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Feasibility and Economic Assessment of a Hybrid Energy System for Bakori Area, Katsina in Nigeria

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ABSTRACT

Electricity is vital to the economic growth of any nation, as access to it, is key to achieving economic development. However, a stable electricity supply is lacking in the country, and with the increasing demand, it will be impossible to attain with the current infrastructure. This paper aims to carry out feasibility study of a hybrid energy system (HES) for sustainable power supply in Bakori Local Government Area, Katsina, Nigeria. The simulation results were generated using HOMER (Hybrid Optimization of Multiple Electric Renewables) software utilizing the solar system, and wind generator resources to satisfy the residential energy requirement for the case study. The proposed HES was compared with other configurations in terms of cost and energy production. The simulation results depict that the PV/Wind/Battery system is a viable hybrid energy system with a Net Present Cost of ₦3.62M and an electricity generation of 1,423,132 kWh/yr compared to the other configurations which produce less energy at a higher Net Present Cost.

Keywords: HOMER, Net Present Cost, Solar PV, Hybrid Energy System, Cost of Energy
JEL Classifications: Q4, Q42, P47

1. INTRODUCTION

Energy demand rises by the year due to factors like technological advancement and improved standard of living. About 1.06 billion people of the world's population do not have access to electricity (Ali et al., 2021). Also, in Nigeria, the areas connected to the grid, do not have a stable supply. Renewable energy solutions offer a means of providing stable energy to many of these areas (Benjamin and Dickson, 2017) (Shrestha et al., 2019). Sustainability is also an issue as their main sources are non-renewable and are fast depleting in availability due to the high magnitude of usage over the years (Babalola et al., 2022) (Emetere et al., 2020) Sources like fossil fuels and nuclear elements have been in use for energy generation for a long time, and these sources have served large populations of high-load demands for years with high efficiency (Faizan Khan et al., 2018) (Orovwode et al., 2018). However, these conventional sources have had adverse effects on the environment like air pollution and global warming due to the effluents being generated and released during their operations (Shafiullah et al., 2020) (Mandal et al., 2018). The wastes generated from conventional sources operations are also health hazardous (Liu et al., 2020).

A large majority of the populace are rural dwellers and as a result, lack necessary infrastructure which improve their standard of living. Many of these regions lack access to electricity and those who do have access, do not have access to stable supply. These areas are usually reliant on kerosene lamps, coal, generators and conventional sources for lighting, cooking and heating. Thus, there is a need to explore less harmful alternatives in solving the energy access problem (Balmaceda, 2018) (Enongene et al., 2019). The authors in (Mishra et al., 2016) compared Wind/Biomass and PV/Biomass energy systems using HOMER based on the cost and environment. The study was considered due to its effect on the expected load demand. The research results revealed that the PV/Biomass hybrid was more suitable for decentralised electrification, considering its reliability, economic benefit and environmental impact.

(Ohijeagbon et al., 2019) compared wind and stand-alone solar systems with hybrid systems and diesel generators in six different states of the North-central region of Nigeria. The study used the load demand of an existing University as the basis for the load demand in all considered locations. The HOMER software was used along with other statistical and analytical modifications to optimise the simulated systems. The result concluded that the hybrid stand-alone were more promising than the standalone PV or Wind systems in Lokoja, Makurdi, Ilorin and Abuja. While in Jos and Minna, the stand-alone wind system was a better option when compared with the others. However, the stand-alone and hybrid systems were more viable in terms of generation and energy cost than diesel generators.

(Usman et al., 2018) compared three configurations in a study based on emission reduction, COE and operating cost; Grid and solar PV, diesel/PV/Batteries, and, Grid alone, were simulated and optimised using HOMER. The result depicted that the PV/Grid system was more economical compared to the others while reducing CO_2 emissions compared to the grid only system. The diesel/PV/Batteries system was determined to be unfeasible due to the high costs in NPC, COE and operating cost.

