A Prototype VA/HA Wind Turbine Design for Electric Power Generation by Moving Vehicles*

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Abstract

Renewable sources of electricity production are being explored in recent years owing to the gradual depletion and increasing cost of fossil fuel. Harnessing wind energy via the use of wind turbines is one of the fastest growing means of producing electricity from renewable energy sources. Though wind turbines are normally placed at coastal areas for maximum power production, other locations along railways and roadways are usually overlooked. This research considers the design and building of prototype Vertical Axis Wind Turbine (VAWT) and Horizontal Axis Wind Turbine (HAWT) to be placed along selected roadways in Ghana to harness the wind energy from moving vehicles to produce electricity. Test results indicated that average voltage levels of 1.59 V and 5.22 V could be obtained from average wind speeds of 4.19 m/s and 5.42 m/s considering prototype wind turbines designed and placed along the Tarkwa-Kumasi highway and the Winneba-Accra highway respectively. Considerable amounts of voltages produced by the prototype wind turbines calls for the creation of pilot projects on some selected busy highways to progressively improve and obtain well-developed highway wind turbines to reduce the load on the national grid; as harnessed wind energy could be used to power street lights and road traffic indicators for substantive periods of time. Pilot projects may determine appropriate heights of wind turbines for different highways and a means of safely combining power produced from such wind turbines. With great improvements in the prototype designs of the VAWT and HAWT, targeted power outputs of 58.11 W and 106.61 W could be respectively derived from the selected highways.

Keywords: Power Generation, Moving Vehicles, Wind Turbine, Vertical Axis, Horizontal Axis

1 Introduction

Wind energy involves the use of wind to provide mechanical power through wind turbines to turn electrical generators. In past years, windmills have been used to perform certain tasks such as milling of grains and pumping of water from wells. Renewable wind power is sustainable as it is usually present during the day and its impact on the environment is minimal. Commercial quantities of wind energy are obtained using wind farms which consist of a collection of individual wind turbines with their outputs combined and synchronised to the electric power grid. In Ghana, Adaramola *et al*. (2014) performed theoretical assessment of wind power generation at selected locations along the coast and observed that wind speeds between 9 m/s and 11 m/s is more suitable for wind energy development along the coastal region of Ghana. Asumadu-Sarkodie and Owusu (2016) assessed the economic viability on the potentials of wind farms in Ghana and proposed a 10 MW wind turbine model with a rated power of 2 000 kW as a good boost to Ghana's grid power.
Research conducted by Santhakumar *et al*. (2018) noticed that the direction of the wind and the road played a vital role when considering the rotation of the vertical axis Savonius rotor blades of the wind turbine located at the median of the highways. After testing the performance of the prototype, it was discovered that the power produced from a single lane vehicular traffic was 30% while a double lane vehicular traffic with accelerated wind speeds contributed a total power of 66% of the power requirements of their test load. Using a three-bladed helical Darrieus VAWT model placed along King Fahad Bin Abdul Aziz highway in Kuwait, Hussein *et al*. (2018) developed power of 48 W as compared with available power of 141 W measured at optimum speeds and turbine height of 1.5 m. For low speeds below 5 m/s, Hussein *et al*. (2018) noted that the overall efficiency of the VAWT was 34.6%. In another research, Nalathambi (2014) employed ANSYS in simulating three different cars and concluded that the speed of cars and their sizes contributed to an increase in wind dispersed around the wind turbine which further caused an increase in generated power. On the other hand, Chaitanya and Gowtham (2015), Joshi *et al*. (2012) and Gupta *et al.* (2016) worked on generating electricity from moving trains where Chaitanya and Gowtham (2015) and Joshi *et al*. (2012) installed the wind turbines between sleepers on the rail tracks. Gupta *et al.* (2016) improved upon existing system by installing the wind turbine on the trains themselves, where gear box arrangement was used to increase and stabilise the speed of varying speed generators. Research conducted by these above-mentioned authors considered harnessing wind power for electricity production using the VAWT.

