



Optimal Design of a Hybrid Renewable Energy System as a Substitute Power Source for HAFEDPOLY Kazaure

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ABSTRACT

A hybrid renewable energy system (HRES) offers a feasible solution for electrifying regions where extending the grid is either unstable, impractical, or too costly. The primary challenge in supplying electric power to the academic areas of Hussaini Adamu Federal Polytechnic (HAFEDPOLY) in Kazaure, Nigeria, has been the inconsistent power distribution from the national grid and the rising costs of diesel and petrol fuels. This has led to unpredictable energy availability for daily academic activities, resulting in water shortages. This study designs Solar PV, Wind Energy, and Diesel Generator systems based on data from an energy audit of HAFEDPOLY's academic area. The designed systems were optimized using the Hybrid Optimization Model for Electric Renewable (HOMER) software for PV-wind-battery and diesel hybrid systems, yielding an HRES tailored for the academic area. HOMER software simulated every possible system configuration and selected the one with the lowest total Net Present Cost (NPC) as the optimal system.

ARTICLE INFO

Article History

Received: December, 2023

Received in revised form: December, 2023

Accepted: February, 2024

Published online: June, 2024

KEYWORDS

PV, Hybrid Renewable energy, Electrical power, HOMER Software, Net Present Cost

INTRODUCTION

Renewable energy sources like Photovoltaic (PV) and wind power are considered environmentally friendly and clean because they are inexhaustible, non-polluting, and have minimal environmental and health impacts compared to fossil fuels (Ahmed *et al.*, 2020; Alam *et al.*, 2020; Chen *et al.*, 2019; Colmenar-Santos *et al.*, 2020; Olowu *et al.*, 2018). As fossil fuel prices continue to rise, renewable energy has gained popularity over the past decades (Musa *et al.*, 2023). However, the unpredictability of renewable energy, due to the varying hours of sunlight and fluctuating wind speeds, raises concerns about its reliability (Hafis *et al.*, 2023; Sulaiman *et al.*, 2024). This variability can lead to unstable power supplies and an inability to meet power demands in certain areas (Abdulwahab *et al.*, 2021; Babaita *et al.*, 2022).

To address these issues, many power system designers have started exploring hybrid

renewable energy systems (HRES) (Adetoro *et al.*, 2023; Thirunavukkarasu *et al.*, 2023). For instance, in (Kartite & Cherkaoui, 2016), an optimization method for hybrid solar-wind-battery systems using the Backtracking Search Algorithm (BSA) was presented, demonstrating that the BSA algorithm can achieve global optimization efficiently and provides superior results compared to other algorithms like the Genetic Algorithm. Another study (Bhandari *et al.*, 2016) detailed an optimization procedure using linear programming to minimize operational costs by maximizing the potential of Renewable Energy Power Systems (REPS), taking into account the monthly fluctuations in generation and electricity demand. The study included a hybrid system comprising hydropower, photovoltaic, and wind components, with results indicating that such an optimized system could facilitate a complete transition from fossil fuel dependency to renewable energy across a wide

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geographic area. Additionally, in (Anoune *et al.*, 2018), recent trends in renewable energy usage and the physical modeling of renewable energy systems have been discussed, highlighting various methodologies and criteria for optimizing HRES. These trends suggest that artificial intelligence could effectively optimize HRES without the need for extensive long-term weather data.

A method for optimizing power generation from HRES aimed at meeting the load demands of a typical household has been presented in (Ajewole *et al.*, 2022; Amer *et al.*, 2013; Hill *et al.*, 2024; Kartite & Cherkaoui, 2016; Nemati *et al.*, 2018; Sopian *et al.*, 2008) demonstrating the potential of various optimization techniques used by researchers to design cost-effective hybrid energy systems. (Sharma & Mishra, 2016) described the optimal design of a hybrid wind-solar power system with battery storage and diesel generators. The study developed a linear programming model to minimize the average production cost of electricity while reliably meeting load requirements, considering environmental factors in both the design and operational phases.

