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Framework of Generating Electricity from Wind Energy Source: African Perspectives

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Abstract:- This article is resolved to demonstrate the variability of generating electricity from wind energy from the African settings. This paper brought to the fore the historical background of wind energy. There are some concerns when generating electricity from wind energy source. This paper disabused some of the concerns and projected the advantages and benefits of generating electricity from wind energy source. The paper also discussed the construction of wind power systems and the components that made up this plants. Harnessing this energy could be done from wind farms, this write up described the types of wind farms: onshore and offshore wind farms. The paper revealed the characteristics of wind energy that could facilitate the generation of electricity from wind source. To prove the suitability of generating electricity from wind energy, the paper tabulated some of the countries in the world that generated significant amount of electricity from this source. The paper also described in depth the perspective of Ghana in the generation of electricity from wind energy. The paper discussed data obtained from Energy Commission of Ghana and settled on eight locations or sites for analysis. The mathematical expressions and equations that encompassed generation of electricity from wind energy source were deliberated on extensively in this write up. The article also brought to the fore the technical and geographical wind potentials of Ghana and modelled mathematically the available power from the output of wind turbines. The carbon dioxide emission that could be reduced by Ghana from this research was also discussed.

***Keywords**:- Electricity, Wind Energy, Onshore, Offshore, Wind Farms, Available Power, Wind Turbines, Carbon Dioxide.*

I. INTRODUCTION

➢ *Wind energy or wind power is the process of generating electricity using the wind, or air flows that occur naturally in the earth's atmosphere. Wind is caused by the uneven heating of the earth's surface by the sun. Since the earth's surface is made of very different types of land and water, it absorbs the sun's heat at different rates. During the day, the air above the land heats up more quickly than the air over water. The warm air over the land expands and rises, the heavier, cooler air rushes in to take its place, creating winds. At night, the winds are reversed because the air cools more rapidly over land than over water. In the same way, the large atmospheric winds that circle the earth are created because the land near the earth's equator is heated more by the sun than the land near the North and South Poles. Today, wind energy is mainly used to generate electricity. Wind is called a renewable energy because the wind will blow as long as the sun shines. There are three main types of wind energy, these are:*

- Utility-scale Wind, this is a generation method whereby power produced ranges from 100 kilowatts to several megawatts. Electricity generated by this method is delivered to the power grid and distributed to the end user by power distributing companies or power system operators.
- Distributed or "Small" Wind, this generation method consists of a single small wind turbine that can produce power below 100 kilowatts. Electricity generated from this technique is not connected to the grid but rather used directly to power a home, farm or small business.
- Offshore Wind, in this generation technique, wind turbines are erected in large bodies of water, usually on the continental shelf. Offshore wind turbines are larger than land-based turbines and can generate more power that ranges into several megawatts.

- Wind Energy is the most matured and developed renewable energy; it is free, clean and readily available, it reduces the emission of greenhouse effect gases and preserves the environment.

The wind turbines have a lifespan of twenty years; they are often grouped together in to what is known as wind farms**.** A wind farm functions as a single power plant and sends electricity to the grid. Installation of Wind Power Generation Plants are increasing astronomically; the leading countries in this regard are China, the United States and Germany. The total global installed capacity of wind power was over 906,000 MW (906 GW) by the close of 2022 **[1].** Windmills and Wind Turbines are sometimes used interchangeably but there are important differences; windmills are used to generate mechanical energy to grind grain, pump water, and do other works. Wind Turbines generates electricity by using the kinetic energy produced by the effect of air currents.

Electricity generated from onshore wind source is inexpensive, in many places it is cheaper than coal or gas plants. Offshore wind is steadier and stronger than on land and offshore farm have less visual impact, but construction and maintenance costs are considerably higher **[2].** Small onshore wind farms can feed some energy into the grid or provide electric power to isolated off-grid locations **[3].**

II. HISTORY OF WIND POWER

It is factual that wind had been used to propel boats for many thousands of years (wind energy was used to propel boats along the Nile River as early as 5,000 BC) before a wind-driven wheel was used to power a machine in the 1st century**.** This machine was invented by a Greek engineer, called Heron of Alexandria**.** By 7th to 9th century windmills were used for practical purposes in the Sistan Region of Iran, near Afghanistan**.** The Panemone windmills were used to grind corn, flour, and to pump water. Figure 1 shows example of historical windmill.

Fig 1 Historical Windmill

The first known wind turbine used to generate electricity was invented in 1887 and built in Scotland. The wind turbine was created by Prof James Blyth of Anderson's College, Glasgow (now known as Strathclyde University). In 1888, inventor Charles Brush created the first known US wind turbine for electricity production. The electricity generated was used to power his mansion in Ohio. Poul la Cour, a Danish scientist, discovered in 1903 wind turbines with fewer blades that spin faster and more efficient than turbines with many blades that spin slowly. He also started the Society of Wind Electricians; this society held its first course on wind electricity in 1904. 72 electricity-generating wind power systems were running across Denmark by 1908**.** Joe Jacobs and Marcellus Jacobs open the “Jacobs Wind” factory in Minneapolis, Minnesota in 1927. Their wind turbines were mainly used on farms. By 1957 the factory had sold approximately 30,000 wind turbines including to customers in Africa and Antarctica. In 1941 the first megawatt-size wind turbine was connected to a local electrical distribution grid. The 1.25-MW Smith-Putnam wind turbine was erected in Castletown, Vermont; the length of its blades was 75feet or 23m **[4].** A former student of Poul la Cour, Johannes Juul in 1957 invented horizontal-axis wind turbine with a diameter of 24 meters and 3 blades very similar in design to wind turbines still used today. The wind turbine has a capacity of 200 kW and it employed a new invention, emergency aerodynamic tip breaks, which is still used in wind turbines today.

In 1975, a NASA wind turbine program to develop utility-scale wind turbines started. This research and development program pioneered many of the multi-megawatt turbine technologies in use today, including: steel tube towers, variable-speed generators, composite blade materials, partial-span pitch control, as well as aerodynamic, structural, and acoustic engineering design capabilities. The large wind turbines developed under this effort set several world records for diameter and power output. In 1975, the first US wind farm was put online, producing enough power for up to 4,149 homes. Tvind school teachers and students produced the world's first multi-megawatt wind turbine in 1978. They had important help from German aeronautics specialists with the construction of a novel wing. This wind turbine is still running today.

The world's first wind farm consisting of 20 wind turbines was put online in 1980; in the same year Denmark started siting offshore wind turbines. By 1990, 46 wind farms were online in the US, providing enough power for up to nearly 300,000 homes. The first offshore wind farm in the world was constructed in southern Denmark in 1991. It was made up of 11 wind turbines manufactured by Bonus Energy, each with a capacity of 450 kW. In 1991, UK's first onshore wind farm was constructed in Cornwall. The wind farm was made up of 10 wind turbines, this wind farm together produced enough electricity for approximately 2,700 homes. The Global wind power capacity reached 6,100 megawatts in 1996. In 2003 UK's first offshore wind farm was opened in North Wales. It was made up of 30 wind turbines, each with a power capacity of 2 megawatts. The first large-capacity floating wind turbine in the world began operating off the coast of Norway in 2009. It used a Siemens wind turbine and was developed by Statoil. In 2009 the Roscoe Wind Farm in Texas was opened; it became the largest wind farm in the world. It has a power capacity of 781.5 megawatts and was made up of 634 wind turbines **[5].**

By 2010, 581 wind farms were online in the US, providing enough power for up to 10 million homes. In the same year, China passed US to become the country with the most cumulative installed wind power capacity in the world. In 2011, Japan announced plans to build multiple-unit floating wind farm (6 wind turbines, each with 2 megawatts of capacity). In 2012, the installed wind power capacity in China reached 75 gigawatts, the most in the world for a single country. UK had the most installed offshore wind power capacity in the world; it had over 3 gigawatts of offshore wind power three times more than Denmark, which came in second. Wind power constituted over 30% of Denmark's electricity needs. Global wind power capacity also reached 282,587 megawatts in 2012. Japan is the first country in the world to install hybrid wind/current-powered turbine in 2013; this hybrid was installed off the coast of Japan. US launched its first offshore wind turbine.

Today, ongoing advancements in wind technology have helped make wind more reliable and efficient than ever as a clean power source. By the end of 2015, there were over 314,000 turbines worldwide generating about 3.7% of the world's electricity **[6].** In 2018, the share of U.S. electricity generation from wind was nearly 7%. Incentives in Europe have resulted in a large expansion of wind energy use there. China is investing heavily in wind energy and now has the world's largest wind electricity generation capacity **[7].** Airborne wind energy systems use airfoils or turbines supported in the air by buoyancy or by aerodynamic lift. The purpose is to eliminate the expense of tower construction, and allow extraction of wind energy from steadier, faster, winds higher in the atmosphere. As yet no grid-scale plants have been constructed. Many design concepts have been demonstrated.

III. CONCERNS OF WIND ENERGY TECHNOLOGY

Even though the unpollutabilty of this technology, the sustainability of the raw material (wind) used and the creation of employment that accompanies generation of electricity from wind source; there are some concerns. The major concerns include initial expenditure; the wind turbine plants have a lot of mechanical components that suffer from wear and tear, therefore need to be maintained regularly. Another disquiet, is that the wind is intermittent and does not always blow when electricity is needed. Wind energy cannot be stored (unless batteries are used); and not all winds can be harnessed to meet the timing of electricity demands. Not all wind can be used to generate electricity, perfect wind sites, good enough to generate electricity are often located in remote areas, far from cities where electricity is most needed. Other concerns are the noise emanating from the wind turbines which is unfriendly to people staying close to wind farms and the menace that the blades of the wind turbines may cause to wildlife (birds and bats may be killed by the rotating blades).

