Economic analysis of wind energy conversion systems using levelized cost of electricity and present value cost methods in Nigeria

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Abstract

Technical electricity generation assessment and economic analysis of six wind energy conversion systems in the categories small, medium, and large (with power ratings of 20, 35, 275, 500, 1,000, and 2,000 kW) were examined in this study. Electricity cost values were estimated based on the levelized cost of electricity (LCOE) and present value cost (PVC) methods for six locations selected across all the geopolitical zones of Nigeria. This was done using wind speed data that span between 25 and 37 years, measured at the height of 10 m. The result showed that the annual average energy output ranges from 2.242 MW h in Uyo with P10-20 turbine to 12,521.55 MW h in Kano using Vestas V80-2 MW wind turbine. Furthermore, of all the selected sites, Kano gave the least costs of electricity production per kilowatt hour with Vestas V80-2 MW model at 67-m hub heights, while the highest is obtained in Uyo with GEV-HP (1 MW) model at 70-m hub heights for the LCOE and PVC height for both the LCOE and PVC methods. In addition, sensitivity of the selected parameters to the levelized cost of electricity was also carried out.

Keyword: Economic analysis, Wind energy, Wind energy conversion system, Capacity factor, Nigeria

Background

Wind, a form of clean energy among other renewable energy sources, has been experiencing rapid growth during the last two decades. The growth may be attributed to the promotion of models of renewable energy sources, energy supply security, fuel diversity concerns, ecological awareness, and economic reasons [1]. It has a major advantage of generating power near load centers, thus eliminating transmission losses especially in rural areas. Wind power capacity in recent years has increased in some countries [2] (Table 1), but the utilization rate in Nigeria is still limited to very few sites that are constructed for water pumping and other low-energy demanding activities, with none yet developed for grid electricity. This may be explained by the country's overdependence on oil and gas as sources of energy for export and other socio-economic activities. The decreasing reserves of these fossil fuels, together with environmental impact through pollution and ozone layer depletion,

have called for the search of alternative sources of energy that are clean and renewable such as wind, solar, biomass, hydro, etc. In addition to these energy resources, solid waste can be classified as renewable energy source and used to generate energy in various forms, such as heat and electricity [3]. This energy source is also in large quantity across the country.

According to Adaramola et al. [4], 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. However, several research works have indicated promising and viable site for wind harvesting in the country (e.g., [5–9]). Some locations are adjudged as good sites for wind turbine installations for electricity generation and other types of wind applications. In spite of all the numerous work carried out so far on wind analysis in Nigeria, only few research studies have been focused on the economic analysis of wind applications in few sites in Nigeria. For instance, Ohunakin and Akinnawonu [10] conducted the economic feasibility of using wind energy conversion systems in Jos, Nigeria, using the present value cost (PVC) method, Ngala et al. [11] carried out an economic assessment on the viability of wind energy as a power source in

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Table 1 Top ten installed wind power capacities (MW)

	Country	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
1	USA	2,554	4,275	4,685	6,374	6,740	9,149	11,603	16,818.8	25,170	35,159	40,200	46,919
2	Germany	6,113	8,754	12,001	14,609	16,628.8	18,427.5	20,622	22,247.4	23,903	25,777	27,214	29,060
3	Spain	2,235	3,337	4,830	6,202	8,263	10,027.9	11,630	15,145.1	16,754	19,149	20,676	21,674
4	China	340	401	468	566	764	1,266	2,599	5,912	12,210	25,104	44,733	62,733
5	India	1,167	1,407	1,702	2,110	2,985	4,430	6,270	7,850	9,645	10,925	13,064	16,084
6	Italy	427	682	788	904	1,265	1,718.3	2,123.4	2,726.1	3,736	4,850	5,797	6,747
7	France	79	85	147	198	390	757.2	1,567	2,455	3,404	4,410	5,660	6,800
8	UK	408	464	552	647.6	900.8	1,353	1,962.9	2,389	3,241	4,070	5,203	6,540
9	Denmark	2,300	2,417	2,880	3,110	3,117	3,128	3,136	3,125	3,180	3,465	3,752	3,871
10	Portugal	100	127	193.8	288.6	562	1,022	1,716	2,130	2,862	3,535	3,702	4,083

From [2].