The primary goal of this research is to design an optimized hybrid renewable energy system (HRES) that combines solar energy, wind energy, and diesel generator power systems for the academic areas of Hussaini Adamu Federal Polytechnic (HAFEDPOLY) Kazaure, utilizing the Hybrid Optimization Model for Electric Renewable energy (HOMER).

B. Framework for the Hybrid Renewable Energy System (HRES)

The power generated by Photovoltaic (PV) systems and Wind Turbines (WT) depends on various factors, with the most influential being the hub height of the wind turbines (which affects wind speed), orientation of PV panels, solar radiation, wind speed and the sizes of DC/AC converters. It is essential to measure the load, vertical and horizontal solar radiation, as well as the hourly wind speeds throughout the year in the area. This research considered three scenarios for the design of the HRES: wind energy data, diesel generator model and solar radiation, illustrated in Figure 1.

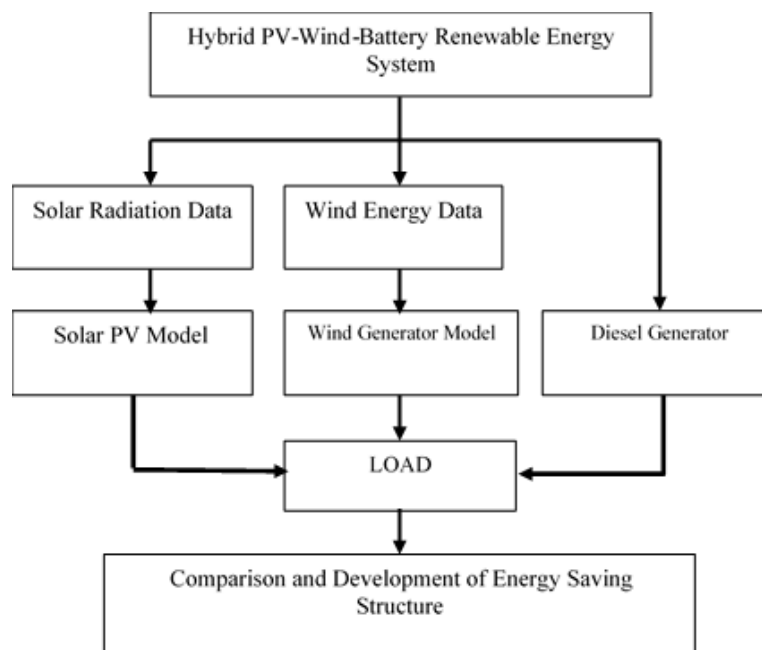


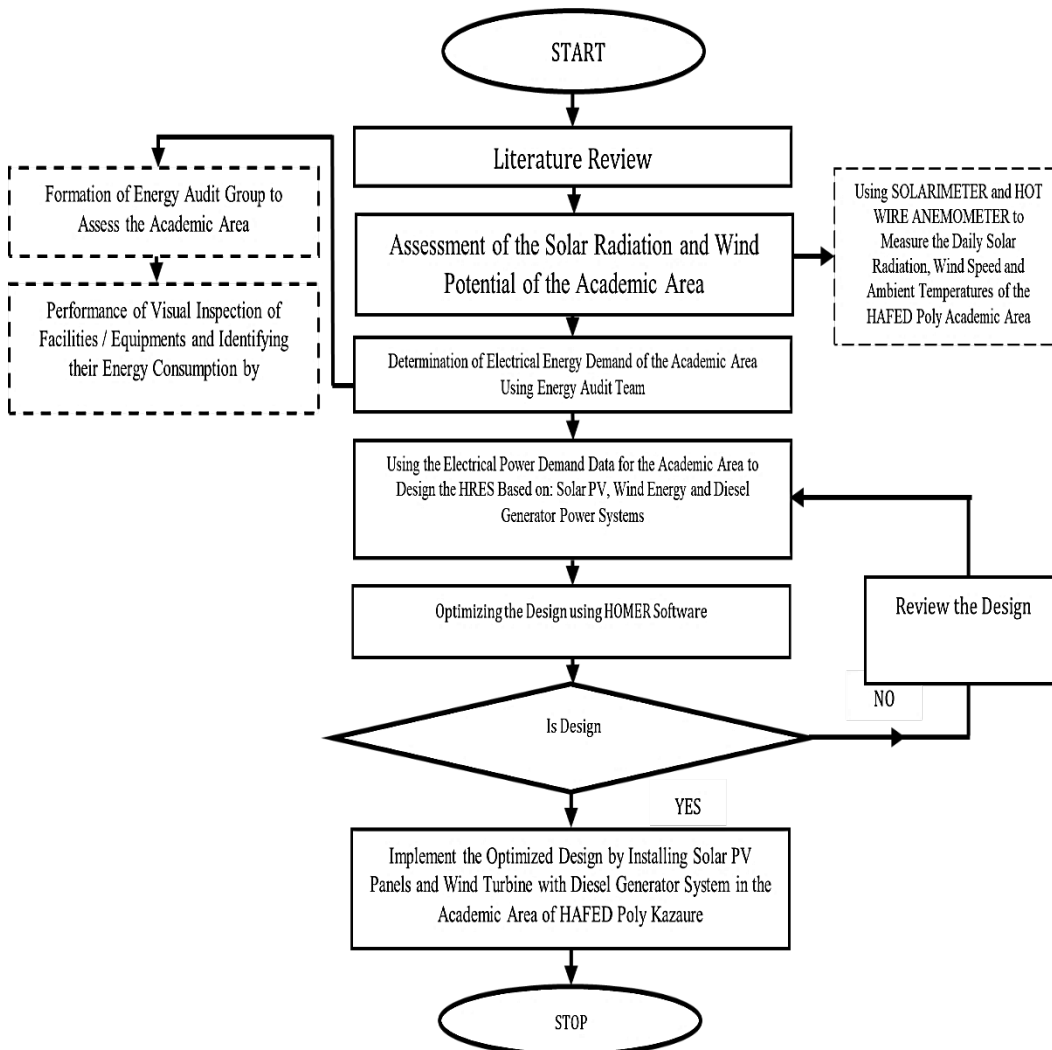
Figure 1: The Framework of the HRES

METHODOLOGY

A feasibility study was carried out to evaluate the environmental factors in the academic area. The activities performed are illustrated in Figure 2. Solar and wind energy were identified as alternative energy sources that can complement conventional sources, especially at HAFEDPoly Kazaure. For this research, wind speed and solar radiation data for

Weather Station at the College of Agriculture, Hussaini Adamu Federal Polytechnic Kazaure, while ambient temperature data was sourced from NASA.

Graph plots for the Wind speed data, Ambient Temperature data and Solar Radiation data for the Academic Area are shown in Figures 3, 4 and 5 respectively.



the academic area were collected from the

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Figure 2: Research Flowchart

