Comparative Study of Electricity Generation Costs from Photovoltaic and Wind Power Systems: A case Study of Kano

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ABSTRACT

The relatively high initial capital cost of renewable energy systems (RES) for electricity generation in comparison with fossil fuel systems give them a significant investment disadvantage in the energy sector. One of the benefits of using renewable energy systems is their substantial lower running and maintenance costs, and this advantage make them to even have lower levelized cost of energy (LCOE) than a fossil fuel system depending on the location and design of the power plant. The cost of electricity generation from dissimilar RES could differ depending on weather condition. Kano state has both wind and solar energy potentials for electricity generation, but installation of the same particular size of photovoltaic system (PVS) and wind power system (WPS) in terms of their power rating in the location, one could not know which among the two systems could give good investment cost. This is what this study is all about; it is a comparative study of electricity generation costs from PVS and WPS in kano state of Nigeria. In the study, each system has 5kW power generation rating for the costs estimate. The LCOE of a PVS is determined and compared with that of a WPS. The LCOE of the PVS is 0.576 \$/kWh and is greater than that of the WPS (0.440 \$/kWh). Conclusively, WPS has lower cost of energy generation in Kano by 23.6 % than using PVS with the same power rating considered in this study.

***Keywords**:* *Photovoltaic system · wind power system · levelized cost of energy · Kano · electricity generation ·*

1. Introduction

The need to reduce greenhouse gases (GHG) emission into the atmosphere encourages the use of clean energy resources. In it known that high concentration of GHG in the atmosphere trap the heat radiated by the Earth [1], and consequently result to global warming that represents a menace to our environment. Electricity generation using renewable energy systems (RES) do not only stabilizes nation's energy cost and supply, but significantly minimize the emission of GHG into the atmosphere [2, 3].

On searching for green energy technologies to address the rising demand of energy in the globe and poisonous emissions of GHG produced by fossil fuel energy generation plants, a photovoltaic system (PVS) and a wind power system (WPS) are two attractive RES that do not represents hazard to the environment. Dependency on weather conditions, low energy conversion efficiency, and inability to produce as large quantities of electricity as fossil fuels power plants, represent some of the disadvantages of RES [4]; PVS and WPS are not exception. Their significant shortcoming is undoubtedly their high initial capital cost, but their substantial lower running and maintenance costs compared to fossil fuels power plants could level off this disadvantage to even have lower levelized cost of energy (LCOE) depending on the location and design of the power plant.

The LCOE by using any of PVS and WPS is not at all times the same in all places around the world; weather conditions (wind velocity, solar irradiation, etc.) may not be the same, and that LCOE depends also on the scale of the RES (i.e., the size and design specifications of the system installed). For example, wind electricity generation cost in South West locations in Nigeria varies between 0.02 €/kWh and 5.03 €/kWh depending on the turbine model installed [5], and the comparison of three configurations of wind turbines (EN 5Kw, JA 20kW, and NP 100kW) each to produce a 100 kW in a location in Canada by Kabir et al. [6] show that electricity price for NP is 0.21$/kWh, whereas EN and JA prices are 65% and 16% higher respectively. The LCOE of solar panels made from China, Europe and USA could vary because of differences of technologies involved in producing them. [7] used TITAN32-300 solar PV module and evaluated the cost of generating approximately 1 MW of energy in kano. Similarly, [8] studied the economic implication of PVS and WPS for generating approximately 1 MW of electricity in some locations in Nigeria, but the costs of energy generation differ with location and the type of RES used.

Recently, the purchase and installation of PVS for homes in Kano is increasing, it is therefore very useful to know the cost of this system for small energy generation and compare it with alternative RES (i.e., the WPS) in the location. This is what this study offers as the knowledge it covers could be very beneficial in decision making by energy home users and investors.

2. Methodology

In this study, 5kW power generation rating is considered for each of the photovoltaic system (PVS) and the wind power system (WPS) for the costs estimate. LCOE of the generation systems is determined and compared. LCOE is the average amount that you will pay for each unit of electricity that your energy system will produce over its lifetime. The LCOE equation is one analytical tool that can be used to compare alternative technologies when different scales of operation, investment or operating time periods exist.