2. METHODOLOGY

In designing a suitable renewable energy system, certain criteria are to be considered. For this study, the following criteria was analysed: case study specifications, the load profile and proposed hybrid energy system, components and economic assessment of the proposed system.

2.1. Case Study Specifications

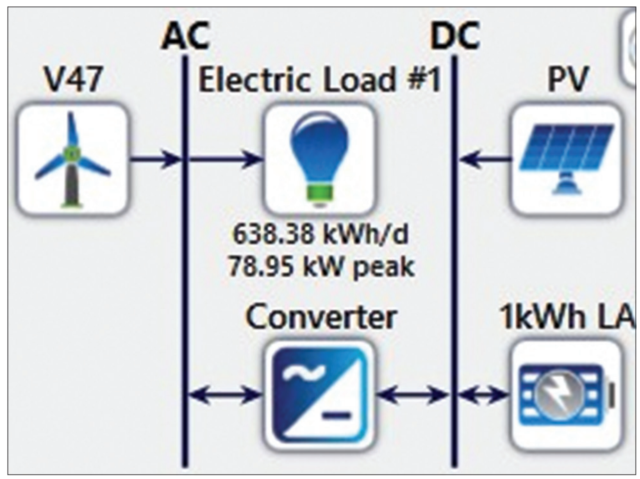
The case study selected is Bakori Local government area (LGA) in Katsina State, situated in the North-West geopolitical zone of Nigeria. The LGA is sited roughly between 11°55’30’’N – 12°43’0’’N (latitude) and 7°30’0’’E – 7°43’30’’ E (longitude) and occupies an area of 679 square kilometres. The main occupation of the area is crop production, usually supplemented by irrigation and rain-fed agriculture (Turner et al., 2017). Figure 1 shows an aerial view of the case study from Google Maps. The HES proposed structure that was simulated is shown in Figure 2, consisting of Solar system, wind, batteries and converter.

2.2. Load Profile

Households in rural areas are simple and do not require electrical energy in large amounts. However, there are usually difficulties in measuring the amount of electrical power consumed. The load profile for the community is estimated considering residential loads and other community loads. The community comprises of 1500 houses, 2 mosques, 2 schools. Table 1 shows the breakdown of the load types considered, the average total consumption is estimated at 638.38kWh/day. The average daily demand is 26.6kW with a peak load of 78.95kW, using a load factor of 0.34. The set

Figure 1: Aerial view of Bakori Local government area, Katsina

Figure 2: Proposed structure of the Hybrid energy system



Day-to-day variability is 10%, and that of the time-step variability is 20% for the simulation. It is also assumed that the load calculated is constant all through the year.

In rural areas, the community dwellers are more often not in their homes, but out for work, resulting in a small load demand during this period. There is an increase in the load demand in the afternoon as some members return home for various activities. And at night, the demand reaches the maximum as all household members are present in the home as given in the daily load curve in Figure 3.

2.3. Resource Assessment of the HES

2.3.1. Solar PV model

The solar GHI resource for Bakori LGA was retrieved online using the HOMER software resource directory; the NASA surface meteorology data. The scaled annual Average irradiance is given as 5.78 kWh/m^2/day. Figure 4 shows the Average monthly daily solar radiation and clearness index distribution over a year for Bakori Area.

The Solar PV mathematical model suggested for the micro-grid is given in Equation (1) (Razmjoo et al., 2019) (Hafez, 2015), considering the de-rating factor of the module, solar irradiance

Table 1: Load profile breakdown

Load type	Rated power	Quantity	H	Energy (Wh/day)	Total energy (kWh/day)	n	Total (kWh/day)
Residences							
TV	60	1	6	360	2.08	300	624
Electric irons	1000	1	1	1000			
CFL	10	5	6	300			
Fan	25	2	6	300			
Miscellaneous	20	1	6	120			
Health centre							
Refrigerator	100	1	8	800	2.48	1	2.48
CFL	20	4	6	480			
TV	80	1	9	720			
Miscellaneous	20	1	24	480			
School							
CFL	25	10	7	1750	3.7	2	7.4
Fan	25	10	7	1750			
Miscellaneous	20	1	10	200			
Mosque							
CFL	25	10	5	1250	2.25	2	4.5
Total							638.38

