

**USMANU DANFODIYO UNIVERSITY, SOKOTO  
(POSTGRADUATE SCHOOL)**

**DEVELOPMENT OF AN ALGORITHM FOR PERFORMANCE EVALUATION  
OF SELECTED WIND ENERGY CONVERSION SYSTEMS FOR SOKOTO,  
MINNA AND POTISKUM, NIGERIA**

**A Dissertation**

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**BY**

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**APRIL, 2019**

## **DEDICATION**

This work is dedicated to my late mother HajiaJamilaAbdulazeez may her soul rest in peace. Ameen

## CERTIFICATION

This Dissertation by ABDULAZEEZ,Sakina (Adm. No. 15210305003) has met the requirements for the award of the Degree of Master of Science (MSc Physics) of the UsmanuDanfodiyo University, Sokoto, and is approved for its contribution to knowledge.

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## ABSTRACT

Wind energy is currently one of the most economically viable renewable energy. Its usage, versatility and ability to use it as a decentralized energy form makes its applications possible even in rural areas. This study evaluates the performance and economic analysis of five small scale wind turbines in three locations of Northern Nigeria. Ten years daily average wind speed data measured at 10m height for the locations were obtained from Nigeria Meteorological Agency (NIMET) and characteristics of the five selected small scale wind energy conversion systems obtained from manufacturer's website were used to evaluate the performance of the selected wind energy conversion systems (WECS) and economic analysis in the selected locations were carried out using the levelised cost analysis method. All the evaluations in this study were done with the developed algorithm. The result shows that the levelised cost of energy per kWh ranges from ₦71.25 for wind turbine e3001 1kW in Sokoto and ₦282.44 for west wind 2.5kW in Potiskum. Sokoto is the most promising site among the three locations considered for energy production and also the most viable site based on unit cost of electricity.

## CHAPTER ONE

### INTRODUCTION

#### 1.1 BACKGROUND OF THE STUDY

Energy is the basis of the world's economy, combining with all other entities that are vital for economies. The quest to meet growing energy demand of the global population initiated numerous researches in a wide range of environmental application of renewable energy (RE) (Park and Law, 2015). Energy is considered a prime agent in the generation of wealth, a significant factor in economic development and the driving force of industrialization (Ohunakin, 2010; Yuksel, 2010).

Energy is also seen as one of the crucial inputs for socio-economic development; it exists in a pure form as electricity whose demand has grown considerably with larger proportion generated using fossil fuels, which causes serious environmental problems such as acid emissions, air pollution and climate changes thereby making current energy trends to be unsustainable thus necessitating a better balance between energy security, economic development, and protection of the environment. At the same time, wind power has become an important option for electricity generation among renewable sources of energies. Being environmentally friendly, it has been gaining more and more ground in many countries across the globe in recent years because it can provide significant quantities of energy to support a country's needs (Ahmed and Hanitsch, 2006; Keyhaniet al., 2010; Ohunakin, 2011a,b).

Renewable energy sources among which are wind, solar, hydro, biomass etc. have been gaining prominence in many developed countries due to increasing efficiencies of their technologies as recorded over the years and the decreasing generating costs associated with deployment of the technology (Gökçeket al.,2007). Many developed and

developing countries around the world have adopted policies to harness renewable energies such as wind and solar in order to reduce their dependency on non-renewable resources of energies (Chaparzadeh, 1999).

Wind power is the use of air flow through wind turbines to mechanically power generators for electric power generation. Wind power as an alternative to burning fossil fuels, is plentiful renewable widely distributed, clean, produces no greenhouse gas emissions during operation and uses little land. Wind energy is currently one of the most economically viable renewable energy apart from hydropower. Its usage versatility and ability to use it as a decentralized energy form make its applications possible even in rural areas where it is technically and economically feasible in many parts of the globe (Fthenakis and Kim, 2009).

The major challenge to using wind as a source of electricity generation is that wind is intermittent in nature; that is, it does not always blow when electricity is needed. However, wind power is one of the most promising and cost – effective renewable (Ahmed *et al.*, 2014). The net effects on the environment are far less problematic than most renewable power sources. Currently, the wind sector stands out as one of the most promising RE as it is an inexhaustible diurnal resource that can provide significant quantities of energy to support the needs of a country (Ackerman and Soder, 2002).

Wind power is becoming the world's fastest growing renewable energy source whose strong growth is attributable to the promotion of models of renewable energy sources, energy supply security, fuel diversity concerns, ecological awareness and economic reasons. Its worldwide acceptance as a clean source of energy showed a reflection in the total installed capacity and annual output that reached 121,188 MW equivalent to 260 TWh respectively at the end of 2008, recording approximately 27% increase above year

2006 and contributing more than 1.5% to global electricity consumption (Ahmet and Guler, 2010; Gökçek and Genc, 2009).Harborne and Hendry(2009)reported that wind has advanced more quickly to commercialization than other technologies such as solar power, fuel cells and wave power with relatively little Research & Development (R&D) expenditure.

Energy supply in Nigeria is a major problem for both large and small scale purposes. Highly centralized generation and distribution units have not been equally distributed thus becomes inadequate in meeting the economic needs of both urban and rural populace.Nigeria has a high population growth rate and is heavily dependent on oil and gas as its main source of revenue, which coupled with policy instability to expose the economy to global energy dynamics, thereby, rendering the industry as one of the most inefficient in satisfying the needs of the populace (Ohunakin, 2010).

With respect to this problem, solar and wind energies are some of the alternative sources of energy that can be exploited to meet some of the needs of the populace. It is therefore necessary to evaluate the wind regimes in any location and assess its potential, for the purpose of installing wind energy conversion system for the generation of electricity. To begin harvesting wind resources for power production involves therefore, the initial effort of resource assessment to ascertain its potential for power generation. Based on this, the northern part of Nigeria has been identified as a region possessing great potential for wind energy utilization for power generation because of the prevailing wind situation of the place (Ajayi, 2009).

The increasing price-competitiveness of wind energy against other conventional fossil fuel energy sources such as coal and natural gas is another positive indication on wind energy (Rechsteiner, 2008). Therefore, a vast amount of researches on types of wind

energy conversion systems (WECS) have been and is still being undertaken intensively. WECS is a structure that transforms the kinetic energy of the incoming air stream into electrical energy. This conversion takes place in two steps, as follows. The extraction device, named *wind turbine rotor* which turns under the wind stream action, thus harvesting a mechanical power. The rotor drives a rotating electrical machine, the generator, which outputs electrical power (Munteanu *et al.*, 2008). WECS consists of three major aspects; aerodynamic, mechanical and electrical. The electrical aspect of WECS can further be divided into three main components, which are wind turbine generators (WTGs), power electronic converters (PECs) and the utility grid (Iov and Blaabjerg, 2009).

The aim of this research is to study the wind speed patterns and also develop an algorithm for the evaluation of wind energy using the characteristics of different wind energy conversion systems and resource potentials in selected locations of Northern Nigeria.

## **1.2 STATEMENT OF THE PROBLEM**

Because Wind energy by its nature is intermittent and varied from place to place, it is not possible to use same WECS on different location and expect optimum outputs, in all the locations. So combining the wind resources of a location and characteristics of wind energy conversion system one can be able to identify which particular WECS can best fit for a particular location, in order to minimise the problems of wrongsiting of WECS for proper efficiencies.

### **1.3 AIM AND OBJECTIVES**

The aim of this research is to study the wind speed pattern of the selected cities and develop an algorithm that can assist in selecting the best WECS that can give optimum energy output in the selected locations.

The specific objectives to be followed for achieving the aim are:

- i. To determine the average wind speed data and Weibull probability distribution functions for the selected locations.
- ii. To identify the best WECS that give optimum performance at each of the selected locations and;
- iii. To evaluate which of the WECS is the most cost effective at each of the selected location.

### **1.4 SIGNIFICANCE OF THE STUDY**

Selection of the appropriate machine for optimum wind energy conversion at different locations is very vital because it minimise wastages due to poor site selection. The algorithm developed, would help in identifying the best WECS that can give the optimum performance at each of the selected location.

### **1.5 SCOPE AND LIMITATION**

Daily average wind speed data used for analysis covers a period of 10 years (2001-2010) which was obtained from Nigerian Metrological Agency (NIMET).The work was limited to use of five selected wind energy conversion systems ranging from (1.0, 1.5, 2.5, 2.5, & 3.0KW) and it was limited to only three locations in the whole of Northern Nigeria (Sokoto, Minna and Potiskum), one from each of the three geopolitical zones of Northern Nigeria.

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 WIND ENERGY POTENTIALS

Wind energy market is continuously growing worldwide. In 2006, about 82 countries used wind to generate energy, and 49 out of these countries increased their installed capacity to double by 2009 (World Wind Energy report, 2009). The Middle East and Africa also recorded a total of 230MW of newly installed capacity with almost 90% growth rate in Morocco and 170% growth in Tunisia. Although these values are small compared with wind energy producing regions like North America, Europe and Asia, the presence of wind energy in remote locations of the world simply highlights the continued rapid growth in global demand for emissions-free wind power, which can be installed virtually everywhere around the globe. Wind energy had over 238GW of installed capacity at the end of 2011 and is expected to play a crucial role in mitigating future greenhouse gas emissions. Wind speed in Nigeria ranges from 1.4 - 3.0m/s in the southern areas and 4.0 - 5.12m/s in the extreme north. Wind speeds are generally weak in the southern part of the country except for the coastal regions and offshore location. Initial study has shown that total exploitable wind energy reserve at 10m height may vary from 8MWh/yr in Potiskum to 51MWh/yr in the mountainous areas of Jos Plateau and it is as high as 97MWh/yr in Sokoto (ECN, 2005).

In order to improve wind technologies, several studies have been carried out in the recent years. De Risiet *al.* (2014) proposed a new cooling system for wind turbine generator, based on nanofluid as heat transfer fluid and the wind turbine tower as heat exchanger. This system is able to dissipate quickly waste heat from electric generator in the environment, increasing the overall efficiency of wind turbines. This fast development of wind technology, as well as energy market, has large implications on

siting of wind farms. Actually, the first critical step towards harnessing wind energy is to estimate the wind resources of a site. In the last years, different authors have studied the wind speed and direction as well as the wind potential in several regions of the world.

Adopting renewable energy resources for electricity production and other energy needs has become a notable objective globally. While countries have started to look at ways of harnessing the abundant environmentally friendly renewable resources, some others have already proved it and are extending their generation capacities. China, United States, Germany, Spain, India are some examples of countries who have annual installed wind power capacities in the regions of some Giga-Watt (GW) of electricity (Ajayi, 2013a; Omole and Ndambuki, 2014). The African continent, though improving in generation capacities, represents the least developed in terms of installed wind power and wind electricity adoption. North Africa, with Egypt (550 MW) and Morocco (286 MW) leads the way. Tunisia (54 MW), South Africa (10 MW) and Kenya are other promising countries. Moreover, projections reveal that in the near future wind power capacities up to few GW can be achieved in places like Egypt, Morocco and South Africa. In sub-Saharan Africa, particularly the West African region, no country has yet generated grid electricity from wind despite the identified opportunities (Ajayi, 2013b).

### **2.1.1 Wind Speed Probability Distribution Models**

Wind potential assessment for any location is an essential and primary task in any wind power generation study. The probability distribution function (PDF) of wind speed is playing a vital role in assessing the wind potential in a given location.

In order to accurately analyse the characteristics of wind speed frequency distribution, a variety of probability density functions have been proposed to describe the distribution

of wind speed in recent years. Currently, such wind speed frequency distributions include(Feijóo and Villanueva, 2016):

- i. Weibull PDF;
- ii. Gamma PDF;
- iii. Logistic PDF;
- iv. Rayleigh PDF;
- v. Lognormal PDF;
- vi. Inverse Gaussian PDF;
- vii. Maximum Entropy Principle (MEP) derived PDF; etc.

The two-parameter Weibull function has been one of the most widely used distributions. Moreover, it is used as a benchmark to estimate the resources of wind energy (Jiang *et al.*, 2017).Arslan*et al.* (2014) also stated that the two-parameter Weibull distribution was deemed highly appropriate for wind speed measured data. The form of the density function of the Weibull distribution changes drastically with the value of the shape parameter  $k$  (Wang *et al.*, 2016).

Typically, these wind speed probability distribution models can be roughly divided into two categories: single distribution model and hybrid distribution model. Single distribution model refers to a single PDF fitting the observed wind speed frequency. These single distribution models range from standard parametric distributions, such as Weibull distribution, Rayleigh distribution, Gamma distribution, Lognormal distribution and Logistic distribution, to non-parametric distributions generated by applying the MEP (Li and Li, 2005; Akpınar and Akpınar, 2007; Safari and Gasore, 2010; Qin *et al.*,2011).

Similarly, there have been numerous studies on the wind speed using probability distribution in Nigeria. (e.g) a study on the wind energy potentials for a number of Nigerian cities from the national wind mapping report in 2004 has shown high wind speeds in Sokoto, Jos and Kano / Funtua. The stations at Maiduguri, Lagos and Enugu also indicated relatively strong wind speeds, sufficient for energy generation by wind

farms. Apart from these sites, other promising regions with usable wind potentials are located at the Nigeria's shoreline (Lahmeyer International, 2004). According to Idris *et al.* (2012), available data on wind speed for some towns in Nigeria indicates very good prospects for wind energy development. The study advocates the inclusion of wind energy in the nation's energy supply mix. This would diversify and reverse the current acute electricity deficit experienced in the country, as well as address environmental concerns and effect of climate change.

Dikko and Yahaya (2012) studied on the evaluation of wind power potential of some selected towns in north eastern part of Nigeria (Gombe, Maiduguri and Yola) and they reported that the north eastern part of Nigeria has higher wind power density for the generation of wind energy and concluded highest power density ( $377\text{W}/\text{m}^2$ ) was found to be in Gombe. Tijjani (2006) studied on the statistical analysis of wind power density based on the Weibull and Rayleigh models in north western Nigeria (Yelwa, Kaduna, Gusau, Sokoto and Kano) using 15 years (1986 to 2000) monthly mean wind speed data of the selected towns. The study found out that the average monthly power density ranges between  $1.87\text{W}/\text{m}^2$  and  $108.8\text{W}/\text{m}^2$  for Kaduna and Sokoto respectively. Ahmed *et al.*, (2014) Reported that Borno has high wind power density  $273.16\text{ W}/\text{m}^2$  for Weibull and  $365.77\text{ W}/\text{m}^2$  for Rayleigh in the month of June as compared to Bauchi with highest power density of  $31.45\text{ W}/\text{m}^2$  for Weibull and  $37.06\text{ W}/\text{m}^2$  for Rayleigh in the month of May in the paper: wind energy potential evaluation of two locations in the north east Nigeria (Bauchi and Borno) which show very close agreement with actual power from measured data. In another development, Fagbenle *et al.* (2011) assessed the wind energy potential of Maiduguri and Potiskum, two sites in North-East, Nigeria. The result showed that average monthly mean wind speed variation for Potiskum ranged from 3.90 to 5.85 m/s, while for Maiduguri, it ranged from 4.35 to 6.33 m/s. Seasonally,

data variation between the dry and wet seasons revealed that, the mean wind speed variation for Potiskum ranged from 4.46 (for dry) to 5.16 m/s (for wet), while for Maiduguri it ranged from 5.10 (dry) to 5.59 m/s (wet). The wind power density variation based on the Weibull analysis ranged from 102.54 to 300.15 W/m<sup>2</sup> for Yola and it ranged from 114.77 to 360.04 W/m<sup>2</sup> for Maiduguri respectively. Moreover, Maiduguri was found to be the better of the sites in terms of monthly and seasonal variation of mean wind speed, but they both can be suitable for stand-alone and medium scale wind power generation.

