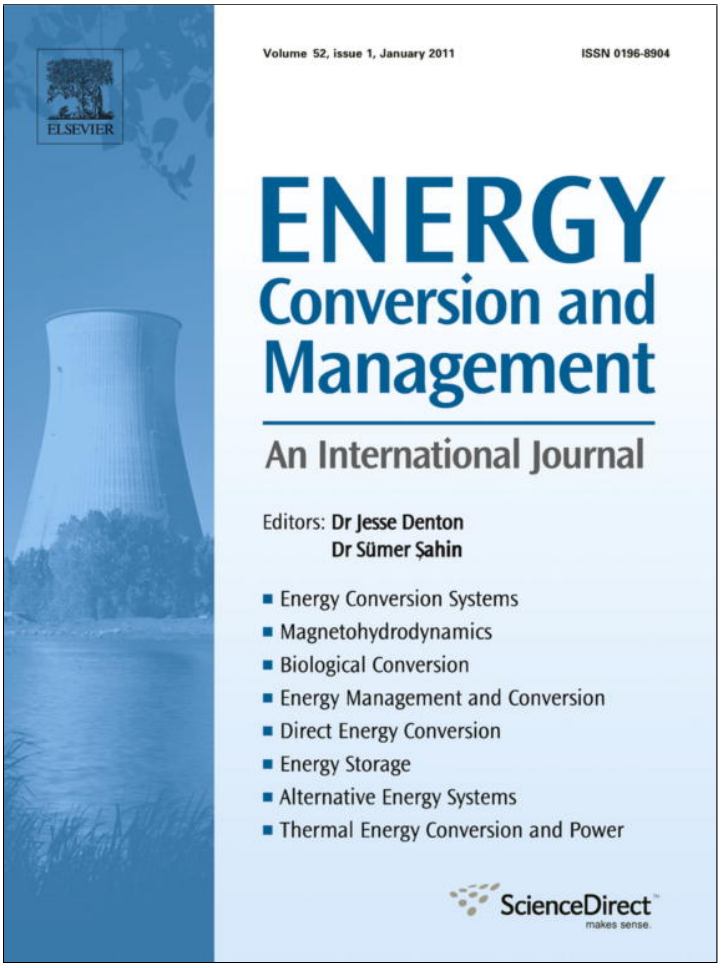
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Assessment of electricity generation and energy cost of wind energy conversion systems in north-central Nigeria

M.S. Adaramola [a,*], S.S. Paul [b], S.O. Oyedepo [c]

[a] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[b] Department of Mechanical and Manufacturing Engineering, University of Manitoba, Winnipeg, Manitoba, Canada
[c] Mechanical Engineering Department, Covenant University, Ota, Ogun State, Nigeria

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ABSTRACT

In this study, the wind energy potential and economic analysis in selected six locations in north central part of Nigeria were investigated using wind speed data that span between 19 and 37 years measured at 10 m height. The performance of small to medium size commercial wind turbine models were examined and economic evaluation of the wind energy in the selected sites was made by using the levelised cost method. The results showed that the cost of energy production per kWh for the selected sites vary between ¢4.02 and ¢166.79. It was shown that Minna is most viable site while Bida is found to be least among the sites considered. Using three selected wind turbine models (in Minna) as case study, an increase in the escalation rate of operating and maintenance cost from 0% to 10%, lead to an increase in the unit energy cost by about 7%. It was further shown that by increasing the escalation rate of inflation from 0% to 5%, the cost of energy decreases by about 29% while the discount rate (return on investment) decreases from 11.54% to 6.23%.

1. Introduction

The increasing global energy demand and the adverse effects of non-renewable fossil fuels on environment had motivated considerable research attention in a wide range of engineering application of renewable resources such as: solar, geothermal, and wind. It is widely accepted that wind energy has become the fastest growing renewable sources of energy in both developed and developing countries. This is because wind energy by nature is clean, abundant, affordable, inexhaustible, and environmentally preferable. It has been estimated that the total available wind power surrounding the earth is of the order of 1011 GW. This is several times more than the current global energy consumption.