Maiduguri, while Adaramola et al. [4] examined the economic viability of wind applications in selected sites in the north-central region using the levelized cost of electricity (LCOE) technique.

In this present study, a brief review of wind energy resource assessment in selected locations across Nigeria is presented. Investigation of wind energy generation and the economic analysis of wind turbine applications in Nigeria are also carried out by comparing LCOE and PVC methods of analysis for the various wind energy conversion system (WECS) with power capacities ranging from small to medium and large size. The levelized cost of an energy resource (per kilowatt hour) represents a constant cost per unit of generation computed to compare one unit's generation costs with other resources over similar periods. LCOE model takes into consideration the net present value of the current and future annual costs, whereas the PVC methods takes into consideration the current value of the total cost of energy investment during the entire lifetime of the energy conversion system. Six locations spreading across the country are selected for this analysis, and the locations are as follows: Kano (NW), Bauchi (NE), Uyo (SS), Owerri (SE), Minna (NC), and Iseyin (SW). The selected sites (Kano, Bauchi, Minna, Iseyin, Owerri, and Uyo) were found in previous works to be the best wind representative for each of the six geopolitical zones in Nigeria [5–9]. This information provided in this paper will be useful to wind energy developers, governments at various levels, and individuals, as well as private organizations that are interested in wind energy development.

Methods
The wind data used in this study were obtained from the Nigerian Meteorological Agency, Oshodi, Lagos. The data for the selected locations were captured at the height of 10 m by a cup-generator anemometer. The recorded wind speeds were obtained on hourly basis and thereafter computed as the mean of the speed for each month.

Wind energy studies in the selected locations
Wind distribution function adopted in this work is the Weibull function because it has been found to give a better fit with experimental data [7,12]. Its probability density function is expressed as:

$$f(u) = \left(\frac{k}{c}\right)\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{k}\right)^{k}\right] \qquad (1)$$

where k and c (m/s) are the Weibull shape and scale factors, respectively and u (m/s) is the wind speed.

Table 2 depicts the wind characteristics and geographical coordinates of the selected locations. It can be observed from this table that the minimum wind speed among the selected locations is 3.17 m/s in Uyo, while the maximum value is 7.77 m/s in Kano. In addition, the power densities (P_D) are 368.92, 120.52, 94.11, 54.96, 26.42, and 19.91 W/m² for Kano, Bauchi, Minna, Iseyin, Owerri, and Uyo, respectively. It can be seen that the maximum P_D is in Kano ($P_D = 368.92$ W/m² > 300 W/m²) and falls under class 6 of the wind resource category based on the Battelle-Pacific Northwest Labs (PNL) wind power classification scheme, while the least exists in Uyo ($P_D = 19.91 < 100$ W/m²) and found within class 1 range [13]. Furthermore, the most probable wind speed (U_{mp}) and wind speed carrying maximum energy (U_{max}) ranged from 3.31 to 7.92 m/s and 3.58 to 9.57 m/s in Uyo and Kano, respectively. The Weibull shape and scale parameters (k and c) showed that k varies from 2.32 (Minna) to 6.36 (Uyo), while c is between 3.42 and 8.57 m/s in Uyo and Kano, respectively. Detailed wind speed characteristics in other selected sites are shown in Table 2, and comprehensive work on these analyses can be found in, e.g., [5–9,11].

Kano has been found to be very suitable for wind turbine applications, while Bauchi may be considered marginally for wind power development though a higher hub height will be better preferred for economical wind power generation; Minna, Iseyin, Owerri, and Uyo, each