Oluseyi *et al.* (2014) studied Wind Energy and Energy Cost of Wind Electricity Generation in south west of Nigeria. The outcome proved that the region's wind profiles and characteristics are suitable for wind power generation. Average wind speeds of between 1.9 and 5.3 m/s are prevalent, while the most probable wind speed ranged between 1.9 and 6.2 m/s. The maximum energy carrying wind speeds ranged between 2.2 and 8.6 m/s across all the stations. Lagos and Oyo states are areas with very high potential for harvesting wind power, while the mountainous regions of Ogun, Ondo and Ekiti would also be suitable. Further to this, the results proved that, apart from sites in Lagos and Oyo States and in mountainous regions, in terms of the rated wind speed ( $V_R$ ), wind turbines with rated speeds of between 10 and 12.0 m/s will be excellent for the sites.

Fagbenle *et al.* (1980) conducted wind speed resource assessment based on the wind data information from 1951 to 1960, from twelve meteorological stations, where they reported that average wind speed across Nigeria is about 3 m/s. In addition, they found that wind speeds are generally higher in the northern part of Nigeria than in the southern part with the highest wind speed of about 3.6 m/s in the Jos area. Ojosu and Salawu, (1990a) reported wind speed data from 1951-1975 from 22 stations across the country

and they concluded that Sokoto area (in northern part) recorded the highest wind speed of about 5.12 m/s in June with annual average of 3.92 m/s. Furthermore, they reported wind speed of about 2 m/s in the middle and southern areas. Further study by Ojosu and Salawu (1990b) using wind speed data (1968-1983) classified wind speeds across Nigeria into four different regimes.

Also, Fagbenle and Karayiannis (1994) did an analysis of 10-years' wind data from 1979 to 1988, and specifically reported that average wind speeds in Nigeria range from about 2m/s to about 4 m/s with highest average speeds of about 3.5 m/s and 7.5 m/s in the south and north areas, respectively. Ngala *et al.* (2007) did a statistical analysis of the wind energy potential in Maiduguri, Borno State. The study employed the Weibull distribution with 10 years (1995–2004) of wind speed data. On the other hand, Adekoya and Adewale (1992) analysed wind speed data for 30 stations in Nigeria and determined the annual mean wind speeds and power flux densities to vary from 1.5 to 4.1 m/s and 5.7 to 22.5W/m<sup>2</sup>, respectively. Fadare (2008) carried out a statistical analysis of wind energy potential for Ibadan, using a Weibull distribution function on 10 years (1995–2004) of daily wind speed data. The outcome showed that the city experienced an average wind speed and power density of 2.947 m/s and 15.484 W/m<sup>2</sup>.

Other studies includes that of Asiegbu and Iwuoha (2007) who studied the wind resource availability in Umudike, South-East, Nigeria using 10 years (1994–2003) of wind speed data. They found that the economic viability of the site required a hub height of 65 m above the ground with an annual mean wind speed of 5.36 m/s. Ogonnaya *et al.* (2007), on the other hand, worked on the prospects of wind energy in Nigeria, where four years' of wind speed data from seven cities (Enugu, Jos, Ikeja, Abuja, Warri, Sokoto and Calabar) cutting across the different geopolitical zones of the federation were employed. The outcome showed that the annual wind speed at 10 m

height for the cities varied from 2.3 to 3.4 m/s for sites along the coastal areas and 3.0–3.9 m/s for high land areas and semi-arid regions. It was also reported that monthly average wind power could be about 50.1 W/m<sup>2</sup> and that it was possible to generate a wind power of 97 MWh/yr from the Sokoto site. As reported in Adaramola et al.(2011) annual mean wind speeds in Nigeria was found to vary between 2 and 9.5 m/s with an overall annual mean wind speed of about 4.62 m/s.Fadare (2010) used artificial neural networks to predict the wind speeds distribution across Nigeria and compared the predicted wind speeds with measurements data from 28 stations that span between 1983 and 2003. This analysis predicted monthly average wind speed ranging from a minimum of 0.8 m/s for Ondo (in south region) to maximum value of about 13.1 m/s for Kano (in north region) with both values occurred in December.

Nnawuike and Emmanuel (2014) investigated the wind speed characteristics and energy potential of five selected locations in the south western part of Nigeria using monthly mean wind speed data of 51 years obtained from the Nigeria Meteorological Agency. The outcome showed that the wind speed measured at a height of 10 m ranged from 1.3 to 13.2 m/s while the modelled wind speed ranges from 3.0 to 5.9 m/s.83.6% of the data were found to be greater than 3.0 m/s. The average monthly wind speed ranged from 2.72 to 7.72 m/s. The annual mean power densities are 65.09, 145.07, 176.96, 387.07 and 87.34 W/m<sup>2</sup> for Abeokuta, Akure, Ibadan, Ikeja and Oshogbo respectively. It was further shown that the respective mean annual values of the most probable wind speed are 3.82, 4.97, 5.23, 7.03 and 4.01 m/s, while the annual values of the wind speed carrying maximum energy are 4.12, 5.48, 5.87, 7.50 and 4.55 m/s. These results indicate that wind speed has the viable potential for wind-to-electricity at height of 10 m for most of the locations assessed but it will be more viable in all the stations at a height above 10m.Furthermore, Chineke (2009)reported the monthly mean wind speed

measured at 10m height from 1961 to 1990 in the 36 states capitals of Nigeria. He reported that the monthly mean wind speed range from 1.3 m/s in Oshogbo in the south west to about 3.9 m/s in Jos (north central) and Katsina (north west) areas.

Ohunakin *et al.* (2011) statistically examine wind characteristics from seven meteorological stations within the North-West (NW) geo-political region of Nigeria using 36-year (1971–2007) wind speed data measured at 10 m height subjected to 2-parameter Weibull analysis. It is observed that the monthly mean wind speed in this region ranges from 2.64 m/s to 9.83 m/s. The minimum monthly mean wind speed was recorded in Yelwa in the month of November while the maximum value was observed in Katsina in the month of June. The annual wind speeds range from 3.61 m/s in Yelwa to 7.77 m/s in Kano. It is further shown that Sokoto, Katsina and Kano are suitable locations for wind turbine installations with annual mean wind speeds of 7.61, 7.45 and 7.77 m/s, respectively. Further reports on the various assessment studies both by researchers and government agencies are profiled in (Ajayi, 2009 and 2010).

### **2.1.2 Economic Analysis of Wind Turbines**

Mostafaeipour (2013) carried out economic evaluation of small wind turbine utilization for city of Kerman in Iran. He analysed the economic importance and evaluated the cost of kWh produced by three small scale wind turbines. The results indicated that the city had an available wind energy potential required for the installation of some small wind turbine models. Mostafaeipour *et al.* (2014) presented an economic evaluation technique and analysed four different wind turbines; they obtained wind power and energy densities of  $89.184 \text{ W/m}^2$  and  $781.252 \text{ kWh/m}^2$  respectively. They recommended the installation of Proven 2.5kW model wind turbine in the region which is according to them the most cost efficient option. Diaf and Notton (2013) studied the wind energy

potential and carried out economic cost analysis of 13 locations in Algeria. Based on the obtained results, the wind resource appears to be suitable for power production in the southern region, which makes it a viable substitute to diesel oil for electricity generation. Ohunakin *et al.* (2013) assessed technical electricity generation and economic analysis of six wind energy conversion systems in the categories small, medium, and large (with power ratings of 20, 35, 275, 500, 1,000, and 2,000 kW) across all the geopolitical zones of Nigeria. Of all the selected sites, Kano gave the least costs of electricity production per kilowatt hour with Vestas V80-2 MW model at 67-m hub heights, while the highest is obtained in Uyo with GEV-HP (1 MW) model at 70-m hub heights.

### **2.1.3 Cost Estimation of Energy Output**

Economic evaluation can compare the costs and consequences of different investments. The aim of economic evaluation is to ensure that the benefits from the projects are greater than the opportunity cost of such projects. It also provides criteria for deciding between different alternative projects that have different costs or consequences. Managements or decision makers need to know the inputs or costs that the projects will need as well as the outputs or benefits that the projects will produce. The decision makers can conduct economic cost analysis to produce comprehensive results that can scientifically be acceptable. Performance of economic evaluation is required for different wind turbines in order to identify the best model (Mostafaeipour *et al.*, 2014).

The wind power electricity generation costs less in regions with high average wind speeds. 75-80% of these costs are upfront costs of physical capital and installation (Mathews, 1998). The remaining costs are dispersed over the life of the wind power system and are comprised of operating, maintenance, and insurances costs

(Ogbonnaya *et al.*, 2007; Amina *et al.*, 2012). Although the wind power generation is financially competitive with grid extension and diesel generators in most regions, the costs are declining in recent time.

#### 2.1.4 Different Measures of Cost

Prior studies have shown that the cost of electricity generated by a wind turbine depends on several factors which include: the site specific factors (e.g. wind speed and quantity of electricity generated, cost of land, and installation cost); cost of wind turbine, and its economic life span; operating and maintenance costs; electricity tariff and incentives and exemptions (Mathew, 2006; Adaramola *et al.*, 2011). Also, in the working paper of IRENA 2012, Cost can be measured in a number of different ways and each way of accounting for the cost of power generation brings its own insights. The costs that can be examined include equipment costs (e.g. wind turbines, batteries, inverters etc.), total installed cost, fixed and variable operating and maintenance costs (O&M), and the levelised cost of energy (LCOE).

## 2.2 THEORETICAL CONSIDERATIONS

### 2.2.1 Wind Energy Conversion System (WECS)

Block diagram of wind energy conversion system (WECS) consists of wind turbine system, rectifier, regulator, battery and inverter connected shown in Figure 2.1.

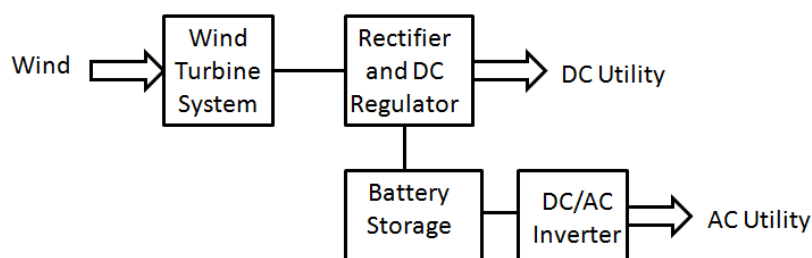


Figure 2.1. A Block Diagram for Stand-alone Wind Energy Conversion System

The **Wind Turbine System** consists of the blades, rotor and stator. The mechanical energy from the wind is converted into electrical energy in the form of AC. The **Rectifier** convert the fluctuating AC voltage produced into pulsating DC; while the **Regulator** remove the pulse from the rectifier into steady DC for storage in battery or to DC loads. **Battery** is used for storage of DC voltage into chemical energy while the **Inverter** converts the DC voltage stored in the battery into AC form (Aldo, 2005).

### 2.2.1.1 Battery

The word battery means any set of devices arranged or used together. An electric battery consists of a number of electrochemical cells connected in series or parallel and is defined as a power generating device capable of converting stored chemical energy into electrical energy (Perez, 1985).

Electricity is stored within the battery in the form of potential chemical bonding between the battery's active materials capable of pushing electrons around. The electron is a very small negatively charged particle which revolves around the centre of all common atoms. Electricity is electrons in motion.

Batteries can be classified as shown in Figure 2.2 (Yahya and Dabai, 2017)

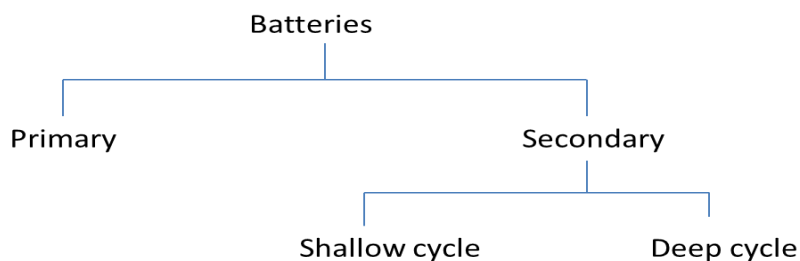


Figure 2.2. Classification of Battery

## 1. Primary Batteries

These are also called **non-rechargeable** batteries. The stored energy in this type is inherently present in the chemical substances and the chemical reaction is not reversible. This type may only be discharged and cannot be recharged. They are designed to have their energy used and then to be discarded. Examples of this type are:

- i. zinc-carbon cell (flash light batteries),
- ii. alkaline batteries used in watches and calculators.

## 2. Secondary Batteries

These are also called **rechargeable** batteries. The chemical reaction within this type (rechargeable) is reversible and can also convert electrical energy into chemical energy. They may be emptied and refilled many times. The energy is induced in the chemical substances by applying an external electrical energy source. Examples include lead-acid cell, nickel-cadmium cell, nickel-iron cell, nickel-zinc cell and high temperature cells like lithium-chlorine cell, sodium-sulphur cell, etc.

### 2.2.1.2 Inverter

An inverter is an electronic device, circuit, or system that has the ability to convert the direct current (DC) electricity from battery or solar photovoltaic cells to alternating current (AC) electricity which is the conventional form that powers many electrical appliances (Mukund, 2006).

In sizing the inverter's capacity, two factors must be considered:

- i. Average power consumed at the same time, and
- ii. Peak power consumption.

