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Techo-Economic Optimization of Hybrid Renewable Energy Resources for Electrical Power Generation: A Case Study Jibia General Hospital

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Research Article

Abstract

The gradual depletion of non-renewable energy sources accompanied by their social, economical and environmental issues has given rise to the adaptation of renewable energy systems. Despite the problems described above, many countries are taking a long time to deploy renewable energy because of the high capital costs and uncertainty. Therefore, this work considered an optimized techno-economic design of a standalone PV, Wind and Battery RES for power generation considering coordinate (13.0931◦N, 7.2248◦E) of Jibia Katsina state Nigeria, using Hybrid Optimization Model for Electric Renewables (HOMER) simulation software system. The simulation was carried out in three scenarios namely; PV and Battery, Wind and Battery, and PV, Wind and Battery. The Levelized Cost of Energy (LCOE) obtained from HOMER was found to be ₦44.14/kWhr, ₦29.63/kWhr and ₦29.48/kWhr respectively. The Loss of Power Supply Probability (LPSP) obtained from HOMER was found to be 0.0328%, 0.0021%, and 0.0137% respectively. The Excess Energy (ExE) produced from HOMER simulation was found to be 4,238kW, 7,710kW, and 3,523kW

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1. Introduction

Due to global warming, Technological advancement, increase in population, the attention of this generation has been drawn towards harnessing Renewable Energy Sources (RES) (Zhou *et al*., 2010). RES has been identified as a feasible alternative for solving the power supply issues in distant and rural locations where the utility grid is unavailable and no existence of other energy sources. (Nadjemi *et al*., 2016). Energy generation of RES can be achieved from natural resources such as sun, wind, biomass, geothermal, and so on. These energy sources will never run out, however, they are uncertain and unpredictable(Kumar et al., 2020). Hybrid power systems are the most reliable renewable energy sources, because these system combines multiple RES consisting of wind, PV, small hydro, geothermal and so on, to enhance the system reliability and performance (Horatian et al., 2018), and can also cater for the sudden increase in load demand within the system which cannot be certified with a single RES (Al-Falahi *et al.*, 2017).

The climate condition in Nigeria is considered favourable for both wind and solar energy generation due to its location. (Modu et al., 2018), these offer the best solution and hope to meet its present and future load demand, and predominantly rural communities that are not grid connected (Sambo, 2009). Hydro Electric Power is the renewable energy source currently being used and connected to the grid. (Charles, 2014). As reported by International Energy Agency (IEA), only 10% of rural and about 30% of Nigerians' total population have access to electricity (Ugwoke *et al.*, 2020) Therefore, this work considered an optimised techno-economic design of a standalone hybrid PV, Wind and Battery RES for power generation considering coordinates (13.0931◦N, 7.2248◦E) of Jibia Katsina State Nigeria using Hybrid Optimization Model for Electric Renewables (HOMER) simulation. This method employed will increase the system reliability, and minimized the system cost and excess energy produced when optimally sized.

In recent years, renewable energy is given more concern due to the increase in highly growing evidence of global warming due to an increase in GHG emissions and population. The need for optimal sizing of RES becomes necessary, to reduce the system's total cost, and excess electrical energy and increase the reliability of the system. The Optimal minimization of system cost, excess energy and increase in system reliability by implementing some of the sizing methodologies becomes a significant area of research. In this paper, an optimize techno-economic design of a stand-alone hybrid PV, Wind and Battery system for power generation in an inaccessible area, using HOMER is presented.

The HOMER is a software that simulates the energy systems, presents the system configuration optimized by cost and lastly presents the sensitivity analyses. The tool is more robust as a result of these three methods than other numerically based optimization tools. Several optimization tools, in addition to the

HOMER, can be used to perform the proposed modelling, these include RET Screen, and iHOGA (Improved Hybrid Optimization by Genetic Algorithms). HOMER is widely used due to its user-friendliness, flexibility, and easy-to-understand. (Bagheri *et al.*, 2018). HOMER searches for the best fit for the stated load profile among the many sizes investigated. The method works by calculating the hourly energy balance to balance demand and supply for various scenarios. (Anoune et al., 2018).The following is how the paper is reset: The technique and implementation methods for HOMER are explained in detail in methods. the findings are presented and discussed.