IV. CONSTRUCTION OF WIND POWER SYSTEMS

The wind is a by-product of solar energy. Approximately, only 2% (3.6×10^9 MW) of the sun's energy reaching the earth is converted into wind energy **[8].** Wind energy is the kinetic energy of air in motion, also called wind. The device used to convert the kinetic energy from the wind is the wind turbine. The wind turbine can convert kinetic energy from the wind into mechanical energy or wind power. This device will be known as wind turbine or wind power plant if the mechanical energy is used to generate electricity. If the mechanical energy is used for grinding purposes such as grains or pumping water the device will be called windmill. **[9].** Therefore, wind turbine is an equipment that is used to capture the kinetic energy in the wind and convert it to mechanical or electrical energy. Wind turbine is sometimes called wind generator. There are two main classes of wind turbines, these are Horizontal wind turbine shown in figure 2 and Vertical wind turbine shown in figure 3. The blades of the horizontal wind turbine rotate on an axis parallel to the ground whereas those of vertical wind turbine rotate on an axis perpendicular to the ground. The vertical wind turbines are not as common as the horizontal wind turbines.

Fig 2 Horizontal Wind Turbine

Fig 3 Vertical Wind Turbine

- *The Major Parts of Wind Turbine are:*

Foundation (Base), Tower, Nacelle, and the Rotor (with two or three Blades attached to the Hub)

- *Foundation*

The foundation of the wind turbine is very critical, if the base is not well constructed the wind turbine may tumble. The construction starts by excavating a hole and placing reinforcement such as steel in the hole. Fill the hole with about 325 yard or 303m of concrete; the dimensions of the foundation should be approximately 55 feet or 17m wide and 8 feet or 2.5m deep in the center. Figure 4 depicts a foundation of wind turbine.


Fig 4 Foundation

* *Tower*

The tower is the most important part of the wine turbine. The other components that are contained in the wind turbine are also supported by the tower. It lifts the wind turbine to a height between 40 to 100 meters if the wind turbine will be used for commercial wind power plants. This height enables the tip of the blades to rotate freely in the sky without any hindrance. It also helps maintain adequately strong wind. The towers used for wind turbine include: tubular steel tower shown in figure 5, lattice tower shown in figure 6, Guyed Pole Tower shown in figure 7 and concrete tower shown in figure 8. In large wind turbine energy plants, tubular steel towers are mostly used.


Fig 5 Tubular Steel Tower

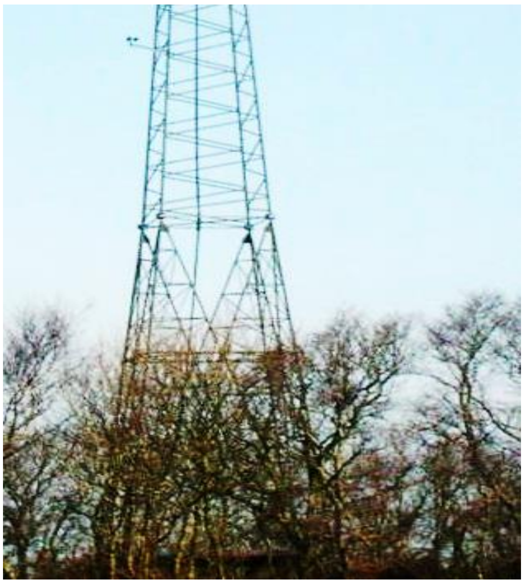

Fig 6 Lattice Tower

Fig 7 Guyed Pole Tower

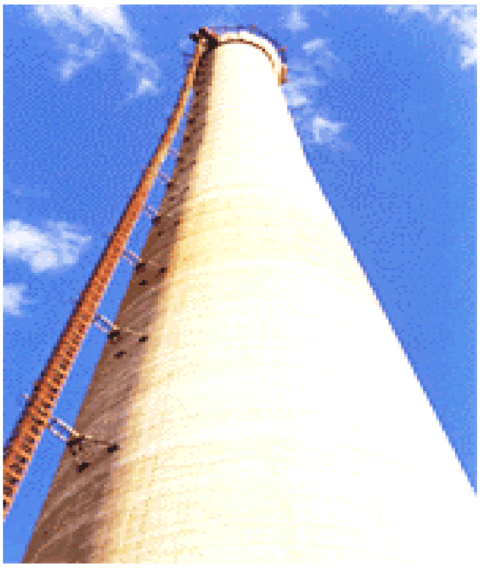

Fig 8 Concrete Tower

- *Nacelle*

The nacelle is a kiosk like object situated on the tower. All the components such as the electrical generator, power converter, gearbox, turbine controller, cables, and yaw drive of a wind turbine are lodged in the nacelle.

- *Rotor (with two or three Blades attached to the Hub)*

The function of the Rotor is to collect energy from the wind. The rotor of a modern wind turbine is composed of two or three metal of fiberglass blades. The three blade types are aligned at an angle of 120 degrees between them. The blades are fixed to the hub; the hub is fixed to the main shaft. The operation of the blades is designed on the principle of either lift or drag. The characteristic of the lift blades has the same attribute that allows a bird, airplane or kite to fly. The drag blades are characterised by the wind virtually pushing the blades out of the way. Wind turbines with lift blades have higher rotational speed than those designed with drag blades. Wind turbines fitted with lift blades are very good for electricity generation. Figures 9 and 10 show the components of a wind turbine.