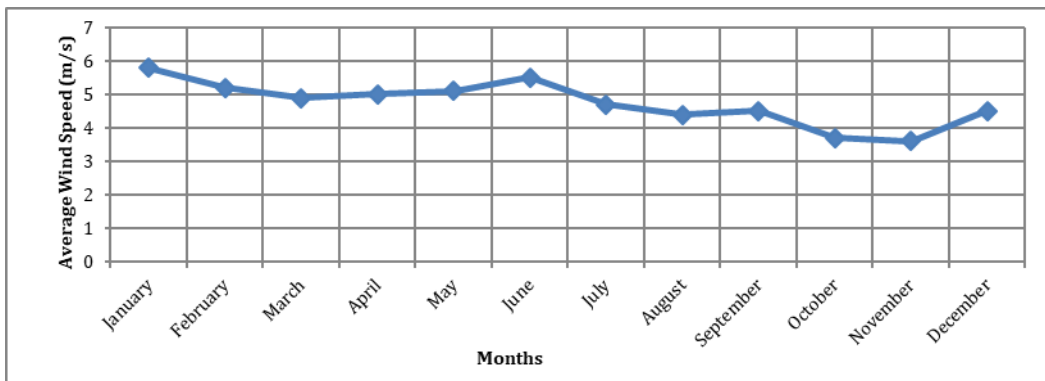
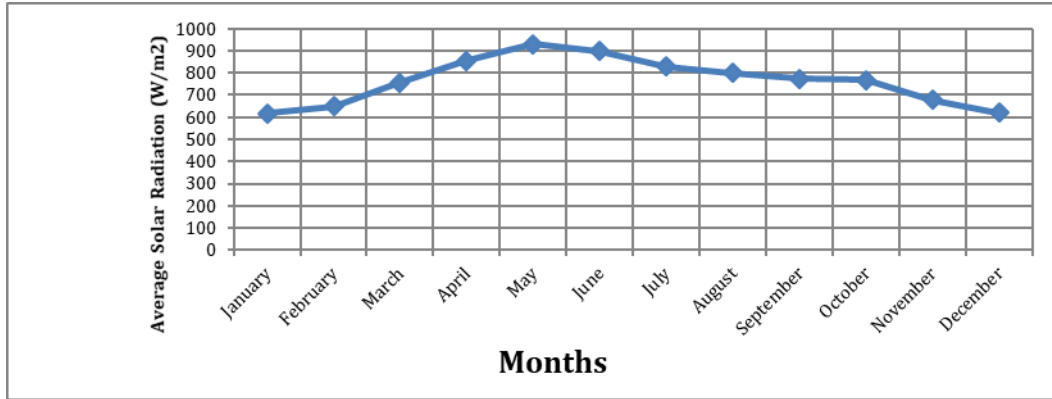


Figure 3: Average Solar Radiation Data for the Academic Area

Figure 4: Average Wind Energy Data for the Academic Area

Figure 1: Average Ambient Temperature Data for the Academic Area

The methodologies employed for the energy audit were:

1. Visual inspection and quantification of Facilities within the Academic area

2. Observations on the working condition of the Facilities

3. Identification / Measurements of energy consumption of the Facilities

4. Computation of the Data described in Figures 6, 7, 8 and 9 respectively. Questionnaires and various measuring instruments such as; Solarimeter, Hot Wire Anemometer and Wattmeter were used to obtain the required data

The Academic area is divided into Main Campus Area A, B, and C and Polytechnic Annex buildings describe by bar chart plots