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1.1 Wind Power Economics

Electricity production by means of wind energy is developing rapidly on the world scene. Research indicates that the global installed capacity of wind power has increased from around 2.5 GW in 1992 to more than 94 GW at the end of 2007 (Anon., 2020a). Anon (2020a) expressed that the total investment cost for foundations, electrical installations and consultancy of an average wind turbine installed in Europe is around € 1.23 million/MW considering 2006 average prices. In addition, transmission costs of electricity generated from wind energy remains a challenge since the best locations for wind energy production is in remote areas which are far from consuming centres. It therefore stands to reason that if the prices in fossil fuels reduce, wind energy may lose its economic viability. Research has showed that fossil fuel is depleting. For instance, Shafiee and Topal (2009) presented a new formula for calculating depletion times of fossil fuel reserves where they indicated that oil, coal and gas will deplete in approximately 35, 107 and 37 years respectively. Also, Höök and Tang (2013) noted that fossil fuel depletion and anthropogenic climate change are tightly connected and need to be treated holistically. Wind energy therefore remains viable as fossil fuel gets depleted and expensive.

1.2 Wind Energy Categories

Analysis of wind currents at various locations has helped to organise wind energy production into onshore and offshore categories. While onshore wind farms shown in Fig. 1 (Anon., 2010a) spread over large areas of land especially in remote rural sectors contributing to loss of habitat, offshore wind farms as shown in Fig. 2 (Anon., 2010b) spread over large areas into the sea with extremely high cost of establishment and maintenance. According to Anon. (2020b), offshore capacity is expected to reach a total of 75 GW worldwide by 2020. Without large capital, wind energy can still be exploited in small quantities usually for stand-alone power applications. This may include generating power from moving trains, moving vehicles and from the coastal sections.

Fig. 1 Onshore Wind Farm

Fig. 2 Offshore Wind Farm

1.3 Wind Turbine

A wind turbine (wind energy converter) is a device that converts the kinetic energy of air-in-motion into electrical energy. Wind turbines consist of a wide range of Vertical Axis (VA) and Horizontal Axis (HA) designs. The parts of a typical wind turbine are shown in Fig. 3 (Anon., 2010c). Installation and operation of onshore wind turbines are relatively cheaper and easily integrates with the grid network as compared to the offshore wind turbine.

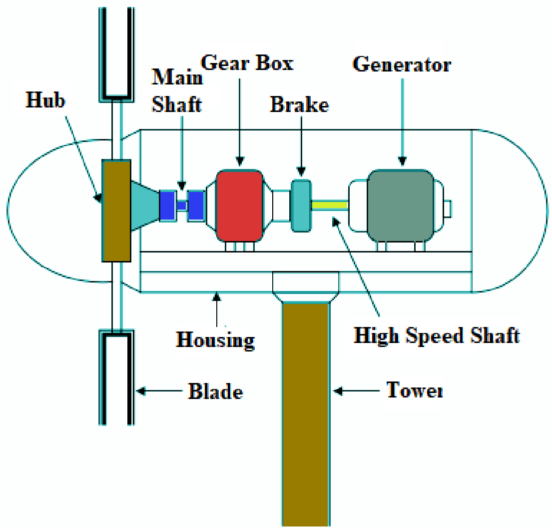


Fig. 3 Parts of a Typical Wind Turbine

The following equations, as obtained from Sarkar and Behera (2012), help to convert the wind's kinetic energy into electric power.

Wind energy flowing through an area A within time period t is given by Equation 1.

$$E = \frac{1}{2}mv^2 \tag{1}$$

where m is the mass of air measured in kg and v is the velocity of air measured in m/s. Mass of air hitting a wind turbine blade per second is given by Equation 2.

$$m = Av\rho \quad (2)$$

where A is the swept area of the wind turbine and ρ is the density of air. Substituting Equation 2 into Equation 1 gives the wind power P incident on the area A given by Equation 3.

$$P = \frac{E}{t} = \frac{1}{2} A\rho v^3 \quad (3)$$

A modified equation for calculating wind power (P) is given by Sarkar and Behera (2012) as shown in Equation 4.

$$P = \frac{E}{t} = \frac{1}{2} A\rho v^3 C_p N_g N_b \quad (4)$$

where, C_p is the coefficient of performance, N_g the generator efficiency and N_b the gear box bearing efficiency.

2 Resources and Methods Used

In this research, a horizontal axis and vertical axis wind turbines were constructed to harness power from moving cars. The research involved the assessment of wind speeds and subsequent building of local wind turbines to help analyse voltage levels produced from moving vehicles along the Tarkwa-Kumasi and the Winneba-Accra highways of Ghana. The Winneba-Accra highway test point, located on the GPS coordinates 5.395837, -0.629450 (represented by GhanaPostGPS digital address CE-235-8513), is closer to the manufacturing centre (Kantanka Automobile Factory) where initial tests were conducted. The Tarkwa-Kumasi highway, located on the GPS coordinates 5.340692, -1.982437 (represented by GhanaPostGPS digital address WT-0239-6387), was selected because of its proximity to the University of Mines and Technology, where the research was conducted. Prior to the obvious selection of the highways, air profile analysis of airflow around moving cars for specific locations on the selected highways was performed using a vane anemometer to ensure the viability of the preferred locations.