Prior studies have shown that the key requirements for proper and beneficial development of wind power at any location are the wind data analysis and accurate wind energy potential assessment. Several studies on renewable sources of energy in Nigeria have been performed to date. The analysis of available data for selected cities has confirmed a high prospect of wind energy resources in Nigeria. A detailed review and discussion of these studies can be found in (e.g. [1–5]) and are not repeated here. Overall, the results of these studies show that the wind speed varies in general from low regime in the southern part of the country to relatively high speed regime in the northern part. The annual mean wind speeds in Nigeria was found to vary between about 2 and 9.5 m/s with an overall annual mean wind speed of about 4.62 m/s.

Although the characteristics and pattern of wind speed across Nigeria have been studied, it is noted that less attention have been given to sites in north central region until recently. For example, based on the wind data from 1971 to 2007 for five selected locations in this region, Ohunakin [6] found that the wind resource in this region can broadly be classified into class 1 category. It should be remarked that the focus of the study like others are limited to wind speed distributions. The economic and performance of wind energy conversion systems has not been thoroughly investigated. The focus of this study therefore, is to evaluate the wind energy potential in six selected locations (Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna) in the north central region and to perform the economic analysis on selected small to medium size commercial wind turbines. This information will be helpful to government and any organization to make an informed decision regarding investment in wind energy resource in this part of Nigeria.

2. Wind characteristics in north-central Nigeria

The wind data used in this study were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi, Lagos. The geographical coordinates of the meteorological stations where wind speed data were captured at 10 m height by a cup-generator

* Corresponding author. Tel.: +47 97690282; fax: +47 3593580.
E-mail address: muyiwa.adaramola@usask.ca (M.S. Adaramola).

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anemometer, are given in Table 1. Monthly wind data that span between 19 and 37 years were obtained for Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna. The acquired data were obtained on hourly basis, from which monthly wind speed and other wind speed parameters were determined. There are many sources of measurement uncertainty in cup-anemometer measurements. The guidelines and steps necessary to minimize these errors are outlined in Mawell et al. [7]. Following the methodologies proposed and explained in the ISO guide [8] to the expression of uncertainty in measurement, the uncertainty in the mean velocities at 95% confidence level was determined to be ±2%.

The two-parameter Weibull probability density function was used to analyse the wind data. The site wind characteristics and Weibull parameters are presented in Table 2 for each location. The annual mean wind speeds are 3.61 m/s, 2.75 m/s, 4.39 m/s, 3.16 m/s, 4.58 m/s and 4.29 m/s for Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna, respectively. The annual most probable wind speed (V_F) varied between 2.77 m/s in Bida and 4.62 m/s in Makurdi, while the annual wind speed carrying maximum energy (V_E) is in range of 3.50 m/s in Bida and 6.80 m/s in Minna. It is noted that the efficiency of a wind turbine is closely related to V_E and that should be as close as possible to the design or rated wind speed of the system [9]. Subsequently, if wind turbines with the same design parameters are installed in all the sites considered in this study, the system will generate highest amount of electricity in Minna and least electricity in Bida. Furthermore, the annual mean power densities are, respectively, 28.89 W/m^2, 16.57 W/m^2, 71.82 W/m^2, 26.09 W/m^2, 76.40 W/m^2 and 94.11 W/m^2 for Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna. Based on PNL wind power classification scheme [10,11], the wind resource in all the sites considered fall into Class 1 wind resource category ($P_D \leqslant 100$). Detailed analysis of wind speed distribution in five of the locations considered in this study can be found in Ohunakin [6].

For a modern wind turbine, cut-in wind speed required in order for turbine to start generating electricity is generally between 3 and 5 m/s and it depends on the size of the turbine, peak power output that can be attained when the wind speed (rated wind speed) is in the range of 10–15 m/s [5]. For water pumping, wind turbine can be operated at lower wind speed; however, they can function effectively when the wind speed is more than 3 m/s. This, however, depends on the required quantity of water. It should also be noted that a site with mean wind speed of about 2.0 m/s can be considered for wind-powered pump application [12]. Therefore, the wind resource in Ilorin, Makurdi and Minna can be used for electricity generation while the wind resource in Abuja, Bida and Lokoja can be efficiently developed for water pumping and small scale electricity generation. It can therefore be concluded that based on the end use of the generated power, the above named locations are suitable for utilization of wind energy.

Table 1
The geographical location of the selected stations.

