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Performance Evaluation of a Hybrid Microgrid System for Sustainable Electricity

Emmanuel, A. U.

Department of Electrical and Electronic Engineering, Federal University Otuoke, Bayelsa State, Nigeria.
Email: amasaeu@fuotuoke.edu.ng

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ABSTRACT

Developing a hybrid microgrid system will support efforts at providing sustainable electricity to rural communities without access to electricity from the national electricity grid in Nigeria. This study considered the design and analysis of a hybrid microgrid system for Okorogba community in Nembe, a coastal settlement in suburbia of Bayelsa State, Niger Delta region of Nigeria, without access to electricity from the national grid. The hybrid design combined a 68-kW capacity solar photovoltaic (PV) and 44-kW wind turbine systems. First, a load survey was carried out for the community to establish the total daily energy demand of the community. Electrical performance analysis and economic analysis of the hybrid system were done using HOMER Pro software. The magnitude of the output power from the hybrid system was significant and cost-effective in meeting the electricity demand of the remote community. Thus, the hybrid system is anticipated to provide clean and sustainable energy access for the community.

1. Introduction

Many people reside in rural locations, where there is typically no access to power grid and minimal energy availability. According to Olatomiwa et al. (2018), the region of sub-Saharan Africa contributes the most to the global energy deficit. Regenerative or non-depletable resources provide the source of renewable energy such as ocean thermal energy, geothermal energy, solar, wind, hydro, wave, and tidal energy. These renewable sources are crucial in the creation of an environmentally benign and long-lasting electrical system (Chel and Kaushik, 2018).

Although, Nigeria has a natural gas reservoir of about 209.5 trillion feet, generates 2.7 billion metric tons of coal and lignite, and produces 1.67 million barrels of crude oil per day (Dim, Onuoha and Ozumba, 2020), there is a great deal of potential for renewable energy resources in addition to conventional energy resources. Research indicates that there are roughly 277 potential locations for small-scale hydropower, which could produce about 734MW of power. On the other hand, solar energy has an annual energy measurement value that is approximately 27 times greater than that of conventional energy sources, with an average of 6.5 hours of sunshine per day (Augustine and Nnabuchi, 2009).

In Nigeria, the lack of access to power has been a severe challenge for most isolated locales and even select urban areas. This lack of power is a fundamental hindrance to the country's scientific and economic advancement. The absence of access to power in most rural places has worsened poverty and posed a substantial barrier to a better way of life. It is estimated that just about 22.6% of rural villages have access to electricity. The national grid is not currently connected to many villages in Nigeria. Due to their geographic location or the fact that they are remote from the distribution network, a great deal of Nigerian towns lack access to power (Ozogbuda and Iqbal, 2022). As a result, renewable energy is a suitable solution to this issue.

In comparison to the present alternative means of power supply in Nigeria, a hybrid system that mixes renewable and conventional resources will be shown to be the most ecologically friendly and cost-effective strategy to deploy. In remote locations without access to electricity, installing a stand-alone hybrid system can enhance the quality of life there. This technique would be desired and would contribute greatly to electricity generation, pollution reduction, and cost-effectiveness, as expanding the grid to these remote regions is not economically conceivable.

This study seeks to lessen reliance on Nigeria's national grid for electricity and to increase awareness of renewable energy sources and how best to utilize them to produce electricity on a much greater scale for the country. The intended location for this study is a remote hamlet in Nigeria, Bayelsa state. This area has no access to electricity and is fully cut off from the national electricity grid. The purpose of this study is to size and design an efficient and cost-effective stand-alone photovoltaic-wind turbine (PV-WT) hybrid system for remote communities in Nigeria.

By building a feasible independent power generation system, the research target seeks to build an effective and economical energy solution for places with this kind of difficulty.

2. Materials and Methods

2.1 Load Profile Design

The load profile explains how the electrical load fluctuates over time. Depending on the nature of the consumer, the load profile will differ from one customer to the next. Customers can be broadly characterized as belonging to a household, a community, or a business. This data was utilized to schedule the flow of power according to time (Gupta et al., 2015).

The household load variance during the period from 1:00 to 23:59 is displayed in Fig. 1. The graph indicates that owing to lighting and television use at night, there was a considerable residential load. Except for the afternoon fan load, there was scarcely much domestic activity during the day. The community load variance during the period from 1:00 to 23:59 hours was illustrated in Fig. 2. The graph illustrates that the lighting load, which symbolizes the community load, was constant from 9:00 to 17:00 hours. In churches and schools, the lighting load was also used during the day.

