



Development of a Savonius Vertical Axis Wind Turbine Operated Water Pump

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PAPER INFO	ABSTRACT
<p>Chronicle: Received: 11 January 2020 Revised: 06 March 2020 Accepted: 04 June 2020</p>	<p>Wind energy is abundant, inexhaustible, affordable, environmentally preferable, and equally sustainable. More researches are emerging in the analysis of wind energy in Nigeria and each have proven that great potential exist for wind power generation in Nigeria but sufficient results is yet to be achieved in terms of application. The present research is intended to apply the technology of wind energy for pumping of water in rural Nigeria. To achieve this, a Savonius vertical axis wind turbine is developed. To ensure, an optimum functioning system was developed and design consideration and conceptual design were drawn. The best conceptual design was selected for development using decision matrix. The system was evaluated for performance and UT363 Anemometer was used to measure the wind speed. Results obtained indicate a swept area of 3.41 m², power of wind of 31.46 watts, blade tip speed and rotational speed wind of 7.38 rpm and 5.05 rpm were required for effective wind turbine operation. Besides, an average wind speed of 3.49 m/sec was required to pump an average 47.77 litres of water at an average time of 3.08 minutes.</p>
<p>Keywords: Wind Energy. Water Pump. Weed Speed. Develop. Savonius Vertical Axis Wind Turbine.</p>	

1. Introduction

The looming exhaustion of non-renewable energy sources, incessant global warming, escalating greenhouse effect, unavailability of power supplies, and the quest to reduce the environmental impacts resulting from it and more importantly to meet the growing sustainable energy demand for the global population had been a huge motivation factor for research attention in a wide range of environmental and engineering application of renewable form of energy. In order to achieve the requirement of Sustainable Development Goals (SDGs) in Nigeria, which encourages the United Nation (UN) member states to focus on access to ecofriendly, sustainable and readily available renewable energy sources [1]. It becomes necessary to assess the potential in the renewable energy sources available at our disposal such as wind energy. Wind as a source of renewable energy is gaining prominence around the world since it can be harness in small or commercial to meet the present-day energy demand especially in sub-Sahara Africa countries that are face with energy crisis [2-5]. Wind Energy Technology (WET) serves as a suitable supplement and alternative to the rising cost of power generation from fossil fuel source and as well contributes towards global legislation against Greenhouse Gas (GHG) emission [6-8].

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DOI: 10.22105/jarie.2020.243507.1186

Wind energy in all ramifications and by nature is clean and abundant, inexhaustible, affordable, and environmentally friendly [9]. In developed countries, such as Germany, United State of America, China, etc., wind energy is extensively used for the production of electricity [10]. But this is not the case in sub-Sahara Africa countries like Nigeria where it is under-utilized [11]. According to a recent study by African Development Bank (AFDB), North African countries like Morocco, Egypt and Tunisia remain the leaders in wind energy market in Africa, while South and Eastern African countries are projected to reduce the gap soon. However, Central Africa and West African countries are still lacking in terms of wind power implementation. Nevertheless, the notion to seek for a sustainable alternative to the intermittent energy situation of Nigeria has prompted the government as well as independent researchers to evaluate the nation's potentials for power generation using wind energy [12-17]. Ojosu and Salawu [18] studied the wind energy potential in Umudike, South-East, Nigeria and assessed its economic viability at a pivot height of 65 m above the ground with annual average wind speed of 5.36 m/s using 10 years (1994–2003) wind speed data. A statistical assessment of wind energy potential in South West Nigeria; a case study of Ibadan was carried out by Fadare [19], and the analysis was based on Weibull distribution model using 10 years (1995-2004) daily wind speed data. Igboekwe and Omekara [20] on the other hand, researched on the stochastic modelling of hourly average wind data collected from Umudike, South-East Nigeria. Ten years of hourly average wind speed data were utilized in their research work mainly to develop a periodic autoregressive integrated moving average model. The model was then applied in simulating the generated wind data and the result showed that the simulated wind behavior was reproducible and matched well with the characteristics of the experimental values. More researches are emerging in the analysis of wind speed for different locations in Nigeria and each of these have proven that great potential exist for wind power generation in Nigeria. However, little has been done in terms of application such as using the technology for water pumping.