Table 2 Wind characteristics and geographical coordinates of the selected sites

Location	Mean wind speed (m/s)	Average power density (W/m^2)	PNL classifications	k	c (m/s)	U_{mp} (m/s)	U_{max} (m/s)	Latitude (°N)	Longitude (°E)	Altitude (m)	Duration	Geopolitical location
Kano	7.77	368.92	6	4.04	8.57	7.92	9.57	12.03	08.12	472.5	1971 to 2007	NW
Bauchi	4.83	120.50	2	2.45	5.44	4.32	7.04	10.17	09.49	609.7	1971 to 2007	NE
Minna	4.291	94.11	1	2.32	4.84	3.73	6.42	09.37	06.32	256.4	1971 to 2007	NC
Iseyin	4.074	54.96	1	3.77	4.51	4.08	5.15	07.58	03.36	330.0	1983 to 2007	SW
Owerri	3.355	26.42	1	6.36	3.62	3.47	3.84	05.29	07.00	91.0	1977 to 2006	SE
Uyo	3.17	19.91	1	6.37	3.42	3.31	3.58	05.30	07.55	38.0	1981 to 2007	SS

location placed under class 1, may only be adequate for non-connected electrical and mechanical applications like battery charging and water pumping. From this assertion, all the regions are suitable for one form of wind energy application or the other; many sites in the North-West regions are suitable for grid-connected applications [7], and most locations in NC, SW, SE, and SS are more applicable to non-connected electrical applications.

Wind speed extrapolation and electrical power output
The selected wind turbines are designed to operate at different hub heights when compared to the available measured wind data; hence, the captured wind speed height (10 m) can be extrapolated to the turbine hub height through the power law expression given as:

$$\frac{U}{U_o} = \left(\frac{h}{h_o}\right)^a \tag{2}$$

where U is the wind speed at the wind turbine hub height h, U_o is the wind speed at original height h_o, and α is the surface roughness coefficient. In most cases, the accurate value of the surface roughness coefficient is not readily available or ascertained. Therefore, another approach is to use the Weibull probability function parameter values determined at the measured height and extrapolate them to the hub heights using the following expressions [14] as:

$$c(h) = c_o \left(\frac{h}{h_o}\right)^n \tag{3}$$

$$k(h) = k_o \left[1 - 0.088 \ln\left(\frac{h_o}{10}\right)\right] / \left[1 - 0.088 \ln\left(\frac{h}{10}\right)\right] \tag{4}$$

where c_o and k_o are the scale and shape factors, respectively, at the measurement height h_o, while h is the hub height. This approach is employed in this study to

determine the capacity factor and mean power output from selected commercial wind turbines. This because it is easier to implement once the shape and scale factors of the Weibull function at the measured height has been determined. The exponent n is defined as [14]:

$$n = [0.37 - 0.088 \ln(c_o)] / \left[1 - 0.088 \ln\left(\frac{h}{10}\right)\right] \tag{5}$$

The performance of any installed wind turbine at any location can be evaluated by the mean power output ($P_{e,ave}$) over a period of time (usually, monthly and annually) and the capacity factor C_f (representing the fraction of the mean power output over a period of time to the rated electrical power P_{eR} of the turbine). The mean power output $P_{e,ave}$ and C_f can be calculated using the following expressions based on Weibull distribution function [15]:

$$P_{e,ave} = P_{eR} \left(\frac{e^{-\left(\frac{U_c}{c}\right)^k} - e^{-\left(\frac{U_r}{c}\right)^k}}{\left(\frac{U_r}{c}\right)^k - \left(\frac{U_c}{c}\right)^k} - e^{-\left(\frac{U_f}{c}\right)^k}\right) \tag{6}$$

$$C_f = \frac{P_{e,ave}}{P_{eR}} \tag{7}$$

U_c, U_r, and U_f are the respective cut-in wind speed, rated wind speed, and cutoff wind speed of the WECS. The capacity factor can be used to identify sites that are suitable for wind energy development and for the selection of wind turbine among available turbine to be installed in a site with known wind speed characteristics. The accumulated annual energy output (E_o) is given by:

$$E_o = P_{e,ave} \times 8760(kW \ h) \tag{8}$$

Economic analysis of selected turbines
Accurate estimate of all the costs involved in generating electricity over the life span of a WECS is essential for

its economic viability in order to produce energy at a low operating cost [16]. The cost of a wind turbine is mostly set by the manufacturer, and it is shown to be dependent on the rated power (and control systems and other accessories) and varies from one manufacturer to another, as depicted in Table 3 [1,16,17]. As expected, new WECS always have low expenditures on operation and maintenance; however, the operation and, especially, the maintenance costs increase as the useful life of the power plant decreases [1]. Other factors which can influence the cost of electricity produced by WECS include cost of construction and other infrastructures, wind speed regime in selected location, turbine lifetime, and discount rate [1,17,18].

