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TECHNO-ECONOMIC ANALYSIS OF WIND POWER GENERATION AT VARYING HUB HEIGHTS FOR WATER PUMPING APPLICATION IN NIGERIA

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Abstract: The lack of access to clean and affordable energy supply is one of the factors affecting people's socioeconomic life and well-being in several local communities in Nigeria. This has birthed several other issues such as a lack of potable water, good healthcare service, etc. Therefore, this paper presents the techno-economic design and analysis of wind power-based water pumping systems, considering the average daily wind speed of a location in Ikeja, Lagos, Nigeria. The wind potential was modelled using a two-parameter Weibull distribution to determine its viability for water pumping in the location. Five 25-kW, pitch-controlled wind turbines (WT1 – WT5) from different manufacturers with dissimilar characteristics were examined at varying hub heights. The annual energy generated, the cost of energy (COE) and the cost/m^3 of water produced ($\mathrm{C_{unit}}$) were then evaluated. The results indicate that WT3 has the least COE ranging from \$0.03/kWh to \$0.13/kWh and $\mathrm{C_{unit}}$ ranges from $\$0.003/\mathrm{m}^3$ to $\$0.012/\mathrm{m}^3$ for hub-heights of $10\mathrm{m}$ to $50\mathrm{m}$, while WT5 has the highest COE ranging from $\$0.011/\mathrm{kWh}$ to $\$0.64/\mathrm{kWh}$ and $\mathrm{C_{unit}}$ ranges from $\$0.011/\mathrm{m}^3$ to $\$0.063/\mathrm{m}^3$ for hub-heights of $10\mathrm{m}$ to $50\mathrm{m}$. The results further reveal that the proposed system is more economically viable than the public utility system.

Keywords: cost of energy, energy supply, hub height, water supply, wind speed

1. INTRODUCTION

The importance of potable water supply to local communities cannot be over-emphasized, as it is not only useful for consumption within the domestic premises but also useful for farming purposes. However, the lack of clean or potable water has been identified as one of the major problems in most rural communities in Nigeria [1]. This has also been attributed to a lack of access to clean and affordable energy supply in most of these communities.

The increase in water demand as a result of population growth has also exerted more pressure on the existing limited infrastructure available in most rural communities [2]. Therefore, the provision of clean and adequate water supply for rural communities will continue to be relevant because it is not just vital for human existence, but also associated with economic development, enhanced standard of living and healthcare, and preservation of ecosystem poverty mitigation in developing countries [3]. In Nigeria, scarcity of potable water has also been noted as a main factor that breeds communal clashes in rural communities [4]. As earlier mentioned, water scarcity experienced in several communities in the country is traceable to a lack of or erratic energy supply and not there is a lack of water resources, as the country has large groundwater potential [5].

Apart from the prevailing situation of the lack of energy access in several rural communities in Nigeria, as a result of being too far from the existing grid network [6-9], there is also the issue of the lack of accessible roads to transport fuels - diesel and petrol to rural areas [10]. This depicts the cause of acute clean water scarcity in these communities despite abundant groundwater resources in the country. This study is interested in how to address the identified challenges by proposing technical solutions to the lack of energy and potable water supply in the local communities in Nigeria. It is motivated by the need to harness available renewable energy resources, which is gaining the attention of the global community as an alternative to conventional energy resources [11-14].

Several studies have been presented in the literature on the application of renewable energy technologies from different perspectives such as for agricultural, lighting, commercial, residential, educational purposes, water pumping, etc. It is of interest in this paper to briefly present some contributions to renewable energy applications that can serve as relevant background. For example, the possibility of utilizing renewable energy pumping systems for off-grid communities has been presented in [15]. The authors examined how to harness abundant renewable energy in the area to provide water for the people, and also compared the performance of a directly-coupled photovoltaic-based water pumping system and a maximum power point tracking DC-DC solar photovoltaic-based water pumping system for domestic purposes in a rural location in Morocco. It was reported that the maximum power point tracking DC-DC solar photovoltaic system has better performance, requires fewer PV modules and is, therefore, more economical than the directly-coupled system.