2. Methods

In this section, the modelling procedures for the HRES system employed using HOMER are presented. The relevant mathematical models and input data have also been discussed.

2.1 Homer

In the determination of suitable configurations, HOMER version 2.68 beta was used for the optimization. Calculating the flow of energy was used to simulate the input data, which was collected for 8760 hours. For comparison, a simulation of PV and Battery, Wind and Battery, and PV, Wind and battery configurations are performed per net present cost. One of HOMER's primary features is sensitivity analysis, which reiterates the optimization procedure for each sensitivity variable given in this study. The analysis shows how the outputs differ when the sensory inputs and decision variables are changed. The size of the PV array, the size of the wind turbines, the number of batteries, and the size of the inverter/converter are among the choice criteria.

a) HDKR (Hay, Davies, Klucher, Reindl) model was used to compute the global irradiance on the PV array given as

$$G_T = (G_b + G_d A_i)R_b + G_d(1 - A_i)\left({(1-\cos\beta)}/{2}\right)\left(1 + FSin^3\frac{\beta}{2}\right) + G\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (1)$$

Where;

G_b = global irradiance [kW/m^2];

G_d = diffuse irradiance [kW/m^2];

G_T = global horizontal radiation on the earth's surface [kW/m^2];

G_O = extra-terrestrial horizontal radiation averaged over the time step [kW/m^2];

Ai = anisotropy index,

R_b = ratio of beam radiation on the tilted surface to beam radiation on the horizontal surface,

F = horizon brightening factor,

β = surface slope

ρ_g = reflectance of ground (albedo)

$Ai = \frac{G_b}{G_O}$

$R_b = \frac{Cos\theta}{Cos\theta_z}$ and $F = \sqrt{\frac{G_b}{G_T}}$

b) The PV array output power base on equation 2:

$$P_{PV} = Y_{PV}F_{PV}\left(\frac{G_T}{G_T,STC}\right)\left[1+\alpha_p\left(T_c - T_c,STC\right)\right] \quad (2)$$

Where;

Y_{PV} = PV array rated capacity, or PV output power under standard test conditions [kW];

F_{PV} = PV derating factor [%];

G_T = solar radiation incident on the PV array [kW/m2];

G_T, STC = incident radiation at standard test conditions [1 kW/m2];

α_p = temperature coefficient [%°C];

T_c = PV cell temperature in the current time step [°C];

T_c, STC = PV cell temperature under standard test conditions [25°C].

c) The hub height of the wind speed using either power law is evaluated as:

$$U_{hub} = U_{anem} \times \frac{\ln\left(Z_{hub}/Z_0\right)}{\ln\left(Z_{anem}/Z_0\right)} \quad (3)$$

$$U_{hub} = U_{anem} \times \left(\frac{Z_{hub}}{Z_{anem}}\right)^{\alpha} \quad (4)$$

Where:

U_{hub} = is the wind speed at the hub height of the wind turbine [m/s],

U_{anem}, is the wind speed at anemometer height [m/s]

Z_{hub} is the hub height of the wind turbine [m], *ln* is the natural algorithm.,

Z_{anem} is the anemometer height [m],

Z_0 is the surface roughness length [m]

α is the power law exponent

d) The maximum power of the storage bank is calculated using.

$$P_{batt,e\max,kbm} = \frac{KQe^{-kdt} + QKC\left(1-e^{-k\Delta t}\right)}{1-e^{-k\Delta t} + C\left(k\Delta t - 1 + e^{-k\Delta t}\right)} \quad (5)$$