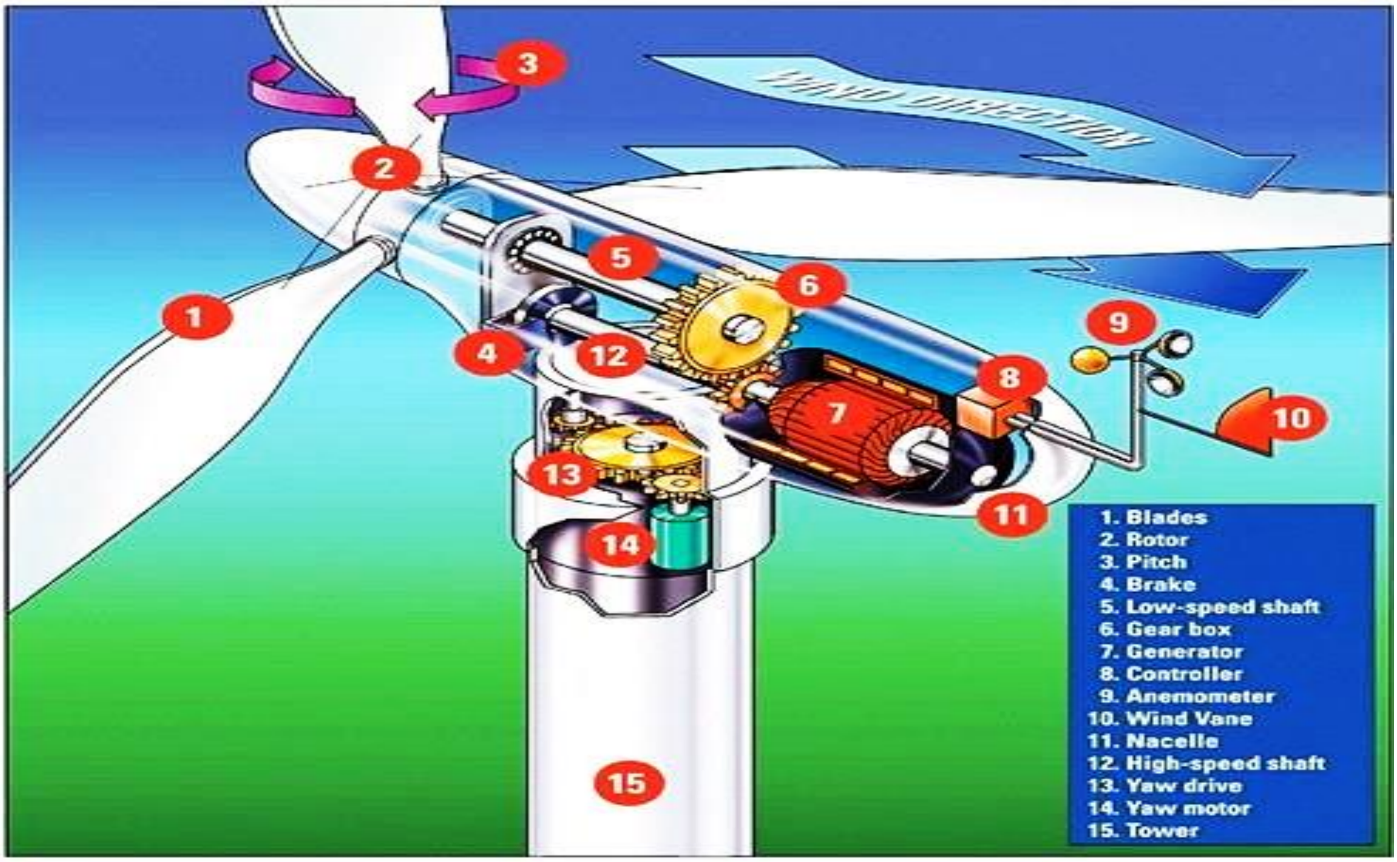

Fig 9 Wind Turbine Components

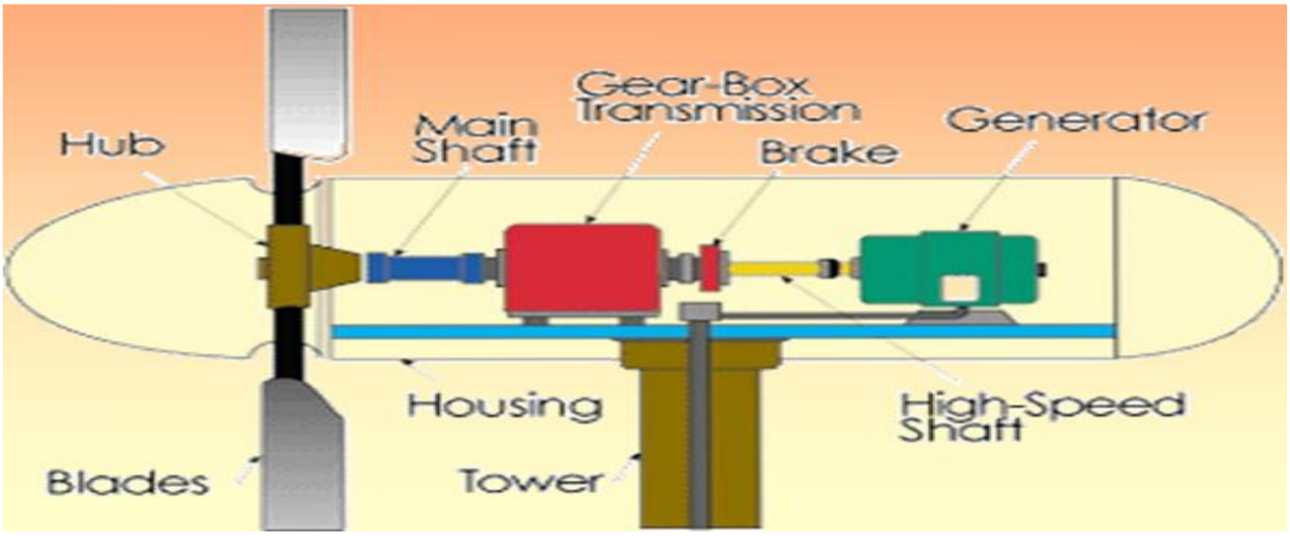

Fig 10 Wind Turbine Components

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The construction of wind turbine comes with a lot of parts. A typical wind turbine will contain as many as 8000 different components**,** of which the tower is a very important part since it carries almost all the other components. A well-constructed foundation keeps the tower in place. The nacelle which is situated on top of the tower can be found behind the blades. The nacelle is the main body of the turbine. The Anemometer and wind vane are mounted at the back of the nacelle. The rotor carries the blades which are fitted to the hub. The low speed shaft is directly connected to the hub and the gearbox. The gearbox is fitted to the generator. The yaw motor that is mounted between the nacelle and the tower is connected to the yaw drive which is linked to the high speed shaft. The high speed shaft is then connected to the brake.

➢ *Wind Farms*

Wind farm is a cluster of wind turbine plants located at the same place with the aim of aggregating their individual electricity production capacity. These individual wind turbines are interconnected with a medium voltage of usually 34.5 kV power collection system and communications network. The wind farm has a substation where a transformer is used to increase the medium voltage to a high voltage which can be connected to a high voltage transmission system. A wind farm may contain hundreds of individual wind turbines and can expand to hundreds of square kilometers land surface. The Gansu Wind Farm (Jiuquan Wind Power Base) in China is the world largest wind farm; it would have when fully completed 7000 wind turbines. These turbines would have installed capacity of 20 GW **[10].** A wind farm as the case may be, will be situated at: On-Shore, Off-shore, Near-shore and Air-borne. On-shore wind farms are generally located three kilometers or more into inland from the nearest coastline. The appropriate areas to locate these farms are open plains, rounded hills top and mountainous regions. Figure 11 shows example of on-shore wind farm.

Fig 11 On-Shore Wind Farm

Off-shore wind farms are generally situated ten kilometers or more from land. They are more expensive to install than their counterpart on land. Even though installation of off-shore wind farms have huge cost implication, their advantages cannot be over emphasized. The wind speeds of offshore are about twenty percent higher than those on-shore. According to the wind power law, the offshore wind power can capture much more power than the onshore one. This indicates that an offshore wind turbine may gain a higher capacity factor than that of its land-based counterpart. Offshore wind speeds are relatively uniform and have lower resistance than on-shore wind speeds; due to these attributes, there is reduction in wears and tears of offshore blades and turbines. Figure 12 shows example of off-shore wind farm.

Fig 12 Off-Shore Wind Farm

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Near-Shore wind farms are generally located within three kilometers from coastline (shoreline) or on water within ten kilometers from land. These areas are good sites for turbine installation, because wind is produced by convection due to differential heating of land and sea each day. Wind speeds in these zones share the characteristics of both onshore and offshore wind, depending on the prevailing wind direction**.** Airborne wind turbines would eliminate the cost of towers and might also be flown in high speed winds at high altitude. No such systems are in commercial operation yet.

- *Operation of Wind Turbine Plants*

Wind speed is behind the generation of electricity by wind turbine. The relationship between wind speed and power is defined by a power curve, which is unique to each turbine model and, in some cases, unique to site-specific settings. In general, most wind turbines begin to produce power at wind speeds of about 4 m/s (9 mph), achieve rated power at approximately 13 m/s (29 mph), and stop power production at 25 m/s (56 mph) **[11].** The blades can also turn sideways automatically during high winds to limit speed.

The electricity generation process starts when the wind blows the rotor blades of the wind turbine. The rotor traps some of the wind's kinetic energy. The rotation of the rotor spins the drive shaft which is connected to it quite slowly. The gearbox that is located inside the nacelle converts the low-speed rotation of the drive shaft of about 16 rpm into high speed of approximately 1600 rpm. **[12].** The rotation at this level is high enough to drive the generator effectively. The generator converts the kinetic energy (mechanical energy) coming from the spinning drive shaft into electrical energy. Cabling system is used to evacuate the electric current produced by the generator to a nearby step-up transformer. The step-up transformer increases the voltage from the generator to about fifty times. This voltage is high enough to be transmitted onto the power grid efficiently. Wind turbine is a complex machine, therefore every wind that get to the blades need to be taken account off, hence anemometer is put in place to automatically measure the speed of the wind. **[13].** Wind vane also measures the direction of the wind. For safety reasons, brakes are connected to the shafts to stop the rotor from rotating in windy or turbulent situations**.** During routine maintenance, the brakes are also used to stop the rotor from turning. Yaw drive and yaw motor are employed to reposition the nacelle to face the wind when the direction of the wind alters; since the nacelle can only extract the full energy from the wind when it faces its direction.

- *Objective*

The aim of this paper is to demonstrate how countries in the world over are using the power of the wind to generate considerable amount of electricity and the prospect of African countries to do same.

V. METHODOLOGY

The methods employed by the researchers in bringing to the fore generation of electricity using wind power include installed wind energy capacity of some countries in the world by 2022 and mathematical analysis of wind power system.

- *Installed Wind Energy Capacity of Some Countries in the World by 2022*

We selected five countries in each continent with high wind energy installed capacity except Africa where all the countries were factored into the studies. The rest of the continents are Europe, America and Asia; for the purpose of this project, Australia was added to Asia. The global non-renewalable energy consumption and its attendance carbon dioxide emission are increasing sharply putting into focus the importance of wind energy. Table 1 illustrated five selected countries and their wind turbine installed capacity by 2022.

Table 1 Five Selected Countries and Installed Wind Turbine Capacity by 2022

2022					
Gigawatts (GW)= 10^9 W					
ASIA					**Total**
China	India	Australia	Japan	South Korea	
366	42	10.1	4.6	1.9	**424.6**
EUROPE					
Germany	Spain	United Kingdom	France	Sweden	
66.3	29.3	28.5	21.1	14.6	**159.8**
AMERICA					
United States	Brazil	Canada	Mexico	Argentina	
140.9	24.2	15.3	7.3	3.3	**191**
AFRICA					
South Africa	Egypt	Morocco	Other Africa	Tunisia	
3.1	1.6	1.6	1.2	0.3	**7.8**

➢ *Installed Wind Energy Capacity of Selected Seventeen African Countries by 2020*

Africa has huge potential of generating significant amount of her electricity needs from wind power, however this has not been realised yet. Even though, some African countries have made giant stride in this sphere, these researchers believe more could be accomplished. Table 2 spelt out 17 African countries which have at least one megawatt (MW) of installed wind energy capacity.

Table 2 Seventeen African Countries with Installed Wind Energy Capacity in MW

2020		
Megawatts (MW) = 10^6 W		
Africa		
1	South Africa	2,465
2	Egypt	1,465
3	Morocco	1,309
4	Kenya	338
5	Ethiopia	325
6	Tunisia	242
7	Mauritania	137
8	Cape Verde	26
9	Libya	20
10	Algeria	11
11	Nigeria	10
12	Mauritius	10
13	Seychelles	6
14	Namibia	5
15	Gambia	1
16	Eritrea	1
17	Chad	1

There are a lot of African countries such as Tanzania and Ghana just to mention a few that have the potential to generate electricity from wind energy source. These countries especially Ghana lacks progress and to a large extend regressing in the development of this facility. The Energy Commission of Ghana researched and tabulated wind energy resource locations in the country. Table 3 illustrates some of the wind energy resource assessment locations in Ghana.

