Wind Power Generation in Sudano-Sahelian Region of Nigeria: A Review

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Abstract. Over a couple of years, the world's energy demand has turned to renewable energy sources due to the menace of global warming, while some African countries still depend on fossil fuels despite their harmful effects. Out of approximately 4 trillion (kWh) of renewable energy that is expected to be generated by the year 2030, wind energy is projected to contribute up to 1.1 trillion (kWh). Wind energy studies will be the centre for future renewable engineering efforts, being one of the most likely economic and affordable alternate energy sources. Furthermore, wind resources analysis has also revealed that the Northern part of Nigeria, which occupies almost all the meteorological locations in the Sudano-Sahelian Ecological Zone, possesses enormous potential for harvesting wind energy. This paper involves a systematic review of relevant literature to identify the outcome of various initiatives of researchers at appraising the prospects of electricity production from wind for sustainable development in the region. It was established that the area is blessed with enormous opportunities for harnessing wind for various applications, having possible average wind speeds reaching as high as 8.70 m/s at 10 m above the ground. The region can adequately utilise wind for power generation if the fundamental challenges facing wind energy utilisation are addressed. There is a need to systematically model and simulate the system's feasibility before actual implementation to assist in other managerial and technical decisions. Wind energy integration will immensely contribute to providing lasting solutions to the energy situation in the region and the country at large.

Keywords: Wind Energy; Sudano-Sahelian Ecological Zone; Wind Turbine; Modeling; Simulation.

INTRODUCTION

The extended demand-supply gaps, heavy burden on the economy, worldwide depletion of fossil fuel reservoirs, devastating effects from climate change, carbon emissions, stormy rain, hurricane, a great flood, as well as other environmental hazards, result in the need for alternative sources of energy that is cost-effective, clean, sustainable and environmentally friendly.

Natural gas in gas turbines is not environmentally friendly as it damages the environment, yet it remains the means of power generation in many African countries. Wind energy is abundant on the earth and has a low or no impact on environmental pollution. The point is generated naturally from the wind; hence fuel needed for wind turbines is free and occurs every day [1]. Although wind power has been one of the most frequently used alternative energy, but still poses the most immediate integration challenge among all modern renewable energy sources.

Since the energy crisis of the 1970, when wind power began its resurgence, wind power installed capacity has been growing drastically; because it has been proven that it is feasible that some countries may receive a reasonable percentage of their electrical energy from wind by 2030.

In Nigeria, especially in the dry season, sufficient water for hydroelectric power plants affects power availability. Climatic variables of high temperatures coupled with low rainfall and drought lead to evapotranspiration, resulting in reduced water volume and hydroelectric power generation and transmission capacities. Hence, exploring alternative renewable energy sources, such as wind or solar, is essential. Besides hydropower, Wind energy is currently the most economical renewable energy due to its versatility. Using it as a decentralised energy form makes its applications possible in rural areas where it is economically and technically viable in the country [2]. Renewable energy technologies that are gradually used to tackle energy deficiencies include wind, solar, biomass, hydropower etc. Still, one of these sources that need more concern is wind energy. Wind energy can be harnessed for electricity generation, water pumping, irrigation, and milling [3].

Promoting an energy mix from renewable resources will ensure a seamless transition into a low-carbon energy economy while enhancing climate change mitigation, livelihood improvement, poverty reduction and sustainable development. The advent of smaller technologies, such as wind power and the photovoltaic system, is currently challenging the conventional method of using large centrally located power plants and grid extension for rural electrification. Therefore, this paper highlights the importance of wind energy to accelerate the sluggish nature of rural electrification programmes in the Sudano-Sahelian region of Nigeria. The methodology adopted in the review involves searching for relevant literature related to the study objectives on search engines. The articles were screened and validated for inclusion or exclusion based on relevancy, content and context.

RESULTS AND DISCUSSION

Wind Energy for Wind Turbine and Wind Farms. Global warming and climate change have dominated seminars, conferences, and discourses for decades in almost all parts of Africa. Climate change is defined as identifiable changes in the average temperature, precipitation, and wind pattern that persists for an extended period, typically decades or longer [4]. The wind is a powerful and abundant source of renewable energy. Onshore and offshore wind power installations have expanded rapidly worldwide to harness wind energy [5]. Wind energy is an indirect form of solar energy, as it's constantly being renewed by the sun. This energy conversion occurs when the natural resource wind generates electricity. Energy is one of the cheapest renewable sources of energy produced. Its technology is one of the fastest-rising technologies in the world's energy generation industry, yet not so much in the Nigerian Sudano-Sahelian region.