Station	Latitude (N)	Longitude (E)	Altitude (m)	Measurement period
Abuja	09.07°	07.48°	536.0	1983–2005
Bida	09.06°	06.01°	144.3	1971–2007
Ilorin	08.29°	04.35°	307.4	1971–2007
Lokoja	07.47°	06.44°	62.5	1971–2007
Makurdi	07.44°	08.32°	112.9	1971–2003
Minna	09.37°	06.32°	256.4	1971–2007

Table 2
Annual and seasonal of the site wind speed characteristics and Weibull parameters at height 10 m.

	V_m (m/s)	P_D (W/m^2)	V_E (m/s)	V_F (m/s)	k	c (m/s)
Abuja	3.613	28.881	4.751	3.565	3.094	4.044
Bida	2.747	16.569	3.495	2.77	3.444	3.06
Ilorin	4.389	71.823	5.797	4.313	3.049	4.913
Lokoja	3.158	26.089	4.08	3.154	3.27	3.526
Makurdi	4.57	76.399	5.789	4.618	3.494	5.086
Minna	4.289	94.113	6.797	3.458	2.024	4.841

3. Electrical power output and capacity factor

A wind energy conversion system can operate at maximum efficiency only if it is designed for a particular site. This is because the rated power, cut-in and cut-off wind speeds must be defined based on the site wind characteristics [13]. It is essential that these parameters are selected so that energy output from the conversion system is maximized.

The performance of a wind turbine installed in a given site can be examined by the amount of mean power output over a period of time (P_{out}) and the conversion efficiency or capacity factor of the turbine. The capacity factor C_f is defined as the ratio of the mean power output to the rated electrical power (P_{eR}) of the wind turbine [13,14]. The mean power output P_{out} can be calculated using the following expression based on Weibull distribution function [13]:

$$P_{out} = P_{eR}\left(\frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k}\right) \quad (1)$$

and the capacity factor C_f of a wind turbine is given as:

$$C_f = \frac{P_{out}}{P_{eR}} \quad (2)$$

Therefore,

$$C_f = \frac{e^{-\left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_r}{c}\right)^k}}{\left(\frac{v_r}{c}\right)^k - \left(\frac{v_c}{c}\right)^k} - e^{-\left(\frac{v_f}{c}\right)^k} \quad (3)$$

where v_c, v_r, v_f are the cut-in wind speed, rated wind speed, and cut-off wind speed, respectively. It is recognized that the capacity factor is a function of the site parameters (which is dependent on the hub height) and the wind turbine design wind speed properties. The cost effectiveness of a wind turbine can be roughly estimated by the capacity factor of the turbine. This factor is a useful parameter for both consumer and manufacturer of the wind turbine system [15]. For an investment in wind power to be cost effective, it is suggested that the capacity factor should be greater than 0.25 [9]. In this study, the performance assessments of selected commercial wind turbine models were examined by the values of their capacity factors.

It is observed that in most cases, the available wind data are measured at height different from the wind turbine hub height. Consequently, the wind speed at the hub height is of interest for wind power application and the available wind speeds can be adjusted to the wind turbine hub height using the following Power law expression (e.g. [5,13]):

$$\frac{V}{V_o} = \left(\frac{h}{h_o}\right)^{\alpha} \quad (4)$$

where V is the wind speed at the required height h, V_o is wind speed at the original height h_o and α is the surface roughness coefficient and is assumed to be 0.143 (or 1/7) in most cases. The surface roughness coefficient can also be determined from the following expression [15]:

$$\alpha = [0.37 - 0.088\ln(V_o)] \Big/ \left[1 - 0.088\ln\left(\frac{h_o}{10}\right)\right] \quad (5)$$

Alternatively, the Weibull probability density function can be used to obtain the extrapolated values of wind speed at different heights. The Weibull parameters at measurement height are related to the parameters at the wind turbine hub height by the following expressions [16]:

$$c(h) = c_o\left(\frac{h}{h_o}\right)^n \quad (6)$$

$$k(h) = k_o\left[1 - 0.088\ln\left(\frac{h_o}{10}\right)\right] \Big/ \left[1 - 0.088\ln\left(\frac{h}{10}\right)\right] \quad (7)$$

where c_o and k_o are the scale factor and shape parameter, respectively at the measurement height h_o and h is the hub height. The exponent n is defined as:

$$n = [0.37 - 0.088\ln(c_o)] \Big/ \left[1 - 0.088\ln\left(\frac{h}{10}\right)\right] \quad (8)$$

