like South East and South-South Nigeria as alternatives to Lithium-ion batteries for mini-grid solutions, thereby increasing the affordability and sustainability of mini-grid solutions in Nigeria.

The paper recommends the categorization of the interventions for renewable energy solution deployments to suit availability of these resources as weighted across the country and hybridization of conversion technologies in areas with abundance of multiple resources for sustainable development.

CRediT authorship contribution statement

Okedu Kenneth: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Oyinna Benneth:** Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft. **Colak Ilhami:** Data curation, Resources, Visualization. **Akhtar Kalam:** Data curation, Funding acquisition, Visualization.

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.

Data availability

Data will be made available on request.

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