The prominent renewable energy source in Nigeria has been restricted to solar energy. This is because wind energy's viability could be better due to low wind speeds in some countries' ecological zones. Wind speed is generally moderate in the southern region, except in coastal and offshore areas. On the other hand, Wind speed is usually considered vital in the northern part, which occupies almost all the states that fall within Nigeria's Sudano-Sahelian Ecological Zone (SSEZ). It is considered most critical in the hilly regions of the north. Wind speed data obtained from the Nigerian Meteorological agency utilised to analyse the viability of wind power in Kano State revealed that the high power supply cost and carbon emission reduction could be realised with the use of wind as the alternative energy source. A Journal article on the analysis of meteorological data collected from some selected weather stations in Nigeria shows that wind power prospect in Nigeria is high and cost-effective. The result demonstrated that the region's wind profiles and qualities are reasonable enough for wind power generation when several small turbines are connected at average wind speeds.

Wind turbine technology has been evolving gradually to resolve the declining rate of fossil fuels and the current emission levels. A wind turbine is an energy conversion device that converts kinetic energy in the wind to mechanical energy by way of shaft and gearbox arrangement. Wind turbine operation involves turning two or three blades (propeller-like shaped) by the wind around a rotor. The rotor, attached to the main shaft, turns a generator to generate electricity. Wind turbines (most miniature types) are used to charge battery units, while the more significant types are used to generate power for domestic applications. Most small-scale wind turbines control their direction using a tail vane. Still, due to high gyroscopic moments during sudden changes in wind direction, there is every possibility for blade breakage. As such, a proper study on the control of yaw movement was suggested for small-scale wind turbines [6]. Authors [5] classified wind turbines and their subsystems as follows:

1. Utility-scale systems. Wind systems that provide power larger than 100 kilowatts (kW) to a grid system.

2. Small-scale systems. Wind systems that use 100 kW or lower wind turbines to power a farm, home, etc.

3. Offshore systems are wind systems that comprise turbines installed on water bodies worldwide. Such a system can power a community, depending on the area's wind speed.

Subsystems of a typical wind turbine include the following:

1. Rotor (consists of blades and hub)

2. Drive train (gearbox, shafts, mechanical brake, electrical generator and couplings)

3. Mainframe and Nacelle (yaw system, bedplate and housing)

4. Tower and foundation

5. Electrical gadgets (converters, cables, transformers, and switchgear)

The four basic types of wind turbines are:

Type 1 – Fixed-speed wind turbines

Type 2 – Variable-slip wind turbines

Type 3 – Wind turbines with doubly fed induction generator (DFIG)

Type 4 – Full-converter wind turbines

Fixed-speed wind turbines are turbines in which the rotor is constrained to move at a particular constant speed, while variable-speed wind turbines are designed to run or operate at a different pace. In a wind turbine with a fixed rate, the rotor speed does not change regardless of wind speed changes. Hence for any other speed from the wind, the turbine efficiency is reduced because any variations in the speed of the wind are communicated as instabilities in the mechanical torque and as a disturbance to the stability of the power grid.

Variable speed wind turbine is aimed to operate at optimal efficiency constantly, consistent tip speed ratio, corresponding to the maximum performance coefficient, by adapting blades velocity at variable wind speed. Therefore, variable-speed wind turbines are the perfect standard for efficient power generation, irrespective of wind speed. However, in the rotor resistance, power lost in heat is problematic. Turbines with a Doubly-fed induction generator (DFIG) address this problem by using a back-to-back AC/DC/AC converter to regain the slip power in the rotor circuit. The Rotor current's flux-vector control lowers the mechanical stresses and maximises wind power extraction. Management in the rotor circuit is handled solely by the converter. Therefore, the machine's total output should not be considered while rating the converter. In complete converter wind turbines, the main power flow route to the grid from the wind turbine is the back-to-back AC/DC/AC converter. These turbines may employ synchronous or induction generators and offer independent real and reactive power control [1].

Wind turbines, based on the direction of spin, can be classified into two [7]: 1) horizontal axis wind turbines (HAWT); vertical axis wind turbines (VAWT).