4. Cost analysis

Prior studies have shown that the cost of electricity generated by a wind turbine depends on several factors which include: the site specific factors (e.g. wind speed and quantity of electricity generated, cost of land, and installation cost); cost of wind turbine, and its economic life span; operating and maintenance costs; electricity tariff and incentives and exemptions [9,17]. Apart from the cost of the wind turbine which is set by the manufacturers, costs of other activities are location dependent. The cost of the wind turbine accounted for about 70% of the all total initial investment cost for wind energy development [9,17,18]. As shown in Table 3, the specific cost of a wind turbine is dependent on the rated power but varies widely from one manufacturer to another [9,17,19]. Since the economic feasibility of the wind energy development depends on its ability to generate electricity at a low operating cost per unit energy, accurate estimate of all the costs involved in generating electricity over the life span of the system is essential.

Different methods are generally used to estimate the operating cost of a unit energy produced by the wind energy conversion system. The most commonly used method however, is the levelised cost of electricity (LCOE) [17]. The LCOE is a measure of the marginal cost of electricity over a period of time and it is commonly used to compare the electricity generation costs from various sources [18]. In addition, the LCOE gives the average electricity price needed for a net present value of zero when a discounted cash flow analysis is performed. The determination of the cost of unit energy involves three basic steps: (i) estimation of energy generated by the wind turbine over a given period (e.g. year); (ii) estimate the total investment cost of the project; and (iii) divide the cost of investment by the energy produce by the system.

The unit cost of energy using LCOE method can be estimated using the following expression [16]:

$$\text{LCOE} = \frac{CRF}{8760P_RC_f}\left(C_I + C_{om(esc)}\right) \quad \text{cost/kWh} \quad (9)$$

where C_I is the total investment cost, $8760P_RC_f$ is the annual energy output of wind turbine in kWh, CRF and $C_{om(esc)}$ are the capital recovery factor and present worth of the annual cost throughout lifetime of the wind turbines expressed as (10) and (11) [17]:

$$CRF = \frac{(1+\varepsilon)^n\varepsilon}{(1+\varepsilon)^n - 1} \quad (10)$$

$$C_{om(esc)} = \frac{C_{om}}{\varepsilon - e_{om}}\left(1 - \left(\frac{1+e_{om}}{1+\varepsilon}\right)^n\right) \quad \text{cost/year} \quad (11)$$

where C_{om}, e_{om}, n and ε are the operation and maintenance cost for the first year, escalation rate of operation and maintenance costs, useful lifetime of turbine, and discount rate, respectively. The discount rate can be corrected for inflation rate (r) and inflation escalation rate (e) using the following expressions [9]:

$$e_a = \{(1+e)(1+r)\} - 1 \quad (12)$$

where e_a is called the apparent escalation rate. The discount rate can be determined from:

$$\varepsilon = \frac{(1+i)}{(1+e_a)} - 1 \quad (13)$$

Table 3
Range of specific cost of wind turbines based on the rated power.

Wind turbine size (kW)	Specific cost/kW	Average specific cost/kW
<20	2200–3000	2600
20–200	1250–2300	1775
>200	700–1600	1150

5. Results and discussion

5.1. Performance of selected wind turbines

For the wind turbine performance assessment and economic analysis, five of the Polaris America commercial wind turbine models with rated power range from 20 kW to 500 kW are selected [20]. The selected wind turbine models and their characteristic properties are given in Table 4. The selected wind turbines are designed to operate at different hub heights. In this study, however, the highest hub heights for each model were used. For each location, the annual energy output and capacity factor based on Weibull distribution function parameters at their respective hub height are determined.