Where:

$$C_{Wh} = {\left(E_L \times AD\right)}/{\left(\eta_{inv} \times \eta_{batt} \times DOD\right)} \quad (6)$$

Where:

E_L = average daily load energy ($KWhr/day$),

AD =Days of autonomy of the battery,

η_{inv} = inverter efficiency,

η_{Batt} = battery efficiency

This maximum storage power is used when making choices such as whether the storage bank can store all available excess renewable energy power or how much surplus power a cycle charging generator should produce.

e) Net Present Cost (NPC) calculation HOMER computes the total net present cost using equation (7).

$$C_{NPC} = \frac{C_{ann,tot}}{CRF\left(i, R_{proj}\right)} \quad (7)$$

Where;
$C_{ann,tot}$ = total annualized cost [\$/yr],
CRF is the capital recovery cost computed as:

$$CRF\left(i, N\right) = \frac{i\left(1+i\right)^N}{\left(1+i\right)^N - 1} \quad (8)$$

Where;
N = no of years,
i = interest rate (%),
R_{Proj} = project lifetime (yr)

f) Levelized Cost of Energy (LCOE) HOMER compute the Levelized Cost of Energy using equation (9).

$$COE = \left(\frac{C_{ann,tot}}{E_{prim,AC}}\right) \quad (9)$$

Where,
$C_{ann,tot}$ = system total annualized cost [\$/yr]; $E_{prim,AC}$ = AC primary load served [kWh/yr].

The unmet load fraction equation is given below. Homer uses an equation to calculate the unmet load fraction. (2.25)

$$f_{unmate} = \frac{E_{unmate}}{E_{demand}} \quad (10)$$

Where:

$$E_{unmate} = total\ Unmate\ load\ \left(KWh/yr\right)$$

$$E_{demand} = total\ annual\ electrical\ demand\ \left(KWh/yr\right)$$

The excess electricity fraction is the proportion of total excess electricity to total electricity produced. At the end of each simulation, HOMER uses the equation to calculate this value. (2.26)

$$f_{excess} = \frac{E_{excess}}{E_{prod}} \quad (11)$$

Where:
E_{excess} = Total excess Electricity [KWhr/yr],
E_{prod} = Total Electricity Produce [KWhr/yr]

This technique is shown as it is implemented in HOMMER in Figure 1.