The commercial load variance during the period from 1:00 to 23:59 Hrs is illustrated in Fig.3. The graph illustrated that due to the market, water pump and the palm oil mill, there was a considerable commercial load during the day. The fluctuation of the combined load across the period from 1:00 to 23:59 Hours is depicted in Fig. 4. The graph demonstrated that the overall load was greater at night because lighting load outweighed all other types of loads. The highest load, which was recorded at 26.53 kW, occurred at night as shown in Fig. 5.

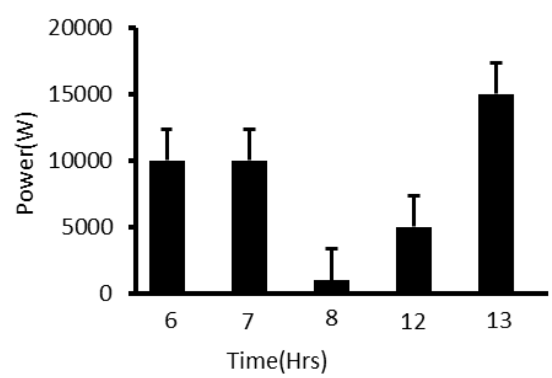

Figure 1: Load Profile for Household Loads. (Error bars on chart are standard error)

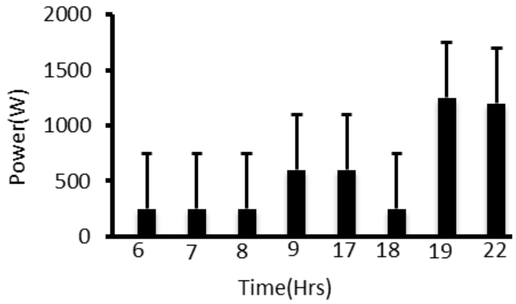

Figure 2: Load Profile for Community Loads (Error bars on chart are standard error)

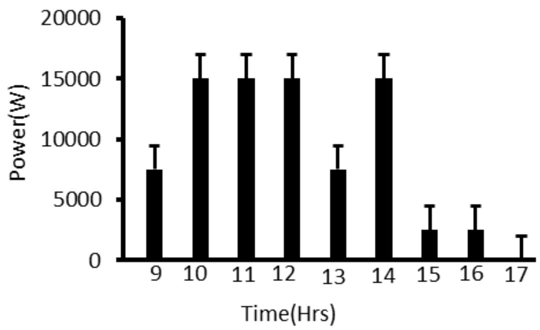

Figure 3: Load Profile for Commercial Loads. (Error bars on chart are standard error)

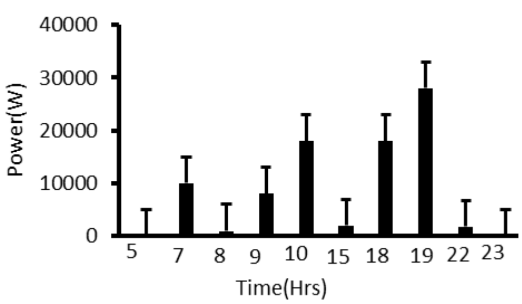

Figure 4: Load Profile for Combined Loads. (Error bars on chart are standard error)

Figure 5: Load Profile on Homer software

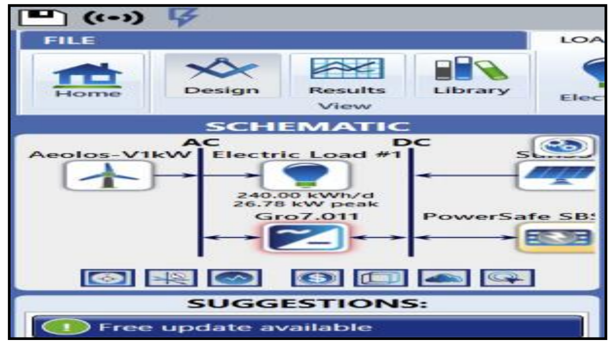

Figure 6: HOMER Representation

Table 1: Consolidated daily energy consumption of the community

Energy	(kWh)
Total daily units consumed	240
Daily units consumed from 17:00 hrs to 6:00 am	131
Total peak load in a day	26.53

2.2 Design of Microgrid

Based on the load information gathered from the household survey, the microgrid's design was created. The components of the Microgrid system were designed using the aggregated daily energy usage (Mamaghani et al., 2016) as shown in Tab. 1.