Water is a basic necessity for life. Human requires water for consumption and to meets basic domestic activities such as washing, laundry, bathing, cooking, and agricultural activities like irrigation process. Besides, there is no access to water in sub-Sahara Africa countries like Nigeria especially those in rural area. As a result, people have to walk a very long distance before they can get water from the river. Some of the major factors that bring unavailability of water in the rural area include pumping machine, and required power source to pump water. Different pumps have been designed to help in pumping water from the ground. Some of these pumps are powered manually, while others have their power source from hydro-electricity and Alternating Current (AC) generators. Due to the high cost involved in some of the above mentioned power source and the negative effect of their by-products like carbon (IV) oxide which increases global warming, expanding greenhouse. Alternative power source that is renewable and can be used to pump water will be a welcome development, thus this research work.

2. Materials and Methods

2.1. Materials

The following materials were used in this research work: aluminium sheet, Polyvinyl Chloride (PVC) pipe, plastic bucket, mild steel sheet, and mild steel angle bar. *Table 1* shows the list of equipment used, purpose, and items used upon.

Table 1. List of equipment used, usage and items used upon.

S/N	Tools/Equipment	Usage	Items Used Upon
1	Anemometer	Measurement of wind speed	A UT363 Anemometer was used to measure the wind speed of the study area Isihor, Nigeria.
2	Welding machine	Welding	Sheets, rods, and bars.
3	Drilling machine	Drilling	Drill holes in sheet metal.
4	Hammer and chisel	Shaping and chipping	Shaping sheet metal, chipping all weed joints and spatter.
5	Wire brush	Cleaning	All components of the machine.
6	Files/fitting machine	Dressing and cutting	All component of the machine.
7	Spraying machine	Painting	External and internal parts of machine.
8	Hacksaw	Cutting	All component of the machine.

The materials used for this research work were carefully selected based on the following properties.

2.1.1. Mechanical properties

The mechanical properties of the materials include Strength, Elasticity, Plasticity, and Machinability Fatigue.

2.1.2. Physical properties

The physical properties of the materials include Density, Structure, and Feasibility shape and size

2.2. Methods

In this research work, the following methods were adopted.

2.2.1. Determination of wind speed of the study area

A UT363 Anemometer was used to measure the wind speed. Fig. 1 shows UT363 Anemometer used in this research work.



Fig. 1. UT363 anemometer

The research area (i.e., Isihor) used in this study is a community located in Ovia North East Local government Area of Edo State, South-South Nigeria.

2.2.2. Design consideration

The following factors were considered:

- Length of the Blade: The turbine blade is designed to have a greater swept area and catch more wind with each revolution. Thus, Aluminium sheet that is light in weight is used.
- Stand Base: Since the stand base will be subjected to the weight of all the components put together and with the presence of drag force of the wind, mild steel materials that possess strength and toughness was used.
- Also was considered the wind structures of the research area.
- Height of the stand base.

2.2.3. Conceptual design

To ensure an optimum functioning Savonius Vertical Axis Wind Turbine was developed, proper consideration was made to specify and identify some problems which could hinder effective performance. Thus, effort was put to identify these factors and constraints as put together:

- Functionality;
- Reliability;
- Durability;
- Safety;
- Cost.

Based on these factors, two conceptual designs were drawn.

Design Concept One. Design concept one has a main rotor shaft arranged vertically. *Fig. 2* shows isometric view of design concept one. This concept utilizes a four truncated cylindrical vessel as the turbine blades, thus, the turbine does not need to point to the wind direction for effectiveness. This is advantageous on a site where the wind direction is highly variable, for instance, in a case where the turbine is integrated into a building. Besides, the gear mechanism can be placed near the ground, using the drive from the rotor assembly to the ground based gearbox thereby improving accessibility for maintenance.