2.1 Solar Energy Cost Estimation Methods

To estimate for the cost of energy generation from PVS, one has to know the mean solar radiation and ambient temperature data of the location of application. The type and the specifications such as the efficiencies, capacity ratings, etc. of the solar panels (depending on the manufacturers), the position of the sun, the orientation and the slope of the photovoltaic surface are equally important in design and cost estimate of solar system. The daily average solar radiation and the daily average ambient temperature of Kano State which is the location considered in this study are shown in Table 1.

Table 1: Distribution of daily average solar radiation of Kano State

Latitude (Degree)	Longitude (Degree)	Solar Radiation ($kWh/m^2/day$)	Average Daily Ambient Temperature (Degree)
12.00	8.53	5.8	41

Source: [9]

2.1.1 Determination of Solar Radiation Normal to Inclined Solar panel

PVS power output depends on the amount of solar radiation reaching the surface area of the solar panel, therefore, the incident solar radiation on a tilted surface is the inclined component of the radiation, which should be calculated from the global horizontal radiation. Mathematical models have to be used to determine some parameters before the solar radiation incident on a horizontal surface is computed, the methods of calculating the parameters are as follows [10]:

1. Declination angle δ: This is the angle between the line joining the centers of the sun and the earth and its projection on the equatorial plane. It is calculated as;

$$\delta = 23.45\, sin\left(360\ \frac{284+n}{365}\right) \tag{1}$$

Where, n is day of the year; taking January 1st as 1 through 365.

2. Hour angle ω: This is the angular displacement of the sun, east or west of the local meridian, due to the rotation of the earth on its axis at 15^0 per hour. The sunset hour angle, ω_s in degree (i.e., the hour angle from sunrise to sunset) is used for the computation, and is given as:

$$\omega_s = cos^{-1}(-\,tan\,\phi\, tan\,\delta) \tag{2}$$

3. Ratio between beam on inclined and horizontal plane: The ratio of daily mean beam radiation incident on the tilted surface to daily mean beam radiation incident on the horizontal surface of the photovoltaic module is given below as;

$$R_b = \frac{Cos(\phi-\beta)Cos\delta Cos\omega_s + Sin(\phi-\beta)\, Sin\,\delta}{Cos\,\phi\, Cos\,\delta\, Cos\,\omega_s + Sin\,\phi\, Sin\,\delta} \tag{3}$$

Where, ϕ is the latitude of the location, and β the angle of the inclined plane which corresponds to the latitude of location of use.

The annual average value of the ratio of daily mean beam radiation incident on the tilted surface to daily mean beam radiation incident on the horizontal surface is obtained from:

$$\bar{R}_b = \frac{\sum_1^n R_b}{n} \tag{4}$$

4. Average extraterrestrial horizontal solar radiation H_o: The average daily extraterrestrial horizontal solar radiation can be calculated as follows:

$$H_o = \frac{24\times3600}{\pi} I_{sc}\left[1-0.033Cos\left(\frac{360n}{365}\right)\right]\times\left[Cos\phi Cos\delta Sin\omega_s + \left(\frac{2\pi\omega_s}{360}\right)Sin\phi Sin\delta\right] \tag{5}$$

Estimated average daily extraterrestrial horizontal solar radiation can be calculated as follows

$$\bar{H} = \frac{\sum_1^n H_o}{n} \tag{6}$$

I_{sc} is the extraterrestrial normal radiation (kW/m^2); ω is the average hour angle for the day (°).

5. Clearness index K_t: This is the ratio of the solar radiation reached the earth's surface to the radiation striking the top of the atmosphere (extraterrestrial radiation). The daily annual mean clearness index is given as:

$$\bar{K}_t = \frac{\bar{H}_m}{\bar{H}} \tag{7}$$

Where, $\bar{H}_m$ is the measured annual mean global horizontal radiation reaching the earth's surface averaged over time interval (kW/m^{2}day) and $\bar{H}$ is the annual mean extraterrestrial horizontal radiation (kW/m^{2}day).

The global solar insolation is obtained by summing up the diffuse and beam radiation which is given by the following equation.

$$\bar{H}_m = \bar{H}_b + \bar{H}_d \tag{8}$$

Where, $\bar{H}_m$ is the global horizontal radiation on the earth's surface averaged over the time step (kW/m^{2}day); $\bar{H}_b$ is the beam radiation (kW/m^{2}day) and $\bar{H}_d$ is the diffuse radiation (kW/m^{2}day).