The benefits of solar-powered water pumping system for groundwater in Nigeria has also been investigated [16]. The authors presented results that revealed the design procedure and economic implications of the proposed energy/water solutions. Also, the authors in [17] carried out an experimental study to determine the performance of a direct-coupled solar-powered DC pump. The experiment and analysis were conducted with two static head configuration pumps and varying solar irradiation. The results of the study show that the proposed system is appropriate for small irrigation systems.

The impact of total head and solar irradiation on PV-based water pumping systems has been examined in [18]. The authors presented the analysis of varying the total head of the water pumping system, and the results show the possibility of achieving the optimal system head suitable for a helical submersible rotor pump. In addition, the possibility of using solar-based electricity to pump groundwater was investigated, using Saudi Arabia as a case study [19]. The results presented by the authors prove the effectiveness of solar energy in groundwater utilization.

These publications have presented meaningful contributions to knowledge, especially in the design and analysis of solar-powered water-pumping systems, and they provide relevant background to this current study. However, this present paper focuses on the viability of wind-powered water pumping systems. Apart from the technical design of the wind power generating system, the study introduced a sensitivity analysis in terms of varying the hub heights of the wind turbine arrangements to ascertain the amount of energy that may be delivered at the different heights. To achieve this, the performance of five 25-kW pitch-controlled wind turbines (WT1–WT5) from different manufacturers with dissimilar characteristics is examined at varying hub heights. The results revealed a detailed performance analysis both on the technical and economic aspects, which may be useful for planning, designing and a better understanding of renewable energy-based water pumping systems.

The remaining part of the paper is arranged as follows: Section 2 focuses on the methodology utilized in this work; Section 3 discusses the results of the analysis, while Section 4 concludes the paper.

2. MATERIALS AND METHOD

This section provides the details of the approach utilized in this work.

▦ Study Area

The study location is the Ikeja area of Lagos State, Nigeria with geographical coordinates 6.35°N and 3.2°E. The Ikeja daily wind speed data measured at a hub height of $10\mathrm{m}$ by an anemometer cup-generator was obtained from the Nigeria Meteorological Agency (NIMET), Oshodi, Lagos State, Nigeria.

▦ Wind Speed Analysis

The monthly mean wind speed (V_{ms}) and the standard deviation (σ_{ms}) of the wind speed data are given by:

$$V_{ms} = \frac{1}{n}\left(\sum_{i=1}^{n} V_i\right) \tag{1}$$

$$\sigma_{ms} = \sqrt{\frac{1}{n}\ \sum_{i=1}^{n}(V_i - V_{ms})} \tag{2}$$

where V_i = $\mathrm{daily\ wind\ speed\ (m/s)}$ and $\mathrm{n = number\ of\ wind\ speed\ data.}$

The Weibull probability distribution function $(f_w(v))$ and the cumulative distribution function $(f_w(V))$ are given by [20]:

$$f_w(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\frac{v}{c}\right]^k \tag{3}$$

$$\text{and}\quad f_w(V) = 1 - \exp\left[-\frac{v}{c}\right]^k \tag{4}$$

where $v = \mathrm{wind\ speed\ (m/s)}, k = \mathrm{shape\ parameter\ (dimensionless)\ and}\ c = \mathrm{scale\ parameter\ (m/s)}$.