2.1 Vehicular Traffic Assessment

Assessment was made to determine the number of vehicles passing by some specified test points along the selected highways. The assessment was conducted on different days. A period of three days was dedicated for the assessment. For each day, an hour was dedicated to determining the number of vehicles passing by the test point where the supposed design could be mounted. Results obtained from the vehicular traffic assessment are shown in Table 1.

Table 1 Vehicular Passage at Test Point / Hour

Days	Tarkwa-Kumasi Highway (v/h)	Winneba-Accra Highway (v/h)
1	52	76
2	55	91
3	61	64
Average	**56**	**77**

Table 1 indicates that an average of 77 vehicles/hour (v/h) passed by the test point located on the Winneba-Accra highway as compared to the test point on the Tarkwa-Kumasi highway that recorded an average of 56 v/h.

2.2 Air Profile Determination on Highways

The next stage involved the use of vane anemometer to determine the air profile at different heights of the selected locations on the highways. Table 2 gives the air profile measurements at the test point along the Tarkwa-Kumasi Highway while Table 3 indicates the air profile measurements for the test point on the Winneba-Accra Highway. From Table 2 and Table 3, wind speeds measured at a height of 1.5 m yielded the maximum averages as compared to averages of wind speeds measured at heights of 1.0 m and 2.0 m. Data obtained in Table 2 and Table 3 were plotted to highlight the variations in the wind speeds. The readings of windspeeds and voltage levels were taken on the shoulders of the road at a distance of 1.0 m from the carriage way.

Table 2 Air Profile Measurements at Test Point on Tarkwa- Kumasi Highway

Wind Speed Measured at Various Heights from Ground (m/s)		
1 m	**1.5 m**	**2 m**
2.9	6.5	3.9
3.2	4.9	6.4
4.1	3.9	4.1
3.0	4.1	3.1
4.4	3.8	4.0
3.5	4.0	2.6
3.9	4.4	2.0
3.5	5.8	4.2
2.8	6.4	2.5
1.9	4.8	2.4
Average = 3.32 m/s	**Average = 4.86 m/s**	**Average = 3.52 m/s**

Table 3 Air Profile Measurements at Test Point on Winneba- Accra Highway

Wind Speed Measured at Various Heights from Ground (m/s)		
1 m	**1.5 m**	**2 m**
2.5	7.1	3.5
3.4	6.5	4.1
3.8	4.2	4.3
4.0	4.1	2.9
3.4	4.9	3.9
2.9	3.7	2.9
3.7	5.2	3.0
3.5	5.8	3.2
3.0	6.1	4.9
2.3	6.6	2.7
Average = 3.25 m/s	**Average = 5.42 m/s**	**Average = 3.54 m/s**

The wind speed variations plotted in Fig. 4 and Fig. 5 show spikes especially in the 2.0 m readings. Further analysis regarding type of vehicle and anemometer height indicated that buses and trucks produced significant wind speeds at higher heights while smaller vehicles gave significant wind speeds at a lower height of 1.5 m.