## 2.2.2 Energy Available from Wind

At any instant of time, the power available for mass flow rate of air  $\dot{m}$  passing through an area  $A$  with kinetic energy  $v^2/2$ , where  $v$  is wind speed is given by (Johnson, 2006; Kothari *et al.*, 2012; Mostafaeipour *et al.*, 2014):

$$P_w = \frac{1}{2} \dot{m} v^2 = \frac{1}{2} (\rho A v) v^2 = \frac{1}{2} \rho A v^3 \quad (2.1)$$

Therefore, power available depends upon many parameters: rotor area, wind speed and air density (a function of temperature, pressure and humidity). But the power produced by the wind turbine depends on the power coefficient,  $C_p$  of the machine which is a function of turbine parameters such as blade design, tip angle and relationship between the rotor speed and wind speed. Its maximum theoretical value known as the Betz limit is  $16/27$  ( $\approx 0.593$ ).

Since speed is proportional to the cubic power of wind speed, knowledge of the wind speed frequency distribution is of paramount importance. Wind speed at a given location is continuously varying which make it difficult to predict the overall energy capture from a site. Hence to make meaningful estimations for long term energy capture, statistical methods are used (Shepherd and Shepherd, 2007; Kothari *et al.*, 2012).

## 2.2.3 Probability Density Functions

The wind speed probability density distributions and their functional forms represent the major aspects in wind related literature. Their use includes a wide range of applications, including identifying the parameters of the distribution functions and analysing the wind speed data as well as wind energy economics (Christofides and Pashardes, 1995; Bivonet *et al.*, 2003; Akpınar and Akpınar, 2005). Statistical analysis can be used to

determine the wind energy potential of a given site and estimate the wind energy output at this site (Mirhosseini *et al.*, 2011).

There are various probability density functions which can be utilized to fit and describe the wind speed frequency over a period of time. These include Weibull, Rayleigh, Gamma, Beta, Gaussian and Lognormal distribution (Mostafaepour *et al.*, 2014).

The Weibull distribution is the most appropriate distribution function for wind speed data as it gives a good fit to the observed wind speed data both at surface and in the upper air (Rehman *et al.*, 1994; Bagiorgas *et al.*, 2007; Bagiorgas *et al.*, 2012). Weibull probability density function can fit different shapes of wind speed frequency with well performance, which is commonly applied in determining the frequency distribution.

The two parameter Weibull probability distribution function is simple in nature and has an acceptable accuracy level with the measured data (Pam *et al.*, 2009; Adaramola *et al.*, 2011; Ohunakin *et al.*, 2011; Mostafaepour *et al.*, 2014; Parajuli, 2016; Jianget *et al.*, 2017; Celik and Kolhe, 2013). It is characterized by two parameters: one is the scale parameter  $c$  and the other is the shape parameter  $k$ . It is given by:

$$f_w(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} \exp\left(-\left(\frac{v}{c}\right)^k\right) \quad (2.2)$$

where,  $f_w(v)$ ,  $v$ ,  $k$  and  $c$  are the probability distribution of wind speed, the wind speed, the shape and the scale parameters respectively. The shape parameter is dimensionless while the scale parameter has dimension of velocity.

These two parameters determine the wind speed for optimum performance of a wind conversion system as well as the speed range over which the device is likely to operate (Weibull, 1951; Ramirez and Carta, 2006; Xiao *et al.*, 2006; Kantar and Usta, 2008; Odo *et al.*, 2012).

The mean wind speed ( $\bar{v}$ ) and standard deviation ( $\sigma$ ) can equally be expressed in terms of Weibull distribution function as reported by Mostafaeipour *et al.*, (2014) using:

$$\bar{V} = \int_0^{\infty} v f_w dv = c\Gamma(1 + 1/k) \quad (2.3)$$

$$\sigma = \sqrt{c^2(\Gamma(1 + 2/k) - [\Gamma(1 + 1/k)]^2)} \quad (2.4)$$

The evaluation of the most probable and maximum energy carrying wind speeds is very important to windenergy assessors. They can be evaluated from the equations given below (Mirhosseini*et al.*, 2011; Nnawuiké and Emmanuel, 2014; Manwell *et al.*, 2002):

$$v_{mp} = c \left[ \frac{k-1}{k} \right]^{\frac{1}{k}} = c \left[ 1 - \frac{1}{k} \right]^{\frac{1}{k}} \quad (2.5)$$

$$v_{maxE} = c \left[ \frac{k+2}{k} \right]^{\frac{1}{k}} \quad (2.6)$$

where:  $v_{mp}$ = most probable wind speed and  $v_{maxE}$ = wind speed carrying maximum energy. Wind turbine system operates at its maximum efficiency at its design or rated wind speed and hence, it is essential that the rated wind speed and the wind speed carrying maximum energy should be as close as possible (Mathew *et al.*, 2002 and Ohunakin *et al.*, 2011).

#### **2.2.4 Methods for Evaluation of Weibull Parameters**

There are various methods for the evaluation of Weibull parameters k and c (Ohunakin and Akinnawonu, 2011; Azad *et al.*, 2014; Khan *et al.*, 2015; Kumar and Gaddada, 2015):

1. Least Square Method (LSQM);
2. Method of Moments (MOM);
3. Standard Deviation Method (STDM);

4. Maximum Likelihood Estimation Method (MLEM);
5. Power Density Method (PDM); and
6. Equivalent Energy Method (EEM).

Using the standard deviation method, the monthly and annual values of shape and scale parameters can be computed as (Adaramola and Oyewola, 2011b; Ohunakin *et al.*, 2011; Ohunakin and Akinnawonu, 2011; Mostafaeipour *et al.*, 2014):

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad (1 \leq k \leq 10) \quad (2.7)$$

$$c = \frac{\bar{v}}{\Gamma(1+1/k)} \quad (2.8)$$

Based on method of moment, the shape and scale parameters can be determined as (Gokcek and Genc, 2009; Islam *et al.*, 2011; Mostafaeipour *et al.*, 2014; Kumar and Gaddada, 2015; Parajuli, 2016):

$$k = \left(\frac{0.9874}{\left(\frac{\sigma}{\bar{v}}\right)}\right)^{1.0983} \quad (2.9)$$

$$c = \frac{\bar{v}k^{2.6674}}{0.184+0.816k^{2.73855}} \quad (2.10)$$

where  $\bar{v}$ ,  $\sigma$  and  $\Gamma(x)$  are average wind speed, standard deviation and gamma function.

### 2.2.5 Mean Power Density

The available power of the wind that crosses the rotor of a wind turbine generator (WTG) is (Burton, *et.al.*, 2001; Johnson, 2006).

$$P_w(v) = \frac{1}{2}A\rho v^3 \quad (2.11)$$

where,

$P_w(v)$  is the power associated with wind speed  $v$ ;  $A$  is the rotor area; and  $\rho$  is the mean air density ( $1.225 \text{ kg/m}^3$ ) at average atmospheric pressure at sea level and at  $15^\circ \text{C}$ , which depends on altitude, air pressure, and temperature (Mahyoub, 2006).

The wind power density distribution for a specific wind site can be obtained using (Carrillo *et.al.*, 2014);

$$e_w(v) = \frac{1}{2} \rho v^3 f(v) \quad (2.12)$$

Therefore, the total wind power density  $P_w$  is:

$$P_w = \int_0^\infty e_w(v) dv = \frac{1}{2} \rho \int_0^\infty v^3 f(v) dv \quad (2.13)$$

When a Weibull PDF is considered, the following equation can be used (Johnson, 2006):

$$P_w = \frac{1}{2} \rho c^3 \Gamma\left(1 + \frac{3}{k}\right) \quad (2.14)$$

### 2.2.6 Extrapolation of Wind Speed and Weibull Parameters to Hub Height

Wind speed data is usually given at the standard anemometer height of 10m. In most cases, the available wind data are measured at height different from the wind turbine hub height. Consequently, since most modern day wind turbines have their operational hub height greater than 10m, the wind speed values measured at 10m height should be extrapolated to reflect the hub height of the turbines.

Consequently, the wind speed at the hub height is of interest for wind power application and the available wind speeds can be adjusted to the wind turbine hub height using the

following Powerlaw expression(Lysen, 1983; Darwish and Sayigh, 1988; Akpinar and Akpinar, 2005; Adaramola and oyewola, 2011b; Adaramola *et al.*, 2011):

$$\frac{v}{v_0} = \left(\frac{h}{h_0}\right)^\alpha \quad (2.15)$$

Where, ‘ $v$ ’ is the wind speed at the required height ‘ $h$ ’, ‘ $v_0$ ’ is wind speed at the original height ‘ $h_0$ ’, and ‘ $\alpha$ ’ is the surface roughness coefficient which lies in the range 0.05–0.5 (Ohunakin, 2011c), but its assumed to be 0.143 (or 1/7) in most open terrain. The surface roughness coefficient can also be determined from the following expression(Ucar and Balo, 2009).

$$\alpha = \left[ \frac{0.37 - 0.088 \ln(v_0)}{1 - 0.088 \ln\left(\frac{h_0}{10}\right)} \right] \quad (2.16)$$

Using Weibulll distribution function, adjusted shape parameter  $k_h$  , scale parameter  $c_h$  and wind speed  $V_h$  at the desired height  $h_m$  are related to the shape parameter  $k_o$  and scale parameter  $c_o$  at measurement height of 10m as (Ucar and Balo, 2009; Mahbub *et al.*, 2011; Adaramola and Oyewola, 2011a; Ohunakin *et al.*, 2011; Paul *et al.*, 2012; Ohunakin *et al.*, 2013; Diaf and Notton, 2013; Mostafaeipour *et al.*, 2014):

$$k_h = \{k_o[1 - 0.088 \ln(h_o/10)]\}/[1 - 0.088 \ln(h_m/10)] \quad (2.17)$$

$$c_h = c_o(h_m/h_o)^\alpha \quad (2.18)$$

$$v_h = v_0(h_m/h_o)^\alpha \quad (2.19)$$

Where  $\alpha$  is as defined in equation 2.16

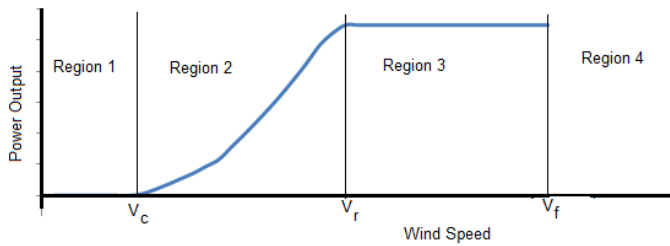
### 2.2.7 Energy Evaluation by Means of Power Curve

The average power produced by a wind turbine,  $P_{ave}$  can be calculated as (Kothari *et al.*, 2012; Duffie and Beckman, 2013):

$$P_{ave} = \int_0^{\infty} p_w(v) f_w(v) dv \quad (2.20)$$

where,  $p_w(v)$  -is the machine power curve model;  $f_w(v)$  -probability density function

The actual power performance of wind turbine can be described by three speed parameters: cut in speed,  $v_c$  ; rated (nominal) speed,  $v_r$  ; and cut out (foil) speed,  $v_f$ . The output power operation pattern of a pitch regulated wind turbine is as shown (Salameh and Safari, 1992) in Figure 2.3.



**Figure 2.3.** A Typical Power Curve of a Pitch Regulated Wind Turbine

Therefore, the power delivered by the wind turbine can be expressed as (Freris, 1990; Salameh and Safari, 1992; Carrillo *et al.*, 2013):

$$P_w(v) = \begin{cases} 0 & v < v_c, v > v_f \\ q(v) & v_c < v < v_r \\ P_r & v_r \leq v \leq v_f \end{cases} \quad (2.21)$$

Based on the power curve of figure 1, equation 13 can be written as:

$$P_{ave} = P_{C-r} + P_{r-f} = \int_{v_c}^{v_r} q(v) f_w(v) dv + \int_{v_r}^{v_f} P_r(v) f_w(v) dv \quad (2.22)$$

where,  $P_{c-r}$  is the power from cut in to rated speed (growth region)

$P_{r-f}$  is the power from rated to cut off speed (rated region)

To find average power from cut in speed to rated speed (power growth region), the output power of the machine has to be determined. The best way is to measure the actual machine output performance; alternatively, manufacturers data can be used through some numerical methods (discrete modelling) or modelling the characteristics of the machine (continuous modelling).

There are many power curve modelling techniques that can be used in the power growth region (Mathew, 2006). Table 2.1 shows some simple models whose coefficients  $a_i$  and  $b_i$  are determined from the two extreme conditions in the region (i.e.  $q(v) = 0$  when  $v = v_c$  ;  $q(v) = P_r$  when  $v = v_r$ ) then solving the equations simultaneously (Brano *et al.*, 2011).

**Table 2.1.** Various Models for Wind Turbine in Power Growth Region

Model Type	Expression	Coefficients		Equation
Linear	$q(v) = a_1 + b_1v$	$a_1 = \frac{-P_r v_c}{v_r - v_c}$	$b_1 = \frac{P_r}{v_r - v_c}$	$q(v) = P_r \left( \frac{v - v_c}{v_r - v_c} \right)$
Quadratic	$q(v) = (a_2 + b_2v)^2$	$a_2 = \frac{-P_r^{\frac{1}{2}} v_c}{v_r - v_c}$	$b_2 = \frac{P_r^{\frac{1}{2}}}{v_r - v_c}$	$q(v) = P_r \left( \frac{v - v_c}{v_r - v_c} \right)^2$
Cubic 1	$q(v) = (a_3 + b_3v)^3$	$a_3 = \frac{-P_r^{\frac{1}{3}} v_c}{v_r - v_c}$	$b_3 = \frac{P_r^{\frac{1}{3}}}{v_r - v_c}$	$q(v) = P_r \left( \frac{v - v_c}{v_r - v_c} \right)^3$
Cubic 2	$q(v) = a_4v^3 - b_4P_r$	$a_4 = \frac{P_r}{v_r^3 - v_c^3}$	$b_4 = \frac{v_r}{v_r^3 - v_c^3}$	$q(v) = P_r \left( \frac{v^3 - v_c^3}{v_r^3 - v_c^3} \right)$
Cubic 3	$q(v) = a_5v^3$	$a_5 = \frac{P_r}{v_r^3}$	-	$q(v) = P_r \frac{v^3}{v_r^3}$
Weibulll based	$q(v) = a_6 + b_6v^k$	$a_6 = \frac{-P_r v_c^k}{v_r^k - v_c^k}$	$b_6 = \frac{P_r}{v_r^k - v_c^k}$	$q(v) = P_r \left( \frac{v^k - v_c^k}{v_r^k - v_c^k} \right)$

A more complex model is a polynomial of a third degree given by:

$$q(v) = av^3 + bv^2 + cv + d \quad (2.23)$$

Then equation for average power can be simplified to (Pam *et al.*, 2009):

$$P_{ave} = \int_{v_c}^{v_r} \left[ (av^3 + bv^2 + cv + d) \left( \frac{k}{c} \left( \frac{v}{c} \right)^{k-1} \exp \left( - \left( \frac{v}{c} \right)^k \right) \right) \right] dv + P_r \left[ \exp \left( - \left( \frac{v_r}{c} \right)^k \right) - \exp \left( - \left( \frac{v_f}{c} \right)^k \right) \right] \quad (2.24)$$

The constants can be evaluated using Gaussian Elimination Technique or Cramer's Rule by applying either Least Square Error Method or Four Cardinal Points Method; while

the integration is carried out using Numerical Method such as Simpson's Rule (Stroud and Booth, 2003; Pam *et al.*, 2009). The derivation of the equation for average power is shown in Appendix viii.