Fig. 6 shows the representation of the hybrid system using Homer software. Wind turbines are connected to the AC bus while the solar panels are connected to the DC bus. Converters (inverters and rectifiers) are connected alongside the storage capacity (batteries).

2.2.1 Solar Panel Arrays

By considering the combined daily energy consumption of all the connected loads in the microgrid, the necessary solar panel array capacity is determined (Nicolas, 2018). The total daily energy use as shown in Tab.1 was calculated to be 240 kWh. The necessary solar array capacity was determined as follows.

Since 240 kWh was the total units consumed, considering that the system's efficiency was 86%, calculating the total unit needed is as follows:

$$\text{Units required (kWh)} = \frac{total\ units\ consumed}{system\ efficiency} \quad (1)$$

$$\text{Units required} = \frac{240}{0.86} = 280\ \text{kWh}$$

Sunshine hours in at Okorogba community = 4.13 hrs.

The required PV capacity is calculated as:

$$\text{PV capacity (kW)} = \frac{units\ required}{hours\ of\ sunshine} \quad (2)$$

$$\text{PV capacity} = \frac{280}{4.13} = 67.796 \sim 68\ \text{kW}$$

Selecting a 250 W panel, the total number of panels required is calculated as:

$$\text{Number of panels} = \frac{total\ PV\ capacity}{Selected\ PV\ panel\ capacity} \quad (3)$$

$$\text{Number of panels} = \frac{68 \times 1000}{250} = 272\ \text{panels}$$

To power the associated loads, 68kW of solar capacity is needed. The 250Wp PV module was chosen to create the necessary PV capacity. The required number of 250Wp panels are installed using an 8 in 1 module mounting structure. The total number of structures required is calculated as: The total number of panels = 272 Panels. Selected mounting structure = 8 in 1 structure. The total number of structures is given by equation 4.

$$\text{No. of structures} = \frac{total\ number\ of\ panels}{8} \quad (4)$$

$$\text{Number of structures} = \frac{272}{8} = 34\ \text{structures.}$$

The installation of 32 module mounting structures arrangement of all the module mounting structures for the selected solar panel installation area. The structures are tilted at an angle of 30° and facing south direction.

2.2.2 Solar Charge Controller

The charge controller is designed to regulate the available power from a PV source. The number of solar MPPT charge controller required is calculated as: PV capacity installed = 68 kW.

Considering the Schneider Electric MPPT 80-600 charge controller (MPPT 80-600 refers to 80A and 600V charge controller).

The charge controller rating (kW) = 4 kW.

The number of charge controllers required is given by equation 5.

$$No. of\ \ charge\ controller = \frac{total\ PV\ capacity}{charge\ controller\ capacity} \quad (5)$$

$$\therefore No. of\ Charge\ controller = \frac{68 \times 1000}{4 \times 1000} = 17$$

2.2.3 Wind turbine array

Since the wind turbine is acting as a backup for the PV system at Night (Sinha and Chandel, 2018). Here we would have to consider the units required in the nighttime being from sunset when the PV system would be less active. The batteries charged by the PV system during the daytime would be used to power the load at nighttime. The AC power from the wind turbine is supplied to the converter and thus converted to DC power which also charges the battery.

Total units consumed at nighttime = 131 kWh

Assuming system efficiency = 90%

$$\text{Units required (kWh)} = \frac{total\ units\ consumed}{system\ efficiency} \quad (6)$$

$$\text{Units required} = \frac{131}{90} = 145.55 \sim 146\ \text{kWh}$$

Wind speed at Okorogba village = 3.36 m/s

The required WT capacity is calculated as:

$$\text{WT capacity (kW)} = \frac{units\ required}{wind\ speed}$$

$$\text{WT capacity} = \frac{146}{3.36} = 43.45 \sim 44\text{kW}$$

Selecting the 250W capacity for the wind turbine system, the total number of wind turbine required is calculated as in equation 7.