Table 3 Results of Wind Energy Resource Assessment in Some Sites in Ghana

Wind Speed in m/s at 50m Height								
Coordinates (Latitude; Longitude)	5.68ºN; 0.07ºE	5.97ºN; 0.44ºE	5.79ºN; 0.52ºE	5.32ºN; 0.20ºE	5.79ºN; 0.55ºE	5.47ºN; 0.55ºE	5.62ºN; 0.07ºE	5.22ºN; 0.35ºE
MONTH	**Kpone**	**Lolonya**	**Pute**	**Aplaku**	**Adafoah**	**Anloga**	**Tema**	**Warabeba**
JAN	7.2	7.6	8	6.9	7.6	6.6	6.8	5.8
FEB	8.8	7.8	6.8	7.1	7.7	7.1	6.9	6.6
MAR	7.6	6.7	7.1	7.6	6.9	6.7	6.6	5.2
APR	6.7	6.9	7.6	6.7	6.8	6.9	6.7	4.7
MAY	6.8	7.2	7.8	6.8	7.2	6.7	6.8	5.7
JUN	6.9	6.9	6.9	7	7.3	6.9	5.9	4.9
JUL	7.1	7.8	7.8	7.1	6.8	7.1	7	6.7
AUG	6.9	6.9	7.9	6.9	6.7	6.8	6.9	4.9
SEP	7.6	7.6	6.9	6.6	7.9	7.2	6.6	5.6
OCT	6.8	6.9	7.8	6.5	6.8	6.5	6.8	4.7
NOV	7.3	7	6.9	7.1	6.6	7	6.5	4.5
DEC	6.5	6.5	6.9	6.7	6.3	6.1	6.4	5.3
AVERAGE	**7.18**	**7.15**	**7.37**	**6.92**	**7.05**	**6.8**	**6.66**	**5.38**

➢ *Mathematical Analysis of Wind Power*

Engineers, scientists and researchers had modeled calculations and equations underpinning generation of electricity using wind energy system. These equations could be employed from the input to the output of the wind turbine to extract the actual power at the output of the turbine. Some of these equations buttressing wind power are as follow:

Wind Energy is the Kinetic Energy (KE) of a moving air and can be expressed as:

$$\mathbf{KE} = \frac{1}{2}\mathbf{mv^2} \quad \text{.....} \quad (1)$$

Where:

m = Mass, in kg

v = Velocity, in m/s

When wind passes through a wind turbine and drives blades to rotate, the corresponding wind mass flowrate is:

$$\mathbf{m} = \boldsymbol{\rho}\mathbf{Av} \quad \text{.....} \quad (2)$$

Where:

$\boldsymbol{\rho}$ = Air Density, $\mathrm{kg/m^3}$

A = Swept Area of Blades, $\mathrm{m^3}$

v = Velocity, m/s

With the mass m= ρAv, the wind power may be expressed as:

$$\mathbf{P_w} = \frac{1}{2}\boldsymbol{\rho}\mathbf{Av^3} \quad \text{.....} \quad (3)$$

Where:

$\mathbf{P_w}$ = Wind Power, W

The area swept by the blade, A can be calculated by:

$$\mathbf{A} = \boldsymbol{\pi}[(\mathbf{l}+\mathbf{r})^2 - \mathbf{r}^2] = \boldsymbol{\pi}\mathbf{l}(\mathbf{l}+2\mathbf{r}) \quad \text{.....} \quad (4)$$

Air Density is one of the parameters that determines production of wind power and hence can be calculated from:

$$\boldsymbol{\rho} = \frac{\boldsymbol{\rho}_l}{\mathbf{RT}} \quad \text{.....} \quad (5)$$

Where:

$\boldsymbol{\rho}_l$ = Local Air Pressure, Pascal (Pa)

R = Gas Constant, (287J/kgK) for air;

T = Local Air Temperature, K

Acceleration due to Gravity affects generation of wind power since it decreases with height above the surface of the earth and can be determined by:

$$\mathbf{g} = \mathbf{g_o}\left(1 - \frac{4\mathbf{z}}{\mathbf{D}}\right) \quad \text{.....} \quad (6)$$

Where:

g = Acceleration due to Gravity, $\mathrm{ms^{-2}}$;

$\mathbf{g_o}$ = Acceleration due to Gravity at the Ground, $\mathrm{ms^{-2}}$;

z = Surface of the Earth, $\mathrm{m^2}$;

D = Diameter of the Earth, m.

The Air density may then be determined from:

$$\boldsymbol{\rho} = \boldsymbol{\rho}_o\left(1 + \frac{\mathbf{cz}}{\mathbf{T_o}}\right)^{-(\mathbf{glcR}+1)} \quad \text{.....} \quad (7)$$

Where:

$\boldsymbol{\rho}_o$ = Air Pressure at the Ground, Pa;

$\mathbf{T_o}$ = Temperature at the ground, K

The available power extracted from the wind is the actual power which can be found at the output of the wind turbine, this is given by:

$$\mathbf{P_o} = \frac{1}{2}\boldsymbol{\rho}\mathbf{Av^3C_p} \quad \text{.....} \quad (8)$$

Where:

$\mathbf{P_o}$ = Output Power or Available Power of the Turbine, W.

$\mathbf{C_p}$ = Coefficient relating to Efficiency or Power Coefficient, it is a constant that has a theoretical value of 59.3% which known as the Beltz's Limit. This is a constant, derived from Beltz's law which states that; the wind turbine blade efficiency is maximum when it slows the wind to one-third of its original velocity (Modern wind turbine blades can approach 80 percent of this limit, i.e., 45% - 50% efficiency).

The Power Coefficient may be determined from:

$$\mathbf{C_p} = \frac{\left(1+\frac{\mathbf{V_o}}{\mathbf{V}}\right)\left[1-\left(1-\frac{\mathbf{V_o}}{\mathbf{V}}\right)^2\right]}{2} \quad \text{.....} \quad (9)$$

Where:

V_o =Downstream wind velocity at the exit of the rotor blades, m/s

V = Upstream wind velocity at the entrance of the rotor blades, m/s;

Another parameter that is important in wind power generation is the Wind Power Density; this is the available wind power in airflow through a perpendicular cross-sectional unit area in a unit time period that can be evacuated at a particular site.

The Wind Power Density is calculated by:

$$\mathbf{P_{\rho} = \frac{P_o}{A}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(10)}$$

Where:

P_{ρ} = Wind Power Density, W/m^2

A= Swept Area of Blades, m^2

The power that is finally fed to the grid from the wind turbine is known as the Effective Power Output and this is expressed by:

$$\mathbf{P_{eff} = \eta_t P_w} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(11)}$$

Where:

$$\mathbf{\eta_t = \eta_{gear}\eta_{gen}\eta_{ele}C_p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(12)}$$

η_{gear} = Gearbox efficiency (power losses in a gearbox are load-dependent power loss and no-load power loss; load-dependent losses consist of gear tooth friction and bearing losses and no-load losses consist of oil churning, windage, and shaft seal losses).

η_{gen} = Generator efficiency (electrical and mechanical losses in a wind generator, such as copper, iron, load, windage, friction, and other miscellaneous losses).

η_{ele} = Electric efficiency (encompasses all combined electric power losses in the converter, switches, controls, and cables)

The Tip Speed Ratio (TSR) is Rotor Efficiency which is very important parameter in wind power generation. It can be determined by finding the ratio between the speed of the tips of the rotor blade and the speed of the wind. Thus:

$$\boldsymbol{\lambda = \frac{(l+r)\omega}{v}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(13)}$$

Where:

λ = Tip Speed Ratio (TSR)

l = Length of the Blade, m

r = Radius of the hub, m

ω = Angular Speed of Blades.

VI. PRESENTATION OF RESULTS & DISCUSSIONS

The discussions on this article centered on global wind energy installed capacity, wind energy installed capacity in Africa and the outlook of generating electricity from wind power source in Ghana.

➢ *Global Wind Energy Installed Capacity*

One cannot leave China out of the equation when discussion on high emitters of carbon dioxide surface or come out, neither can China be left out when generation of electricity from renewable energy source is mentioned. From whatever angle one looks at China from, they are very important in the affairs of the world. By the close of 2022, the world has more than 906 GW of Wind Power installed capacity from both onshore and offshore. This installed capacity constitutes a paltry 3% of the world total electricity generation. Out of the world total wind power, China contributed a significant amount; its installed capacity stood at 366 GW by the end of 2022. China's installed capacity is more than twice that of United States (140.9 GW), the second highest and more than a fifth of Germany (66.3 GW), the third highest. South Africa has installed capacity of 3.1 GW, the highest in Africa. By 2020, Denmark had wind power penetration of more than 56%; Uruguay had 40%, Lithuania 36%; the penetration of Ireland was 35%, in UK, 24%, 23% in Portugal and Germany; Spain achieved 20% penetration, Greece had 18% penetration, Sweden 16%; United States 8% penetration whilst China 6%. Figure 13 portrays wind power installed capacity of some selected countries in the world by 2022.