Using Weibull based model, the equation for average power can be simplified to (Akpınar and Akpınar, 2005; Adaramola *et al.*, 2011; Paul *et al.*, 2012; Musa and Gowma, 2013; Ajayi *et al.*, 2014; Abdulkarim *et al.*, 2017):

$$P_{ave} = P_r \left[ \frac{[\exp(-(\frac{v_c}{c})^k) - \exp(-(\frac{v_r}{c})^k)]}{(\frac{v_c}{c})^k - (\frac{v_r}{c})^k} - \exp\left(-\left(\frac{v_f}{c}\right)^k\right) \right] \quad (2.25)$$

Due to wind speed variability, a wind turbine rarely operates at its rated output, therefore the capacity factor (CF) is commonly used to estimate its average energy production which in turn can be used for the economic appraisal of wind power projects and for the ranking of potential sites.

It is given by (Mathew, 2006; Kothari *et al.*, 2012; Duffie and Beckman, 2013).

$$CF = \frac{1}{P_r} \int p_w(v) f_w(v) dv = \frac{\text{average power output during a period}}{\text{rated power output}} \quad (2.26)$$

For a period of one year, the CF can be calculated as (Duffie and Beckman, 2013):

$$CF = \frac{\text{measured energy produced in the year (Wh)}}{\text{Rating of the turbine (W)} \times 8760 (h)} \quad (2.27)$$

Monthly average energy produced,  $E_{avem}$  is given by:

$$E_{avem} = P_{ave} \times \text{No of days in the month} \times 24 \text{ hours per day} \quad (2.28)$$

The capacity factor  $C_f$  is defined as the ratio of the mean power output to the rated electrical power ( $P_{eR}$ ) of the wind turbine. Based on Weibull based model, it is given as (Balouktis *et al.*, 2002; Akpınar and Akpınar, 2005; Adaramola *et al.*, 2011):

$$C_f = \frac{P_{out}}{P_{eR}} = \frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_o}{c}\right)^k} \quad (2.29)$$

where,  $v_c$ ,  $v_r$ ,  $v_o$  are the cut-in wind speed (minimum speed for WECS to start generating), rated wind speed (at which the rated power is achieved), and cut-offwind speed, respectively.

It is recognized that the capacity factor is a function of the site parameters (which is dependent on the hub height) and the wind turbine design wind speed properties. The cost effectiveness of a wind turbine can be roughly estimated by the capacity factor of the turbine. This factor is a useful parameter for both consumer and manufacturer of the wind turbine system (Ucar and Balo, 2009). For an investment in wind power to be cost effective, it is suggested that the capacity factor should be between 0.25-0.40 (Mathew, 2006).

### **2.2.8 Economic Analysis of the Energy Conversion Systems**

Evaluation of cost of unit energy produced by any system involves (Paul *et al.*, 2012):

- a) Estimation of energy generated over a given period (e. g. a year);
- b) Estimation of the total investment cost of the project.

The **Life-Cycle Cost** of any energy system includes:

- i. Initial costs including equipment (array/wind turbine, battery bank, inverter), construction/ installation and land costs etc;
- ii. Operating costs, periodic maintenance, insurance and miscellaneous recurring charges;
- iii. Interest charges if money is borrowed and Taxes;
- iv. Cost of replacement of any subsystem; and

v. Salvage value.

Different methods are generally used to estimate the operating cost of a unit energy produced by the wind energy conversion system. The most commonly used method however, is the levelised cost of electricity (LCOE) (Adaramola *et al.*, 2011). The LCOE is a measure of the marginal cost of electricity over a period of time and it is commonly used to compare the electricity generation costs from various sources (Hearps and McConell, 2011).

Costs are basically divided into investment (or installed capital costs) and recurrent costs. The investment cost is a cost incurred once in the lifetime of a project while the recurrent costs occur periodically over the entire period of operation of the WECS, which include operation and maintenance costs.

Some of the key concepts and parameters include:

- a) The time value of money and the present worth factor
- b) Levelising and capital recovery factor
- c) Net present worth.

The determination of the cost of unit energy involves three basic steps:

- i. estimation of energy generated by the wind turbine over a given period (e.g. year);
- ii. estimate the total investment cost of the project; and
- iii. divide the cost of investment by the energy produced by the system.

Cost of energy system can be quantified in three different ways: cost per kilowatt, cost per unit rotor area, and cost per unit kilowatt hour of electricity produced (Paul *et al.*, 2009).

The **Life Cycle Cost (LCC)** or **Net Present Worth (NPW)** of any project is obtained by adding the Investment cost, the present worth of the recurrent cost and present worth of any subsystem replacements (Nafeh, 2009). It is given by:

$$NPW_C = C_c + \left[ \frac{(1+r_o)^L - 1}{r_o(1+r_o)^L} \right] C_{om} + \left( \frac{1}{1+r_o} \right)^n R_C - S \left( \frac{1}{1+r_o} \right)^n \quad (2.30)$$

If both interest and prevailing inflation rate are considered, it is given by:

$$NPW_C = C_c + C_{om} \left( \frac{1+i}{r_o+i} \right) \left[ 1 - \left( \frac{1+i}{1+r_o} \right)^n \right] + \left( \frac{1+i}{1+r_o} \right)^n R_C - S \left( \frac{1+i}{1+r_o} \right)^n \quad (2.31)$$

**Levelised Cost of Energy (LCOE)** is the sum of annual levelised cost of the system divided by the annual energy production. It can be expressed as:

$$LCOE = \frac{\text{Levelised Annual Costs}}{\text{Annual Energy Production}} = \frac{(NPW_C)(CRF)}{E_{WT}} \quad (2.32)$$

$$E_{WT} = P_{eR} C_f \times 8760 \quad (2.33)$$

$$CRF = \frac{r_o(1+r_o)^L}{(1+r_o)^L - 1} \quad (2.34)$$

where:  $C_c$  - total capital/initial costs;  $C_{om}$  - operation & maintenance cost for the first year;

$r_o$  - Interest rate;  $i$  - inflation rate;  $L$  - useful life of the system;  $n$  - year of replacement;

$E_{WT}$  - Annual energy output;  $P_{eR}$  - rated power;  $C_f$  - capacity factor of the turbine.

**CHAPTER THREE**  
**MATERIALS AND METHOD**

**3.1 MATERIALS**

The materials/data required for this include:

1. Wind speed data (average daily mean and standard deviation data) for all the locations;
2. Software tools for statistical analysis of the data (Microsoft Excel, Minitab, etc);
3. Performance Parameters of the wind turbines (power rating, rated speed, cut out speed, hub height of the turbine, etc);
4. Electrical characteristics of the inverter and the battery.

**3.1.1 Selected Locations**

In this work, three locations from Northern Nigeria were chosen. To have fair representation of the Northern Nigeria, one location was selected from each of the three geopolitical zones (North East, North Central and North West). Geographical information of the selected locations is as shown in Table 3.1.

**Table 3.1.** Geographical Information of the Selected Locations

<b>S/N</b>	<b>Geographical Zone</b>	<b>Location</b>	<b>Latitude</b>	<b>Longitude</b>	<b>Altitude (m)</b>
1	North East	Potiskum	11.42°N	11.02°E	415
2	North Central	Minna	9.6°N	6.6°E	251
3	North West	Sokoto	13.0°N	5.7°E	305

### 3.1.2 Meteorological Data for the Locations

Daily average wind speed data of all the three selected locations were obtained from Nigerian Meteorological Agency (NIMET) for a period of ten years (2001-2010).

The wind speed data unit was in knots therefore converted to standard SI unit of m/s using the relation:

$$1knot = 0.514444m/s \quad (3.1)$$

The mean wind speed and standard deviation were calculated using equations(3.2) and(3.3) respectively.

$$v_m = \frac{1}{n} \sum_{i=1}^{i=n} v_i \quad (3.2)$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{i=n} (v_i - v_m)^2} \quad (3.3)$$

where:  $v_m$  is the mean speed;  $\sigma$  is the standard deviation;  $v_i$  is the  $i^{th}$  speed and  $n$  is the number of variables.

The results obtained for monthly average wind speed and standard deviations for the three locations were summarized into one year data as shown in Table 3.2.

**Table 3.2.** Mean Wind Speed and Standard Deviation of the Locations

Months	SOKOTO		MINNA		POTISKUM	
	$v_m$ (m/s)	$\sigma$ (m/s)	$v_m$ (m/s)	$\sigma$ (m/s)	$v_m$ (m/s)	$\sigma$ (m/s)
Jan	6.60	3.40	4.76	2.40	4.83	1.98
Feb	6.67	3.25	4.78	2.55	5.15	2.16
Mar	5.93	3.35	4.49	2.30	5.38	1.92
Apr	5.26	2.73	4.44	2.25	5.42	1.63
May	5.07	3.30	4.13	2.40	5.68	1.84
Jun	5.26	2.70	3.95	2.14	5.47	2.23
Jul	5.04	3.05	4.00	2.20	5.24	1.95
Aug	4.31	2.50	3.74	2.04	4.43	1.74
Sep	3.73	2.03	3.44	1.90	3.92	1.54
Oct	3.98	2.30	3.14	1.73	4.00	1.56
Nov	5.36	2.85	3.38	2.00	4.22	2.04
Dec	6.07	3.40	4.54	2.50	3.93	1.87

### 3.1.3 Wind Turbine

The wind turbines considered in this study are three bladed as shown in Appendix 4. For performance analysis of wind turbines, the following characteristics of the turbine are required: Rated power, Cut-in speed, Rated speed, Cut-out speed and Hub height of the turbine.

In this work, five different models of small scale turbines were considered. Their characteristics which were obtained from the manufactures website are as shown in Table 3.3 and their prices are shown in Appendix ix.

**Table 3.3.** Performance Parameters of the Selected Turbines

Model No.	e3001 1000W	Ge power System 1.5SL	e400nb 2.5kW	West Wind 2.5kW	GV- 3Kw
Power Rating (kW)	1	1.5	2.5	2.5	3
Cut-in Speed (m/s)	2.5	3	3.25	4	2
Rated Speed (m/s)	10.5	11.8	11	14	12
Cut-out Speed (m/s)	25	25	24	17	25
Hub-Height (m)	15	10	15	18	8

### 3.1.4 Inverter and Battery

Wind turbines usually generate electricity in the form of AC and converted to DC by rectification. Since wind is intermittent in nature, storage is necessary for the system. Usually, **Battery** is used for storage of DC voltage into chemical energy and converts the chemical energy stored into electricity in the form of DC. Since most of the appliances required electricity in the form of AC, **Inverter** is incorporated in the system to convert the DC voltage stored in the battery into AC form.

The electrical characteristics required for selecting battery are: voltage rating and capacity rating. In this work, four different deep cycle batteries were selected. Their electrical characteristics are as shown in Table 3.4 while their prices are as shown in Appendix x.

**Table 3.4.** Electrical Characteristics of the Battery

Model No.	Voltage (V)	Capacity (Ah)
1 Compact Power 75Ah	12	75
2 Volta 65B100 100Ah	12	100
3 Dural SC 150Ah	12	150
4 PVX-2120L 200Ah	12	200

The electrical characteristics required for selecting inverters are: voltage rating in V and power rating in kVA. In this work, four different inverters were selected. Their electrical characteristics are as shown in Table 3.5 while their prices are as shown in Appendix xi.

**Table 3.5.** Electrical Characteristics of the Inverters

	Model No.	Voltage (V)	Power (kVA)
1	Nordic 1000VA 1.0kW	12	1.0
2	XantrexXPower1.5kW	12	1.5
3	Emerson CP 70i 01 2.5kW	12	2.5
4	Delta RPI H3 3kW	12	3.0

### 3.2 METHODOLOGY

Performance evaluation of Wind Energy Conversion System (WECS) involves many processes such as: determination of meteorological data of the location, determination of probability density function parameters, extrapolation of machine parameters to hub height of the turbine, calculation of average power produced by the turbine, etc.

In this work, the analysis was carried out by the developed algorithm using Microsoft Excel. Algorithm is a precise step-by-step plan for a computational procedure that begins with an input value and yields an output value in a finite number of steps (Knuth, 1997).

The methodology of the algorithm is as shown in Figure 3.1 presented on a flowchart. A flowchart is a type of diagram that represents an algorithm, workflow, or process, showing the steps as boxes of various kinds, and their order by connecting them with arrows.