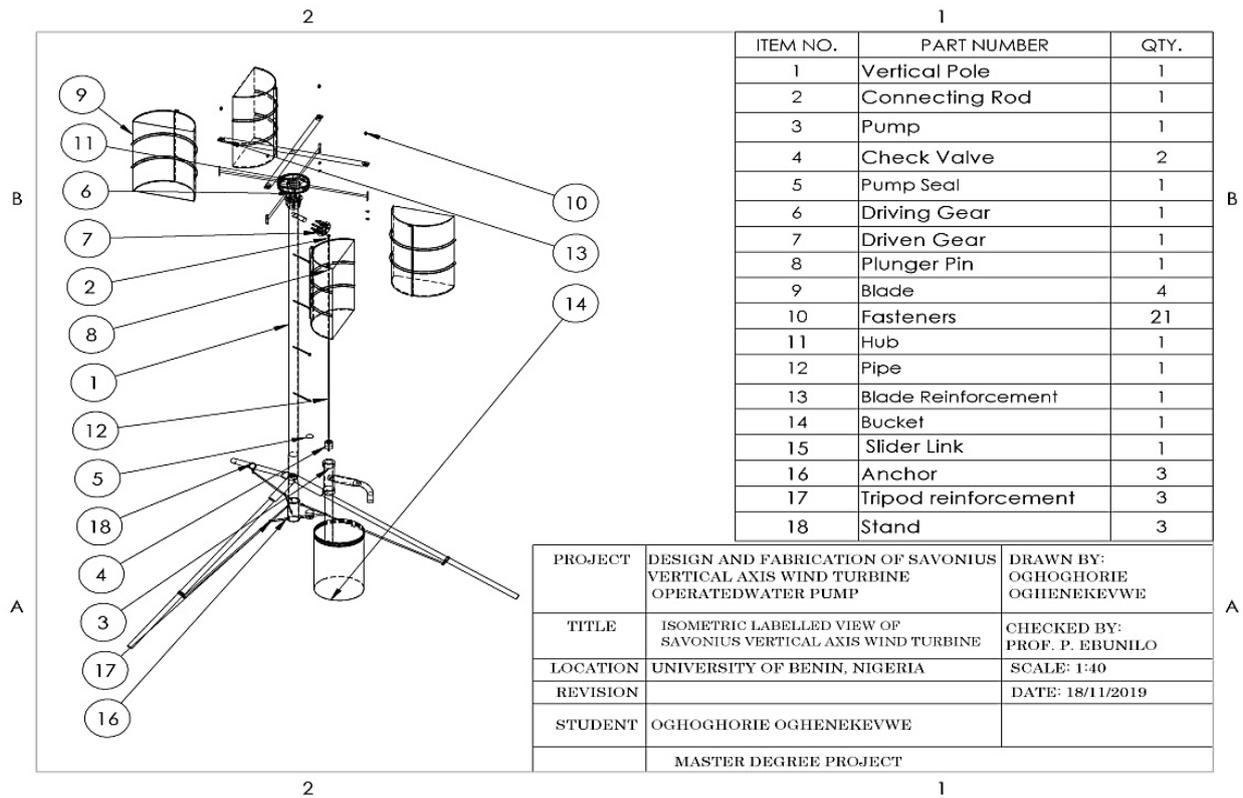


Fig. 2. Isometric view of design concept one.

Design Concept Two. Just like design one, same components are present except for the number of blades. With three blades in use, there will be need for proper orientation with respect to wind direction. Fig. 3 shows the isometric view of design concept two.



Fig. 3. Isometric view of design concept three.

For the best conceptual design to be selected for detail design, a decision matrix was drawn based on the following design considerations:

- Cost;
- Safety;
- Functionality;
- Reliability.

Table 2 shows the decision matrix used for selecting the best conceptual design.

Table 2. Decision matrix used for selecting the best conceptual design.

Criteria	Concept 1		Concept 2		
	Weight	Rating	Score	Rating	Score
Cost	3	8	24	6	18
Safety	2	9	18	8	16
Functionality	3	8	24	5	15
Reliability	2	7	14	4	8
Total			80		57

*Weight Factor from 1-4 and Rating 1-10 *Score=Rating x Weight

Based on the ranking, design concept one with a ranking of 80 has the best ranking, hence selected.

2.2.4. Detailed design

The following parameters and components were designed.

Swept Area of Wind Turbine. For a vertical axis wind turbine, the area depends on both the diameter and blade length of turbine.

Thus,

$$A_s = D_t l_b. \quad (1)$$

where,

A_s = Swept area of a turbine (m^2).

D_t = Diameter of the turbine (m) = 1.45 m.

l_b = Length of the turbine blades (m) = 2.35 m.

$A_s = 1.45 \times 2.35 = 3.41 m^2$.

Power of Wind. The power of the wind is directly proportional to air density, area of the segment of wind being considered, the natural wind speed. Fig. 4 shows packet of air moving with speed (V).

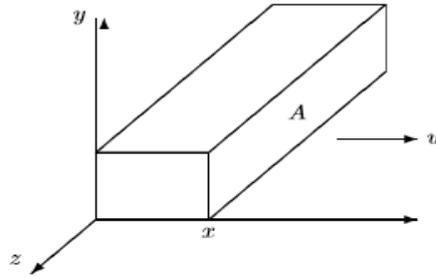


Fig. 4. Packet of air moving with speed (V).