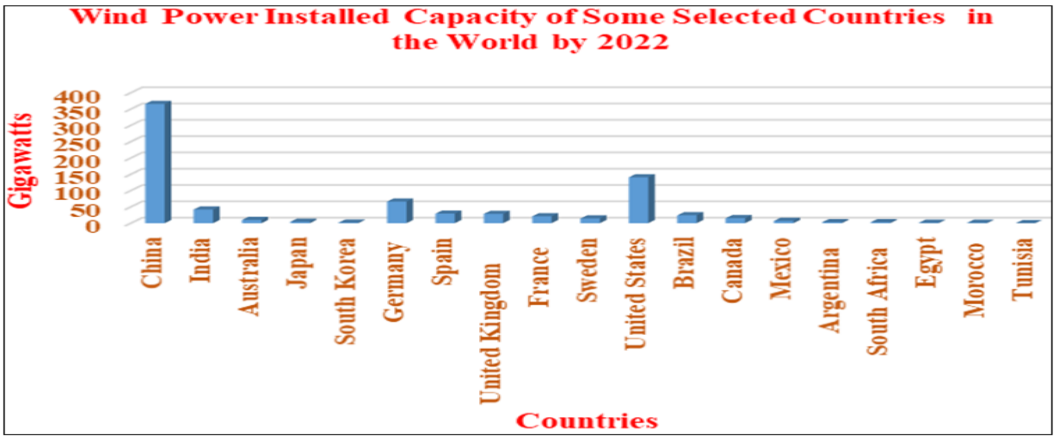

Fig 13 Wind Power Installed Capacity of Some Selected Countries in the World by 2022

Asia has the highest installed wind energy capacity; its installed capacity constituted 54% of the global total. This capacity was highly influenced by China's installation. It was followed by America which contributed 24% and was closely followed by Europe that added 21% to the world's number. Africa, even though has a huge potential contributed insignificantly 1%. According to a research conducted by Price Water House Coopers, Africa technically has wind resource potential of up to 59,000 GW out of which only 0.01% is currently utilised. Figure 14 illustrates the continents wind energy installed capacity by 2022.

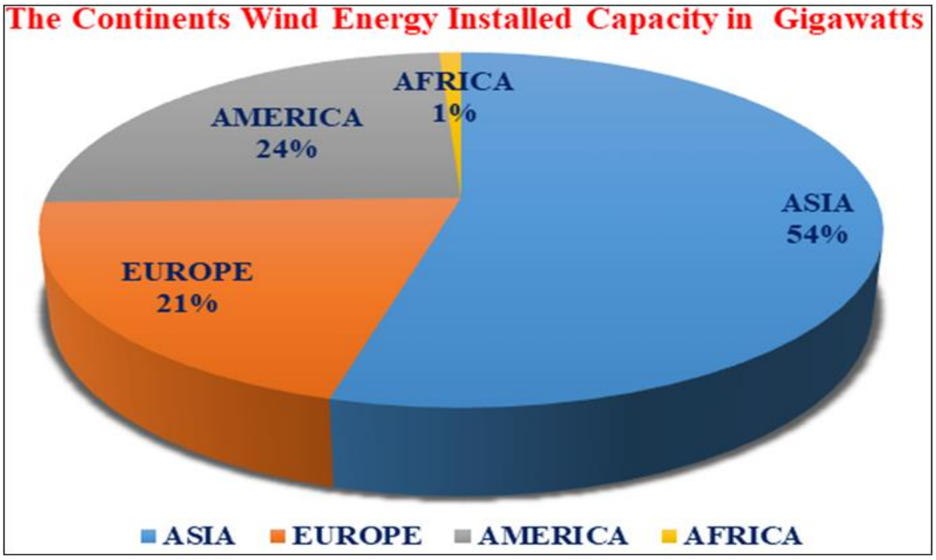

Fig 14 Continents Wind Energy Installed Capacity in GW by 2022

- *Wind Energy Installed Capacity in Africa by 2020*

As already alluded to, Africa could general substantial amount of its electricity needs from wind energy but lack of capital and to a large extend, commitment on the part of some African leaders have curtailed this feat. That notwithstanding, some Africa countries are doing fairly well in this regard. The total electricity installed capacity more than one megawatt from wind energy source by the end of 2020 stood at 6,372 MW or 6.372 GW. Out of this total, South Africa alone generated 39%, the second country with the highest installed capacity Egypt generated 23%; followed closely by Morocco 21%. Kenya and Ethiopia both accounted for 5% each of the total, Tunisia generated 4%, Mauritania 2% and the rest of Africa 1% constituting 91 MW. Figure 15 illustrates African countries with at least one megawatt installed capacity.

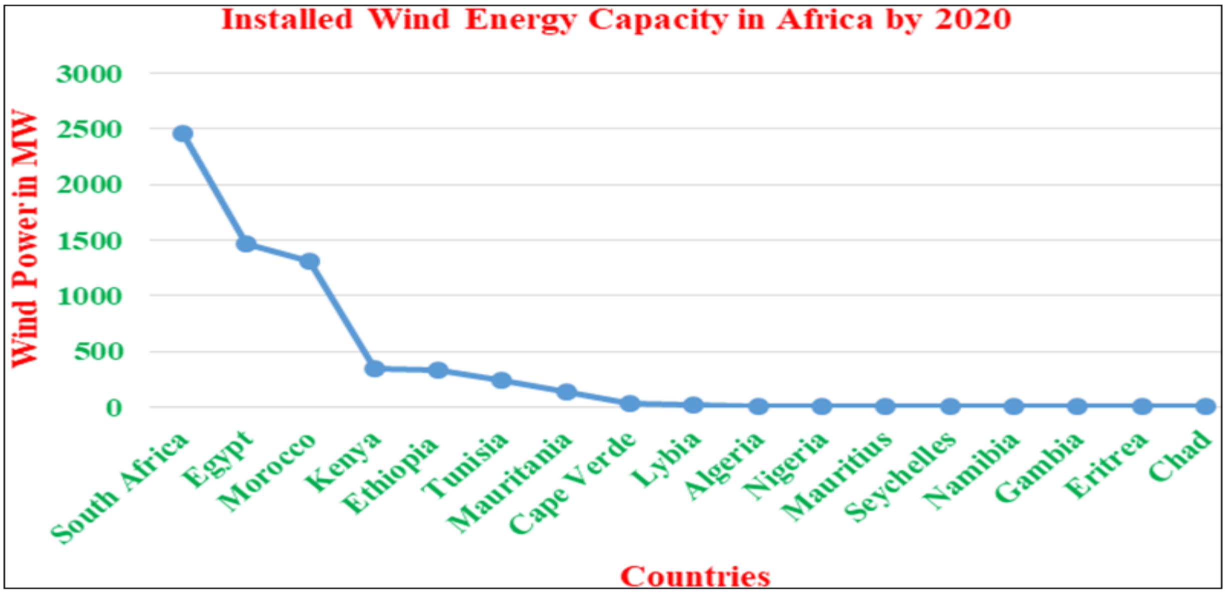

Fig 15 African Countries with at Least One Megawatt Installed Capacity of Wind Power.

North African countries produced 48%, almost half of the total installed capacity; South African countries powered by South Africa generated 39%. Namibia, the only South African country that contributed to the 39% generated 5 MW. East Africa contributed 10% of the total; while no country in Central Africa is known to have installed more than one megawatt, West Africa produced 3% constituting 175 MW. Figure 16 depicts regional distribution of installed wind energy capacity of African countries by 2020.

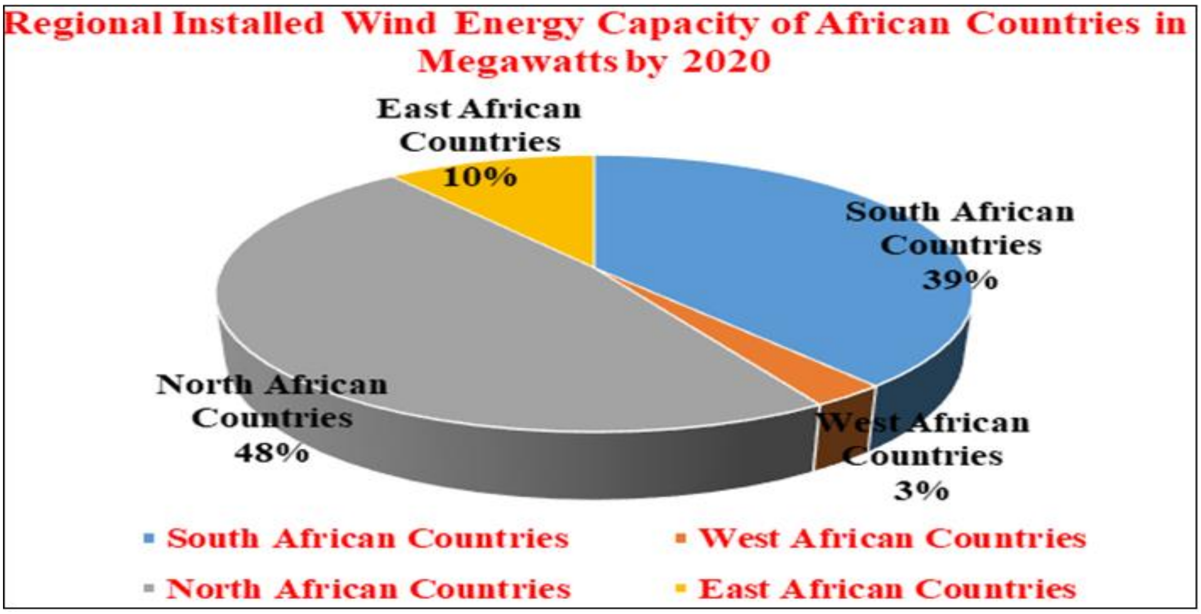

Fig 16 Regional Distribution of Installed Wind Energy Capacity of African Countries by 2020

➢ *Outlook of Generating Electricity from Wind Power Source in Ghana*

Even though the prospect of generating electricity from wind energy in Ghana is vast, up till today there is no power emanated from this source. It is estimated by Energy Commission of Ghana that, the country has over 2,000 Megawatts (MW) of wind energy capacity. This assertion was further amplified by a scientific spatial or three dimensional analyst-based tool known as ArcGIS **[14].** ArcGIS is a virtual or online cloud-based geographic information system (GIS) software that is used for mapping, data storage, map sharing and analysing visualized geographical statistics. Ghana specific data is as shown in table 4; it articulates its technical and geographical wind potential.