Out of the three different ways of quantifying the cost of wind turbines (cost per unit kilowatt, cost per unit rotor area, and cost per unit kilowatt hour of electricity produced) as expressed in [17], cost of electricity per unit kilowatt hour is adopted in this work and computed by comparing the LCOE with PVC to examine the economic analysis of the selected WECS. LCOE and PVC are computed using the following expressions given by [16,19] as:

$$ \text{LCOE} = \frac{\text{CRF}}{E_{\text{WT}}} \left(1 + C_{\text{om(esc)}} \right) \quad Cost/kW\ h \tag{9} $$

$$ \text{PVC} = \frac{1}{E_{\text{WT}}} \left[I + C_{\text{om}} \left(\frac{1+i}{r_o - i} \right) \times \left[1 - \left(\frac{1+i}{1+r_o} \right)^n \right] \right. $$
$$ \left. -S \left(\frac{1+i}{1+r_o} \right)^n \right] \tag{10} $$

where I is the total capital/initial cost, $E_{\text{WT}} = 8{,}760 P_{\text{eR}} C_{\text{f}}$ is the annual energy output of wind turbine in kilowatt hour, and CRF and $C_{\text{om(esc)}}$ are the capital recovery factor and present worth of the annual cost throughout the lifetime of the WECS, respectively, and expressed in Equations 11 and 12 as given by[1]:

$$ \text{CRF} = \frac{(1+r)^n r}{(1+r)^n - 1} \tag{11} $$

$$ C_{\text{om(esc)}} = \frac{C_{\text{om}}}{r - e_{\text{om}}} \left[1 - \left(\frac{1 + e_{\text{om}}}{1+r} \right)^n \right] \tag{12} $$

where C_{om}, e_{om}, n, r, r_o, and i are the operation and maintenance costs for the first year, escalation of operation and maintenance, useful lifetime of the turbine,

discount rate, interest rate, and inflation rate, respectively. The discount rate can be corrected for inflation rate (i) and inflation escalation rate (e) using the following expressions [4,17]:

$$ e_a = (1 + e)(1 + i) - 1 \tag{13} $$

e_α is the apparent escalation rate, and the real rate of discount (r) adjusted for both inflation and escalation can be obtained from the expression [4,17] as:

$$ r = \frac{(1 + r_o)}{(1 + e_a)} - 1 \tag{14} $$

In using the LCOE and PVC methods to evaluate the costs of kilowatt hour of energy produced by the WECS at the selected sites, the following assumptions were taken into consideration:

1. The lifetime (n) of each turbine is considered to be 20 years.
2. Interest rate (r) and inflation rate (i) were taken as 15% and 12%, respectively.
3. The actual total of other initial costs depends on, among other factors, the available infrastructure in the selected location. For instance, it was reported that the cost of wind turbines and towers accounts for about 65% to 75% of the total initial costs in developed countries, while the cost of infrastructure, installation, and grid connection represents about 30% to 50% of the total capital cost in developing countries [20]. Considering the level of infrastructure development in most of the rural areas of Nigeria in locations included in this study, other initial costs such as that for land, infrastructure, installation, and grid integration are assumed to be 40% of the total initial cost (or about 67% of the wind turbine and tower cost).
4. Next to the wind turbine and other civil work initial capital costs, operating and maintenance cost (C_{om}) is next significant source of expenditure. The annual operation and maintenance costs have been reported to vary from about 1% to 7% of the initial system cost [20,21] and 2% to 16% of the wind turbine cost [20], depending on the rated power and age of the wind turbine. In this study, operating and maintenance cost is assumed to be 7% of the initial capital cost of the wind turbine installation system (system price/lifetime).Considering the higher assumed initial operation and maintenance costs, the escalation rate of operation and maintenance ($C_{\text{om(esc)}}$) is assumed to be 0% in this analysis.
5. Scrap value was assumed to be 0% of the turbine price and civil work. It is expected that the unit price of electricity will be slightly higher based on this