The two Weibull parameters (k and c) can be estimated by [20]:

$$k = \left[\frac{\sigma_{ms}}{V_{ms}}\right]^{-1.086} \tag{5}$$

$$c = \frac{V_{ms}}{\Gamma\left(1+\frac{1}{k}\right)} = \frac{V_{ms} \times k^{2.6674}}{0.184+(0.816 \times k^{2.73855})} \tag{6}$$

where Γ is the gamma function given by

$$\Gamma(x) = \int_0^\infty e^{-t}\, t^{x-1} dt \qquad (7)$$

The most probable wind speed (V_{mps}) and the wind speed associated with maximum energy (V_{emax}) are given by [21]:

$$V_{mps} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \qquad (8)$$

$$V_{emax} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \qquad (9)$$

At times, the wind speed is usually measured at a reference hub height (h_0) and needs to be adjusted to the relevant wind turbine hub height (h). By using the relevant power law equation, the new wind speed (V_h), scale factor (c_h) and shape factor (k_h) is given by [22]:

$$V_h = V_0\left(\frac{h}{h_0}\right)^{\propto} \qquad (10)$$

$$c_h = c_0\left(\frac{h}{h_0}\right)^{n} \qquad (11)$$

$$k_h = k_0\left\{\frac{\left[1-0.088\ln\frac{h_0}{10}\right]}{\left[1-0.088\ln\frac{h}{10}\right]}\right\} \qquad (12)$$

$$n = \frac{[0.37-0.088\ln c_0]}{\left[1-0.088\ln\frac{h}{10}\right]} \qquad (13)$$

where $\propto$ is the site surface roughness coefficient assumed to be 0.143 [23].

Estimation of Wind Power Energy Density

The wind power density is a measure of the capacity of the wind resources in a particular location. It is given by [24]:

$$P_{WPD} = \frac{1}{2}\rho A V_{ms}^3 = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \qquad (14)$$

Therefore, the wind energy density can be expressed as:

$$E_{WPD} = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) t \qquad (15)$$

where $\rho =$ air density of site $(1.225\ \mathrm{kg/m^3})$, $A =$ swept area of rotor blades $(\mathrm{m^2})$ and $t =$ time.

Estimation of Wind Turbine Output Power and Capacity Factor

The wind turbine output power is of a significant benefit (economic indicator) compared to its rated power. The wind turbine output power, i.e. power curve, is modelled via four parameters: the cut-in wind speed (V_{ci}), the cut-off wind speed (V_{co}), the rated wind speed (V_r) and the rated power of the turbine (P_r). For a pitch-controlled turbine, the power curve model can be approximated by a parabolic law, given by [25]:

$$P = P_r \begin{cases} \dfrac{V_{ms}^2 - V_{ci}^2}{V_r^2 - V_{ci}^2} & V_{ci} \le V_{ms} \le V_r \\ 1 & V_r \le V_{ms} \le V_{co} \\ 0 & V_r \le V_{ci} \text{ and } V_{ms} \ge V_{co} \end{cases} \qquad (16)$$

The average power output (P_{ave}) of a wind turbine is given by [25]:

$$P_{ave} = P_r\left[\frac{e^{-\left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_r}{c}\right]^k}}{\left[\frac{V_r}{c}\right]^k - \left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_{co}}{c}\right]^k}\right] \qquad (17)$$

The capacity factor (CF_w) of a wind turbine is the ratio of average power to the turbine-rated power and is given by [25]:

$$CF_w = \frac{P_{avr}}{P_r} = \left[\frac{e^{-\left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_r}{c}\right]^k}}{\left[\frac{V_r}{c}\right]^k - \left[\frac{V_{ci}}{c}\right]^k} - e^{-\left[\frac{V_{co}}{c}\right]^k}\right] \qquad (18)$$

The annual energy generated by the wind turbine is given by:

$$E_{ae} = CF_w \times P_r \times t \qquad (19)$$

where t is usually 1 year (8760hrs).