Mathematically, the relationships between density, area of the segment of wind and wind speed is given by Eq. (2).

$$P_w = \frac{1}{2} \rho AV^3 C_p. \quad (2)$$

Where,

P_w = Power of the wind (watts).

ρ = Density of air (1.23 kg/m³).

A = Area of a segment of the wind being considered (m²).

V = Wind speed (m/sec) = 3.66 m/s (Determined with UT363 Anemometer).

C_{pmax} = Power coefficient = 0.56.

However, at a standard pressure and temperature, Eq. (2) becomes,

$$P_w = \frac{1}{2} \rho AV^3 C_p. \quad (3)$$

$$P_w = \frac{1}{2} \times 1.23 \times 3.41 \times 3.66^3 \times 0.56 = 31.46 \text{ watts.}$$

Mechanical Power Develop. The mechanical power extracted is the difference between the input and output power in the wind and is given by Eq. (3).

$$P_{m,ideal} = \frac{1}{2} \rho \left(\frac{16}{27} AV^3\right). \quad (4)$$

The factor $16/27 = 0.593$ is sometimes called the Betz coefficient. It shows that an actual turbine cannot extract more than 59.3 percent of the power in an undisturbed tube of air of the same area.

$$P_{m,ideal} = \frac{1}{2} \rho \left(\frac{16}{27} AV^3\right).$$

$$P_{m,ideal} = \frac{1}{2} \times 1.23 \times \left(\frac{16}{27} \times 3.41 \times 3.66^3\right) = 60.93 \text{ watts.}$$

Blade Tip Speed. The blade tip speed can be calculated from the rotational speed of the turbine and the length of the blades used in the turbine using Eq. (3).

$$\text{Blade Tip Speed} = \frac{\text{Rotational speed (rpm)} \times \pi \times D}{60} \quad (5)$$

But,

$$\omega = \frac{V}{r} \quad (6)$$

Where,

$$\begin{aligned} \omega &= \text{Rotational speed of wind.} \\ V &= \text{Wind of speed} \\ r &= \text{Radius of wind turbine blade} \\ \omega &= \frac{V}{r} = \frac{3.66}{0.725} = 5.05 \text{ rpm.} \end{aligned}$$

Therefore,

$$\text{Blade Tip Speed} = \frac{5.05 \times \pi \times 1.45}{60} = 7.38 \text{ rpm.}$$

Tip Speed Ratio. The tip speed ratio is proportional to the windmill's productivity. It determines the number of times the blades rotation is greater than the wind speed. Tip speed ratio is given by Eq. (7).

$$\text{Tip Speed Ratio } (\lambda) = \frac{\text{Blade Tip Speed}}{\text{Wind Speed}} \quad (7)$$

$$\text{Tip Speed Ratio } (\lambda) = \frac{7.38}{3.66} = 2.02 .$$

Design for Torque.

$$\text{Power (P)} = \frac{\text{Force} \times \text{Linear Distance}}{\text{Time}} \quad (8)$$

$$P = \frac{\frac{\text{Torque } (\tau)}{r} \cdot (r \cdot \omega \cdot t)}{t} \quad (9)$$

$$P = \tau \omega \quad (10)$$

$$\tau = \frac{P}{\omega} = \frac{60.93}{5.05} = 12.07 \text{ Nm.}$$

Circular Pitch of Driver Gear. The circular pitch is given by Eq. (11).

$$P_c = \frac{\pi D}{T} \tag{11}$$

D = Diameter of the pitch circle = 200 mm, and

T = Number of teeth on the wheel.

Thus, circular pitch of driver gear

$$P_c = \frac{\pi D}{T}$$

$$P_c = \frac{\pi \times 200}{8} = 78.55 \text{ mm.}$$

Circular Gear of Driven Gear. Also, circular pitch of driven gear

$$P_c = \frac{\pi \times 200}{8} = 78.55 \text{ mm.}$$

Diametral Pitch. It is the ratio of number of teeth to the pitch circle diameter. It is denoted by p_d . Mathematically, it is given by Eq. (12).

$$P_d = \frac{T}{D} = \frac{\pi}{P_c} \tag{12}$$

Where,

P_d = Diametral Pitch

T = Number of teeth, and

D = Pitch circle diameter

$$P_d = \frac{\pi}{P_c} = \frac{3.142}{78.55} = 0.04 \text{ mm.}$$

Module. The module is given by Eq. (13).