Figure 3: Community hourly daily load profile

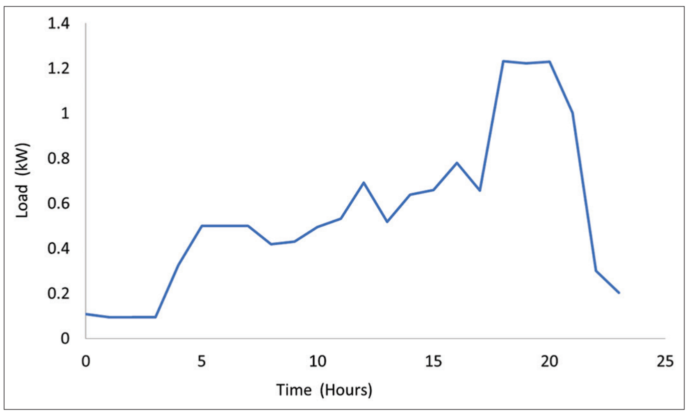
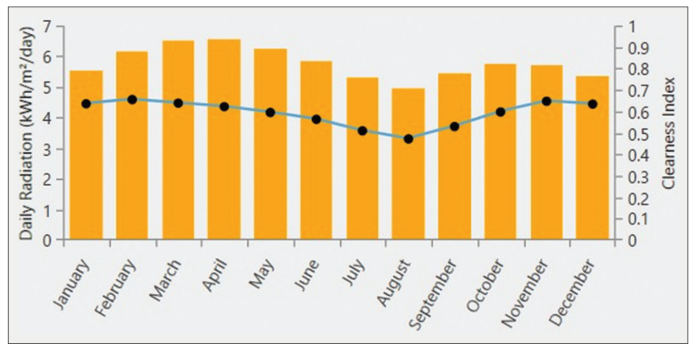


Figure 4: Average monthly daily Solar radiation and clearness index for Bakori Area



on the Photovoltaic array, temperature coefficient of power, the incident radiation, and temperature of PV cell.

$$P_{PV} = P_r f_d \left[\frac{H_T}{H_{T,STC}}\right]\left(1 + T_C - T_{C,STC}\right) \quad (1)$$

Where, P_{pv} = PV output power, P_r = PV module rating capacity (kW), f_d = PV de-rating factor, H_T = solar radiation incident of the area (kW/m²); $H_{T,STC}$ = incident radiation under standard test conditions (1 kW/m²), α_p = power temperature coefficient (°C) for the selected Solar PV module, T_c = PV temperature of cell (°C), $T_{c,STC}$ = Solar cell temperature (25°C), T_{amb} =Ambient temperature (°C).

$$Tc = T_{amb} + (0.0256 \times H_T) \text{ Change}$$

2.3.2. Wind model

From previous literature, it has been established that Northern Nigeria has a higher wind resource potential compared to the south and is suitable for energy production through this resource on a large-scale commercial basis (Salisu et al., 2019). Katsina state has a wind power density 36 between 259.52 and 832.60 Wm², and Global Wind Atlas was used to evaluate the wind speed distribution in Bakori. The mean wind speed in Bakori was found to be 5.95 m/s, with a mean power density of 22 W/m², at an anemometer height of 50 m, making the case study a potential site for wind energy harnessing.

The data source for the wind resource was obtained from NASA database in HOMER. Figure 5 shows the Average monthly speed of wind for over a year in the proposed location.