Estimation of Water Pumping Capacity of Wind Turbine

The net hydraulic output power (P_{out}) required to deliver water at the required head is given by [26]:

$$P_{out} = \frac{\rho_w g Q_w H}{\eta_p} \qquad (20)$$

P_{out} is also given by:

$$P_{out} = \eta_p \times P_{in} = \eta_p \times CF_w \times P_r \tag{21}$$

Therefore,

$$Q_w = \frac{CF_w \times P_r \times \eta_p^2}{\rho_w \times g \times H} (\mathrm{m^3/s}) \tag{22}$$

where $Q_w =$ Volumetric flow rate $(\mathrm{m^3/s})$, $\rho_w =$ density of water $(1000\ \mathrm{kg/m^3})$,
$g =$ acceleration due to gravity $(10\ \mathrm{m/s^2})$,
$H =$ pump head assumed to be $15\mathrm{m}$ and $\eta_p =$ pump efficiency assumed to be 65%.
The annual volume of water produced (V_w) is given by:

$$V_w = 24 \times 365 \times Q_w \tag{23}$$

Economic Cost Analysis

Estimating the unit cost of energy (COE) and the unit cubic meter of water (C_{unit}) produced is a way of knowing the most viable wind turbine to select for this study. The cost analysis involves the determination of individual component cost that makes up the entire system such as investment, operation, maintenance and replacement costs. The life cycle cost (C_{LCC}) of the system is taken to be 20 years and is given by [27]:

$$C_{LCC} = C_{inv} + C_{opm}\left(\frac{1+i}{d-i}\right)\left(1-\left(\frac{1+i}{1+d}\right)^n\right) \tag{24}$$

where C_{opm} is taken to be 0.1% of investment cost, $i =$ inflation rate (8.4%) and $d =$ discount rate (11%), $r =$ interest rate (15%) and $n =$ life time of project $(20\mathrm{yrs})$.
The annualized life cycle cost (C_{ALCC}) is given by:

$$C_{ALCC} = C_{LCC} \times CRF \tag{25}$$

where CRF is the capital recovery factor given by [28]:

$$CRF = \frac{i\,(1+i)^n}{(1+i)^n - 1} \tag{26}$$

The unit cost of energy is given by [20]:

$$COE = \frac{C_{ALCC}}{8760 \times P_r \times CF_w} \tag{27}$$

The unit cubic cost of water is given by [29]:

$$C_{unit} = \frac{C_{ALCC}}{V_w} \tag{28}$$

In this study, five different turbines from different manufacturers were considered and are represented by WT1, WT2, WT3, WT4 and WT5 respectively, with their characteristics shown in Table 1.

Table 1. Characteristics of Wind Turbines

Characteristics	WT1	WT2	WT3	WT4	WT5
Rated power P_r (kW)	25	25	25	25	25
Rotor diameter (m)	15	15	15	15	15
Cut-in wind speed V_{ci} $(\mathrm{m/s})$	2.0	2.5	3.0	3.5	4.0
Rated wind speed V_r $(\mathrm{m/s})$	16	18	15	17	19
Cut-off wind speed V_{co} $(\mathrm{m/s})$	25	27	23	28	30
Investment cost $\$/\mathrm{kW}$	1300	1300	1300	1300	1300

3. THE RESEARCH FINDINGS AND DISCUSSION

Wind Characteristics of the Location

The wind speed characteristics for the Ikeja location are shown in Table 2. The results presented in Table 2 demonstrate increasing wind characteristics as the turbine hub heights are increased.

Table 2. Wind Speed Characteristics of Ikeja

Hub height (m)	V_{ms} (m/s)	k	c $(\mathrm{m/s})$	V_{mps} $(\mathrm{m/s})$	V_{emax} $(\mathrm{m/s})$	P_{WPD} $(\mathrm{W/m^2})$	E_{WED} $(\mathrm{W/m^2/day})$
10	10.64	6.89	11.35	11.09	11.78	793	19.04
20	11.75	7.34	12.73	12.48	13.16	1121	26.89
30	12.45	7.63	13.73	13.48	14.15	1407	33.77
40	12.97	7.85	14.53	14.28	14.95	1669	40.06
50	13.39	8.03	15.21	14.96	15.64	1916	45.98