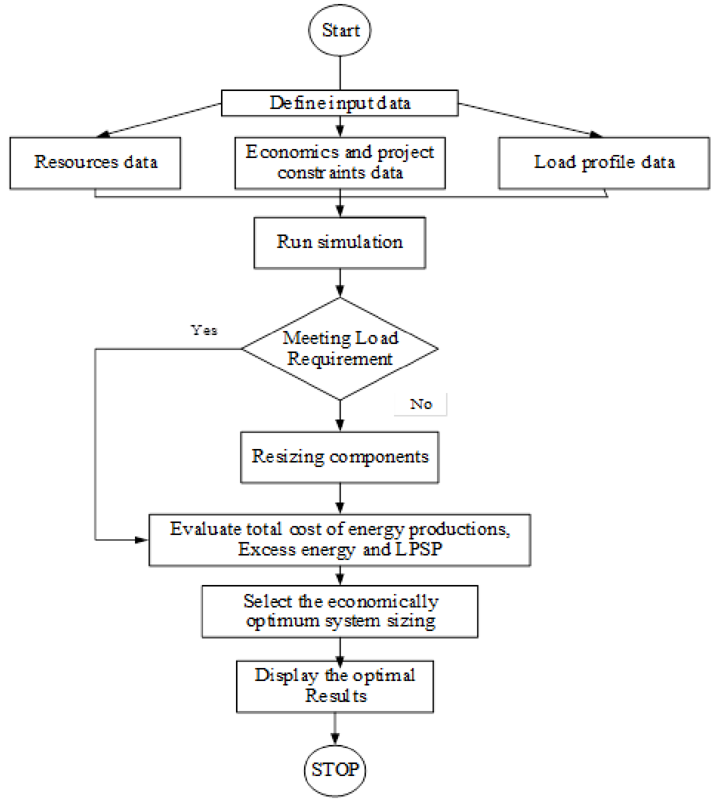

Figure 1: Implementation Procedures Using HOMER

The implementation procedure given in Figure 1, is initialised by first defining the input data. The input data in this research include solar irradiation, solar temperature, wind speed and load profile collected for the general hospital in Jibia remote area of Katsina state Nigeria with coordinate (13.0931◦N, 7.2248◦E). Figure 2, illustrates the solar irradiation and wind speed pattern employed while the load profile is given in Figure 3. Then, the design simulation given in Figure 4 was implemented.

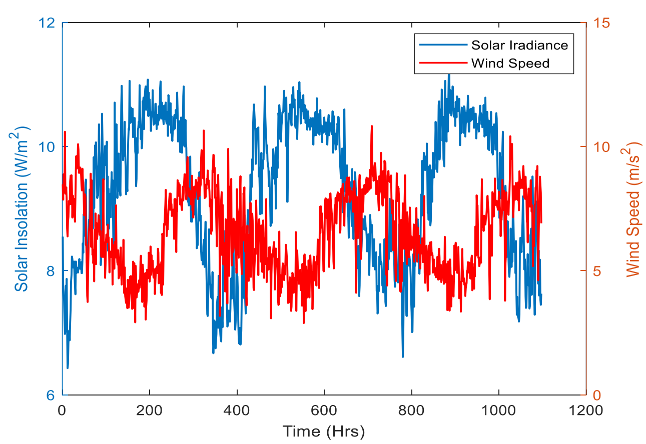

Figure 2: Wind and Solar Insolation Data

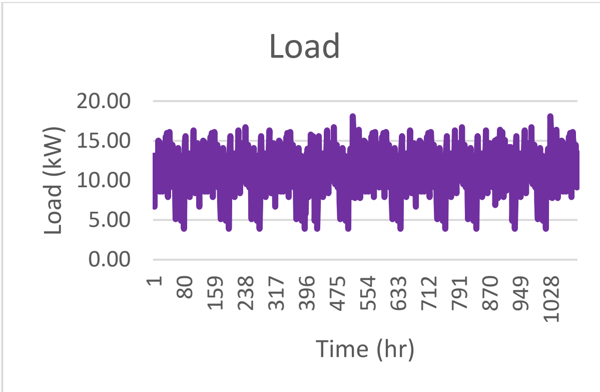

Figure 3: Load Profile Data

In this article, the required weather data for the wind turbine and PV system are described as resource data. The economic and constrain data and the penalty assigned to the sizing state of each component and the objective functions. Whereas the load profile is the hourly load data collected from the selected study area described above. Figure 4 shows the schematic diagram of the designed implementation in Homer.

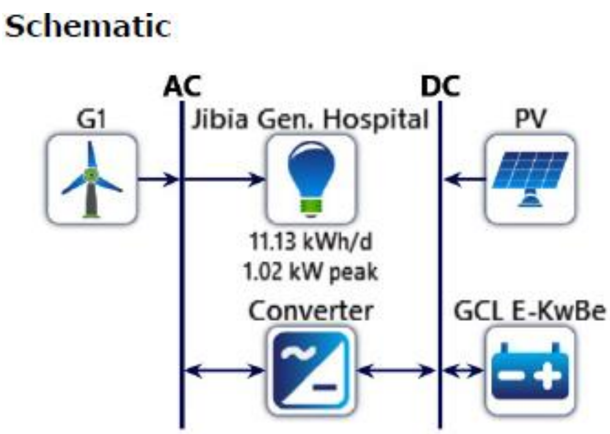

Figure 4: Schematic Diagram of the Designed Implementation in HOMER

3. Results and Discussion

In this section, the results obtained using HOMER on the design of HRES are presented