$$\therefore \text{Number of turbines} = \frac{total\ WT\ capacity}{Selected\ WT\ capacity} \quad (7)$$

$$\therefore \text{Number of panels} = \frac{44 \times 1000}{250} = 176\ \text{turbines.}$$

2.2.4 Wind Charge Controller

WT capacity installed = 44kW. Charge controller rating = 3kW. Number of wind turbine charge controller is given by equation 8.

$$No.of\ charge\ controllers\ = \frac{total\ WT\ capacity}{charge\ controller\ capacity} \quad (8)$$

$$\therefore \text{No. of charge controllers} = \frac{44 \times 1000}{3 \times 1000} = 15$$

2.2.5 Battery Bank

Solar power-based microgrids are affected by the power fluctuation due to varying weather. Since solar energy is only available during daytime, the energy storage is very much required. Daily units needed from battery = 131 kWh. Considering system efficiency = 90 %, units to be stored in battery = 144.8 kWh. Battery depth of discharge = 50%. The installed battery capacity is calculated as in equation 9.

$$Installed\ battery\ capacity = \frac{units\ to\ be\ stored\ in\ the\ battery}{battery\ depth\ of\ discharge} \quad (9)$$

$$\therefore Installed\ battery\ capacity = \frac{144.8}{0.5} = 290\text{kWh}$$

Selecting the system voltage of 48V, the battery bank is given by equation 10.

$$\text{Batter bank capacity (Ah)} = \frac{installed\ battery\ capacity}{battery\ system\ voltage} \quad (10)$$

$$\therefore \text{Batter bank capacity} = \frac{290 \times 1000}{48} = 6041.7 \text{ Ah}$$

Using standard battery bank capacity, it is then approximated to 6000 Ah.

2.2.6 Inverter

The inverter was designed to convert the available DC power from a PV and battery to AC. The selected inverter was also designed to convert the AC power from the wind turbine system to DC power. This converted DC was used to charge the battery when the PV is not available. The inverter required was then calculated. Let, the peak load without losses (kW) = 26.53 and assuming system losses = 18%, then

$$\text{Total load with losses} = \frac{Peak\ load\ with\ losses}{Percentage\ of\ loss} \quad (11)$$

$$\therefore \text{Total load with losses} = \frac{26.53 \times 1000}{0.18}$$

$$\therefore \text{Total load with losses} = 147.4 \text{ kW}$$

Choosing the Schneider Context XW+8548 with the rating of 7000W. The number of inverters needed is calculated using equation 12.

$$No.of\ inverters\ needed = \frac{Total\ load\ with\ losses}{inverter\ capacity} \quad (12)$$

$$\therefore No.of\ inverters\ needed = \frac{147.4 \times 1000}{7000}$$

$$\therefore No.of\ inverters\ needed = 12$$

2.3 Tools Used for the Design

2.3.1 Sizing Tools

There are various sizing tools available, including Homer Pro, REOpt, iHOGA, Hybrid 2, RETScreen, Insel, and others. However, for this study, Homer Pro was used. Homer Pro simulates micro-power systems with one or more sources such as solar photovoltaics' (PV), wind turbines, run-of-river hydro, diesel generators, cogeneration micro-turbines, batteries, grids, fuel cells, electrolyzers, etc.

2.3.2 Simulation Tools

For this research, HOMER pro simulation program was used. Other simulation tools include openDss, PVSol-Premium, and others. Continuous system simulation is essential for assessing the system's performance in real-world scenarios (Mamaghani et al., 2016).

2.4 System Sizing

2.4.1 Site Selection and Electrical Loads

The chosen location is in Nigeria's Okorogba Bayelsa State. The location is situated at these coordinates: (562101 Okoroba Bayelsa) on Google Maps as shown in Fig. 7.

It is a village with a total of around 250 dwellings. The three main economic activities are farming, fishing, and livestock husbandry. There are 30 percent permanent homes in the hamlet, 60 percent semi-permanent residences with concrete walls, and the balance homes are made of wooden boards. . The area, which has two health care facilities, three churches, and three schools; two of them are elementary and primary schools is situated near to a fishing harbor. Additionally, this neighborhood contains a market area where a variety of goods and services are provided and purchased. According to experimental PV data measurements, there was 4.13 kWh/m2/day of solar irradiation from diverse resources during the year's dry season. Throughout the year, the solar irradiation intensity changes from 3 to 6 kWh/m2, with an average solar irradiation of 4.13 kWh/m2/day as shown in Fig. 8. A 3.36 m/s yearly average wind speed is also observed in the area as shown in figure 9. The microgrid's size is selected by considering the month with the lowest irradiation over the course of the year. Additionally, the typical yearly values of solar irradiation are considered to make sure that the microgrid system functions economically throughout the year.