Then again, considering how the turbine spins, two kinds of wind turbines can be defined. In both types of turbines, the direction of spin differs, but the mechanism remains the same. Horizontal axis wind turbines (HAWT) are wind turbines that rotate along their horizontal axis, while vertical axis wind turbines (VAWT) are wind turbines that spin about their vertical axis. In the horizontal axis wind turbine (HAWT), the rotor's rotational axis is parallel to the wind stream or ground. Its electrical generator and rotor shaft must directly face the wind at the tower's peak. The number of blades in HAWTs has no limit; it can be two, three or more, depending wholly on the designer. In the Soviet Union, in 1931, using one of the first modern horizontal-axis wind turbines. The turbine rated 100 kW connected to the country's 6.3 kV power distribution system was placed on a 30-m tall tower. It was accounted for to have had a yearly capacity factor of about 32%, which shares close similarity to the efficiency exhibited by current wind machines. A typical horizontal axis wind turbine rating ranges from 500 kW to 5 MW and remains the prevalent technology upon applications at the utility scale.

The main rotor shaft in vertical axis wind turbines is arranged vertically, hence the name. The fact that the turbine does not need to follow the wind direction to show high efficiency remains the major pro of this arrangement. Also advantageous is its ability to be mounted on a building because it is much less steerable. The drive train and electrical machine can also be positioned close to the ground with a direct drive from the rotor arrangement to the ground-based gearbox, enhancing availability for repairs. Its severe drawback is energy efficiency which still needs improvement over time. Another critical disadvantage also includes the relatively low rotational speed. The advantages of using a vertical axis turbine are simple and robust construction with minimal moving parts, which allows for a cost-efficient wind power plant with respect to maintenance, investment and operation. Other advantages include lower noise levels, independence of wind direction, simple blade profiles and less sensitivity to turbulence.

Wear can reduce turbine efficiency. Examination of 3128 wind turbines about ten years or older in Denmark demonstrated that half of them did not diminish in efficiency, while the other observed a decrease of 1.2% per year. Vertical turbine efficiency is lower than their horizontal counterparts [8]. Arrays of large turbines, called wind farms, are being utilised to generate power to reduce fossil power generation in developed countries.

Nigerian Sudano-Sahelian Ecological Zone (SSEZ). One-third of Nigerian total land mass is occupied by a sizeable ecological zone called Sudano-Sahelian Ecological Zone (SSEZ). As depicted in figure 1, the area lies between longitudes 40 E and 140 E and latitudes 100 N and 140 N. The selected regional meteorological locations include Sokoto, Kano, and Katsina, which fall within the Sudan savanna, and Maiduguri and Nguru, which fall within the extreme Sahel savanna ecological zone [9].

The Northern part of Nigeria comprises three ecological zones: the Sudan savanna, Guinea savanna, and Sahel savanna. The Sudano-Sahelian Ecological Zone falls within the Sudan and Sahel savanna regions. Areas in this region enjoy a tropical continental climate with two distinct seasons, wet and dry. The dry season lasts about eight months, while the wet season lasts only 3–4 months. Temperatures are generally high, particularly during the dry season, with a mean maximum temperature of 39 °C and a mean minimum temperature of 19.5 °C. The region's mean annual rainfall ranges from 600 mm to only 400 mm in the Sudan savanna and extreme Sahel savanna zone, respectively [10]. Mean wind regimes in the north lie between 4.0–7.5 m/s at 10 m above the ground [11].

The climatic zone consisting of Sahel and Sudan vegetation is overlaid by Savanna vegetation with a density of scattered trees and other plants decreasing along the northward direction. These two ecological zones are in one place referred to as the Sudano-Sahelian Ecological Zone (SSEZ).

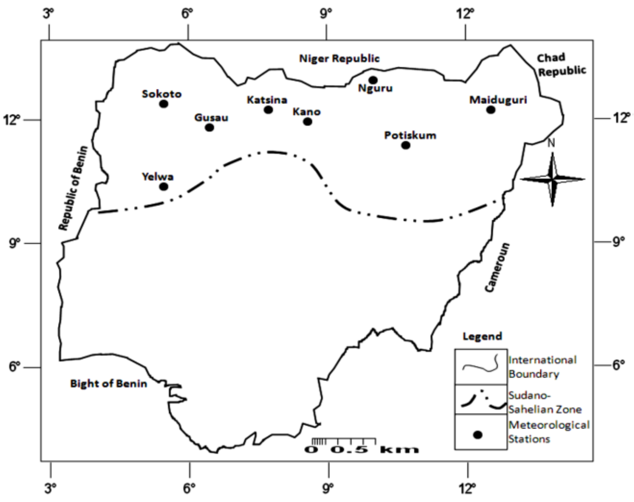

Figure 1 – The Sudano-Sahelian Ecological Zone of Nigeria [12]

Wind energy integrations in the zone will contribute immensely to achieving the sustainable development goals of 2030 (Table 1) proposed by the Nigerian energy sector.