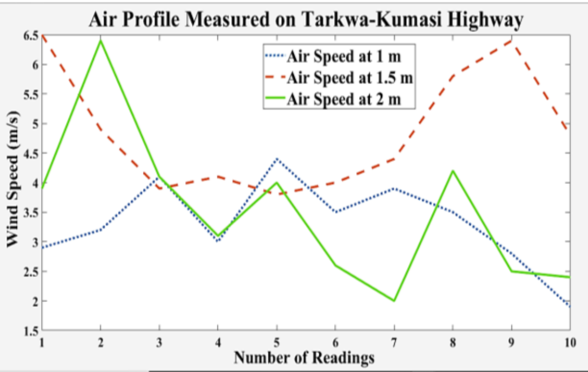


Fig. 4 Tarkwa-Kumasi Air Profile Variations

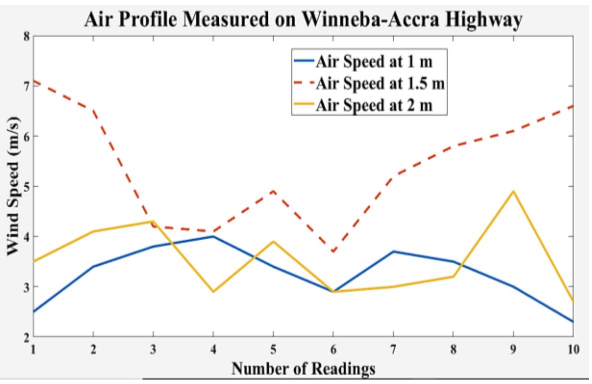
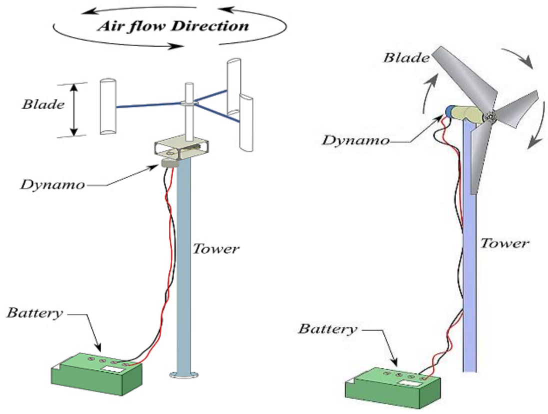


Fig. 5 Winneba-Accra Air Profile Variations

Wind speeds recorded at 1.0 m anemometer height were low. Hence spikes noted in the 2.0 m readings could be as a result of large vehicles that passed by the test sites at the time of the recording. Varying speeds of vehicles could also contribute to the spikes.

2.3 Experimental Design Considerations

The main components designed and assembled for the prototype wind turbines were the turbine blades, the tower, dynamo and the battery. Charge controller was not used since the research interest was only to determine the voltage levels that could be obtained from the design. With the charge controller installed, the level of sustainability of power produced could be determined. Fig. 6 shows the computerized designs of the prototype VAWT and HAWT. The VAWT was the first to be designed.



a. VAWT **b. HAWT**

Fig. 6 Computer Designs of Prototype Turbines

The design and final building of the VAWT consisted of a galvanised pipe of height 1.5 m (≈ 59.10 inches) and four plastic turbine blades of dimensions 0.13 m (≈ 5 inches) by 0.30 m (≈ 12 inches) each and supported by 90°-spaced aluminium rods fixed to a vertical spindle. The completed built-up prototypes are shown in Fig. 7 and Fig. 8. The height of the built-up HAWT was also 1.5 m with the same specifications of dynamo as the VAWT design. The only difference in the two designs is the orientation of the blades and axis containing the dynamo. A total cost of USD 37.79 (GH¢ 215.06) with the breakdown shown in Table 4 was spent on each construction. Prices in Table 4 were obtained from local electrical and welding shops in Accra and Tarkwa. The cost of each blade includes the price of plastic material and cost of shaping to specified dimensions. The cost of tower likewise includes price of galvanized pipe and cost of welding to specified dimensions. All cost calculations were based on exchange rate given by Anon. (2019).

Table 4 Cost Breakdown (Building Cost)

Item	Quantity	Cost (USD)
12 V 3000 rpm DRC-775 Model Dynamo	1	7.03
Lead Acid Battery	1	26.36
Blade (plastic and shaping)	4	1.76
Tower (pipe and welding)	1	2.64
Total Cost (USD)		**37.79**

2.4 Installations and Voltage Measurements

Installation of the prototype wind turbines required the mounting of the device along the roadside. Various possible mounting architectures were reasoned as shown in Fig. 9, Fig. 10 and Fig. 11.