The annual energy output from the selected wind turbine models at all the locations is presented in Fig. 1. The annual energy output ranges from about 7.53 MWh in Bida with P10-20 model to 1581.19 MWh in Minna using P50-500 model. Among the 50 kW model turbines, P15-50 model produced more power than P17-50. This is because P15-50 model have lower cut-in wind speed and rated wind speed when compared with P17-50 model. Regardless of the location, the P50-500 wind turbine model produce highest quantity of annual energy output while P10-20 model generated least energy. For P10-20, the annual energy output vary from 7.53 MWh in Bida to 61.50 MWh in Minna while in the case of P50-500, the annual energy output varies between 205 MWh in Bida and 1581.19 MWh in Minna. Based on the amount of electricity produced, P50-500 model is the best choice for all the locations considered in this study.

The selected wind turbine models capacity factors are presented in Fig. 2. The P50-500 model has the highest value among the models considered for all the sites. This is because its hub height is highest among the models considered in this study. The C_f values for this model are 14.78%, 4.70%, 26.34%, 8.60%, 24.73% and 36.10% for Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna, respectively. Furthermore, the P17-50 model has the least capacity factors for each site. This is due to its cut-in wind and rated wind speeds which are highest compared with other low rated power ($\leqslant$50 kW) wind turbine models. The capacity factors for P10-20, P15-50 and P50-70 are equal and greater than the suggested value recommended before an investment can be considered worthwhile in Ilorin and Makurdi. In addition, the P19-100 model can be marginally considered for wind energy development in Ilorin and

Table 4
Characteristics of the selected wind turbines [20].

	Polaris P10-20	Polaris P15-50	Polaris P17-50	Polaris P19-100	Polaris P50-500
Rated power (kW)	20	50	50	100	500
Hub height (m)	36.6	36.6	36.6	60	70
Rotor diameter (m)	10	15.2	16.5	19.1	50
Cut-in wind speed (m/s)	2.5	2.5	2.7	2.5	2.5
Rated wind speed (m/s)	10	10	11	12	12
Cut-out wind speed (m/s)	25	25	25	25	25

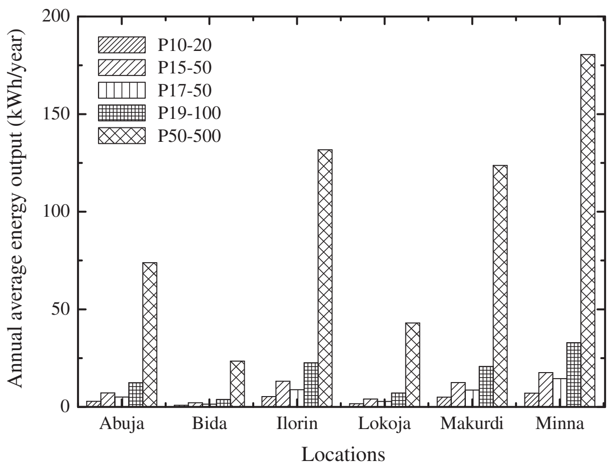

Fig. 1. The annual power output from the selected wind turbine models for all the locations.

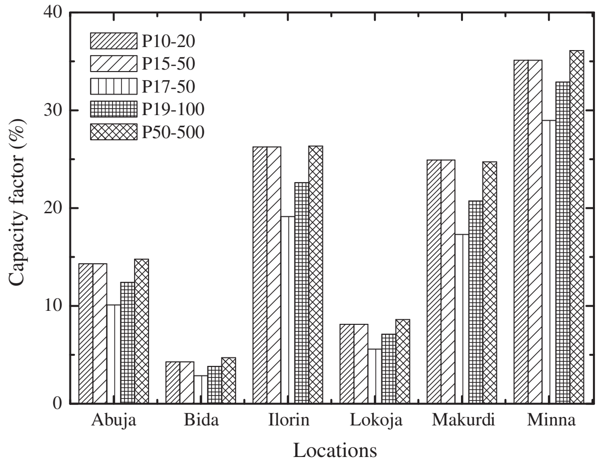

Fig. 2. The capacity factor for the selected wind turbine models for all the locations.

Makurdi. In addition, all the models are good choice for wind energy development in Minna.

The capacity factors for the models for Abuja, Bida and Lokoja indicate that they may not be good sites for wind energy development for electricity generation but small scale applications. However, by re-design the selected wind turbine models to operate at higher hub heights and lower rated wind speed compared with their current design parameters both the annual energy output and capacity factor in these sites (especially, Abuja) could significantly be improved.

Table 5
Cost analysis for selected wind turbines ($/kWh).