6. Determination of diffuse radiation from clearness factor: The diffuse fraction of solar radiation incident on the photovoltaic surface is a function of clearness index as follows:

$$\bar{H}_d = \bar{H}_m \begin{cases} 0.99 & for\ K_t \le 0.17 \\ 1.188 - 2.272K_t + 9.473K_t^2 - 21.865K_t^3 + 14648K_t^4 & for\ 0.17 < K_t < 0.75 \\ -0.54K_t + 0.632 & for\ 0.75 < K_t < 0.80 \\ 0.2 & for\ K_t \ge 0.80 \end{cases} \tag{9}$$

7. Determination of global solar radiation on inclined plane: The solar radiation at inclined angle equal to the latitude of the location was estimated from the expression:

$$\bar{H}_T = \bar{H}_b\bar{R}_b + \bar{H}_d\left(\frac{1+cos\,\beta}{2}\right) + \bar{H}_m\rho_g\left(\frac{1-cos\,\beta}{2}\right) \tag{10}$$

Where, ρ_g is 0.04, 0.03 or 0.28 as the diffuse reflectance of surroundings for tall grassland, short grassland and desert surfaces respectively.

2.1.2 Solar Power Output

The total size of the solar panels considered in this study is 5kW. The output power of the system, P_o depends on the system panels derating factor, and is computed from:

$$P_o = P_s \times f_s \tag{11}$$

Where, P_s is the photovoltaic solar power system capacity in kW; $f_s = 0.7$ is the photovoltaic derating factor (losses due to temperature, dirt, manufacturer's tolerance, shading, orientation, tilt angle, voltage drop, inverter, irradiance level, distribution and transmission) [11].

The numbers of a given rated solar panel for a desired system total capacity can be computed from:

$$N_{pv} = \frac{P_s}{R_s} \tag{12}$$

Where, R_s is the power rating of the selected solar panel.

The daily electricity energy generated by the solar power system is computed from [12]:

$$E_s = N_{pv} \times \eta_g \times A_s \times \bar{H}_T \qquad 13$$

The annual electricity energy generation by the solar power system is thus:

$$E_t = N_{pv} \times \eta_g \times A_s \times \bar{H}_T \times 365 \quad (14)$$

$$\eta_g = \eta_r \times \eta_{pt}\big(1 - \beta_t(T_c - T_r)\big) \quad (15)$$

$$T_c = T_a + \frac{\bar{H}_T(T_{c,NOCT} - T_{a,NOCT})}{G_{T,NOCT}} \quad (16)$$

Table 2 shows the parameters (obtained from the manufacturer) of the selected solar panel; it is a polycrystalline solar panel made by Haitai Solar - China.

Table 2 Parameters of the selected solar panel

R_{pv}	η_r	β_t	η_{pt}	$T_{c,NOCT}$	$T_{a,NOCT}$	T_r	A_s
300W	17.35%	-0.365%	0.9	42°C	20°C	25°C	1.727m^2

2.1.3 Solar Power LCOE Model

The cost of the electricity generated by a PV system is determined by the capital cost, the discount rate, the operation and maintenance cost (variable costs), the amount of solar irradiation and the efficiency of the solar cells. The capital cost of a PV system includes the PV module cost and the Balance of system (BOS) cost (that is, the cost of other items of the system) [13]. The cost of photovoltaic solar panel depends on the country of the manufacturer; policies on solar renewable energy technology from one country to the other. The average cost of photovoltaic solar panel λ_{lcs} made in China is 0.133 $/W [14].

The total cost of photovoltaic solar panel is computed from:

$$C_s = P_s \times \gamma_s \quad (17)$$

Where, P_s is the photovoltaic solar power system capacity kW; γ_s is the cost per watt of photovoltaic solar power system.

The balance of system (BOS) and installation costs for small scale systems comprise 55% to 60% of total PV system costs [13]. The annual cost of operation and maintenance of solar power system is 10% of the system cost [15].

$$LCOE = \frac{(C_s + C_s\lambda) + (mC_s + mC_s\lambda)\left[\frac{(1+r)^n - 1}{r(1+r)^n}\right]}{E_t} \quad (18)$$

Where, $(C_s + C_s\lambda)$ is capital or investment cost; $(mC_s + mC_s\lambda)$ is the annual operation and maintenance cost of the solar power system; $\lambda = 60\%$ is the percentage of PV investment cost as the BOS and installation cost; $m = 10\%$ is the percentage of the total PV system investment cost as the annual operation and maintenance cost; E_t is the annual electricity generated based on the assumption that the daily energy generated is constant; r is the discount rate; $n = 25$ years, the economic life of the solar power system.