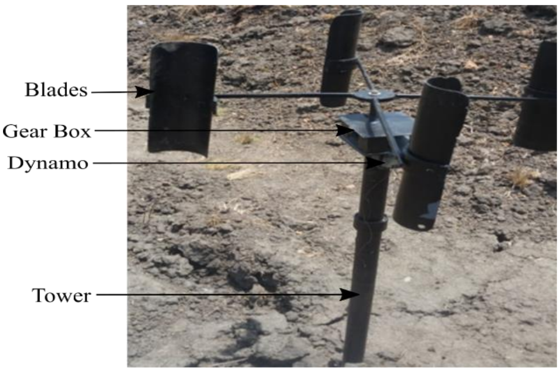


Fig. 7 First Prototype Constructed: VAWT

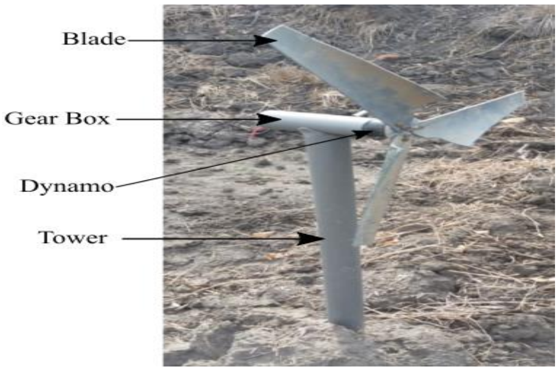


Fig. 8 Second Prototype Constructed: HAWT

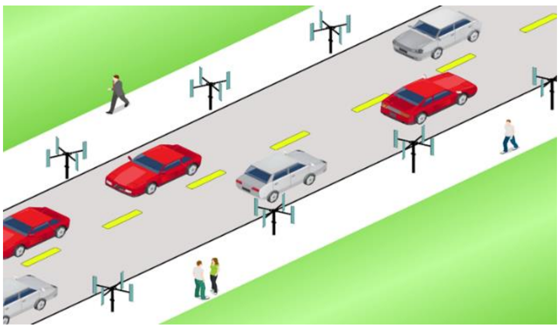


Fig. 9 VAWT Mounted at Outer Sides of Road

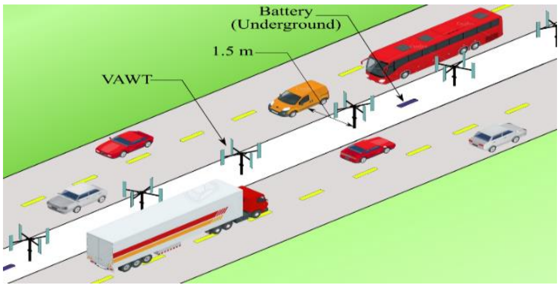


Fig. 10 VAWT Mounted on Middle Rib of Road

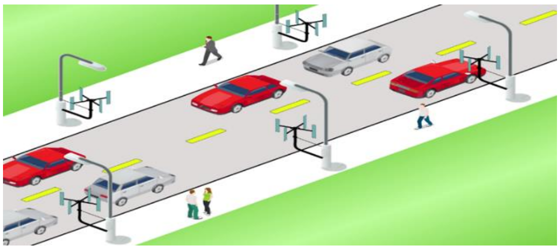


Fig. 11 VAWT Mounted on Street Lights

Considering the test points on the Winneba-Accra highway and the Tarkwa-Kumasi highway, the possible mounting method adopted for the prototype turbines was that shown in Fig. 9.

3 Results and Discussion

The results obtained are discussed and then compared with results calculated from the same set of wind speed readings simulated using MATLAB/Simulink.

3.1 Experimental Results

The results obtained from the voltage measurement using the prototype wind turbines are shown in Table 5 and Table 6. Voltages obtained from the experiments were converted to power using the equation $P=V^2/R$ where maximum power is assumed for a resistance of 1 Ω.

Table 5 Recorded Wind Speeds and Voltages at Test Point on Tarkwa-Kumasi Highway

Wind Speed (m/s)	Voltage (V)	Maximum Power (W)
3.60	1.47	2.16
4.80	1.80	3.24
3.90	1.50	2.25
3.00	1.24	1.54
6.20	2.06	4.24
5.80	2.01	4.04
1.60	0.90	0.81
5.20	1.89	3.57
3.30	1.32	1.74
4.50	1.72	2.95
Average = 4.19	**Average = 1.59**	**Average = 2.65**

Table 6 Recorded Wind Speeds and Voltages at Test Point on Winneba-Accra Highway

Wind Speed (m/s)	Voltage (V)	Maximum Power (W)
4.8	4.51	20.34
5.4	4.72	22.28
6.9	7.34	53.88
6.5	7.09	50.27
4.4	4.30	18.49
3.9	2.95	8.70
5.0	4.59	21.07
5.5	4.80	23.04
5.1	4.65	21.62
6.7	7.20	51.84
Average = 5.42	**Average = 5.22**	**Average = 29.15**

3.2 Calculated Results Using MATLAB

Equation 3 could be obtained from Equation 4 with an assumption of ideal case scenario where coefficient of performance, generator efficiency and the gear box bearing efficiency are unity. Considering Equation 3 and assuming a wind incident area of 1.0 m^2, the MATLAB circuit of Fig. 12 can be simulated. The density of wind used, according to International Standard Atmosphere (ISA), was 1.225 kg/m^3 (Will, 2019).