Table 4 Ghana Specific Technical and Geographical Wind Potential

Ghana	Total area PCS (km^2)	Grid restriction		No grid restriction	
		Total available for wind farm (km^2)	% of the area availability	Total available for wind farm (km^2)	% of area availability
Geographical	244,728	20,674	8.45%	20,674	8.45%
Technical	Energy (TWh/year) no grid restriction	Energy (TWh/year) grid restriction	Energy (TWh/year) CF > 20%	Electricity TFC (TWh)/annum	
	82.8	82.8	0	6.9	

Analysis from table 4 indicated that, Ghana has a land surface area of 244,728 km^2 out of this, 20,674 km^2 is suitable for wind farm operations. This implies that, the country has a geographical potential of 8.45% of total available land surface area for electricity generation. The table also suggested that the capacity factor (CF) for wind in Ghana is more than 20% (> 20%). The capacity factor in wind turbine is actually the ratio of its average power output to its maximum capability or nameplate capacity. The figure further inferred that, the yearly technical potential for wind energy in Ghana would be 82.8 Terawatts-hour (TWh), while the Total Final Electricity Consumption (TFC) per annum currently stands at 6.9 TWh. From this analysis it can be observed that the technical potential to generate electricity from wind power is 12 times more than the country's total final electricity consumption yearly. This also implies that, 100% electrification in Ghana can be achieved employing wind energy.

From above information, it can be concluded that, Ghana has comparative advantage in generating electricity cost effectively from wind energy source. With this in mind, these researchers selected eight sites in the country with good geographical wind potential for analysis. These sites that are located in Greater Accra, Central and Volta regions are: Kpone, Lolonya, Pute, Aplaku, Adafoah, Anloga, Tema and Warabeba. The monthly average wind speed in meter per second (m/s) of these sites at 50 meters height is depicted in figure 17.

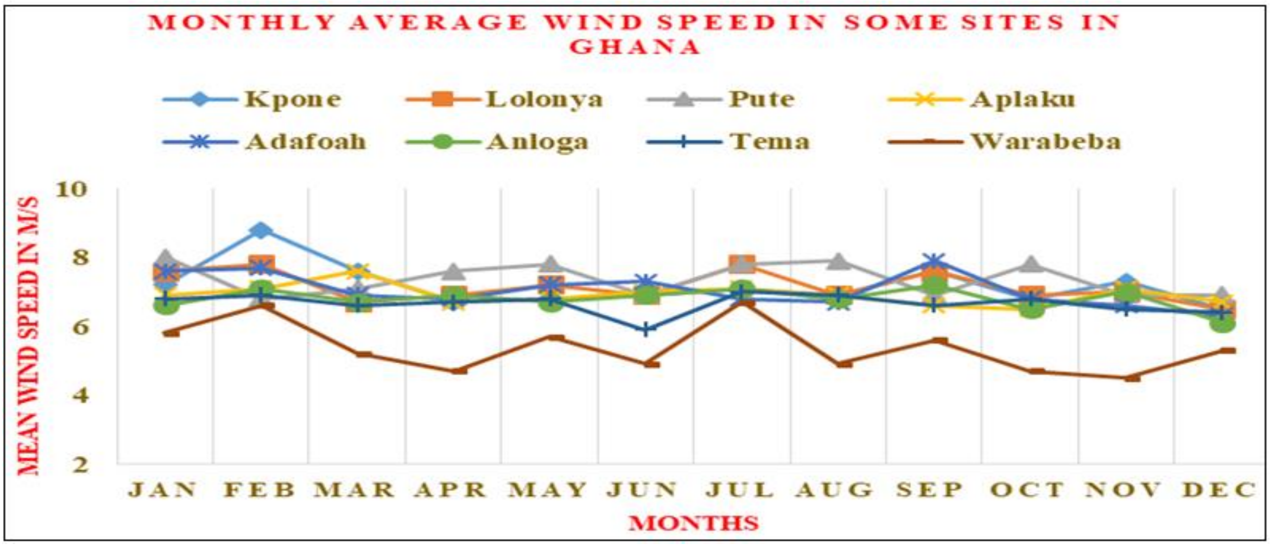

Fig 17 Monthly Average Wind Speed in Meter per Second (m/s)

From this figure, the month with the highest wind speed of 8.8 m/s occurred in February at Kpone in the Greater Accra region and the one with the lowest wind speed of 4.5 m/s happened in November at Warabeba in the Central region. The monthly mean wind speed in m/s at a height of 50m for the sites is illustrated in table 5.

Table 5 Monthly Average Wind Speed in m/s at 50 m Height

Sites	Coordinates (Latitude; Longitude)	Monthly Average Wind Speed in m/s at 50m
Kpone	5.68ºN; 0.07ºE	7.18
Lolonya	5.97ºN; 0.44ºE	7.15
Pute	5.79ºN; 0.52ºE	7.37
Aplaku	5.32ºN; 0.20ºE	6.92
Adafoah	5.79ºN; 0.55ºE	7.05
Anloga	5.47ºN; 0.55ºE	6.8
Tema	5.62ºN; 0.07ºE	6.66
Warabeba	5.22ºN; 0.35ºE	5.38

To help with vertical extrapolation of wind speed at the various sites, wind logarithmic profile as expressed in equation 14 was employed to calculate the mean wind speed, **V(z)** at a height, **z** from known measurement $\mathbf{V_r}$ at a reference height $\mathbf{z_r}$. The wind turbines for this experiment were sited at farmland with open appearance, hence the roughness length which is a constant **0.05** was used. This constant is obtained from the table of roughness lengths.

$$\mathbf{V(z) = V_r \frac{\log\left(\frac{z}{z_0}\right)}{\log\left(\frac{z_r}{z_0}\right)}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathbf{(14)}$$

Where:

$\mathbf{z}$ = Height in Question, m

$\mathbf{z_0}$ = Roughness Length, 0.05m (constant)

$\mathbf{z_r}$ = Reference Height, m

$\mathbf{V_r}$ = Wind Speed at Reference Height, m/s

$\mathbf{V(z)}$ = Mean Wind Speed at Height in Question z, m/s

The mean wind speed and the altitude of the turbine at the various sites were modelled using table 5 and equation 14 to obtain figures 18 a, b, c, d, e, f, g, h. From the figures, the highest height is 100 m, therefore the height of the turbine for this research is 100m. The researchers also adopted diameter of the rotor blade to be 80 m. It should be noted that, the higher the turbine rotor the higher the wind speed, this is evident in all the sites (figures 18 a, b, c, d, e, f, g, h) under study. Also, the bigger the diameter of the rotor blade the more wind that can be captured.

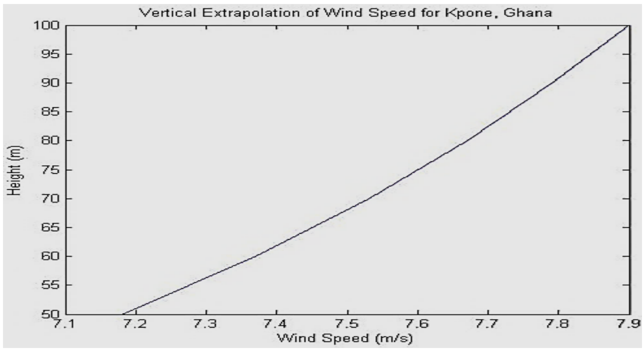

Fig 18(a) Vertical Extrapolation of wind Speed (m/s) for Kpone

In this figure the monthly average wind speed at 50 m was 7.18 m/s, at 100 m the speed is 7.9 m/s.