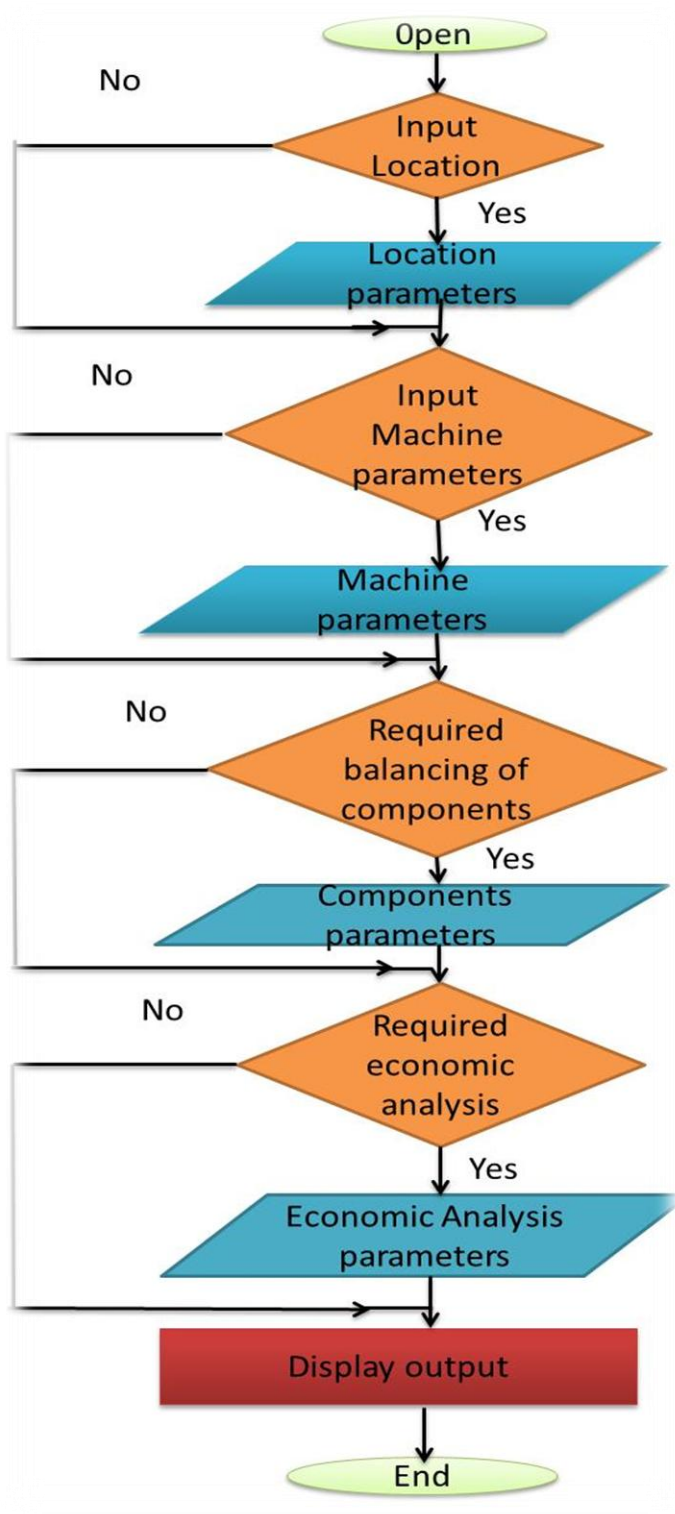


Figure 3.1. Methodology of the Algorithm on a Flowchart

From the flowchart it can be seen that the algorithm consists of the input and the output

### **3.2.1 Input**

Input refers to the act of entering data into a computer or data processing system. Plate 3.1 shows the input layout of the algorithm. There are four inputs on the flowchart which includes;

#### **3.2.1.1 Input 1 (Location Parameters)**

This is the first input where location parameters are entered. They are:

1. Location name.
2. Monthly mean wind speed.
3. Monthly mean standard deviation.

#### **3.2.1.2 Input 2 (Machine Parameters)**

The second input is the machine parameters which are:

1. Rated power.
2. Cut-in speed.
3. Rated speed.
4. Cut-out speed.
5. Hub height.

#### **3.2.1.3 Input 3 (Other Components Parameters)**

On this input the parameters are:

1. **Battery:** Voltage rating and Capacity rating.
2. **Inverter:** Voltage rating and Power rating.

### 3.2.1.4 Input 4 (Economic Analysis Parameters)

The economic analysis parameters are as follows:

1. Cost of the turbine.
2. Cost of unit battery.
3. Cost of inverter.
4. Interest rate.
5. Inflation rate.
6. Operation and maintenance cost.
7. Scrap value of the components.

	A	B	C	D	E	F	G	H	I	J	K	L	M	
1	<b>PERFORMANCE EVALUATION OF DIFFERENT MACHINES</b>													
2	CLICK HERE TO START/CLOSE													
3	<b>START</b>		NO OF MACHINES: TWO			OTHER PARAMETERS								
4			FINANCIAL ANALY: YES			INVERTER 1				INVERTER 2				
5			TURBINE PARAMETERS:			POWER RATING: 2.5 kW				POWER RATING: 3 kW				
6			MODEL NO: e400nb2			INPUT VOLTAGE: 12 volt				INPUT VOLTAGE: 12 volt				
7	LOCATION PARAMETERS		RATING POWER (kW): 2.5			USEFUL LIFE: 5 Years				USEFUL LIFE: 5 Years				
8	NAME:	MINNA	CUT-IN SPEED (m/s): 3.25			UNIT COST: 120000 NGN				UNIT COST: 160000 NGN				
9	LATITUDE:	9.6°N	RATED SPEED (m/s): 11			SALVAGE VALUE: 10 % INIT. CC				SALVAGE VALUE: 10 % INIT. COST				
10	LONGITUDE:	6.6°E	CUT-OUT SPEED (m/s): 24			BATTERY				COST OF TURBINE: 719,629.00 NGN				
11	ALTITUDE:	251m	HUB-HEIGHT (m): 15			MODEL NO.: PVX-2120L 12V 200Ah				INSTALLATION COST: 20 % INIT. COST				
12	WIND PARAMETERS		TURBINE PARAMETERS:			CAPACITY RATING: 200 Ah				OTHER INIT. COST: 0 NGN				
13	MONTH	SPEED (m/s)	STDEV	MODEL NO: GV-3kW			NOMINAL VOLTAGE: 12 volt				OPER. & MAINT. COST: 2 % INIT. COST			
14	JAN	4.76	2.40	RATING POWER (kW): 3			TYPE: Deep Cycle				TURBINE USEFUL LIFE: 20 Years			
15	FEB	4.78	2.55	CUT-IN SPEED (m/s): 2			DOD: 55				TURBINE SALVAGE VALUE: 10 % INIT. COST			
16	MAR	4.49	2.30	RATED SPEED (m/s): 12			LIFE SPAN: 4 Years				COST OF TURBINE: 838,593.00 NGN			
17	APR	4.44	2.25	CUT-OUT SPEED (m/s): 25			UNIT COST: 95000 NGN				INSTALLATION COST: 20 % INIT. COST			
18	MAY	4.13	2.40	HUB-HEIGHT (m): 8			SALVAGE VALUE: 10 % INIT. CC				OTHER INIT. COST: 0 NGN			
19	JUN	3.95	2.14				OTHER RATES:				OPER. & MAINT. COST: 2 % INIT. COST			
20	JUL	4.00	2.20				DEPOSIT INTEREST RATE: 20				TURBINE USEFUL LIFE: 20 Years			
21	AUG	3.74	2.04				INFLATION RATE: 15				TURBINE SALVAGE VALUE: 10 % INIT. COST			
22	SEP	3.44	1.90											
23	OCT	3.14	1.73											
24	NOV	3.38	2.00											
25	DEC	4.54	2.50											
26													360	
27														

Plate 3.1. Input Layout of the Algorithm.

### 3.2.2 Output

Output refers to the product or outcome of the data that was entered into a computer or data processing system. On the flowchart the output box is one comprising of all what is been computed. Plate 3.2 shows the output of the algorithm.

MACHINE 1								MACHINE 2								
MONTHS	PD	kh	ch	vh	Pout	Cf	Energy	MONTHS	kh	ch	vh	Pout	Cf	Energy		
JAN		118.69	2.18157	5.880221	5.21	0.51	20.3%	377.59	JAN		2.06308351	5.37	4.530847	0.46	15.2%	339.97
FEB		127.57	2.051888	5.899353	5.23	0.54	21.8%	368.91	FEB		1.940444052	5.39	4.551521	0.50	16.8%	341.70
MAR		101.24	2.144374	5.557504	4.92	0.45	17.9%	332.10	MAR		2.027907597	5.07	4.269263	0.41	13.6%	303.96
APR		96.82	2.169628	5.498364	4.87	0.43	17.1%	307.88	APR		2.051789281	5.01	4.220575	0.39	13.0%	280.94
MAY		91.00	1.869863	5.108265	4.54	0.42	16.9%	313.97	MAY		1.768305971	4.64	3.923165	0.41	13.8%	308.48
JUN		73.24	2.017774	4.906475	4.35	0.34	13.7%	247.34	JUN		1.908183577	4.45	3.74742	0.33	11.1%	239.28
JUL		77.37	1.985014	4.964183	4.40	0.36	14.5%	270.05	JUL		1.877202764	4.51	3.796101	0.35	11.7%	261.79
AUG		62.65	2.002985	4.653827	4.12	0.30	11.9%	222.10	AUG		1.894197521	4.22	3.544509	0.29	9.8%	219.37
SEP		49.46	1.975939	4.291681	3.80	0.24	9.6%	172.38	SEP		1.868620563	3.88	3.255056	0.25	8.2%	176.88
OCT		37.50	1.981276	3.930511	3.48	0.18	7.2%	133.73	OCT		1.87366781	3.54	2.965819	0.19	6.4%	143.70
NOV		51.04	1.833507	4.206577	3.74	0.26	10.2%	184.49	NOV		1.733923876	3.80	3.19845	0.27	9.0%	193.97
DEC		113.29	1.982427	5.608706	4.97	0.50	19.9%	370.76	DEC		1.874756519	5.12	4.319342	0.47	15.7%	350.52
						0.38	15.1%	3301.31						0.36	12.0%	3160.57
NPW		2,127,110.88							NPW		2,500,119.23					
CRF		0.205356531							CRF		0.205356531					
Ann. En		3301.311138							Ann. En		3160.571545					
LCOE		132.32							LCOE		162.44					

**Plate 3.2.**Output Layout of the Algorithm.

#### 3.2.2.1 Determination of Weibull parameters

From the literature, there are various probability density functions which can be utilized to fit and describe the wind speed frequency over a period of time. Two Parameter Weibull probability distribution function was used for this study.

The two parameter Weibull probability distribution function was chosen because is simple in nature and has an acceptable accuracy level with the measured data (Pam *et*

*al.*, 2009; Adaramola *et al.*, 2011; Ohunakin *et al.*, 2011; Mostafaipouret *al.*, 2014; Parajuli, 2016). It is being expressed as shown in equation (2.2).

There are various methods for the evaluations of Weibull parameters  $k$  and  $c$ . In this work, method of standard deviation was adopted. Based on method, the shape and scale parameters are determined using equation (2.7) and equation (2.8) respectively.

### **3.2.2.2 Extrapolation of wind speed and Weibull parameters to hub height**

Wind speed data is usually given at the standard anemometer height of 10m. Consequently, since most modern day wind turbines have their operational hub height greater than 10m, the wind speed values measured at 10m height should be extrapolated to reflect the hub height of the turbines. In this work, adjusted shape parameter  $k_h$ , scale parameter  $c_h$  and wind speed  $v_h$  at the desired height  $h_m$  are related to the shape parameter  $k_o$  and scale parameter  $c_o$  at measurement height of 10m as given by equations (2.16) to (2.19).

### **3.2.2.3 Average power output and capacity factor**

In this work, the power growth region of the turbine is calculated based on Weibull method. The average power of the turbine is given as shown by equation (2.25).

Due to wind speed variability, a wind turbine rarely operates at its rated output, therefore the capacity factor (CF) is commonly used to estimate its average energy production which in turn can be used for the economic appraisal of wind power projects and for the ranking of potential sites. It is given as shown (Mathew, 2006; Kothari *et al.*, 2012; Duffie and Beckman, 2013) given by equation (2.29) and the monthly average energy produced,  $E_{avem}$  is given by equation (2.28).

### 3.2.2.4 Selection of inverter and battery

For this work, all the turbines selected are  $\leq 3kVA$ ; therefore the system voltage was assumed to be 12V for all the machines.

The size (power rating) of the inverter was assumed to be equal to the power rating of the turbine. As such the size of the inverter and the corresponding turbine matching is as shown in Table 3.6.

**Table 3.6.** Inverter and Turbine Matching

Inverter Model	Turbine Model
Nordic 1000VA 1.0kW	e3001 1000W
XantrexXPower1.5kW	Ge power System 1.5SL
Emerson CP 70i 01 2.5kW	West Wind 2.5kW e400nb 2.5kW
Delta RPI H3 3kW	GV-3kW

Solar is available only during the day therefore all usage at night has to be stored in the battery; but wind is intermittent in nature available during both day and night. For optimum performance of wind turbines, the capacity factor should be in the range of 20% to 45%. In this work, the battery storage is designed in such a way that it should be able to store the energy generated at 20% capacity factor. Therefore, battery capacity requirement can be expressed as:

$$Ah \text{ requirement} = (\text{Turbine power rating}) \times 24 \times 0.20 \quad (3.4)$$

where: the factor “24” is the number of hours in a day; and the factor “0.20” is the capacity factor energy to be stored.

Therefore, number of total battery requirement  $N_{BT}$  can be expressed as:

$$N_{BT} = \frac{Ah \text{ requirement}}{(\text{Battery voltage})(\text{Battery capacity})} \quad (3.5)$$

Table 3.7 shows the Ah requirement for each of the selected turbines and the quantity of “2412V, 200Ah” battery required evaluated using equations (3.1) and(3.2) respectively.

**Table 3.7.**Battery Requirements for the Turbines

	Model No.	Ah Requirement	No of 12V 200Ah battery
1	e3001 1.0kW	4800	2
2	Ge Power System 1.5kW	7200	3
3	e400nb 2.5kW	12000	5
4	West wind 2.5kW	12000	5
5	GV-3kW	14400	6

The number of Battery in Series,  $N_{BS}$  ; and in parallel  $N_{BP}$ ; can be expressed as:

$$N_{BS} = \frac{\text{System voltage}}{\text{Battery Nominal voltage}} \quad (3.6)$$

$$N_{BP} = \frac{\text{Total No of Battery}}{\text{Battery in Series}} \quad (3.7)$$

For this work, all the turbines selected are  $\leq 3kVA$ ; therefore the system voltage was assumed to be 12V for all the machines. Using equation 3.6 gives:

$$N_{BS} = \frac{\text{System voltage}}{\text{Battery Nominal voltage}} = \frac{12}{12} = 1$$

Therefore, all the battery for these small turbines will be connected in parallel.

### 3.2.2.5Economic cost analysis

The economic analysis of the selected wind turbine models was carried out using LCOE method. The cost of kWh of energy produced by the turbines at the sites was estimated by taking into consideration the following assumptions:

- i. The lifetime of the wind turbines used in this study is 20 years
- ii. Interest rate (r) and inflation rate (i) were taken as 20 and 15% respectively

- iii. Operating and maintenance cost (Com) was assumed to be 2% cost of the wind turbine.
- iv. Installation cost was assumed to be 25% of the wind turbine.
- v. Scrap value was assumed to be 10% of the turbine price

The net present worth of the cost, levelised cost of energy and capital recovery factor can be evaluated from equations (2.31), (2.32) and (2.34).

The cost of turbine, battery and inverters are as shown in the Appendix ix, x and xi.

## CHAPTER FOUR

### RESULT AND DISCUSSION

#### 4.1 RESULTS

All the parameters were estimated using a self-developed algorithm on Microsoft Excel spread sheet (2007). The results obtained at the end of this study are tabulated while some are shown graphically. Table 4.1 shows the monthly and annual variation of mean wind speed, Weibull parameters and power densities for the locations at 10m height for all the locations. It can be deduced from the table that all the locations have an annual mean wind speed above 4.07 m/s.

For Sokoto, the monthly minimum mean wind speed is recorded as 3.73 m/s in the month of September while the maximum is 6.67 m/s in February. The annual mean wind speed is 5.27 m/s. The shape and scale parameter ranges from 1.59 and 4.21 m/s to 2.18 and 7.53 m/s. The annual values are 1.91 and 5.94 m/s. The monthly mean power density varies between 61.99 W/m<sup>2</sup> and 323.45 W/m<sup>2</sup>.