The rated output power from the wind generator is calculated using equation (2) is expressed in (Olatomiwa et al., 2015):

$$P_{wind} = \frac{1}{2} \times \rho \times C_b \times A \times V^3 \quad (2)$$

Where ρ denote density of air (1.225 kg/m³), V denote the speed of the wind in 0 and C_b denote the coefficient of power of the wind generator.

2.3.3. Batteries model

The batteries serve as a storage medium for the power output of the PV and Wind generator. Ensuring proper sizing is critical in the system design, as it ensures that the battery can support the load through periods when the sun or wind is not accessible. To determine the battery storage capacity equation (3) was deployed (Olatomiwa et al., 2015):

Figure 5: Hourly mean monthly wind velocity

$$C_{Wh} = \left(E_L \times A_D\right) / \left(\eta_{inv} \times \eta_{Batt} \times DOD\right) \quad (3)$$

Where:

E_L denotes the daily average load energy (kWh/day), A_D= the battery's daily autonomy, and *DoD* = depth of discharge of the battery. The efficiency of the battery and inverter are represented by η_{Batt} and η_{inv} respectively.

2.3.4. Converter

The converter is used in maintaining the continuity of the power supply among AC and DC components. It comprises a rectifier and inverter for AC to DC conversion and vice versa, respectively.

2.4. Economic Assessment of the HES with HOMER

This study also considered economic assessment of the Hybrid energy system applying some economic models including Cost of Energy (COE) and Net Present Cost (NPC) in determining the economic viability of the proposed system. HOMER software was used for simulating the HES economic assessment of the study. The software economic model evaluates the power system cost and identifies. The minimal cost of generating power supply that matches the community load profile, thereby gives the opportunity to design the HES for the Bakori Area, in Nigeria.

The generic PV panel rated at 300W is selected for the system for the simulation, with a capital and replacement cost of ₦49,000. The Operation and Maintenance (O&M) cost is ₦5000, and its lifetime is 25 years for one of the panels. This panel was selected from the available panels on HOMER due to the fact that it did not take temperature effects into consideration, as opposed to the other available options. This sizing can be further adjusted based on the result of the simulation. For this system, an inverter is required to convert the DC power from the PV panels and batteries into AC power for the AC load demand. A generic system converter was selected with a 1kW rating and inverter efficiency of 95%.

A 660kW Vestas V47 turbine of 50 m hub height and lifetime of 20 years is also considered for the system to take advantage of the wind speed. The capital cost and replacement cost are set at ₦110,000, with the operation and maintenance costs set to ₦1100, for each wind generator.

For the battery model, the lead acid battery (12V, 83.4 Ah) with a modified kinetic model was adopted. (Ugwoke et al., 2020). The cost of one battery is ₦75,000 and its replacement cost is ₦75,000, the lifetime span is 10 years and the maintenance cost is $10/year. The economic cost models are presented in equations 4-7 were deployed for the study. The mathematical representation of the NPC is given by (Olatomiwa et al., 2015): HOMER calculates the NPC cost using the equations (3)

$$C_{NPC} = \frac{C_{AC}}{CRF\left(i, Z\right)} \quad (4)$$

Where C_{AC} represents total annual cost ($/year) and capital recovery factor (*CRF*) which is a function *annual real interest rate* (*i*) and the project lifespan z (years). The CRF is presented in equation (5) (Gebrehiwot et al., 2019). The annual real rate of interest (%) is given in equation (6) (Olatomiwa et al., 2015):

$$\mathrm{CRF}\left(i, z\right) = \frac{i\left(1+i\right)^z}{i\left(1+i\right)^z - 1} \quad (5)$$

$$i = \frac{i' - f}{1 - f} \quad (6)$$

$$\mathrm{COE}\left(\frac{\$}{\mathrm{kWh}}\right) = \frac{T_{AC}\ (\$)}{P_{L(kW)} * (8760\mathrm{h\ year})} * \mathrm{CRF} \quad (7)$$

Where:

i = the annual real interest rate (%), f = inflation rate (%), i' = nominal interest rate
Z = project lifetime, C_{rf} is the capital recovery factor
P_L = the actual annual energy production by the systems (kW h).