Table 3 Cost of wind turbines based on the rated power

Wind turbine size (kW)	Specific cost (US$/kW)	Average specific cost (US$/kW)
10 to 20	2,200 to 2,900	2,550
20 to 200	1,500 to 2, 300	1,900
200>	1,000 to 1,600	1,300

Table 4 Characteristics of the selected wind turbines

Characteristics	P10-20	G3120	GEV-MP	P50-500	GEV-HP	Vestas V80-2 MW
Hub height (m)	36.6	42.7	60	70	70	67
Rated power, P_r (kW)	20	35	275	500	1,000	2,000
Rotor diameter (m)	10	19.2	32	50	62	80
Cut-in wind speed, U_c (m/s)	2.5	3.5	3.5	2.5	3	4
Rated wind speed, U_r (m/s)	10	8	15	12	15	16
Cutoff wind speed, U_f (m/s)	25	25	20	25	25	25

From [22–27].

assumption than if non-zero percentage is assumed for the scrap cost.

6. In practice, the annual mean wind speed in the selected locations may vary from year to year. However, it will be difficult to estimate the level of variation in the wind speed and, hence, the energy produced over the entire useful life of the wind energy conversion systems. Therefore, it is assumed in this study that the wind turbine produces the same amount of energy output in each year during its useful lifetime.

Results and discussion

Performance of wind turbines

Six (small, medium, and large) wind turbines with power ranging from 20 kW to 2 MW [22–27] were selected for performance assessment and economic analysis. The characteristic properties of the selected wind turbines using their respective designed hub heights are shown in Table 4. In [16], the factors influencing energy produced by any WECS at sites taken into consideration during the related time period are the power response of the WECS to different wind velocities, wind regime, and wind speed distribution. Hence, the annual average power and energy outputs, together with the capacity factors of the turbines for the selected locations, are computed using Equations 6, 7, and 8, and the computed results are listed in Table 5. It can be observed that the annual average energy output ranges from 2.242 MW h in Uyo with P10-20 turbine at 36.6-m hub

heights to 12,521.55 MW h in Kano using Vestas V80-2 MW wind turbine at a 67-m hub height. Even though P50-500 and GEV-HP wind turbines have higher hub heights than Vestas V80-2 MW turbine, higher energy generation is possible with Vestas V80-2 MW because its higher rated power when compared with P50-500 and GEV-HP, respectively. Since the energy yield depends on the availability and strength of the wind speed at a given site and the particular WECS adopted [1], it can be readily seen that irrespective of the location, P10-20 turbine produces the least energy, with the most being given by V80-2 MW wind turbine. Hence, V80-2 MW model at 67-m hub height may be considered as the best type for energy generation at all the locations. Kano, among the considered sites in this work, exhibited the best situation from the energy production point using any of the selected WECS.

Figure 1 depicts the capacity factors for the selected wind turbines. The capacity factor reflects how effectively the turbine could harness the energy available in the wind spectra; it is expressed in an annual basis and as a function of the turbine as well as the wind regime characteristics [16]. The capacity factor for a reasonably efficient turbine at a potential site may range from 0.15 to 0.4 [7,28,29]. The least value of capacity factor, 0.22%, is obtained with GEV-HP turbine at 70-m hub heights, while the highest, 89.8%, is obtained in Kano with G3120 model at 42.7-m hub heights. Generally, from the figure, it can be observed that the lowest values of capacity factors across the WECS are obtained in Uyo,

Table 5 Mean annual power (kW/year) and accumulated annual energy outputs (MW h/year) for selected WECS