In case of Minna, the monthly mean wind speed ranged from 3.14 m/s in the month of October to 4.78 m/s in February. The annual mean wind speed is 4.07 m/s. The shape and scale parameter ranges from 1.77 and 3.54 m/s to 2.10 and 5.39 m/s. The annual values are 1.94 and 4.58 m/s. The monthly mean power density varies between 37.50 W/m<sup>2</sup> to 127.57 W/m<sup>2</sup>.

In Potiskum, the monthly minimum mean wind speed varies between 3.92 m/s in the month of September to 5.68 m/s in May. The annual mean wind speed is 4.81 m/s. The shape and scale parameter ranges from 2.20 in November and 4.40 m/s in September to 3.69 in April and 6.32 m/s in May. The annual values are 2.80 and 5.39 m/s

respectively. The monthly mean power density varies between 53.78 W/m<sup>2</sup> to 149.99 W/m<sup>2</sup>.

**Table 4.1.** Monthly and Annual Variation of Mean Wind speed, Weibull Parameters and Mean Power Density for the Locations.

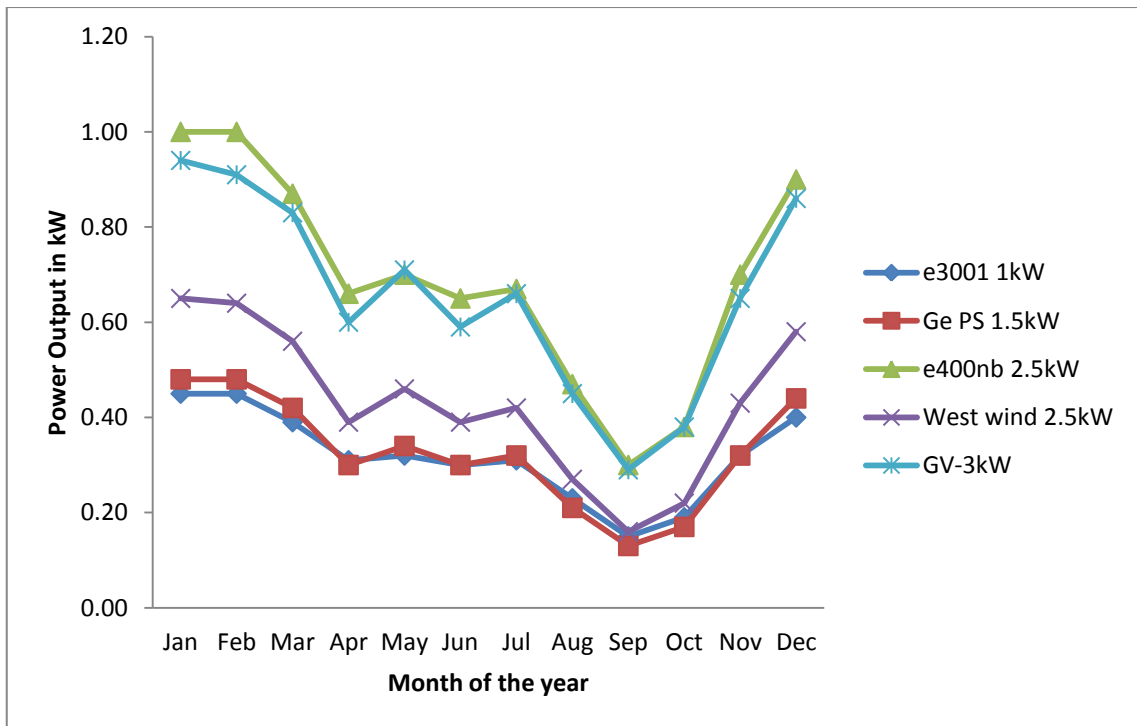
Month	Sokoto				Minna				Potiskum			
	$v_m$ (m/s)	$K$	$c$ (m/s)	$P_D$ (W/m <sup>2</sup> )	$v_m$ (m/s)	$k$	$c$ (m/s)	$P_D$ (W/m <sup>2</sup> )	$v_m$ (m/s)	$k$	$c$ (m/s)	$P_D$ (W/m <sup>2</sup> )
Jan	6.60	2.06	7.45	323.45	4.76	2.10	5.37	118.69	4.83	2.63	5.44	103.73
Feb	6.67	2.18	7.53	315.74	4.78	1.98	5.39	127.57	5.15	2.54	5.80	128.74
Mar	5.93	1.86	6.68	260.19	4.49	2.07	5.07	101.24	5.38	3.06	6.02	130.84
Apr	5.26	2.04	5.94	165.02	4.44	2.09	5.01	96.82	5.42	3.69	6.01	122.62
May	5.07	1.59	5.65	196.55	4.13	1.80	4.64	91.00	5.68	3.40	6.32	146.13
Jun	5.26	2.06	5.94	163.12	3.95	1.95	4.45	73.24	5.47	2.65	6.15	149.99
Jul	5.04	1.73	5.65	174.28	4.00	1.91	4.51	77.37	5.24	2.93	5.87	123.99
Aug	4.31	1.81	4.85	103.19	3.74	1.93	4.22	62.65	4.43	2.76	4.98	77.61
Sep	3.73	1.94	4.21	61.99	3.44	1.91	3.88	49.46	3.92	2.76	4.40	53.78
Oct	3.98	1.81	4.48	80.88	3.14	1.91	3.54	37.50	4.00	2.78	4.49	56.86
Nov	5.36	2.00	6.05	179.22	3.38	1.77	3.80	51.04	4.22	2.20	4.76	79.36
Dec	6.07	1.88	6.84	276.23	4.54	1.91	5.12	113.29	3.93	2.24	4.44	63.16
Ave	5.27	1.91	5.94	191.65	4.07	1.94	4.58	83.32	4.81	2.80	5.39	103.07

**Table 4.2.** Monthly and Annual Variation of most probable wind speed and wind speed carrying maximum energy for the Locations.

Month	Sokoto		Minna		Potiskum	
	$v_{mp}(m/s)$	$v_{max}E(m/s)$	$v_{mp}(m/s)$	$v_{max}E(m/s)$	$v_{mp}(m/s)$	$v_{max}E(m/s)$
Jan	5.69	10.98	4.16	7.80	4.65	7.00
Feb	5.95	10.69	4.02	8.15	4.91	7.60
Mar	4.75	10.54	3.88	7.44	5.38	7.30
Apr	4.51	8.79	3.87	7.30	5.57	6.89
May	3.43	10.10	3.22	7.50	5.78	7.42
Jun	4.54	8.73	3.28	6.81	5.28	7.91
Jul	3.75	9.45	3.28	6.97	5.19	7.25
Aug	3.36	7.82	3.09	6.48	4.32	6.29
Sep	3.08	6.45	2.81	6.01	3.83	5.56
Oct	3.12	7.20	2.57	5.48	3.91	5.66
Nov	4.15	9.11	2.58	6.23	3.78	6.73
Dec	4.91	10.72	3.72	7.92	3.55	6.21
Ave	4.30	9.22	3.37	7.01	4.68	6.82

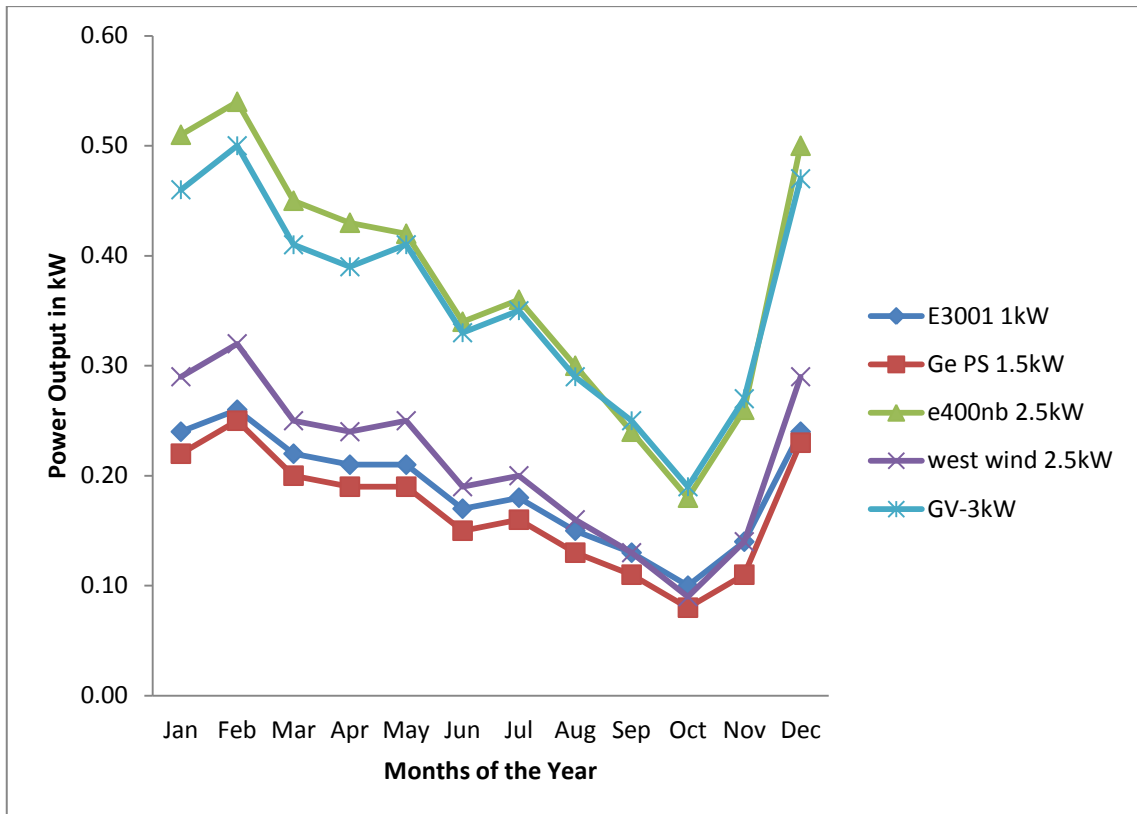
From Table 4.2 The monthly most probable wind speed and wind speed carrying maximum energy ranged from 2.57 m/s and 5.56 m/s to 5.95 m/s and 10.98 m/s respectively.

The monthly power output of the selected turbines for all the locations is shown in Figure 4.1 to 4.3



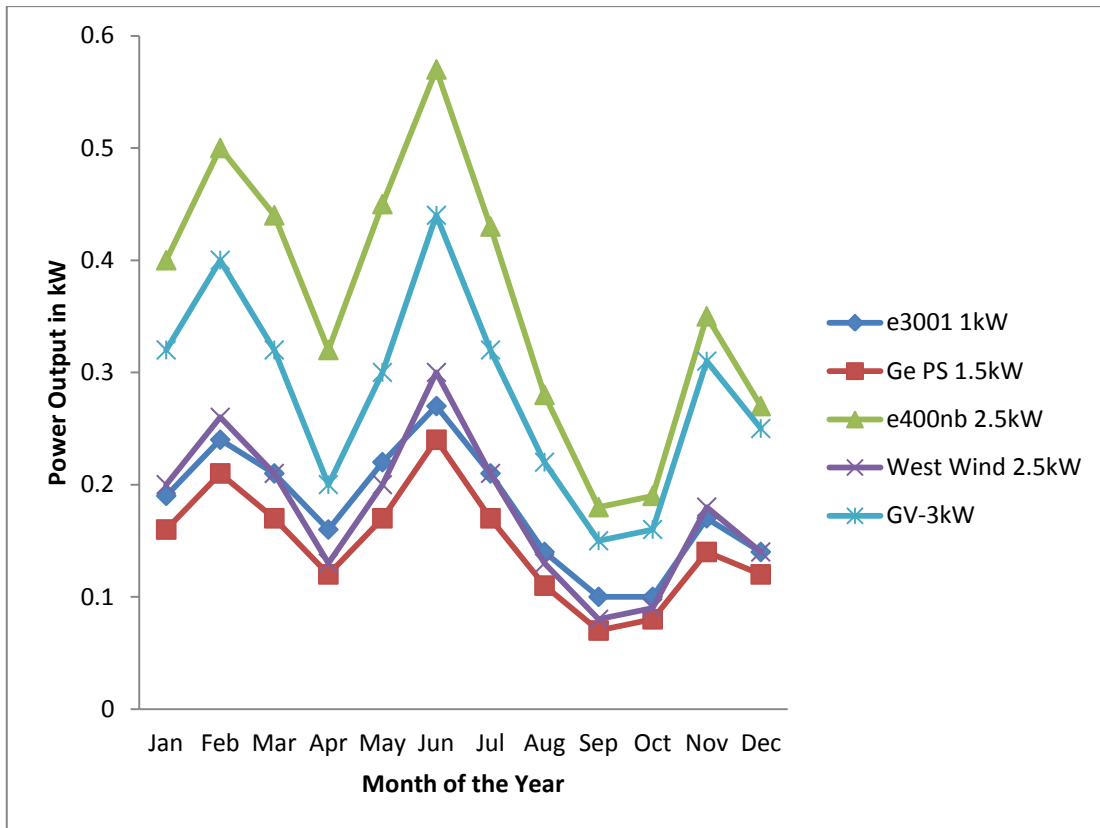
**Figure 4.1.** Monthly Power Output for the selected wind turbines in Sokoto.

From Figure 4.1 it is observed that all the turbines have their highest power output in January and February except for GV-3kW where there's a slight difference while the lowest output was in September.



**Figure 4.2.** Monthly Power Output for selected wind turbines in Minna.

From Figure 4.2 the highest power output can be observed in February while the lowest output is in October.



**Figure 4.3.** Monthly Power Output for selected wind turbines in Potiskum.

From Figure 4.3 it is observed that all the turbines have their highest power output in June while the lowest output is in September.

**Table 4.3.**Annual Capacity Factor in Percentage (%)

Location	e3001 1kW	Ge PS 1.5kW	e400nb 2.5kW	West wind 2.5kW	GV-3kW
	Sokoto	31.9	21.7	27.7	17.2
Minna	18.8	11.2	15.1	8.4	12.0
Potiskum	18.0	9.8	14.6	7.1	9.6

**Table 4.4.**Cost of Energy of the Turbines for the Locations

Wind turbines	Levelised Cost of Energy (NGN)		
	Sokoto	Minna	Potiskum
e3001 1kW	71.25	120.93	126.67
Ge PS 1.5kW	98.60	191.28	220.07
e400nb 2.5kW	72.19	132.32	137.02
West wind 2.5kW	115.81	236.39	282.44
GV-3kW	91.16	165.70	211.98

## 4.2 DISCUSSION

This section interprets the results that were obtained in this study.