The parameters and cost of the selected energy components are shown in Table 2.

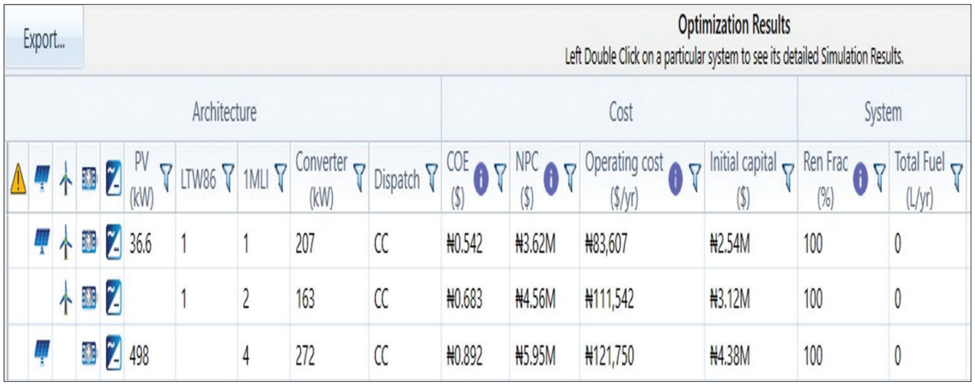
3. RESULTS AND DISCUSSION

HOMER simulates the inputs; capital cost, O&M, and components' replacement cost involved in the system design. Using the inputs, HOMER generated the NPC, COE and the cash flow of the systems and evaluates the system performance.

HOMER was used to runs a comparative analysis on the system based on `criteria such as the cost of energy and NPC. the simulation result of the optimal system configuration is as shown in Figure 6. The result depicted that the optimal configuration involved Solar PV, wind and storage system with the least NPC, COE and operating cost. Of ₦3.62M, ₦0.542, and ₦83,607 respectively while also generated the highest amount of energy. The simulation result, also gave the energy production of 774,475kWh/year from the Solar PV and 648,658kWh/year from the wind generator as depicted in Table 3, which far exceeds the consumption of 638 (kWh/year).

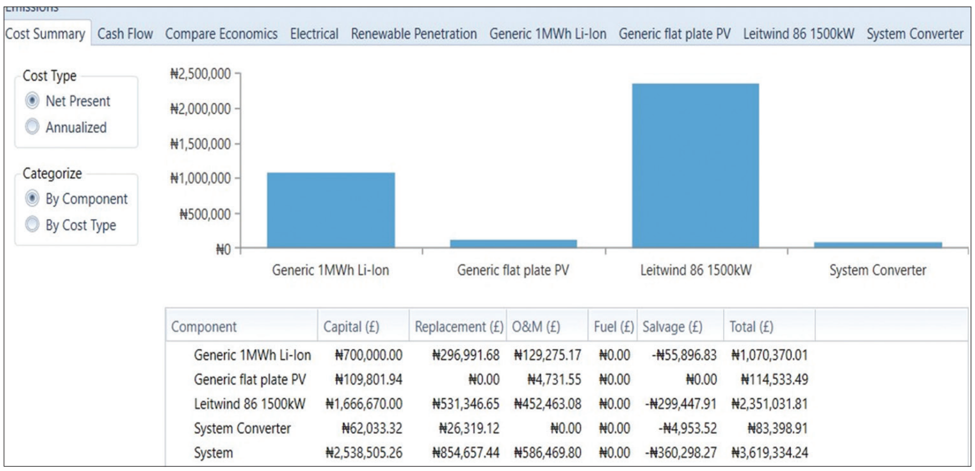
A cash flow summary was also generated from the Homer simulation, to give a better understanding of the costs involved in each system design. Figure 7 shows the cash flow summary for the proposed system reflecting the replacement, cost, fuel, salvage and operating costs with respect to the NPC. The result