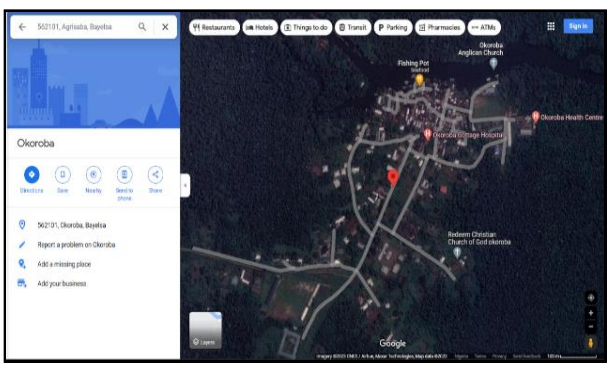

Figure 7: Location of the Site under Consideration in Okorogba Community, Bayelsa State; Nigeria (Source: Google Map, 2023).

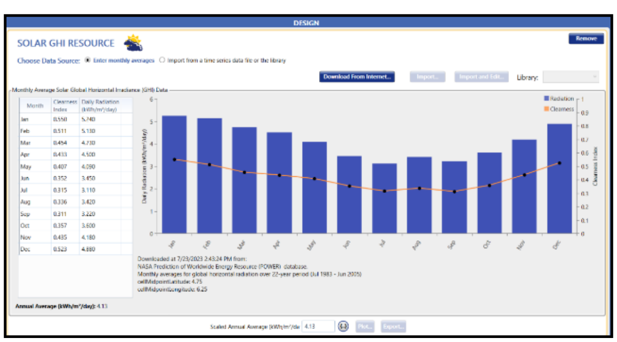

Figure 8: Solar Irradiance of Selected Location Provided by HOMER Pro.

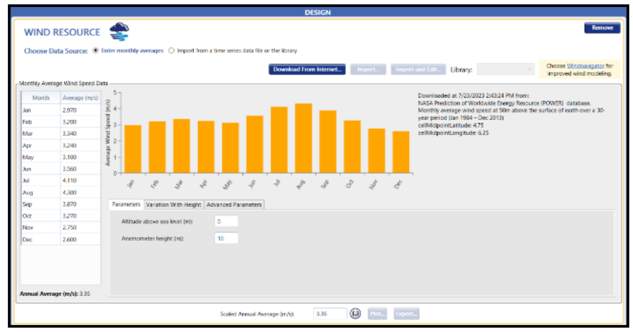

Figure 9: Wind Speed of location.

3 Results and Discussion

3.1 *Analysis of the Hybrid System*

A feasibility analysis of the hybrid system for the potential site under consideration was conducted based on the simulation. The hybrid system in HOMER was designed considering a life cycle of 25 years, an inflation rate of 2%, a discount rate of 8% (Gupta, Kumar, and Bansal, 2015).

The optimization considers a combined photovoltaic (PV) capacity of 68 kilowatts (kW) and a combined wind capacity of 44 kW. The town's daily energy consumption amounts to 240 kilowatts (kW), with 131 kW being used during the overnight period from 5:00 PM to 6:00 AM. A daily average peak load of 26.531 kW was required. The wind turbine served as a backup for the PV system at nighttime, when the PV system was less active. The converter receives alternating current (AC) electricity from the wind turbine and converts it into direct current (DC) power. This DC power is then used to charge the battery. The batteries, which were charged during the day by the photovoltaic (PV) system, would provide electrical power to the load during the night and would also be replenished by the wind turbine as it gives electrical power to the load.

With a 50% wind penetration, the Aeolos-V1kW wind turbine can run for 6,623 hours a year at its total rated power of 66kW. The time series plot on HOMER pro software as shown in Fig. 11 also reveals that the WT system has a simulated maximum electricity generation of 98kW, and the wind turbine power output varies regularly during different hours of the day when the desired area's wind speed is either greater or lesser than typical.