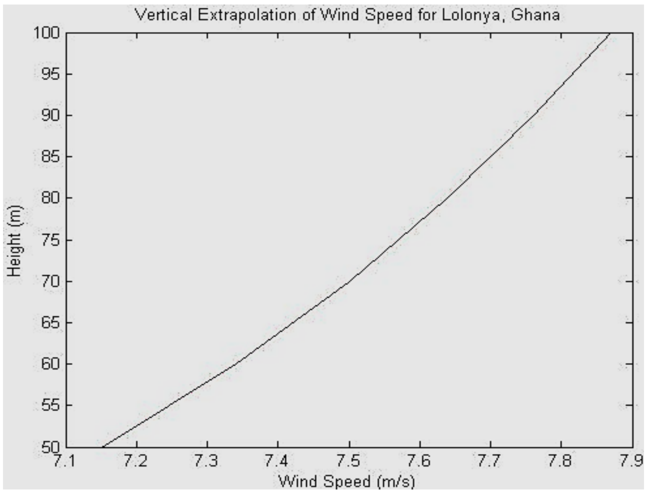

Fig 18(b) Vertical Extrapolation of wind Speed (m/s) for Lolonya

In this figure the monthly average wind speed at 50 m was 7.15 m/s, at 100 m the speed is 7.85 m/s.

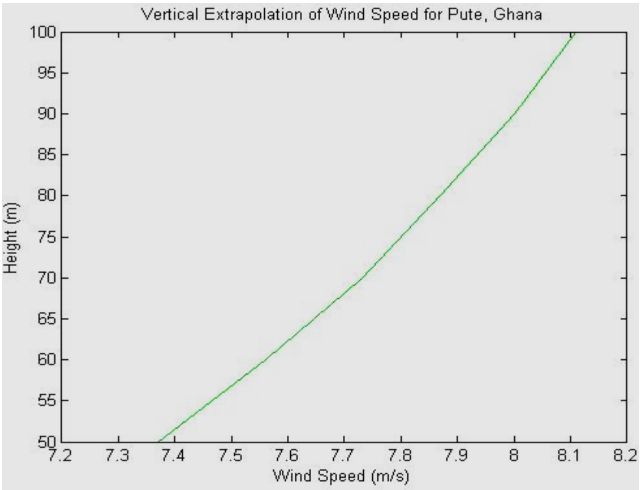

Fig 18(c) Vertical Extrapolation of wind Speed (m/s) for Pute

In this figure the monthly average wind speed at 50 m was 7.37 m/s, at 100 m the speed is 8.1 m/s.

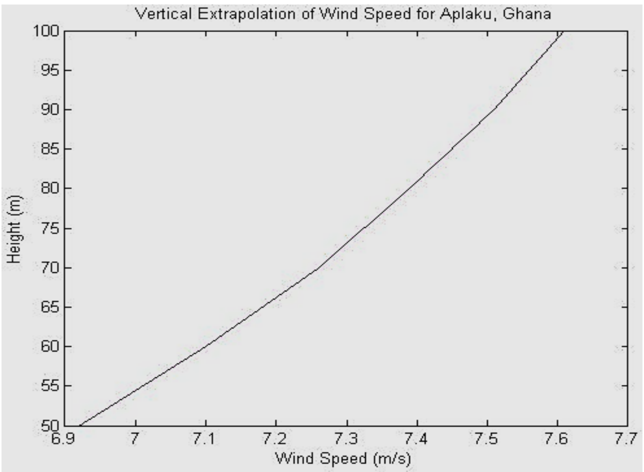

Fig 18(d) Vertical Extrapolation of wind Speed (m/s) for Aplaku

In this figure the monthly average wind speed at 50 m was 6.92 m/s, at 100 m the speed is 7.61 m/s.

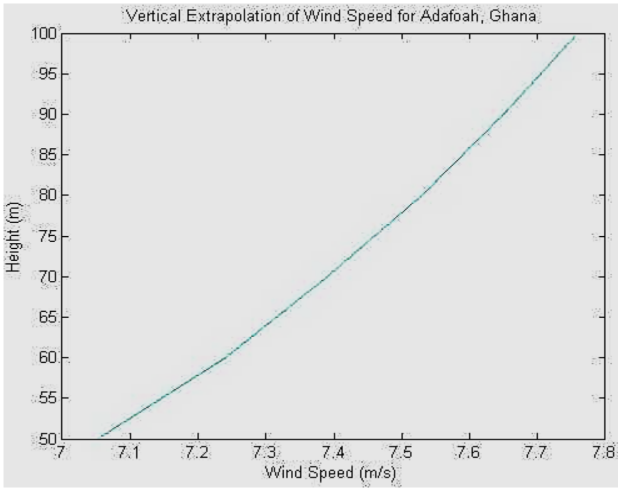

Fig 18(e) Vertical Extrapolation of wind Speed (m/s) for Adafoah

In this figure the monthly average wind speed at 50 m was 7.05 m/s, at 100 m the speed is 7.75 m/s.

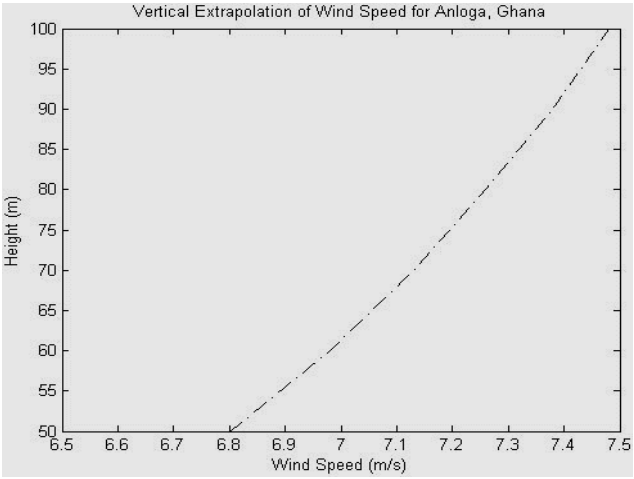

Fig 18(f) Vertical Extrapolation of wind Speed (m/s) for Anloga

In this figure the monthly average wind speed at 50 m was 6.8 m/s, at 100 m the speed is 7.48 m/s.

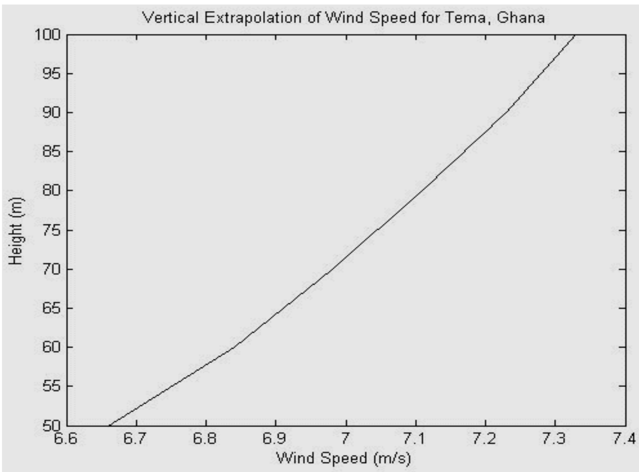

Fig 18(g) Vertical Extrapolation of wind Speed (m/s) for Tema

In this figure the monthly average wind speed at 50m was 6.66 m/s, at 100 m the speed is 7.32 m/s.

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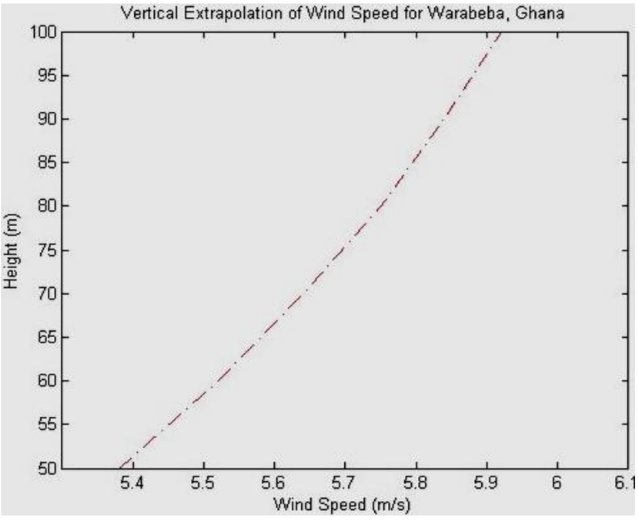

Fig 18(h) Vertical Extrapolation of wind Speed (m/s) for Warabeba

In this figure the monthly average wind speed at 50 m was 5.38 m/s, at 100 m the speed is 5.91 m/s.

The researchers further modelled mathematically the following parameters for the eight sites using the design specifications in table 6 and turbine specifications in figure 19.