### 4.2.1 Wind speed Characteristics and Weibull parameters

The observed trend in the monthly mean wind speed is related to the elevation of each site above sea level and their weather condition during the year. Two seasons (dry and rainy) are prominent in Nigeria; these seasons vary from one region to the other due to the changing prevailing winds as witnessed across the year by the respective zones. It is noticed that there is sudden rise in monthly mean wind speeds from December to February in Sokoto and Minna while the upsurge is experienced from February to May in Potiskum, it is observed that the months with high wind speed falls under the harmattan period which is dry, cold and dusty (SERC, 2010). The varying wind speeds noticeable may be connected to: (i) changing temperature stratification and (ii) vertical exchange in momentum more prominent in the morning during the dry season due to the decrease in temperature, thus causing an increase of wind speed as a result of thermal convection (Ohunakin and Akinnawonu, 2011). Furthermore, the table reflect an increase in wind speed from December to February (dry season) in Sokoto and Minna due to the aggressive NE winds blowing strongly over the region from the Sahara (Adaramola *et al.*, 2011).

With regards to the Weibull shape parameter  $k$  for Sokoto, wind speed is most uniform in February while it is least uniform in May. Shape parameter expresses the uniformity of the wind speed. The high values of the Weibull shape parameter explain that the wind speeds tend to be very close to a certain speed and the distribution is skewed towards higher wind speeds. The scale parameter indicates that September is least windy while February is most windy, which is in agreement with what was presented by

Argungu *et al.* (2018). Base on the international system of wind classification (Ilinca *et al.*, 2003), the monthly mean power density fall into Class 1 to Class 5 category in all the months. The annual mean power density for this location is  $191.65 \text{ W/m}^2$  which falls into Class 3 wind resource category as was classified by Ohunakin *et al.* (2011).

The Weibull shape parameter  $k$  for Minna implies that wind speed is most uniform in January while it is least uniform in November. The scale parameter indicates that October is least windy while February is most windy. Additionally, the annual mean power density for this location is  $83.32 \text{ W/m}^2$  which falls into Class 1 wind resource category. This is in line with the study conducted by Adaramola *et al.* (2011).

For Potiskum, the Weibull shape parameter  $k$  indicates that wind speed is most uniform in April while it is least uniform in November. The scale parameter indicates that September is least windy while May is most windy. The annual mean power density for this location is  $103.32 \text{ W/m}^2$  which falls into Class 2 wind resource category, which is in agreement with Ohunakin (2011c).

In summary, the monthly minimum mean wind speed for these locations is recorded as  $3.14 \text{ m/s}$  in October at Minna whereas the maximum is  $6.67 \text{ m/s}$  in February at Sokoto. Sokoto also has the highest value of annual power density. Therefore, it can be considered as the best site for wind energy development among the three locations considered in this study. Furthermore, the monthly shape parameter vary from 1.59 in May at Sokoto to 3.69 in September at Potiskum and the monthly scale parameter varies between  $3.54 \text{ m/s}$  in October at Minna and  $7.53 \text{ m/s}$  in January at Sokoto. In addition, the monthly mean power density varies between  $37.50 \text{ W/m}^2$  and  $323.45 \text{ W/m}^2$  and the annual mean power density for the locations are 191.65, 83.32 and  $103.07 \text{ W/m}^2$  respectively.

The annual most probable wind speed and wind speed carrying maximum energy for the locations are 4.30, 3.37, 4.68 m/s and 9.22, 7.01, 6.82 m/s for Sokoto, Minna and Potiskum respectively. However, monthly consideration shows that Sokoto has the highest value of 5.95 m/s in February for  $v_{mp}$  and the highest value of 10.98 m/s in January for  $v_{maxE}$  respectively while Minna is having the least monthly values in October with 2.57m/s and 5.48m/s in  $v_{mp}$  and  $v_{maxE}$  respectively. According to Bagiorgaset *al.* (2007), the most probable wind speed ( $v_{mp}$ ) is a statistical characteristic which is not directly connected to wind energy. Therefore, it does not necessarily mean that Sokoto has much higher wind potentials than other locations considered. However, the efficiency of a WECS is closely related to these parameters especially  $v_{maxE}$  which should be as close as possible to design or rated wind speed of the system.

#### **4.2.2 Power Output**

The annual power and energy outputs for the five wind turbines operating at their designed parameters based on Weibull distribution function parameters are presented in Appendix v to vii for the selected sites. The selected wind turbines are designed to operate at different hub heights. In this study, however, the hub heights for each model were used. Appendix i to iii depicts the values of the extrapolated mean wind speed, Weibull shape and scale parameter at turbine hub heights for the locations. Five small scale wind turbine were studied but the extrapolated table shows three different hub height because two of the turbines have the same hub height and one of it has it hub height at 10m. It was observed that the turbine with the lowest hub height also has the lowest extrapolated values at all locations.

The characteristic properties of these wind turbines are given in Table 3.3. The annual power and energy output are computed with equations (2.25) and (2.28) respectively. As

expected, the monthly power output follows the same trend as the mean wind speed. It is observed that the monthly power and energy output ranges from 0.07kW and 51.57kWh (September) in Potiskum with Ge PS 1.5kW to 1.00kW (January and February) and 747.18kWh (January) in Sokoto with e400nb 2.5kW.

It can be observed that irrespective of the wind turbine model, Sokoto seems to be the best of all the sites. This is expected because when compared with other sites, Sokoto has the highest annual mean wind speed. It can be observed that accumulated power output using west wind 2.5 kW (18m hub height) wind turbine ranges from 0.08kW/year (Potiskum) to 0.43kW/year (Sokoto). Similar trend is observed for the other wind turbines in all the locations. However, the highest annual energy output is recorded using e400nb 2.5kW with 6037.78kWh in Sokoto while the lowest is estimated for Potiskumas 1279.20kWh with Ge power system 1.5kW. The highest power output is recorded in Sokoto because the value of  $v_{maxE}$  is nearest to the  $v_{rated}$  of the wind turbines there. Therefore, if investment decision has to be primarily based on annual energy output, e400nb or wind turbines with similar designed characteristics will be best suited for all the locations considered in this study.

The annual energy output using e3001 model (with least rated power of 1kW) is higher than that of Ge power system (1.5kW) for Minna and Potiskum and almost comparable with energy generated in Sokoto. This is due to its low rated wind speed of 10.5m/s, which is lower than that of Ge power system.

#### **4.2.3 Capacity Factor of the Turbines**

Regardless of the site, e3001 1kW turbine has the highest value of capacity factor among all the models considered. The capacity factors for these models are 31.9%, 18.8% and 18.0% for Sokoto, Minna and Potiskum respectively.

In general, table 4.3 shows that for given wind turbine model, a wind turbine sited in Sokoto would generate more power than Minnaand Potiskum. This may be related to the ratio of the rated wind speed to the mean wind speed ( $v_{rated}/v_{mean}$ ) for the site which is closer to the suggested value of 1.3 for site with trade winds (Mathew, 2006). The capacity factor decreases with increasing value of  $v_{rated}/v_{mean}$  for the all the sites. The performance of a wind turbine could be influenced by both the designed rated and cut-in wind speeds of the turbine.

Best correlation that gives optimum performance are those at capacity factor  $25 \geq Cf \leq 40$ , where capacity factor less than 25% indicates that the models performs poorly while the capacity factor greater than 40 indicates that the models would easily be stressed out. e3001 1kW and e400nb 2.5kW can excellently perform well at Sokoto and poor performance would be experienced with all other wind turbines in most locations.

However, the cost effectiveness of a wind turbine can be roughly estimated by the capacity factor of the turbine. This factor is a useful parameter for both consumer and manufacturer of the wind turbine system (Ucar and Balo, 2009).

#### **4.2.4 Cost of Electricity**

The results of the levelised cost of energy in all the sites for the selected wind turbines are as shown in Table 4.4. From the table, the least LCOE is obtained for Sokoto as ₦71.25 with e3001 1kw while the highest LCOE is obtained with west wind 2.5kW for Potiskum as ₦282.44, it can be observed that LCOE depends on the cost of the wind turbine and site wind characteristics which is represented by the turbine capacity factor. The cost of energy per kWh vary from ₦71.25 to ₦115.81 for Sokoto, it ranges between

₦120.93 and ₦236.39 for Minna and ranged from ₦126.67 to ₦282.44 in Potiskum for all the turbines.

The least LCOE per kWh is obtained with e3001 1kW turbine as ₦71.25, ₦120.93 and ₦126.67 and the highest LCOE is obtained with west wind 2.5kW turbine as ₦115.81, ₦236.39 and ₦282.44 for Sokoto, Minna and Potiskum. From this result, it can be deduced that based on the value of LCOE for each wind turbine and the assumptions considered in this study, the LCOE for e3001 1kW turbine in Sokoto is most economically viable. This is due to its low cut-in and rated wind speed whereas on the other hand west wind 2.5kW has the highest cut-in and rated wind speed among all the turbines.

## CHAPTER FIVE

### SUMMARY, CONCLUSION AND RECOMMENDATIONS

#### 5.1 SUMMARY

The daily average wind speed data of all the three selected locations used in this study was obtained from Nigerian Meteorological Agency (NIMET) which covers a period of ten years (2001-2010). The wind speed data unit was converted to standard SI unit of m/s using equation 3.1. Two parameter Weibull probability distribution function (shape and scale parameter) was used for this study. Consequently, the wind speed values measured at 10m height were extrapolated to reflect the hub height of the selected turbines. The power output of the turbine was calculated based on Weibull method and the capacity factor is commonly used to estimate the average energy production of a turbine, which is an important factor for the economic appraisal of wind power projects. LCOE method was used to carry out the economic analysis of the selected turbines.

The Weibull parameters, power output, capacity factor, average energy and the levelised cost of electricity were evaluated using the developed algorithm. The result obtained showed that Sokoto has the highest wind speed value of 6.67 m/s in February and the least value was recorded as 3.14 m/s in October at Minna. The optimum wind energy conversion system among all the selected wind turbines is e3001 1kW with annual capacity factor of 31.9%, 18.8% and 18% for Sokoto, Minna and Potiskum. e3001 1kW is the most cost effective with ₦71.25/kWh as cost of kWh for Sokoto and west wind 2.5kW as the worst particularly for Potiskum where cost of energy is as high as ₦282.44/kWh.

## **5.2CONCLUSION**

At the end of this study the major findings can be summarised as follows;

- I. Average monthly wind speeds values of 5.27, 4.81 and 4.07 m/s were recorded for Sokoto, Potiskum and Minna respectively. Sokoto recorded the highest mean wind speed value of 6.67 m/s in the month of February and minimum wind speed value of 3.73 m/s in the month of September, while Minna recorded the least values of highest wind speed value of 4.78 m/s in the month of February and least wind speed value of 3.14 m/s in the month of October.
- II. The highest performance was obtained using e400nb 2.5kW for all the three locations with annual power output of 0.69kW, 0.38kW and 0.36kW for Sokoto, Minna and Potiskum location respectively, even though the optimum wind energy conversion system is e3001 1kW with annual capacity factor of 31.9%, 18.8% and 18.0% for Sokoto, Minna and Potiskum location respectively.
- III. The e3001 1kW is the best WECS and most cost effective particularly for Sokoto where the cost of kWh is ₦71.25/kWh and west wind 2.5kW is the worst particularly for Potiskum where cost of energy per kWh is as higher as ₦282.44/kWh.

## **5.3RECOMMENDATIONS**

From the finding in this study the following recommendations was drawn

- i. This research should be carried out for at least all the state capitals in Northern Nigeria.
- ii. Further research should be conducted with larger scale wind turbines.

- iii. It is recommended that the algorithm should also be developed using visual basic for comparison.

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## APPENDICES

### Appendix i. Extrapolated speed, Weibull shape and scale parameter at machine

hub height for Sokoto

Months	8m			15m			18m		
	$k_h$	$C_h(m/s)$	$v_h(m/s)$	$k_h$	$C_h(m/s)$	$v_h(m/s)$	$k_h$	$C_h(m/s)$	$v_h(m/s)$
Jan	2.02	7.14	6.32	2.13	8.06	7.14	2.17	8.35	7.39
Feb	2.14	7.22	6.39	2.26	8.14	7.21	2.30	8.43	7.47
Mar	1.82	6.38	5.67	1.93	7.25	6.43	1.96	7.52	6.67
Apr	2.00	5.66	5.02	2.11	6.47	5.73	2.15	6.73	5.96
May	1.56	5.39	4.84	1.65	6.17	5.52	1.68	6.42	5.74
Jun	2.02	5.66	5.02	2.14	6.47	5.73	2.18	6.73	5.96
Jul	1.69	5.39	4.81	1.79	6.18	5.49	1.82	6.42	5.71
Aug	1.77	4.60	4.10	1.87	5.32	4.73	1.91	5.55	4.93
Sep	1.90	3.98	3.53	2.01	4.64	4.11	2.04	4.85	4.30
Oct	1.78	4.25	3.78	1.88	4.93	4.38	1.91	5.15	4.57
Nov	1.95	5.77	3.13	2.06	6.59	5.84	2.09	6.85	6.06
Dec	1.84	6.54	3.81	1.95	7.42	6.58	1.98	7.69	6.82

**Appendix ii.** Extrapolated speed, Weibull shape and scale parameter at machine

hub height for Minna.