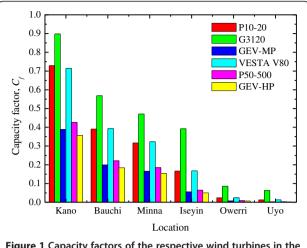| WECS (hub height)	Kano		Bauchi		Minna		Iseyin		Owerri		Uyo	
	Mean annual power output	Energy output	Mean annual power output	Energy output	Mean annual power output	Energy output	Mean annual power output	Energy output	Mean annual power output	Energy output	Mean annual power output	Energy output
P10-20 (36.6 m)	14.58	127.689	7.80	68.345	6.33	55.451	3.32	29.101	0.48	4.170	0.26	2.243
G3120 (42.7)	31.43	275.327	19.90	174.302	16.48	144.317	13.73	120.249	2.99	26.184	2.21	19.377
GEV-MP (60 m)	106.84	935.897	54.86	480.596	45.46	398.208	15.32	134.181	2.063	18.068	0.69	6.023
P50-500 (70 m)	213.20	1,867.632	110.75	970.170	92.50	810.300	32.20	282.072	4.45	38.982	1.55	13.578
GEV-HP (70 m)	356.90	3,126.444	184.30	1,614.468	153.90	1,348.164	49.90	437.124	6.70	58.692	2.20	19.272
Vestas V80-2 MW (67 m)	1,429.40	12,521.544	786.40	6,888.864	646.00	5,658.960	335.40	2,938.104	49.60	434.496	26.60	233.016

Figure 1 Capacity factors of the respective wind turbines in the selected locations.

whereas the highest values are recorded in Kano for all the models selected. Hence, considering the capacity factor of all the WECS for all the selected sites, Kano has a strong wind regime and hence a suitable potential for energy generation.

Economic analysis of selected wind turbines

Table 6 shows the economic result of comparing the LCOE and PVC method of cost analysis for the selected WECS in the respective locations. The computed values of LCOE and PVC are based on previously listed assumptions (see 'Economic analysis of selected wind turbines' in the 'Methods' section) and the average cost values of wind turbine bands shown in Table 3 (wind turbine cost band). The calculated cost values based on the two methods follow similar trends, with cost values increasing from Kano, Bauchi, Minna, Iseyin, Owerri, to Uyo, in that order, for all the turbine models adopted, as shown in the table. Whereas the least costs are estimated as US$0.0238/kW h and US$0.0182/kW h with Vestas V80-2 MW model at 67-m hub heights for the LCOE and PVC values, respectively, in Kano, the highest costs are determined as US$7.7275/kW h and US$5.9229/kW h in Uyo with GEV-HP (1 MW) model at

70-m hub heights for the LCOE and PVC values in that order. In addition, the lowest predicted cost values in all the locations with the selected turbine models is in Kano due to the high wind potential in this location. Hence, viable power generation is obtainable in high wind potential sites. Nigerian power tariff witnessed an upward review from 8.50 NGN (previously being implemented since July 1, 2008) to 10.00 NGN/kW h in April 1, 2011 [30], equivalent to US$0.0654 (US$1 ≈ 157.60 NGN [31]). Through this, the market became viable for renewable energy sources and independent power producers through a tariff system that ensures fair return on investment. Comparison of the new power tariff with the cost per kilowatt hour of electricity generated based on the LCOE and PVC methods (determined in the study) showed that Kano (models P10-20, G3120, GEV-MP (PVC), P50-500, GEV-HP (PVC), Vestas V80-2 MW), Bauchi (G3120, P50-500 (on PVC), Vestas V80-2 MW), Minna (G3120, Vestas V80-2 MW), and Iseyin with G3120 will be economically viable for wind power generation. With government supports in the form of hidden financial favors, subsidies, and any other incentives given to assist renewable energy exploitation in Nigeria, Kano, Bauchi, and Minna will be viable for power generation with all the wind turbine models.

It should be noted that the costs computed using LCOE methods are higher than those computed using the PVC method in all the location irrespective of the turbine model. This may be attributed to the following: (1) the sensitivity of LCOE to small changes in input variable and assumptions and (2) because the LCOE technique has discounted and annualized the PVC over the lifetime of the wind turbine. This is not available with PVC, thus leading to an underestimation of values as reflected in the computed values.