3.2 Electrical Performance Analysis

HOMER Pro was used to simulate 4,422 hours of operation per year for the SunPower 330SPR-P17-330-COM photovoltaic system. A PV penetration of 91.3% and a maximum output of 58.1 kW as displayed in Fig. 10. This shows that the PV power production spans from 12kW to 50kW during the day, from early morning hours of 7:00 to late afternoon hours of 17:00.

The region being studied currently experiences notable amounts of wind speed and sun exposure. An ENERSYS Powersafe SBS XC 780 battery with a 12-year long life was optimized by HOMER software as illustrated in Fig. 12. According to HOMER Pro, the project needs a total of 220 batteries with a rated bus voltage of 60V. The battery with a string size of 5 and 44 in parallel. Furthermore, HOMER Pro generated simulations with a yearly output of 35,620 kWh, and 1,084 kWh for total annual losses, 90.1 kWh for annual storage depletion, and 36,075 kWh and 35,082 kWh for total energy intake and output respectively.

Additional HOMER calculations show a 1,650 kWh/yearly useful nominal capacity, a 0.00214 $/kWh storage wear cost, and 165 hours of battery autonomy, based on the project's simulated findings of the battery's electrical performance over the course of a year, all of this information was acquired using HOMER pro.

HOMER pro systems' inverter simulations as shown in Fig. 13, indicates that the inverter operates for 7,285 hours annually. The inverter's annual energy input and output are 58,313 kWh and 56,272 kWh, respectively. The maximum output of the inverter is 23.7 kW, with annual losses of 2,041kWh.

The simulated hours of operation for the PV system and the WT system are 4,422 hours and 6,623 hours, respectively, per year. The findings of the simulation as shown in Fig. 14 below indicates that the wind turbine and solar PV systems both record their highest energy output in the month of August.

The HOMER software also evaluated the efficiency of the hybrid system, particularly the electricity generation from the solar PV and wind systems.

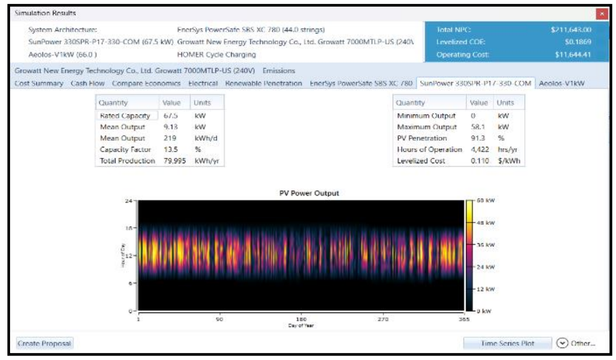

Figure 10: PV Power Output Performance

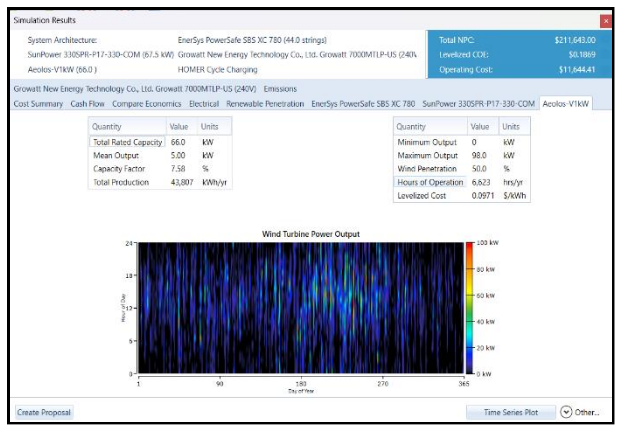

Figure 11: Wind Turbine Power Output Performance

Figure 12: Batteries Electrical Performance

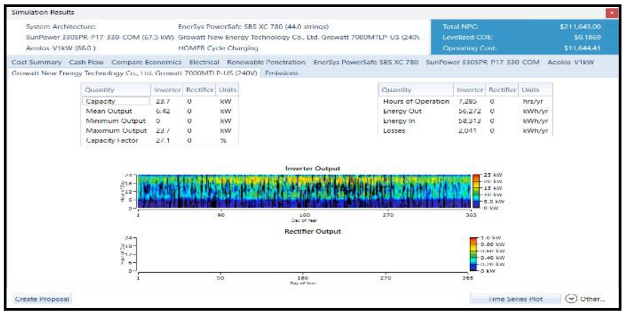

Figure 13: Inverter Performance

The total annual AC primary load is 87,595 kWh. This load is met by the combined power generation of a solar PV system producing 79,995 kWh per year and a wind turbine producing 43,807 kWh per year.