Estimation of Capacity Factor and Energy Yield of Wind Turbines

Table 3 presents the results of CF_w and annual energy output (E_{ae}) of each turbine for hub heights. It also presents the annual wind energy production of each turbine as obtained from the wind power curves shown in Figure 1. The results demonstrate that WT1 has CF_w of ≥ 0.25 at hub-heights of $30\mathrm{m}$ to $50\mathrm{m}$, WT2 has **CF_w of ≥ 0.25** at hub-heights of **50m**, WT3 has **CF_w of ≥ 0.25** at hub-heights of **20m to 50m**, WT4 has **CF_w of ≥ 0.25** at hub-heights of **40m to 50m**, while WT5 does not have any **CF_w ≥ 0.25**.

WT3 has the highest annual energy yield of **32.03 MWh to 144.82 MWh** while WT5 has the least annual energy yield of **6.29 MWh to 36.65 MWh** at hub heights of **10 m to 50 m** respectively. Figure 1 shows the power curves of the various turbines. For uniformity of comparison, each turbine considered were **25 kW** ratings with a different cut-in and rated wind speed.

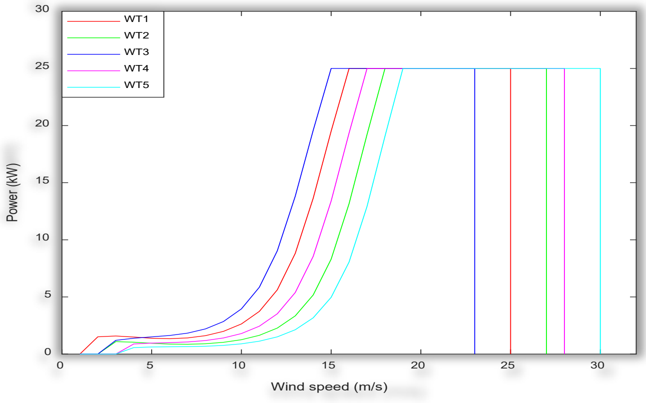

Figure 1. Power Curves of Wind Turbine

Table 3. Capacity Factor and Annual Energy Yield of Wind Turbines

	WT1		WT2		WT3		WT4		WT5	
Hub-Height (m)	CF_w	E_{ae} (MWh)	CF_w	E_{ae} (MWh)	CF_w	E_{ae} (MWh)	CF_w	E_{ae} (MWh)	CF_w	E_{ae} (MWh)
10	0.09	20.56	0.04	9.13	0.15	32.03	0.06	13.53	0.03	6.29
20	0.19	40.79	0.08	17.27	0.29	63.46	0.12	26.26	0.05	11.61
30	0.30	65.27	0.13	27.67	0.44	95.71	0.19	42.55	0.08	18.32
40	0.41	90.45	0.18	40.51	0.56	123.21	0.28	61.68	0.12	26.61
50	0.52	113.44	0.25	55.53	0.66	144.82	0.37	81.93	0.17	36.65

Cost Estimation of Energy and Water

Table 4 presents the cost of energy **(COE)** for pumping water and the unit cost per cubic meter of water **(C_{unit})** for various turbines at different hub heights, respectively. For WT3, COE ranges from $0.03/kWh at 50m hub height to $0.13/kWh at 10 m hub height. In addition, Cunit ranges from $0.003/m3 at 50m hub height to $0.012/m3 at 10 m hub height. WT5 shows the worst performance (highest cost) for both COE and Cunit at all hub heights. For WT5, COE ranges from $0.11/kWh at 50 m hub height to $0.64/kWh at 10 m hub height. Also, C_{unit} ranges from $0.011/m^3 at 50 m hub height to $0.063/m^3 at 10 m hub height.