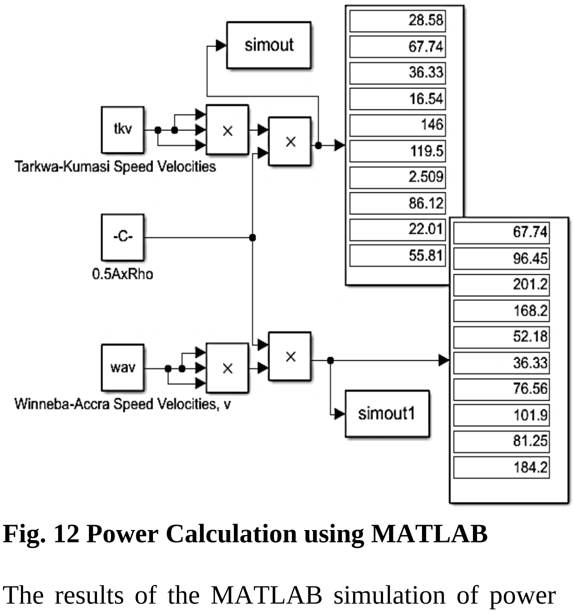


Fig. 12 Power Calculation using MATLAB

The results of the MATLAB simulation of power outputs, using wind speeds obtained from the selected highways and applying Equation 3 with the assumptions mentioned, are shown in Table 7.

Table 7 Calculated Power Using Recorded Wind Speeds from Test Points on Selected Highways

Tarkwa-Kumasi Highway		Winneba-Accra Highway	
Wind Speed (m/s)	Calculated Power (W)	Wind Speed (m/s)	Calculated Power (W)
3.60	28.58	4.80	67.74
4.80	67.74	5.40	96.45
3.90	36.33	6.90	201.21
3.00	16.54	6.50	168.21
6.20	145.98	4.40	52.18
5.80	119.51	3.90	36.33
1.60	2.51	5.00	76.56
5.20	86.12	5.50	101.90
3.30	22.01	5.10	81.25
4.50	55.81	6.70	184.22
Average = 4.19	**Average = 58.11**	**Average = 5.42**	**Average = 106.61**

3.3 Discussion

Table 5 and Table 6 provide some promising results regarding voltages obtained from moving cars. The results indicate that, substantive amount of power can be obtained from moving cars. The huge variations noticed in the measured power and the calculated power is as a result of basic factors which include:

(i) choice of coupling unit for free turning of the turbine blades;
(ii) gearbox bearing efficiency;
(iii) efficiency of the dynamo;
(iv) correct positioning and firm mounting of the turbines along the carriage way; and
(v) choice of materials used in the design to enhance maximum capture of wind and free turning of blades.

Optimum values of these factors may greatly improve the power derived from the local turbines. Even with these factors not fully considered, substantive amounts of electricity were obtained using the locally designed wind turbines. From Table 7, considering calculated power outputs from ideal-case scenarios, it is evident that an improvement in the design of the prototype wind turbines can produce maximum power outputs. Addition of sensitivity analysis on the critical variables such as the wind speed can contribute to the robustness of the system.

4 Conclusions and Recommendations

The research has shown that, in addition to coastal areas, highways have promising potentials of producing practical voltages that may contribute positively to a country's grid power. With average wind speeds of 4.19 m/s and 5.42 m/s, respective average voltage levels of 1.59 V and 5.22 V were obtained. Calculated power outputs of 58.11 W and 106.61 W can be respectively derived from a locally designed wind turbine located at a distance of one meter from the carriage roads of specified test points on Tarkwa-Kumasi highway (5.340692, -1.982437) and the Winneba-Accra highway (5.395837, -0.629450) if certain factors such as generator and gearbox efficiencies are considered. The implemented designs may contribute to electrical energy productivity of highways with resultant reduction of loading on the national grid.

It is therefore recommended that, for improved voltage production, the prototype designs could be mounted in the middle rib section of double lane highways as confirmed by Santhakumar *et al*. (2018), with a modification to restrict movement of the turbine blades in one direction. Pilot projects could be established on some selected busy highways to progressively improve and obtain well-developed highway wind turbines. Total overhaul of the designs could also be made with much emphasis on increasing generator and gear box bearing efficiencies. Future mounting of improved wind turbines could be considered on the streetlights so that power outputs, fed through rectifier-battery-inverter, could be fed directly to the streetlights for sustained power delivery.

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