Months	8m			15m			18m		
	$k_h$	$C_h(m/s)$	$v_h(m/s)$	$k_h$	$C_h(m/s)$	$v_h(m/s)$	$k_h$	$C_h(m/s)$	$v_h(m/s)$
Jan	2.06	5.11	4.53	2.18	5.88	5.21	2.22	6.12	5.42
Feb	1.94	5.13	4.55	2.05	5.90	5.23	2.09	6.14	5.44
Mar	2.03	4.82	4.27	2.14	5.56	4.92	2.18	5.79	5.13
Apr	2.05	4.76	4.22	2.17	5.50	4.87	2.21	5.73	5.08
May	1.77	4.41	3.92	1.87	5.11	4.54	1.90	5.33	4.73
Jun	1.91	4.22	3.75	2.02	4.91	4.35	2.05	5.12	4.54
Jul	1.88	4.28	3.80	1.99	4.96	4.40	2.02	5.18	4.59
Aug	1.89	3.99	3.54	2.00	4.65	4.12	2.04	4.86	4.31
Sep	1.87	3.67	3.26	1.98	4.29	3.80	2.01	4.49	3.98
Oct	1.87	3.34	2.97	1.98	3.93	3.48	2.01	4.12	3.65
Nov	1.73	3.59	3.20	1.83	4.21	3.74	1.86	4.40	3.91
Dec	1.87	4.87	4.32	1.98	5.61	4.97	2.02	5.84	5.18

**Appendix iii.** Extrapolated speed, Weibull shape and scale parameter at machine  
hub height for Potiskum.

Months	8m			15m			18m		
	$k_h$	$c_{h(m/s)}$	$v_{h(m/s)}$	$k_h$	$c_{h(m/s)}$	$v_{h(m/s)}$	$k_h$	$c_{h(m/s)}$	$v_{h(m/s)}$
Jan	2.58	5.18	4.60	2.73	5.95	5.29	2.78	6.19	5.51
Feb	2.49	5.53	4.91	2.64	6.33	5.63	2.68	6.58	5.85
Mar	3.00	5.74	5.13	3.18	6.56	5.87	3.23	6.82	6.11
Apr	3.62	5.73	5.16	3.82	6.55	5.92	3.89	6.80	6.16
May	3.34	6.04	5.42	3.53	6.88	6.19	3.59	7.14	6.43
Jun	2.60	5.87	5.22	3.03	6.70	5.96	2.79	6.96	6.20
Jul	2.87	5.60	4.99	2.32	6.41	5.72	3.09	6.66	5.96
Aug	2.71	4.73	4.21	2.86	5.46	4.87	2.91	5.69	5.08
Sep	2.71	4.18	3.71	2.86	4.85	4.33	2.91	5.07	4.52
Oct	2.73	4.26	3.79	2.88	4.95	4.41	2.93	5.17	4.61
Nov	2.16	4.52	4.01	2.28	5.24	4.64	2.32	5.46	4.84
Dec	2.20	4.21	3.73	2.32	4.89	4.33	2.36	5.11	4.52

**Appendix iv.**Image of a Wind Turbine



Source: [pressreleases.responsesource.com](http://pressreleases.responsesource.com)

**Appendix v. Annual power and energy output of the selected WECS for Sokoto**

Months	e3001 1kW		Ge PS 1.5kW		e400nb 2.5kW		West wind		GV-3Kw	
	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy
	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)
Jan	0.45	332.25	0.48	360.25	1.00	747.18	0.65	482.26	0.94	698.56
Feb	0.45	303.14	0.48	323.43	1.00	681.06	0.64	433.21	0.91	620.28
Mar	0.39	291.43	0.42	311.64	0.87	645.12	0.56	416.73	0.83	619.41
Apr	0.31	221.08	0.30	216.29	0.66	473.39	0.39	283.87	0.60	431.16
May	0.32	241.71	0.34	254.95	0.70	522.63	0.46	339.06	0.71	528.44
Jun	0.30	219.35	0.30	213.50	0.65	469.21	0.39	279.66	0.59	424.80
Jul	0.31	232.12	0.32	237.78	0.67	498.46	0.42	315.90	0.66	488.99
Aug	0.23	169.10	0.21	158.78	0.47	346.69	0.27	204.41	0.45	337.76
Sep	0.15	110.14	0.13	93.65	0.30	212.56	0.16	114.26	0.29	210.00
Oct	0.19	142.56	0.17	128.76	0.38	284.68	0.22	162.51	0.38	281.47
Nov	0.32	232.57	0.32	232.05	0.70	501.39	0.43	306.68	0.64	462.90
Dec	0.40	300.83	0.44	323.92	0.90	668.67	0.58	433.14	0.86	641.40
Ann	0.32	2789.91	0.33	2848.84	0.69	6037.78	0.43	3763.65	0.66	5732.20

**Appendix vi.** Annual power and energy output of the selected WECS for Minna.

Months	e30011 1kW		Ge PS 1.5kW		e400nb 2.5kW		West wind		GV-3Kw	
	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy
	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)
Jan	0.24	181.77	0.22	167.38	0.51	377.59	0.29	21388	0.46	339.97
Feb	0.26	176.27	0.25	167.04	0.54	368.91	0.32	216.23	0.50	341.70
Mar	0.22	162.45	0.20	146.70	0.45	332.10	0.25	185.52	0.41	303.96
Apr	0.21	151.35	0.19	135.26	0.43	307.88	0.24	170.15	0.39	280.94
May	0.21	155.17	0.19	142.98	0.42	313.97	0.25	182.34	0.41	308.48
Jun	0.17	125.45	0.15	109.50	0.34	247.34	0.19	135.71	0.33	239.28
Jul	0.18	136.02	0.16	120.31	0.36	270.05	0.20	150.20	0.35	261.79
Aug	0.15	114.91	0.13	97.95	0.30	222.10	0.16	119.68	0.29	219.37
Sep	0.13	92.21	0.11	75.68	0.24	172.38	0.13	90.33	0.25	176.88
Oct	0.10	74.88	0.08	58.17	0.18	133.73	0.09	67.05	0.19	143.70
Nov	0.14	97.97	0.11	82.50	0.26	184.49	0.14	100.00	0.27	193.97
Dec	0.24	179.18	0.23	168.26	0.50	370.76	0.29	216.78	0.47	350.52
Ave	0.19	1644.57	0.17	1469.22	0.38	3295.58	0.21	1844.87	0.36	3154.76

**Appendix vii.** Annual power and energy output of the selected WECS for Potiskum.

Months	e3001 1kW		Ge PS 1.5kW		e400nb 2.5kW		West 2.5kW		wind	GV-3kW
	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy	P <sub>out</sub>	Energy
	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)	(kW)	(kWh)
Jan	0.19	144.75	0.16	120.81	0.40	294.85	0.20	147.68	0.32	235.51
Feb	0.24	161.55	0.21	140.29	0.50	336.17	0.26	174.98	0.40	269.84
Mar	0.21	159.12	0.17	128.09	0.44	328.26	0.21	155.06	0.32	234.95
Apr	0.16	115.50	0.12	83.46	0.32	233.01	0.13	96.64	0.20	146.03
May	0.22	161.68	0.17	124.61	0.45	333.17	0.20	148.51	0.30	220.54
Jun	0.27	193.12	0.24	169.67	0.57	407.18	0.30	212.91	0.44	319.93
Jul	0.21	157.04	0.17	128.34	0.43	323.53	0.21	156.14	0.32	239.31
Aug	0.14	104.54	0.11	82.43	0.28	206.14	0.13	97.41	0.22	164.38
Sep	0.10	69.30	0.07	51.57	0.18	130.14	0.08	58.30	0.15	109.23
Oct	0.10	75.09	0.08	56.27	0.19	142.18	0.09	64.01	0.16	117.68
Nov	0.17	125.82	0.14	107.36	0.35	250.00	0.18	131.74	0.31	225.97
Dec	0.14	105.44	0.12	86.29	0.27	203.41	0.14	103.19	0.25	187.21
Ann	0.18	1572.96	0.15	1279.20	0.36	3188.04	0.18	1546.56	0.28	2470.58

### Appendix viii. Derivation of Power Output from Turbine Models

The electrical power output,  $P_e$  developed by a wind machine as a function of speed is given by;

$$P_e = \begin{cases} 0 & v < v_{ci} \\ a + bv^k & v_{ci} < v < v_r \\ P_{eR} & v_r < v < v_f \\ 0 & v > v_f \end{cases}$$

where,  $a = P_{eR} \frac{v_{ci}^k}{v_{ci}^k - v_r^k}$  and

$$b = P_{eR} \frac{1}{v_r^k + v_{ci}^k}$$

$$P_e = \int_{v_{ci}}^{v_r} (a + bv^k) \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv + \int_{v_r}^{v_f} P_{eR} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \quad (1)$$

Substituting a and b into the above equation;

$$P_e = \left\{ \begin{aligned} & \int_{v_{ci}}^{v_r} P_{eR} \frac{v_{ci}^k}{v_{ci}^k - v_r^k} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \\ & + \int_{v_{ci}}^{v_r} P_{eR} \frac{1}{v_r^k + v_{ci}^k} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \\ & + \int_{v_r}^{v_f} P_{eR} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \end{aligned} \right\} \quad (2)$$

$$P_e = P_{eR} \{(A + B + C)\} \quad (3)$$

$$A = \int_{v_{ci}}^{v_r} \frac{Q_c}{Q_c - Q_r} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \quad (4)$$

$$B = \int_{v_{ci}}^{v_r} \frac{c^{-k}}{Q_r - Q_c} \cdot v^k \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \text{ and} \quad (5)$$

$$C = \int_{v_r}^{v_f} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} dv \quad (6)$$

where  $Q_c = \left(\frac{v_c}{c}\right)^k$ ,  $Q_r = \left(\frac{v_r}{c}\right)^k$  and  $Q_f = \left(\frac{v_f}{c}\right)^k$

Let  $Y = \left(\frac{v}{c}\right)^k$ ,  $v = CY^{\frac{1}{k}}$ ,  $dv = \frac{c}{k} Y^{\frac{1}{k}-1} dy$

$v = v_{ci}$  becomes  $Y = \left(\frac{v_c}{c}\right)^k = Q_c$

$v = v_r$  becomes  $Y = \left(\frac{v_r}{c}\right)^k = Q_r$

$v = v_f$  becomes  $Y = \left(\frac{v_f}{c}\right)^k = Q_f$

Therefore,

$$A = \int_{Q_c}^{Q_r} \frac{Q_c}{Q_c - Q_r} \left(\frac{k}{c}\right) \left(\frac{c}{v}\right) \left(\frac{v}{c}\right)^k e^{-\left(\frac{v}{c}\right)^k} \cdot \frac{c}{k} Y^{\frac{1}{k}-1} dY$$

Substituting the value of v and Y in the above equation;

$$A = \int_{Q_c}^{Q_r} \frac{Q_c}{Q_c - Q_r} \left(\frac{k}{c}\right) \left(\frac{c}{cY^{\frac{1}{k}}}\right) Y \cdot e^{-Y} \cdot \frac{c}{k} Y^{\frac{1}{k}-1} \cdot \frac{1}{Y} dY$$

$$A = \int_{Q_c}^{Q_r} \frac{Q_c}{Q_c - Q_r} \cdot e^{-Y} \cdot dY = \frac{Q_c}{Q_c - Q_r} \cdot -e^{-Y} \Big|_{Q_c}^{Q_r}$$

$$A = \frac{Q_c - Q_r + Q_r}{Q_c - Q_r} [\exp(-Q_c) - \exp(-Q_r)]$$

$$A = \left[ 1 + \frac{Q_r}{Q_c - Q_r} \right] [\exp(-Q_c) - \exp(-Q_r)] \quad (7)$$

$$B = \int_{Q_c}^{Q_r} \frac{1/c^k}{Q_r - Q_c} \cdot v^k \left( \frac{k}{c} \right) \left( \frac{v}{c} \right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \cdot \frac{c}{k} Y^{\frac{1}{k}-1} dY$$

$$B = \int_{Q_c}^{Q_r} \frac{1/c^k}{Q_r - Q_c} \left( cY^{\frac{1}{k}} \right)^k \left( \frac{k}{c} \right) \left( \frac{c}{v} \right) \cdot Y \cdot e^{-Y} \cdot \frac{c}{k} Y^{\frac{1}{k}-1} \cdot \frac{1}{Y} dY$$

$$B = \int_{Q_c}^{Q_r} \frac{1}{Q_r - Q_c} Y \cdot e^{-Y} \cdot dY$$

Solving the above equation by partial integration

$$\text{Let, } u = Y, \quad du = 1$$

$$dv = e^{-Y}, \quad v = -e^{-Y}$$

$$uv - \int v du = -Ye^{-Y} - \int -e^{-Y} dY$$

$$B = \frac{1}{Q_r - Q_c} \cdot -Ye^{-Y} - e^{-Y} \Big|_{Q_c}^{Q_r}$$

$$B = \frac{-1}{Q_r - Q_c} [Q_r \exp(-Q_r) - \exp(Q_r) - Q_c \exp(-Q_c) + \exp(-Q_c)] \quad (8)$$

$$C = \int_{Q_r}^{Q_f} \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^k \left(\frac{c}{v}\right) e^{-\left(\frac{v}{c}\right)^k} \cdot \frac{c}{k} Y^{\frac{1}{k}-1} dY$$

$$C = \int_{Q_r}^{Q_f} e^{-Y} dY = -e^{-Y} \Big|_{Q_r}^{Q_f}$$

$$C = [\exp(-Q_r) - \exp(-Q_f)] \quad (9)$$

But  $P_e = P_{eR}(A + B + C)$

Therefore,

$$P_e = P_{eR} \left\{ \left[ \exp(-Q_c) - \exp(-Q_r) + \frac{Q_r}{Q_c - Q_r} \exp(-Q_c) - \frac{Q_r}{Q_c - Q_r} \exp(-Q_r) \right] + \left[ \frac{Q_r}{Q_c - Q_r} \exp(-Q_r) - \frac{Q_c}{Q_c - Q_r} \exp(-Q_c) - \frac{1}{Q_c - Q_r} \exp(-Q_r) + \frac{1}{Q_c - Q_r} \exp(-Q_c) \right] + \left[ \exp(-Q_r) - \exp(-Q_f) \right] \right\}$$

$$P_e = P_{eR} \left\{ \left[ \exp(-Q_c) + \frac{Q_r}{Q_c - Q_r} \exp(-Q_c) - \frac{Q_c}{Q_c - Q_r} \exp(-Q_c) - \frac{1}{Q_c - Q_r} \exp(-Q_r) + \frac{1}{Q_c - Q_r} \exp(-Q_r) - \exp(-Q_f) \right] \right\}$$

But  $\frac{-Q_c}{Q_c - Q_r} \exp(-Q_c) = \left[ -1 - \frac{Q_r}{Q_c - Q_r} \right] \exp(-Q_c)$

$$P_e = P_{eR} \left\{ \left[ \exp(-Q_c) + \frac{Q_r}{Q_c - Q_r} \exp(-Q_c) - \exp(-Q_c) - \frac{Q_r}{Q_c - Q_r} \exp(-Q_c) \right] - \left[ \frac{1}{Q_c - Q_r} \exp(-Q_r) + \frac{1}{Q_c - Q_r} \exp(-Q_c) - \exp(-Q_f) \right] \right\}$$

$$P_e = \left[ \frac{\exp(-Q_c) - \exp(-Q_r)}{Q_c - Q_r} - \exp(-Q_f) \right] \cdot P_{eR} \quad (10)$$

**Appendix ix. Average Cost of Wind Turbines**

Wind Turbine	Average Cost in Naira
1kW	402,840± 21429
1.5kW	496,620± 43380
2.5kW	701,636± 17993
3kW	838,593± 61389

**Appendix x. Cost of the Inverters**

Inverter Model	Cost in Naira
Nordic 1000VA 1.0kW	50,000
Xantrex XPower 1.5kW	80, 000
Emerson CP 70i 01 2.5kW	120, 000
Delta RPI H3 3kW	160,000

**Appendix xi. Cost of Battery**

Model	Cost in Naira
Compact Power 75Ah	20,000
Volta 65B100 100Ah	45, 000
Dural SC 150Ah	75, 000
PVX-2120L 200Ah	95,000