Table 4. Cost of Energy and Cubic Meter of Water

h (m)	WT1		WT2		WT3		WT4		WT5	
	COE ($/kWh)	C_{unit} ($/m^3)	COE ($/kWh)	C_{unit} ($/m^3)	COE ($/kWh)	C_{unit} ($/m^3)	COE ($/kWh)	C_{unit} ($/m^3)	COE ($/kWh)	C_{unit} ($/m^3)
10	0.20	0.019	0.44	0.043	0.13	0.012	0.30	0.029	0.64	0.063
20	0.10	0.010	0.23	0.023	0.06	0.006	0.15	0.015	0.35	0.034
30	0.06	0.006	0.15	0.014	0.04	0.004	0.09	0.009	0.22	0.022
40	0.04	0.004	0.10	0.010	0.03	0.003	0.07	0.006	0.15	0.015
50	0.04	0.003	0.07	0.007	0.03	0.003	0.05	0.005	0.11	0.011

Sensitivity Analysis

This paper also presents the dependency of a given system variable on some defined input variables. The variables considered are the effect of variable wind speed on **COE and C_{unit}** and that of the pumping system head on **C_{unit}**. The results shown in Figures 2 to 4 reveal that **COE and C_{unit}** decrease with increasing wind turbine speed.

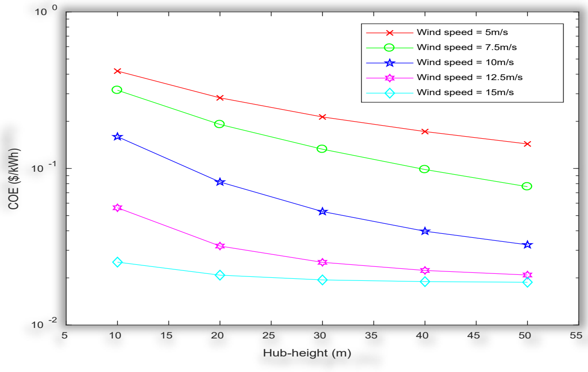

Figure 2. Sensitivity analysis showing the relationship between wind speed and COE for WT3

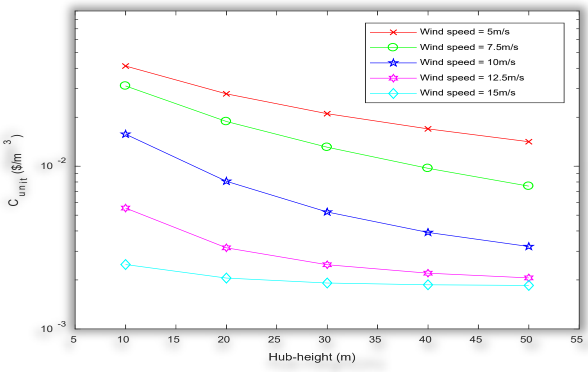

Figure 3. Sensitivity analysis showing the relationship between wind speed and C_{unit} for WT3

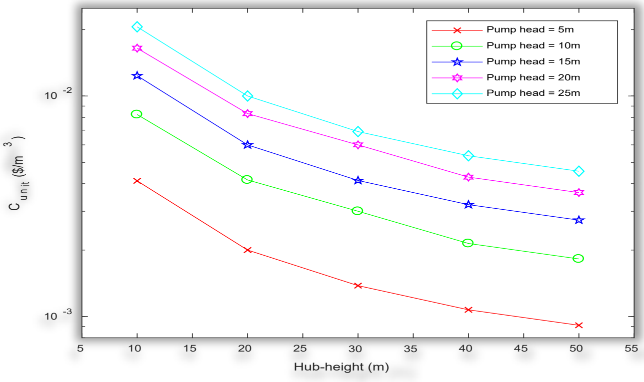

Figure 4. Sensitivity analysis showing the relationship between pump head and C_{unit} for WT3

Based on the results presented in Table 2, it is obvious that wind turbine hub height is a major factor that determines if a site is viable for wind energy conversion or not. Furthermore, the result shows that the study location is a viable site for on-grid application because the wind power density at the hub height of $10m$ is $> 400\,W/m^2$. This is buttressed by a similar study presented in [30].