Table 1 – Summary of renewable electricity sources and targets [13]

No	Energy resource	Short-term in MW (2015)	Medium-term in MW (2020)	Long-term in MW (2030)
1	Hydro (LHP)	2,121.00	4,549.00	4,626.9
2	Hydro (SHP)	140.00	1,607.22	8,173.81
3	Solar	117.00	1,343.17	6,830.97
4	Biomass	55.00	631.41	3,211.14
5	Wind	50.00	57.40	291.92

Notes: LHP – Large HydroPower; SHP – Small HydroPower.

Assessment of wind energy potentials. Models for wind turbines were developed and tested, yet the simulation of wind farms is scarce. Research that analysed the relationship between output power concerning wind speed and turbine speed was modelled by [8]. Matlab/Simulink was used to simulate this turbine to capture the wind energy associated with the wind for driving the electrical generator, which feeds the load. The model eventually demonstrates that wind energy could be extracted at varying wind speeds in the region. Another detailed model showing a wind energy conversion system was designed by modelling differential equations for each block and then simulated in a SIMULINK environment. The Squirrel Case Induction Generator, a horizontal axis wind turbine system with complexities of all three parts of the wind turbine model, was analysed using mathematical equations. Ogoja community's wind speed data in the southern part of Nigeria was used to assess the simulation performance. The system simulation tested works satisfactorily with different wind speeds, giving proportionate mechanical torque and turbine speed [1].

An agent-based modelling and simulation framework that helps compose different model components, design valuation and forecasting energy generation cost-effectively and productively for the rapid prototyping of wind power plants was proposed by [7]. The model was demonstrated by conceptualising the design of the foundation wind energy plant in Sindh, Pakistan, and the development of its agent-based model. Five different time-series forecasting models were used on the actual data to further compare the forecasts with the time series analysis after the short-term and long-term electricity generation profiles obtained were validated with the actual data. The time series analysis and simulation model proposed was consistent with the real data having a root mean square deviation of about 9 MW. Modelling and simulating a grid-connected wind-driven electricity generation system with a wind-turbine-driven Permanent Magnet Synchronous Generator (PMSG), diode rectifier, and DC/AC inverter as unit features were developed and implemented in MATLAB/Simulink by [14]. The system was recommended to offer better performance due to the higher efficiency, less maintenance and cost-effectiveness of a Permanent Magnet Synchronous Generator (PMSG) than other generators.

Using modelling and simulation as a tool for analysis can assist in managerial and technical decisions. This suggestion was made based on [15] findings after they modelled a small wind power plant connected to a grid in Modelica/Dymola. The mini power plant consists of an internal DC-grid interconnected with one grid connection and three wind power units with 3 kW nominal power. Models were developed, tested and evaluated by running several simulations to pull up the small grid. The research finally shows the essentiality of considering wake losses when positioning the turbines, as it maximises energy production. A systematic approach to simulate an offshore wind farm for intelligent cities was developed by [16]. Rotor blades drive train, induction generator, and other variable-pitch wind turbine subsystems were modelled to form a wind farm. The total output power of the wind farm by considering multiple wind turbines with the wake losses (using the Jensen wake model) was simulated with any input wind speed. A study was conducted on a German offshore wind farm called NordseeOst. The simulation shows promising results with an average error of approximately 5% compared with the wind farm's real-time output. The simulation results disclosed that wind farm feasibility tests, which often needed more exact information, are viable before site implementation, especially in smart cities.

Authors [17] conducted a study on assessing wind potential in Nigerian south-south coastal states using the Weibull distribution. His findings, as depicted in Figure 2, revealed that better and higher values of wind energy density could only be achieved when meteorological data are collected above 10 m high.