$$m = \frac{D}{T} \tag{13}$$

Since both the driver and driven gear arrangement has the same number of teeth and same diameter, Therefore,

$$m = \frac{200\text{mm}}{8} = 25 \text{ mm.}$$

2.2.5. Assembly of the Savonius vertical axis wind turbine operated water pump

The assembly process involves the joining of the different component parts of the wind turbine. The joint can be temporary or permanent. Some parts/components of the wind turbine was assemble temporary while other parts/components permanently. *Fig. 5* shows the picture of the developed Savonius vertical axis wind turbine operated water pump.



Fig. 5. Fabricated Savonius vertical axis wind turbine operated water pump.

3. Results and Discussion

In this research work, Savonius vertical axis wind turbine operated water pump was successfully developed. Swept area of 3.41 m^2 and power of wind of 31.46 watts were required for the wind turbine effective operation. The mechanical power extracted which is the difference between the input and output power in the wind was determined as 60.93 watts. The blade tip speed and rotational speed wind were calculated as 7.38 rpm and 5.05 rpm. According to Akshath et al. [21], wind turbines with low tip speed ratios are suitable for low speed applications such as water pumping and other. Besides, a wind turbine cannot extract 100% of the winds energy because some of the winds energy used in pressure changes occurring across the blades of the wind turbines. This is because the pressure change causes velocity to decrease and thus usable energy. The torque and diametric pitch of the gear were obtained as 12.07 Nm and 0.04 mm, respectively. Also, the calculated values for circular gear of driven gear and circular pitch of driver gear were the same (78.55 mm), thus, both the driver and driven gear meshed perfectly.

Furthermore, the Savonius vertical axis wind turbine was simple to design and is relatively cheap to build. It was observed that it generates power at a minimum wind speed and it requires simple installation and maintenance. Also, it produces less noise and it operate closer to the ground, thus, placement or replacement of heavy equipment is easy. *Fig. 6* shows the results of average wind speed at different period of the day in the study area. The outcome of the results revealed that wind speed range between 2.88 to 3.39 m/s in Isihor, Ovia North East local government area, and South-South,

Nigeria. This finding agreed with the research work of Olusey [22] that reported an average wind regime in the Northern and Southern Nigeria to lie between 4.0 to 7.5 m/s and 3.0 to 3.5 m/s, respectively at 10 m above the ground. Also, it was observed that during the evening, there is an increased in wind speed generation unlike in the morning and afternoon. Thus, for better utilization of wind speed such as pumping of water in the study area, wind speed generation, storage and conversion will be efficient during the evening.

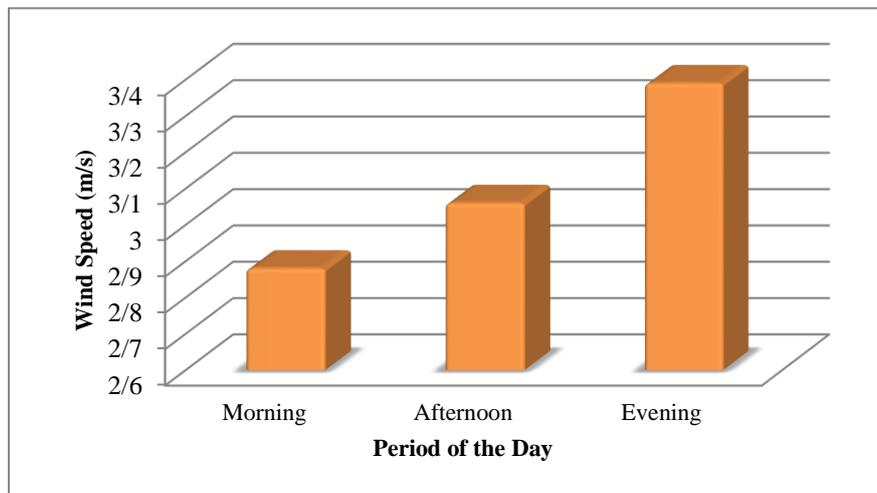


Fig. 6. Bar Chart showing average wind speed at different period of the day in Isihor.