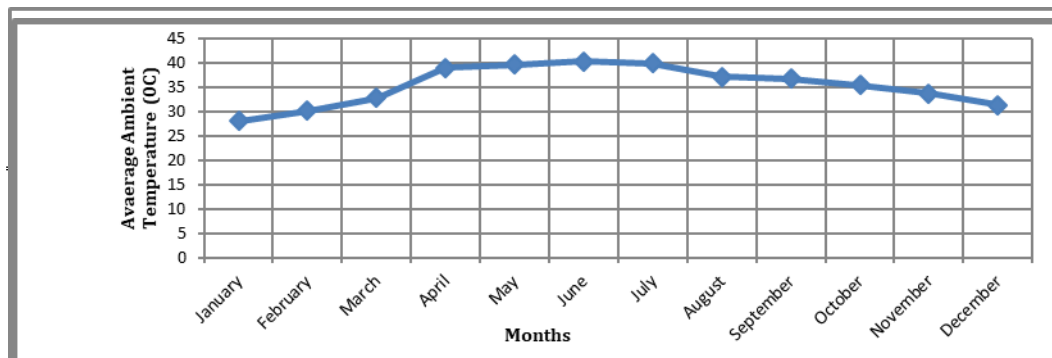


Figure 6: Power Consumption Data for the Main Campus Area

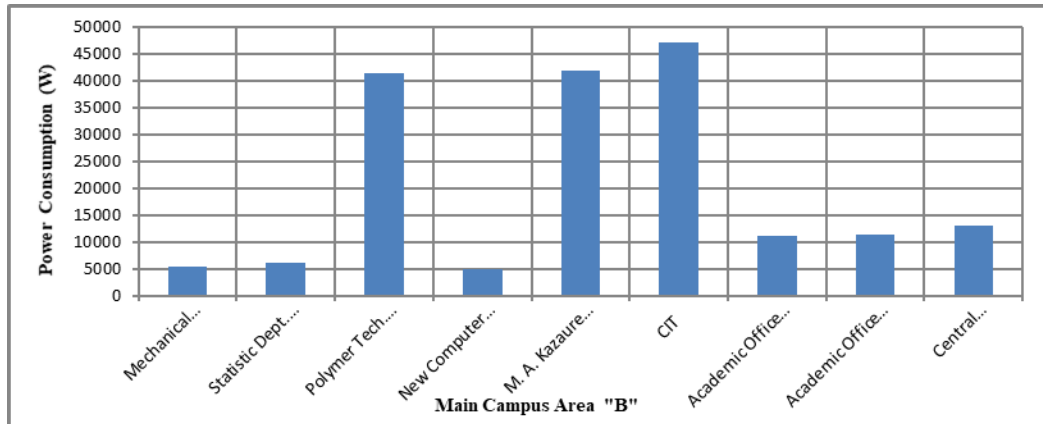


Figure 7: Power Consumption Data for the Main Campus Area

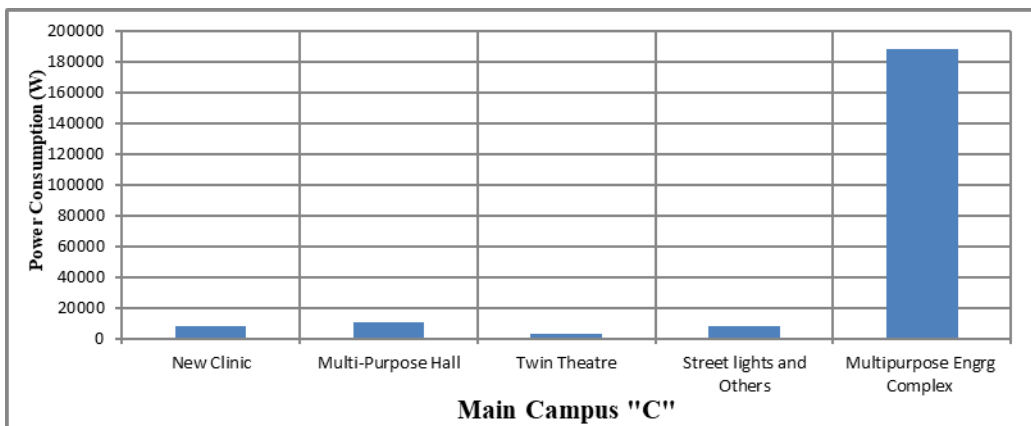


Figure 8: Power Consumption Data for the Main Campus Area

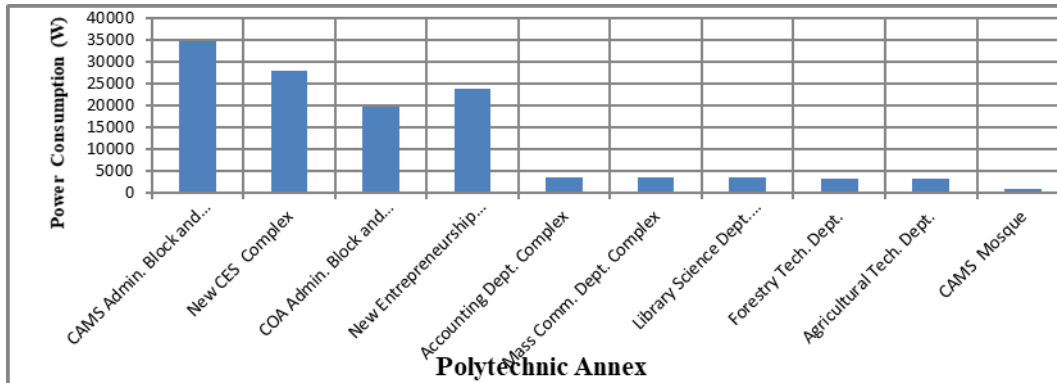


Figure 9: Power Consumption Data for the Polytechnic Annex Buildings

DESIGN OF THE HYBRID RENEWABLE ENERGY SYSTEM

The Power Consumption data for the academic area of HAFED Poly Kazaura shown in Figures 6, 7, 8 and 9 were used to design the Hybrid Renewable Energy Systems (Solar PV system and the Wind energy system) in this research. From the Figures, the TOTAL Energy Consumption of the Academic Area was determined to be 664,329W.

A. Design of Solar PV System

i. Power Ratings

Values for Power Ratings described in Figure 10 were obtained using 8 operating hours of the PV System by taking into consideration of Diesel-Powered Generator and National Grid.

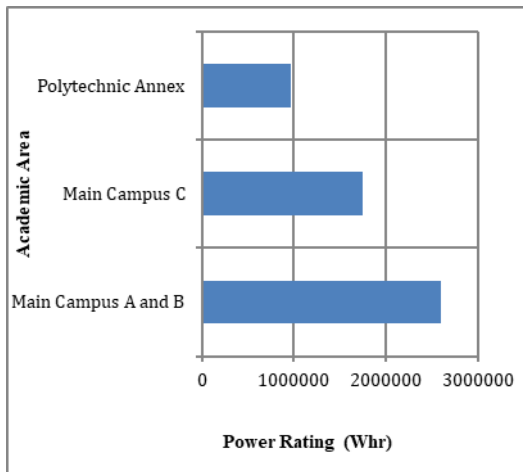


Figure 10: Power Ratings of the Academic Area

II. Number of PV Solar Panels