3.1 Optimal PV Design

The optimal size and power output of the photovoltaic system are presented in Figure 5 and Table 1. The rated PV array capacity under standard test conditions was 1kW

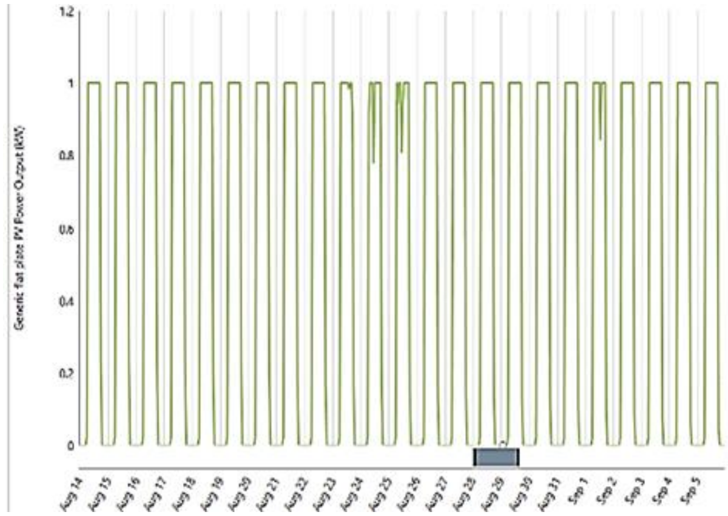

Figure 5:PV Power Output

Table 1: Generic Flat Plate PV Analysis

Summary of Electrical parameters

Quantity	Value	Units
Min Output	0	kW
Max Output	17.7	kW
PV Penetration	74.5	%
Hours of Operation	4,446	hrs/yr
LCOE	24.1	₦/kWh
Statistical Summary		
Rated Capacity	54.9	kW
Mean Output	5.28	kW
Mean Output	127	kWh/d
Capacity Factor	9.61	%
Total Energy Production	46,213	kWh/yr

.
The mean power generated by the photovoltaic system over a year was determined to be 1.80kW. The capacity factors for the PV system were obtained to be 24.9%. The PV Penetration was 25.4%. The total generated power for one year was obtained to be 15,785 kWh/year. The total hour of operation of PV was determined to be 4,446hrs/yr. The LCOE of the PV system was 8.23₦/kWh.

3.2 Optimal Wind Turbine Design

The optimal simulation results for wind size are depicted in Figure 6 and Table 2. The peak likely power amount from the wind turbine(s) was 16.1kW. The wind turbine(s) total power output per year was 91,280 kWh/yr.