Fig. 7 shows the graph of wind speed against volume of water pump in litres, pumping time in minutes, and volumetric flow rate (Lit. /min) while Fig. 8 shows the average values generated. The outcome of the results revealed that volume of water pump is as a function of wind speed. It was observed, that the higher the wind speed, the higher the volume of water pump and vice-versa. Moreover, the pumping time was minimal whenever there is an improved wind speed. However, the scenario differ whenever, there is drop in wind speed. Thus, a higher wind speed will lead to more volume of water pump at a minimal pumping time. Also, as wind speed increases steadily, volumetric flow rate increases likewise. Therefore, the higher the wind speed, the higher the volumetric flow rate and the lesser the time requires for pumping of water.

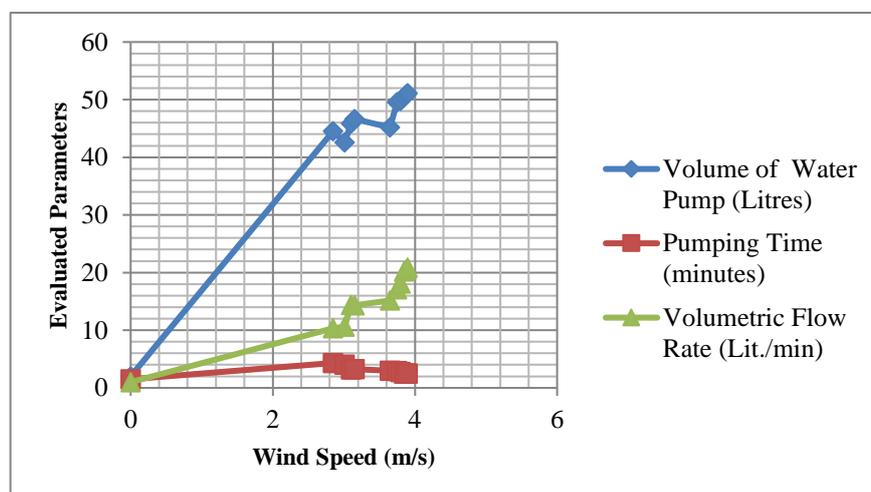


Fig. 7. Graph of wind speed against volume of water pump, pumping time and volumetric flow rate.

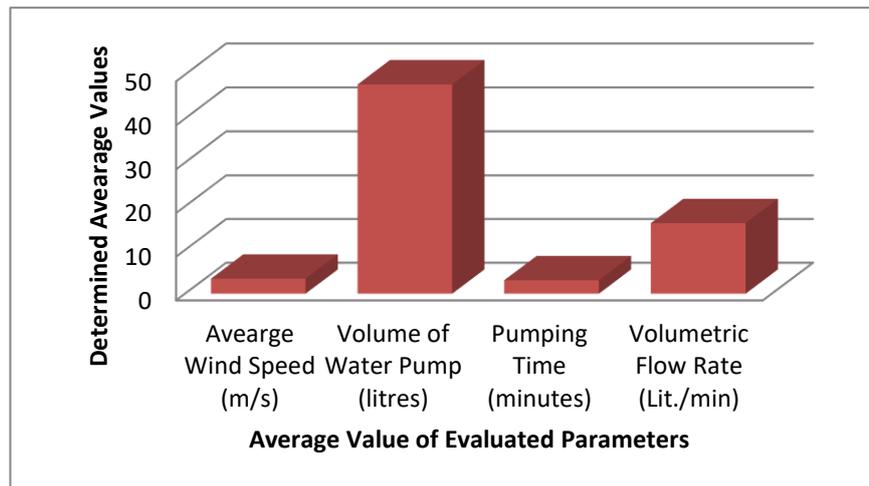


Fig. 8. Bar chart showing average values of parameters used for evaluating the performance of developed Savonius vertical axis wind turbine.

4. Conclusion

A Savonius vertical axis wind turbine operated water pump was successfully developed and this was aimed at solving the problem of unavailability of drinkable water especially in the rural area of Nigeria. Test performance evaluation was carried out on the developed system to determine the volume of water pump, volumetric flow rate, wind speed, and pumping time. The results obtained shown that an average wind speed of 3.49 m/sec was required to pump an average 47.77 litres of water at an average time of 3.08 minutes. These parameters were used to determine the volumetric flow rate which was obtained as an average value of 16.16 lit. /min. From all indication, the developed wind turbine will greatly enhance availability of water for Nigerian populace. Besides, the wind turbine performance was satisfactory and can be used locally and industrially in small scale.

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