Figure 6: Simulation results



PV (kW)	LTW86	1MLI	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)
36.6	1	1	207	CC	₦0.542	₦3.62M	₦83,607	₦2.54M	100	0
	1	2	163	CC	₦0.683	₦4.56M	₦111,542	₦3.12M	100	0
498		4	272	CC	₦0.892	₦5.95M	₦121,750	₦4.38M	100	0

Figure 7: Cash flow summary of the hybrid energy system



Component	Capital (£)	Replacement (£)	O&M (£)	Fuel (£)	Salvage (£)	Total (£)
Generic 1MWh Li-Ion	₦700,000.00	₦296,991.68	₦129,275.17	₦0.00	-₦55,896.83	₦1,070,370.01
Generic flat plate PV	₦109,801.94	₦0.00	₦4,731.55	₦0.00	₦0.00	₦114,533.49
Leitwind 86 1500kW	₦1,666,670.00	₦531,346.65	₦452,463.08	₦0.00	-₦299,447.91	₦2,351,031.81
System Converter	₦62,033.32	₦26,319.12	₦0.00	₦0.00	-₦4,953.52	₦83,398.91
System	₦2,538,505.26	₦854,657.44	₦586,469.80	₦0.00	-₦360,298.27	₦3,619,334.24

Table 2: Technical and cost parameters of the proposed system

Component	Variable	Value	Unit
Solar photovoltaic	Rated capacity	300	W
	Installed capacity	23	kW
	Capital cost	49,000	₦/W
	Replacement cost	49,000	₦/W
	O and M	5000	₦/year
	Lifetime	25	Years
Wind turbine	Rated capacity	1.5	kW
	Capacity	1	kW
	Capital cost	110,000	₦/kW
	Replacement cost	110,000	₦/kW
	O and M	1000	₦/kW
	Lifetime	20	Years
	Hub height	40	m
Battery storage	Nominal voltage	6	V
	Maximum capacity	1670	Ah
	Roundtrip efficiency	90	%
	Maximum charging current	1.67	kA
	Minimum state of charge	40	%
	Capital cost	75,000	₦
	Replacement cost	75,000	₦
	O and M	5000	₦/year
Converter	Rated capacity	6	kW
	Rectifier efficiency	90	%
	Inverter efficiency	95	%
	Capital cost	175,000	₦/kW
	Replacement cost	175,000	₦/
	O and M	5000	(₦/kW/y)
	Lifetime	15	Years

Table 3: Production summary

Production	kWh/year	Percentage
Generic flat plate PV	774,475	54.4
Vestas V47	648,658	45.6
Total	1,423,132	100

Table 4: Summary of energy consumption

Consumption	kWh/year	Percentage
Primary AC load	232,827	100
Primary DC load	0	0
Total	232,827	100

in Figure 7 depict that the wind generator had the highest capital cost, replacement cost and operation and maintenance cost when compared to the other energy generating sources.

Table 4 depict the HES Consumption Summary, indicating that the load demand was mainly AC load with 0% DC load.

4. CONCLUSION

A feasibility and economic assessment of a hybrid energy system was carried out for Bakori area, Katsina, in Nigeria. HOMER software tool. With the rising energy demand and the current challenges in the power sector, the need to provide affordable, sustainable electricity has become very important.

The study assessment carried out on the comparative analysis, shows that the proposed system is viable for a HES application in the proposed case study area. The result also gave the optimal configuration of the proposed energy sources, choosing solar-wind-battery.

The study revealed that there is a need to harness the available energy resources in the country and also shows an economical and environmentally friendly approach towards achieving such power supply system. This result shows that the solar-wind-battery configuration is the most economical viable to implement in an off-grid hybrid renewable systems for rural communities. Further research could be done to include more generating sources such as biomass.

5. ACKNOWLEDGMENT

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