2.2 Wind Energy Cost Estimation Method

For determination of cost of energy generation from WPS, this study has adopted the LCOE estimated by [16] for Kano. In their work, the assumption to determination of LCOE was based on 5kW rated WPS at 20m height, and assumed discount rate of 12%. Wind speed data of Kano and characteristic of the wind turbine considered were used in determining the power output of the WPS for the location.

The LCOE measures the overall life cycle costs of a technology per unit of electricity produced by the WPS and is given as [17]:

$$\mathrm{LCOE} = \frac{\sum_{t}^{T} \frac{C_t + O_t + F_t + D_t}{(1+r)^t}}{\sum_{t}^{T} \frac{E_t}{(1+r)^t}} \quad (19)$$

Where, *C* is the capital cost; *O* is operations and maintenance (O&M) cost; *F* is fuel cost; *D* is the decommissioning cost; *E* is the amount of energy produced (kWh); *r* is the discount rate (%); and *t* is the year in which a cost occurs during the project lifetime *T*.

3.0 Results and Discussion

The results of the study for the PVS and that for the WPS (as adopted from the work of [16]) are presented in Table 3. For the PVS cost calculation, Table 1 and equations 1 to 10 were used in the order of how they are presented (one after the other) and determined the global solar radiation, H_T. The annual electric energy generation by the PVS was then calculated using equation 13 (equations 10, 11, and 12 were computed first). By using the calculated annual energy generation, E_t and the total cost of photovoltaic solar panel (equation 17), the LCOE was then determined using equation 18.

Table 3. LCOE of PVS and WPS

S/No.	Energy System	LCOE (*$/kWh*)
1	PVS	0.576
2	WPS	0.440

It can be seen in Table 3 and as presented in pie chart (Figure 1) that the LCOE of the PVS is 0.576 *$/kWh* which is greater than of WPS (0.440 *$/kWh*). That means for the two energy generation systems, WPS has lower cost of energy generation in Kano by 23.6 % at the same power rating (5Kw) considered in this work. It was also found from the study by [8] that the LCOE from the WPS are comparatively lower than those from the PVS in kano for generation of many Mega-Watts (power) of electricity. It thus shows more profitable WPS is for electricity generation in Kano than utilizing PVS.

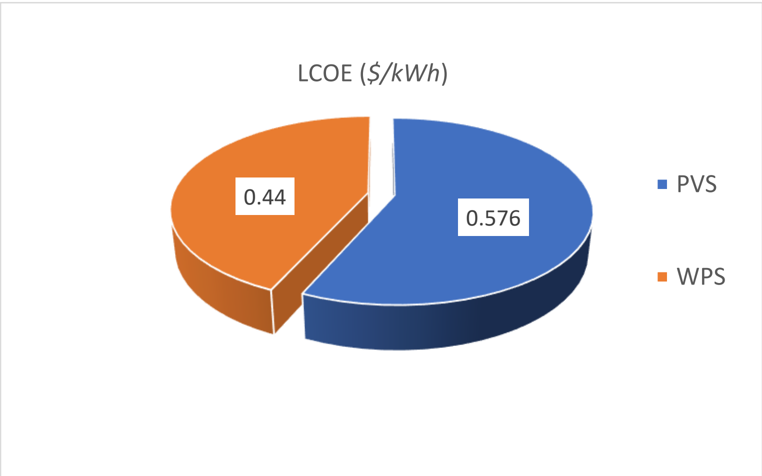

Figure 1. LCOE of the two electricity generation systems

4.0 Conclusion

A comparative study of electricity generation costs from a PVS and a WPS for Kano was carried out. The LCOE of a PVS was estimated for the selected location and compared with that of a WPS with the same power rating (5kW). The LCOE of the PVS is 0.576 *$/kWh* and is greater than that of the WPS (0.440 *$/kWh*);

WPS has lower cost of energy generation in Kano by 23.6 % than using PVS with the same power rating considered in this study. It thus shows that WPS is more profitable for electricity generation in Kano than utilizing PVS.

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