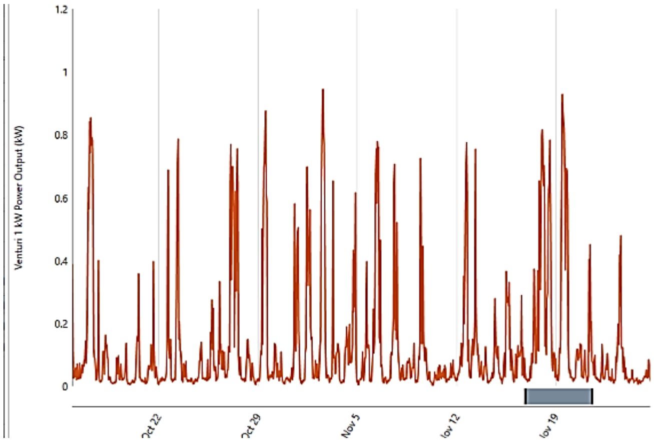

Figure 6: Wind Turbine Power Output

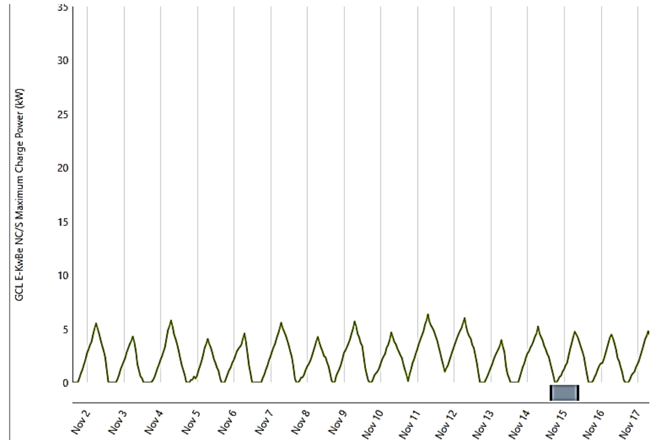

Figure 7: Battery Maximum Charge Power

Table 2: Venturi 1 kW Electrical Summary

Quantity	Value	Units
Min Output	0.652	kW
Max Output	8.71	kW
Wind Penetration	60.1	%
Hours of Operation	8,760	hrs/yr
LCOE	23.0	₦/kWh
	Statistical Summary	
Total Rated Capacity	8.00	kW
Mean Output	4.26	kW
Capacity Factor	53.2	%
Total Production	37,280	kWh/yr

The wind turbine's minimum power output was found to be 2.55 kW. The wind turbine's maximum power output was found to be 16.1kW. The wind Penetration (the ratio of the average power output of the wind turbine(s) to the average primary load) was 147%. The LCOE of the wind turbine(s) was ₦4.87/kWh.

3.3 Optimal Battery Size

For the optimal battery size, Figure 7 and Table 3 show the simulation's optimal battery size. The number of batteries observed from the collection was 17. A total of one storage string is connected in parallel. The storage array's voltage is 55.5V, which is obtained as a product of the storage voltage and string size in volts. The nominal capacity was 98.1kWh. It was discovered that the lifetime is 28,930kWh. The estimated life of the storage bank, or the number of years it will survive before it needs to be replaced, is 10 years. The average cost of the energy used to power the storage was ₦0/kWh.

The entire energy charged to the storage was discovered to be 2,937kWh/yr. The entire quantity of energy discharged from the storage was 2,849kWh, according to the results. The difference in storage charge state from the beginning to the end of the year is 0kWh/yr. Storage inefficiency results in annual energy losses of 88.1 kWh. The total amount of electrical energy that passed through the battery bank throughout the year was 2,893 kWh/yr.

Table 3: GCL E-KwBe NC/S Properties

Quantity	Value	Units
Batteries	15.0	qty.
String Size	1.00	Batteries
Parallel Strings	15.0	Strings
Bus Voltage	55.5	V
GCL E-KwBe NC/S Result Data		
Average Cost of Energy	0	₦/kWh
Energy In	8,344	kWh/yr
Energy Out	8,110	kWh/yr
Storage Depletion	17.3	kWh/yr
Losses	251	kWh/yr
Annual Throughput	8,235	kWh/yr
GCL E-KwBe NC/S Statistics		
Autonomy	9.78	Hr
Storage Wear Cost	24.2	₦/kWh
Nominal Capacity	86.6	kWh
Usable Nominal Capacity	69.3	kWh
Throughput Lifetime	80,130	kWh
Expected Lifetime	9.73	Yr

3.4 Optimal Converter/Rectifier Size

The simulation results in Figure 8 and Table 4 show the following variables. The maximum output power capacity is 58.0 kW, the converter means values are 0.790kW, and the converter minimum and maximum output power are 0 and 14.4kW respectively.