	WT-model	$LCOE_{min}$	$LCOE_{max}$	$LCOE_{ave}$
Abuja	P10-20	0.3186	0.4344	0.3765
	P15-50	0.1810	0.3331	0.2571
	P17-50	0.2564	0.4718	0.3641
	P19-100	0.2087	0.3840	0.2964
	P50-500	0.0982	0.2244	0.1613
Bida	P10-20	1.0652	1.4525	1.2589
	P15-50	0.6052	1.1136	0.8594
	P17-50	0.9065	1.6679	1.2872
	P19-100	0.6784	1.2482	0.9633
	P50-500	0.3088	0.7059	0.5074
Ilorin	P10-20	0.1736	0.2367	0.2052
	P15-50	0.0986	0.1815	0.1401
	P17-50	0.1354	0.2492	0.1923
	P19-100	0.1146	0.2109	0.1628
	P50-500	0.0551	0.1259	0.0905
Lokoja	P10-20	0.5615	0.7656	0.6636
	P15-50	0.3190	0.5870	0.4530
	P17-50	0.4630	0.8537	0.6584
	P19-100	0.3644	0.6704	0.5174
	P50-500	0.1687	0.3855	0.2771
Makurdi	P10-20	0.1829	0.2495	0.2162
	P15-50	0.1039	0.1913	0.1476
	P17-50	0.1437	0.2754	0.2096
	P19-100	0.1249	0.2299	0.1774
	P50-500	0.0586	0.1340	0.0963
Minna	P10-20	0.1298	0.1770	0.1534
	P15-50	0.0738	0.1357	0.1048
	P17-50	0.0895	0.1646	0.1271
	P19-100	0.0788	0.1449	0.1119
	P50-500	0.0402	0.0918	0.0660

5.2. Electricity cost

The economic analysis of the selected wind turbine models was carried out using LCOE method. The cost estimation per unit kWh of energy produced by models was estimated based on the following assumptions:

i. The lifetime (n) of each of the Polaris wind turbine used in this study is 20 year [20].
ii. The interest rate (i), and inflation rate (r) were to be 16% and 4%, respectively; while the inflation escalation rate (e) was assumed to vary between 0% and 5%.
iii. Operating and maintenance cost (C_{om}) was assumed to be 25% of the annual cost of the wind turbine (system price/lifetime) and the escalation rate of operation and maintenance ($C_{om(esc)}$) is assumed varying between 0% and 10%.
iv. Other initial costs including that for land, installation, and grid integration are assumed to be 30% of the wind turbine cost.
v. It is further assumed that the wind turbine produces the same amount of energy output in each year during its useful lifetime.

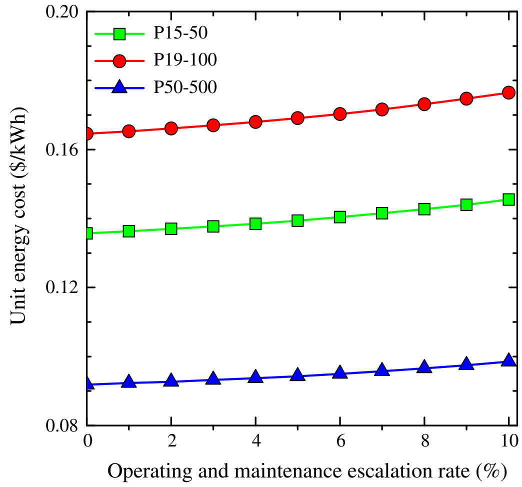

Fig. 3. Effect of operating and maintenance escalation rate on LCOE for three selected wind turbines in Minna.