Table 6 Design Specifications

DESIGN SPECIFICATIONS	
Air Density	**1.23 kg/m³ (Constant)**
Power Coefficient, Cp	**43%= 0.43**
Number of Blades, n	**3**
Unit of Turbine: Onshore	**1**
Kpone	**7.9 m/s**
Lolonya	**7.85 m/s**
Pute	**8.1 m/s**
Aplaku	**7.61 m/s**
Adafoah	**7.75 m/s**
Anloga	**7.48 m/s**
Tema	**7.32 m/s**
Warabeba	**5.91 m/s**

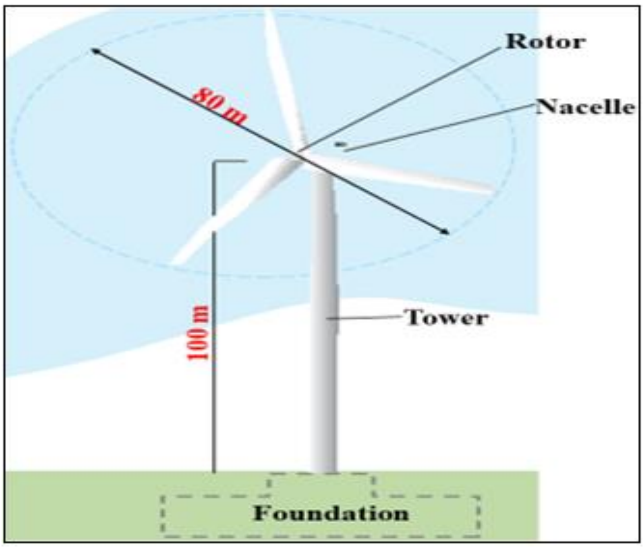

Fig 19 Turbine Specifications

- Wind Power at the Input of the Turbine (P_w), W
- Wind Power at the Output of the Turbine P_o , also known as available Power of the Turbine, W
- Wind Power Density (P_ρ), W/m^2
- Optimum Tip Speed Ratio (ג)

The values of these parameters were obtained employing equations 3, 8 and 10

Kpone

- $P_W = \frac{1}{2}\rho A v^3$
  - $A = \frac{\pi D^2}{4}$

$$A = \frac{3.142 * 80^2}{4} = \mathbf{5026.55\ m^2}$$

$$P_W = \frac{1}{2} * 1.23 * 5026.55 * 7.9^3$$

$$P_W = \mathbf{1524144.86\ W = 1.52\ MW}$$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$$P_o = 1.52 * 0.43 = \mathbf{0.\ 654\ MW}$$

- $P_\rho = \frac{P_o}{A}$

$$P_\rho = \frac{655382.29}{5026.55} = \mathbf{130.38\ W/m^2}$$

- $\lambda = \frac{4\pi}{n}$

$$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$$

Lolonya

- $P_W = \frac{1}{2}\rho A v^3$
  - $A = \frac{\pi D^2}{4}$

$$A = \frac{3.142 * 80^2}{4} = \mathbf{5026.55\ m^2}$$

$$P_W = \frac{1}{2} * 1.23 * 5026.55 * 7.85^3$$

$$P_W = \mathbf{1495388.69\ W = 1.495\ MW}$$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$$P_o = 1.495 * 0.43 = \mathbf{0.\ 643\ MW}$$

- $P_\rho = \frac{P_o}{A}$

$$P_\rho = \frac{643017.14}{5026.55} = \mathbf{127.92\ W/m^2}$$

- $\lambda = \frac{4\pi}{n}$

$$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$$

Pute

- $P_w = \frac{1}{2}\rho A v^3$
  - $A = \frac{\pi D^2}{4}$

$A = \frac{3.142 * 80^2}{4} = \mathbf{5026.55\ m^2}$

$P_w = \frac{1}{2} * 1.23 * 5026.55 * 8.1^3$

$P_w = \mathbf{1642858.58\ W = 1.643\ MW}$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$P_o = 1.643 * 0.43 = \mathbf{0.706\ MW}$

- $P_\rho = \frac{P_o}{A}$

$P_\rho = \frac{706429.19}{5026.55} = \mathbf{140.54\ W/m^2}$

- $\lambda = \frac{4\pi}{n}$

$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$

Aplaku

$P_w = \frac{1}{2}\rho A v^3$

- $A = \frac{\pi D^2}{4}$

$A = \frac{3.142*80^2}{4} = \mathbf{5026.55\ m^2}$

$P_w = \frac{1}{2} * 1.23 * 5026.55 * 7.61^3$

$P_w = \mathbf{1362382.62\ W = 1.362\ MW}$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$P_o = 1.362 * 0.43 = \mathbf{0.585\ MW}$

- $P_\rho = \frac{P_o}{A}$

$P_\rho = \frac{585824.52}{5026.55} = \mathbf{116.55\ W/m^2}$

- $\lambda = \frac{4\pi}{n}$

$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$

Adafoah

$P_w = \frac{1}{2}\rho A v^3$

- $A = \frac{\pi D^2}{4}$

$A = \frac{3.142 * 80^2}{4} = \mathbf{5026.55\ m^2}$

$P_w = \frac{1}{2} * 1.23 * 5026.55 * 7.75^3$

$P_w = \mathbf{1438965\ W = 1.439\ MW}$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$P_o = 1.439 * 0.43 = \mathbf{0.619\ MW}$

- $P_\rho = \frac{P_o}{A}$

$P_\rho = \frac{618754.95}{5026.55} = \mathbf{123.1\ W/m^2}$

- $\lambda = \frac{4\pi}{n}$

$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$

Anloga

$P_w = \frac{1}{2}\rho A v^3$

- $A = \frac{\pi D^2}{4}$

$A = \frac{3.142*80^2}{4} = \mathbf{5026.55\ m^2}$

$P_w = \frac{1}{2} * 1.23 * 5026.55 * 7.48^3$

$P_w = \mathbf{1293748.69\ W = 1.294\ MW}$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$P_o = 1.294 * 0.43 = \mathbf{0.556\ MW}$

- $P_\rho = \frac{P_o}{A}$

$P_\rho = \frac{556311.93}{5026.55} = \mathbf{110.68\ W/m^2}$

- $\lambda = \frac{4\pi}{n}$

$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$

Tema

$P_w = \frac{1}{2}\rho A v^3$

- $A = \frac{\pi D^2}{4}$

$A = \frac{3.142 * 80^2}{4} = \mathbf{5026.55\ m^2}$

$P_w = \frac{1}{2} * 1.23 * 5026.55 * 7.32^3$

$P_w = \mathbf{1212490.56 = 1.213\ MW}$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$P_o = 1.213 * 0.43 = \mathbf{0.522\ MW}$

- $P_\rho = \frac{P_o}{A}$

$P_\rho = \frac{521370.94}{5026.55} = \mathbf{103.72\ W/m^2}$

- $\lambda = \frac{4\pi}{n}$

$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$

Warabeba

$P_w = \frac{1}{2}\rho A v^3$

- $A = \frac{\pi D^2}{4}$

$A = \frac{3.142*80^2}{4} = \mathbf{5026.55\ m^2}$

$P_w = \frac{1}{2} * 1.23 * 5026.55 * 5.91^3$

$P_w = \mathbf{638127.65 = 0.638\ MW}$

- $P_o = \frac{1}{2}\rho A v^3 C_p$

$P_o = 0.638 * 0.43 = \mathbf{0.274\ MW}$

- $P_\rho = \frac{P_o}{A}$

$P_\rho = \frac{274394.89}{5026.55} = \mathbf{54.59\ W/m^2}$

- $\lambda = \frac{4\pi}{n}$

$\lambda = \frac{4*3.142}{3} = \mathbf{4.2}$

From the calculation analysis, it is observed that, all the selected sites for the research have the same Swept Area of Blade (A) of $\mathbf{5026.55\ m^2}$ and same Optimum Tip Speed

Ratio (λ) of **4.2** for the wind turbine. This is so, because the same design specifications were used in the eight locations. The total value of the input power, P_w obtained from the eight units of the wind turbine from the eight sites selected for the experiment was **10.604 MW.** The total Wind Power Density, (P_ρ), was $\mathbf{907.48\,W/m^2}$**;** this density is the quantitative measure of wind energy available at the locations. The total result of the available power, P_o obtained from the sites was **4.559 MW.** This available power also known as output power is the energy that can be used to operate a device. This available power converted into megawatt-hour will be **109.416 MWh = 109416 kWh.** Assuming this renewable electrical power so generated emanated from non-renewable energy source such as crude oil; there would have been carbon dioxide (CO_2) emission. This emission could be estimated using Emission Factor of 7.0555 x10^{-4} Metric Tons CO_2 per kWh; hence:

$$\mathbf{CO_2 = \frac{7.0555\,x10^{-4} Metric\ Tons * 109416\ kWh}{1kWh} = 77.2\ Metric\ Tons}$$

Therefore the carbon dioxide that would have been released by Ghana into the atmosphere will be reduced by $\mathbf{77.2\ Metric\ Tons.}$

VII. CONCLUSION

The wind is a by-product of the sun, therefore when the sun shines, the wind blows. The various methods that the wind energy can be harnessed to generate electricity have many moving components. Due to over 8000 components that are in the wind thermal plant, its maintenance cost is very high. The lifespan of wind turbine plant is more than twenty years, this compensate for the high initial capital. Even though the advantages of using wind to generate electricity are enormous, the few disadvantages such as the threat wind turbine blades pose to wildlife are always a challenge that need to be overcome. A good number of countries in the developed world continue to use wind energy to generate electricity. China is a leader in this sector, according to IEA (International Energy Agency), it was responsible for approximately 70% of the world's total wind energy generation in 2021. China's advancement in wind turbine technology cannot be over emphasized; it has been able to manufacture the biggest offshore wind turbine in the world. This turbine has a unit nameplate capacity of 16 MW, diameter of 242 meters, blade length of 118 meters and swept area of 46,000 m^2. Africa is a continent that has significant wind potential but accounts for less than 1% of total wind energy installed capacity in the world. As at 2022, more than half of the population in Africa has no access to electricity; wind energy could be a source to solve this problem. Some of the factors militating against electrification in the continent include lack of governmental financial resources, creditworthiness of some countries to persuade the private sector to invest, conflicts and security concerns in some wind rich areas. This notwithstanding, Lekela Power (Great Britain/ Netherlands); a joint venture, comprising of Mainstream Renewable Power and Actis, private sector investors are developing 225 MW Ayitepa wind farm in Greater Accra, Ghana. This project is estimated to cost 525 million US dollars.

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