In order to investigate the effects of uncertainty or changes in some of the input parameters (such as wind turbine cost, interest rate, operation and maintenance cost, useful life of the wind turbine, and other initial capital cost) on the unit cost of electricity, sensitivity analysis was also carried out on GEV-MP wind turbine model in Kano (as a case study). The results of this

Table 6 Cost analysis per kilowatt hour (in US dollar) for WECS based on LCOE and PVC

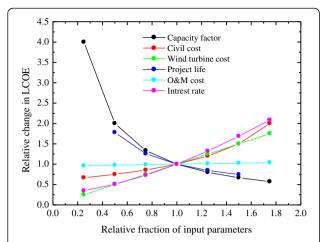|	P10-20		G3120		GEV-MP		P50-500		GEV-HP		Vestas V80-2 MW	
	LCOE	PVC	LCOE	PVC	LCOE	PVC	LCOE	PVC	LCOE	PVC	LCOE	PVC
	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)	($/kW h)
Kano	0.0458	0.0351	0.0277	0.0212	0.1467	0.0323	0.0399	0.0306	0.0662	0.0507	0.0238	0.0182
Bauchi	0.0855	0.0655	0.0437	0.0335	0.0852	0.0653	0.0768	0.0588	0.0922	0.0707	0.0432	0.0331
Minna	0.1054	0.0808	0.0528	0.0405	0.1028	0.0788	0.0919	0.0704	0.1105	0.0847	0.0526	0.0403
Iseyin	0.2008	0.1539	0.0634	0.0486	0.3052	0.2339	0.2640	0.2023	0.3407	0.2638	0.1014	0.0777
Owerri	1.4011	1.0739	0.2909	0.2230	2.2662	1.7370	1.9102	1.4641	2.5374	1.9448	0.6855	0.5254
Uyo	2.6052	1.9968	0.3931	0.3013	6.8002	5.2121	5.4840	4.2033	7.7275	5.9229	1.2782	0.9797

Figure 2 Sensitivity analysis of selected input parameters of LCOE for GEV-MP wind turbine model in Kano.

analysis are presented in Figure 2. It can be observed from this figure that the LCOE is sensitive to all the input parameters. The degree of sensitivity can be classified into two different groups. The first group comprises the capacity factor and useful life of the wind turbine. These parameters affect the LCOE very positively, that is, LCOE decreases as their values increase. This explains why a site with wind resource that provides high wind turbine capacity factor is desirable (economically). In addition, by increasing the project from 20 to 25 years, the LCOE is observed to decrease by about 15% (from US$0.0438/kW h to US$0.0370/kW h). The second group is made up of the wind turbine cost, the civil work and infrastructure costs, the interest rate, and the operation and maintenance costs. This figure indicates that with increasing value of these parameters, the LCOE increases, and hence, they have negative impact on the economic viability of wind energy system development in this location (and any other location in general). For example, there is an increase of about 20% in the unit cost of electricity if the percentage of civil work cost is increased from 40% to 50% of the total initial cost. It should be noted that the degree of influence of these parameters is not the same. It can be further observed that the cost of operation and maintenance has insignificant effect on the LCOE.

Conclusions

In this study, wind turbine performance assessment and economic analysis of selected commercial WECS were examined across all geopolitical zones in Nigeria. The findings are summarized as follows:

1. The annual average energy output ranges from 2.242 to 12,521.55 MW h in Uyo (P10-20 model) and Kano using Vestas V80-2 MW wind turbine. The highest

energy generation is also possible with Vestas V80-2 MW because of its high rated wind speed among all the considered WECS.

2. In all the locations, P10-20 turbine model produces the least energy, with the largest being given by V80-2 MW wind turbine, thereby making V80-2 MW model at 65-m hub height considerably the best type for energy generation for all the locations.

3. The capacity factor has the least value in Uyo, 0.22%, with GEV-HP turbine at 70-m hub heights, whereas the highest is obtained in Kano, 89.8%, with G3120 model at 42.7-m hub heights.

4. The least costs of electricity production per kilowatt hour are estimated as US$0.0238/kW h and US$0.0182/kW h with Vestas V80-2 MW model at 67-m hub heights in Kano, while the highest is found to be US$7.7275/kW h and US$5.9229/kW h in Uyo with GEV-HP (1 MW) model at 70-m hub heights for the LCOE and PVC values, in that order.

5. The sensitivity analysis shows that increasing the capacity factor and useful life of the wind turbine can have a positive impact on the cost of electricity produced by the WECS, while other input parameters lead to increase in LCOE as their values increase.

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