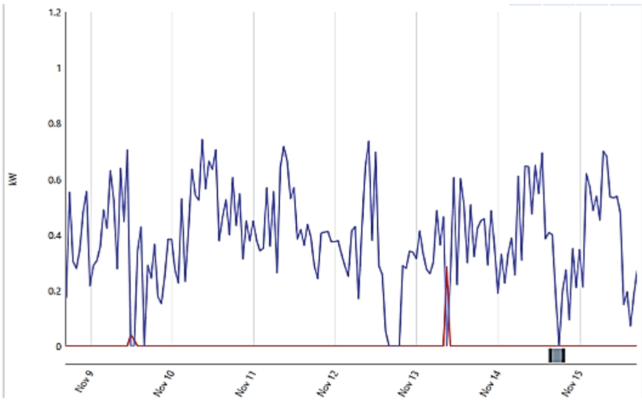

Figure 8: Inverter/Rectifier power output

Table 4: System Converter Electrical Summary

Quantity	Value	Units
Operation Hours	7,052	hrs/yr
Energy Out	26,769	kWh/yr
Energy In	28,178	kWh/yr
Losses	1,409	kWh/yr

	Statistical Summary	
Capacity	16.5	kW
Mean Output	3.06	kW
Minimum Output	0	kW
Maximum Output	16.5	kW
Capacity Factor	18.5	%

The total input energy is 7,282kWh/yr and the total output energy is 6,918kWh/yr, and the inverter capacity factor was computed to be 1.36%.

3.5 Cost Analysis

The cost summary provided in Tables 5 summarizes the cash flows as a present value or annualized cost, with each component or cost type categorized. The levelized cost of the system is calculated using the cost analysis. ₦32.98/kWh. This value justifies the economic viability of the hybrid systems as the contractor can recover the costs of designing and operating the hybrid generation system for the assumed financial life of the systems for as little as ₦32.98/kWh.

Table 4.1: Cost Analysis

		Net Present Costs				
Name	Capital	Operating	Replacement	Salvage	Resource	Total
GCL E-KwBe NC/S	₦1.86M	₦1.38M	₦2.02M	- ₦284,379	₦0.00	₦4.98M
Generic flat plate PV	₦8.62M	₦10.8M	₦0.00	₦0.00	₦0.00	₦19.4M
Other	₦0.00	₦396.36	₦0.00	₦0.00	₦0.00	₦396.36
System Converter	₦8,568	₦0.00	₦0.00	₦0.00	₦0.00	₦8,568
Venturi 1.8kW WT Turbine	₦1.52M	₦194,307	₦0.00	₦0.00	₦0.00	₦1.71M
System	₦12.0M	₦12.4M	₦2.02M	- ₦284,379	₦0.00	₦26.1M
		Annualized Costs				
GCL E-KwBe NC/S	₦145,502	₦108,000	₦158,322	-₦22,246	₦0.00	₦389,578
Generic flat plate PV	₦674,045	₦846,269	₦0.00	₦0.00	₦0.00	₦1.52M
Other	₦0.00	₦31.01	₦0.00	₦0.00	₦0.00	₦31.01
System Conv.	₦670.24	₦0.00	₦0.00	₦0.00	₦0.00	₦670.24
1.8kW WT	₦118,905	₦15,200	₦0.00	₦0.00	₦0.00	₦134,105
System	₦939,122	₦969,500	₦158,322	-₦22,246	₦0.00	₦2.04M

4. Conclusion

This work presents new optimization methods for sizing off-grid hybrid renewable power systems using the Hybrid Optimization Model for Electric Renewables (HOMER). Satellite meteorological data for Jibia Katsina State Nigeria, obtained from NASA is used to model the developed methods. HOMER was used in sizing different configurations consisting of PV/Battery, Wind/Battery and PV/Wind/Battery using, LCOE, LPSP and ExE as performance metrics. Results analysis shows that PV/Wind/Battery configuration performs better at ₦29.48/kWhr Levelized Cost of Energy, compared to ₦44.14/kWh and ₦29.63/kWh from PV/Battery, Wind/Battery respectively; while the Loss of Power Supply Probability (LPSP) obtained from PV/Battery, Wind/Battery, and PV/Wind/Battery was 0.0328%, 0.0021%, and 0.0137% respectively, and the Excess Energy (ExE) produced was 4,238kW, 7,710kW, and 3,523kW.

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