The results of the LCOE without operating and maintenance and inflation escalation rates in all the sites for selected wind turbines are shown in Table 5. It can be observed that LCOE depends on the specific cost of each wind turbine and site wind characteristics (represented by the turbine capacity factor). For a given wind turbine, the least LCOE is obtained for Minna while the highest LCOE is calculated for Bida. For the lowest specific cost of each turbine, the least cost of unit energy per kWh is obtained with P50-500 model for Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna as 0.0982 $/kWh, 0.3088 $/kWh, 0.0511 $/kWh, 0.1687 $/kWh, 0.0586 $/kWh and 0.0402 $/kWh, respectively. For the highest specific cost of each turbine the LCOE vary between 0.0918 $/kWh in Minna for P50-500 model to 1.6679 $/kWh in Bida for P17-50 model. The current cost of electricity in Nigeria is about N10.00 [21] or 0.0654 $/kWh (1$ ≈ N153, [22]). From this result, it can be inferred that based on the average LCOE value for each wind turbine models and under the assumed conditions in this study, the LCOE for P50-500 model in Minna shows to be most economically viable option. However, if subsidy of about N6.00 (or $0.0400) per kWh is provided by the government to encourage investment in wind energy development, P50-500 model (in Ilorin and Makurdi), and P15-50 and P19-100 models (in Minna) could also be economically worthwhile.

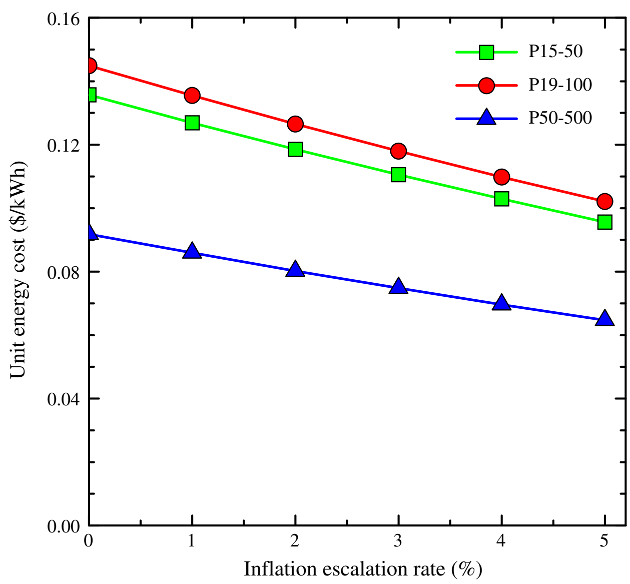

Fig. 4. Effect of inflation escalation rate on LCOE for three selected wind turbines in Minna.

In general, the operating and maintenance costs increase as the turbine lifetime decreases and the changes in inflation rate reveal a strong effect on both cost of electricity and discount rate or return on investment. The effect of operating and maintenance escalation rate on the average LCOE for P15-50, P19-100 and P50-500 models in Minna are presented in Fig. 3. When the operating and maintenance escalation rate increases from 0% to 10%, there is a gradual increase in the unit energy cost by about 7.24%, 7.23% and 7.30%, respectively, for P15-50, P19-100 and P50-500 models. However, with increasing inflation escalation, LCOE for these models decreases by about 29.0% (Fig. 4), while the discount rate or return on investment decreases from 11.54% to 6.23%.

6. Conclusion

In this study, the wind energy potential and economic analysis in selected six locations in north central part of Nigeria were investigated. In addition, the performance of selected commercial wind turbine models designed for electricity generation located in these sites were examined. The findings from this study can be summarized as follows:

- The annual mean wind speeds are 3.61 m/s, 2.75 m/s, 4.39 m/s, 3.16 m/s, 4.58 m/s and 4.29 m/s for Abuja, Bida, Ilorin, Lokoja, Makurdi and Minna, respectively and the respective annual mean power densities for these locations are 28.88 W/m^2, 16.57 W/m^2, 71.82 W/m^2, 26.09 W/m^2, 76.40 W/m^2 and 94.11 W/m^2.
- The capacity factor was found to vary between 2.86% in Bida with P17-50 model and 36.10% in Minna for P50-500 model.
- The economic analysis showed that the average LCOE varies between 0.0660 $/kWh for P50-500 in Minna and 1.2872 $/kWh for P17-50 in Bida.
- In term of energy production and capacity factor, Minna is most promising site for wind energy development follow by Makurdi and Ilorin among the locations considered. However, based on unit cost of electricity, Minna is the most viable site.
- Increasing the operating and maintenance escalation rate from 0% to 10% for P15-50, P19-100 and P50-500 models in Minna increase the estimated LCOE by about 7%. However, by increasing the inflation escalation rate from 0 to 5% lead to decrease in the LCOE by about 29% but return on investment is found to decrease from 11.54% to 6.23%.

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