3.3 Economic Analysis

The software (Homer Pro) offers a tool named "compare economics". This tool assists in evaluating numerous configurations that may be produced based on the ideal findings to select the most economical and dependable system to apply for a certain load system. From the comparative economics study, measuring the base system's Net Present Cost (NPC), the total net present cost in this scenario is found to be $211,643.00, with a levelized COE of $0.1869. The annual system operating cost of $11,644.41 is shown by the HOMER simulation data of Fig. 15.

By analyzing economics using the HOMER tool as shown in Fig. 16, the simulation revealed a base system having a similar solar PV, battery and converter with a total NPC of $248,428.40. This demonstrates how much more economical the hybrid system is than the base system. Like the base system, which consists only of a solar PV system for the same project, the hybrid system likewise has a high rate of energy production because its total power output is substantially more than that of the base system.

This goes to highlight that the HOMER program gives the best viable simulation that incurs a reasonable cost with higher energy output that best suit the location.

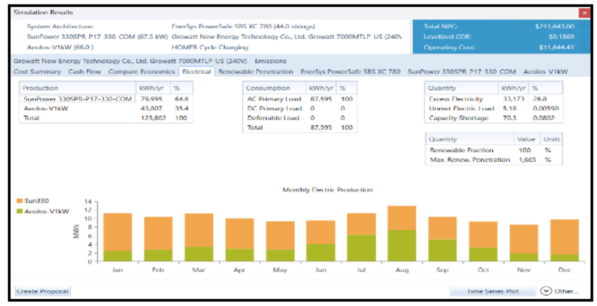

Figure 14: Monthly Power Output for the Hybrid System

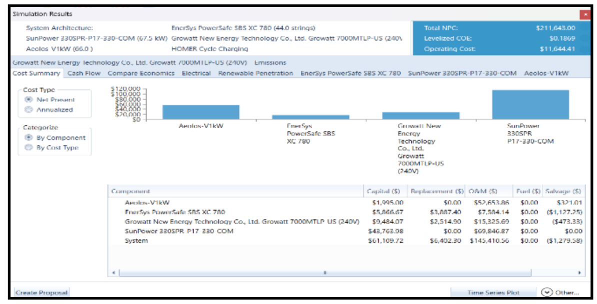

Figure 15: System's Net Present Cost (NPC)

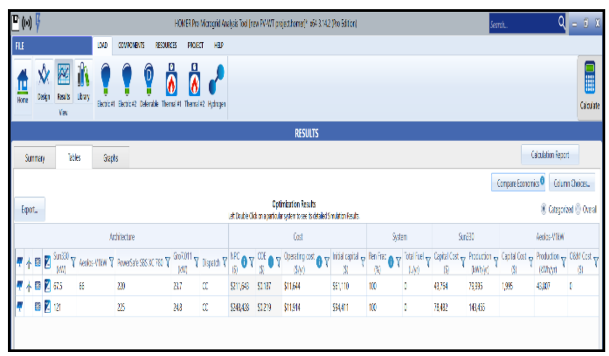

Figure 16: System Optimization Results

4.0 Conclusions

This study focuses on the design and analysis of a photovoltaic-wind turbine hybrid system for Okorogba community in the Nembe coastal town. The system consists of a 68kW sized solar photovoltaic and a 44-kW capacity wind turbine. Both the simulation findings and the actual system demonstrate that solar PV and wind turbine systems provide a substantial amount of energy due to the high sun irradiation throughout the year.

The simulated PV system has an annual production of 79,995 kWh/yr, while the simulated WT system has an annual output of 43,807 kWh/yr. Therefore, the combined annual output of the system is 123,802 kWh/yr, which is significant and has the capacity to meet the simulated annual primary load consumption of 87,595 kWh/yr for the community.

HOMER Pro provided a comprehensive simulated economic analysis for the PV-WT hybrid system with a total NPC of $211,643.00 as compared to the base case NPC of $248,428.40 for a similar standalone PV system. This goes to highlight that the HOMER program gives the best viable simulation that incurs a reasonable cost with higher energy output that best suit the location under consideration.

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