More so, it was previously established that any wind turbine with a capacity factor ≤ 0.25 is not suitable for grid integration [24]. Hence, a wind turbine with a capacity factor ≥ 0.25 is the best for any site [24]. The values of the capacity factor for almost wind turbines are above 0.25 at the specified hub heights, which are consistent with the constraint mentioned in [24]. It is obvious from this study that WT3 has the highest CF_w followed by WT1, WT4, WT2 and WT5, respectively as presented in Table 3. These are comparable with some other studies in the literature such as those in [9, 18, 19, 26, 27].

This study justifies the cost as being the criteria for deciding which turbine is to be selected for the water pumping system. This is the basis for Table 4, which demonstrates that increasing the hub heights (h) of wind turbines will automatically bring about a reduction in the overall cost of both energy and the unit cost of water. This is also supported by other studies in [16, 18, 29]. The study finds that energy yield is directly proportional to the hub height. The results shown in Figures 2 to 4 are attributed to the fact that wind turbine generates more energy at higher wind speed.

In addition, part of the results demonstrates that the unit cost decreases as the pump head decreases. This is because a decrease in pump head is accompanied by an increase in the volume of water produced, the impact of which reduces the cost. According to the Nigerian Electricity Regulatory Commission, the electricity tariff in Nigeria for residential "Band A" customers with a daily minimum of 20 hours of electricity availability is **$0.13** at an official exchange rate of **$1** to **N 400.** Hence, the generation of electricity using wind turbines of WT1 at a hub height$\geq 20m$, WT2 at a hub height$\geq 40m$, WT3 at a hub height$\geq 20m$, WT4 at a hub height$\geq 30m$ and WT5 at a hub-height $\geq 50m$ are very economical compared with utility grid supply. Also, the C_{unit} for all the wind turbines (WT1 – WT5) are far less than the public rate which ranges between $\$0.375$ to $\$0.6/m^3$ [27] with WT3 having the best (least) cost compared to other wind turbines.

4. CONCLUSION

This study has carried out a detailed techno-economic analysis on the selection of an appropriate wind turbine for water pumping application in a selected location in Lagos State, Nigeria. The study utilized the average daily wind speed for 10 years obtained from NIMET. Five different wind turbines of the same ratings (25 kW) were used for the wind energy conversion system. The study reveals the following:

- The study location is viable for both grid integration and water pumping system.
- WT3 has the highest CF_w, which ranges from 0.15 to 0.66 at hub heights of 10 to 50m. This is a major determinant in turbine selection.
- WT3 has the least COE, which ranges from **$0.03kWh to $0.13kWh** and C_{unit} **ranging from** $\$0.003/m^3$ to $\$0.012/m^3$, all at a hub-height range of 10m to 50m. Hence, WT3 should be selected as the most suitable and cost-effective option among other wind turbines.
- WT5 has the highest **COE** (ranges from **$0.11kWh to $0.64kWh**) and C_{unit} (**ranges from** $\$0.011/m^3$ to $\$0.063/m^3$), all at a hub-height range of 10m to 50m.
- It is more efficient to utilize wind turbines at an optimal hub height to maximize the wind speed of the location.
- The use of wind energy for a water pumping system with a cost of $0.375/m³, is more economical than the public utility, which costs $0.600/m³.
- The wind speed of a location and the rated wind speed of the turbine are the major determinants for the technical feasibility and economic viability of utilizing wind energy for applications such as water pumping system

Future studies will consider using deep sensitivity and multi-criteria analysis techniques that can provide deeper insights into planning, design, simulation and managing of water pumping systems for local communities. Such a technique will be useful for a better understanding of water pumping systems design and decision-making.

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