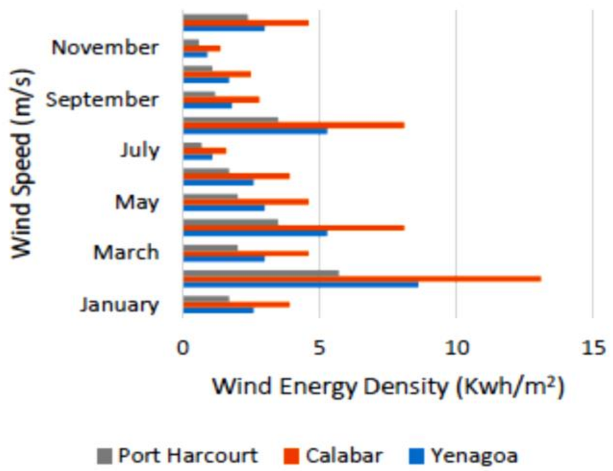

Figure 2 – Wind Energy Density versus Wind Speed at 10 m height [17]

A research paper that outlines some of the characteristics and layout of the Katsina wind farm described the wind as both an efficient and reliable form of a clean source of renewable energy, as well as an excellent method of harnessing renewable energy from locations where there is the availability of land [3]. Heipany, a town in Jos, was recommended as an ideal location to construct windmills. This suggestion by [2] resulted from a discovery that the maximum power intensity which could be extracted from the wind in the area was found to be 14.23 W/m^2 out of the estimated available wind power intensity of 24.00 W/m^2. The energy density available in the wind has also been calculated to be 1126.28 KWh/year.

In 2003, the federal government of Nigeria, after noticing the potential of wind utilisation as depicted in Table 2, introduced policies that support wind energy integration with other energy resources and provide necessary measures to ensure that wind energy is harnessed at a justifiable cost. Despite this fact, this cheap, easily accessible, naturally applicable, enormously available, environmentally friendly, non-depleting and non-toxic source of valuable and usable energy is still inadequate and inconsistent, particularly in the Sudano-Sahelian Ecological Zone of the country.

Table 2 - Potential of Wind Utilisation According to End Use [18]

No	AREA	Electric Power Supply
1	Semi-Arid, Hot, dry areas: Sokoto, Kano Katsina, and Borno States	GP
2	Along the shores of Lake chad	GP
3	Temperate Areas: Plateau, Bauchi and Gongola States.	GP
4	Along the shores of Rivers Niger and Benue	LP
5	Offshore	GP

Notes: GP – Good Potential; LP – Limited Potential

Authors [18] researched the wind energy reserve at 10 m height based on data analysis from 10 wind stations across the North West, North East, North Central, South East and South West geopolitical zones. The research showed some promise as it inferred that the sites are potential wind farm areas with moderate wind regimes, having wind regimes between 3.6 and 5.1 m/s according to the Beaufort scale. This is because most wind turbines start generating electricity at wind speeds (cut in rate) of around 3–4 m/s.

Authors [11] looked into the wind energy potentials and the extent to which these potentials were utilised in Nigeria for a sustainable environment. It was established from their findings that the absence of local manufacturing for wind energy components, the reluctance of the government to encourage wind technologies, and low financing were the challenges facing wind energy utilisation in the country. Therefore, addressing the aforementioned associated challenges will put the country's energy situation in a better run.

CONCLUSIONS

Wind energy integration is increasing globally. Nigeria is blessed with enormous opportunities for harnessing wind for various applications, more specifically in the core northern region of the country. Renewable energy (wind) can effectively be produced in the Sudano-Sahelian Ecological Zone of Nigeria as suitable wind corridors are available. A mean wind regime in the region was found to lie between 4.0–7.5 m/s at 10 m above the ground. Variable-speed wind turbines are preferable as they are ideal for efficient power generation, irrespective of wind speed. Model simulation of wind energy systems assists in estimating the extent of electrical energy produced at given conditions using the wind potential available at the region's corridors and aid in the realistic analysis of the future dynamics of electricity demand and supply, hence helping in effective energy planning. Poor government motivation for wind energy technology (WET) and lack of adequate research and development tailored towards WET, to mention just a few, remains the associated challenges hindering the technology despite its vast prospects. This transition into a low-carbon energy system in the Sudano-Sahelian Ecological Zone of Nigeria is feasible. It will help address the energy shortfall, enhance climate change mitigation, and assist in sustainable human development and continued economic growth, especially if the associated challenges are overcome.

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