The number of PV solar panels to satisfy the daily load requirements of the academic area is described in Figure 11.

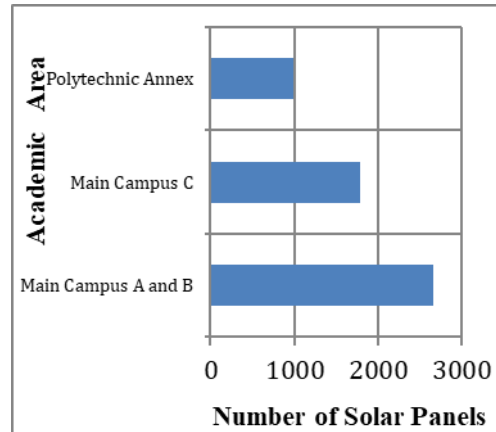


Figure 2: Number of PV Panels for the Academic Area

The total number of PV Panels for the Academic Area of the Polytechnic has been determined to be 5,445.

iii. Determination of Power Converter Size

The power electronic circuit, specifically an inverter, is employed to transform DC into AC at the desired frequency for the load. The DC input to the inverter can originate from



either the DC output of the variable-speed wind power system or the DC output of the photovoltaic (PV) power system. In order to meet the daily load requirements within the academic area at maximum power, two 450kVA converters will be necessary.

iv. Determination of the Number of Solar Batteries

Typically, it is advised that the system voltage be augmented with the increase of the total load. A 12V system voltage is suitable for minor daily loads, while a 24V system voltage is appropriate for intermediate daily loads. In cases of heavier loads, a 48V system voltage is recommended. The transition points, depicted in Figure 12, occur approximately at daily loads of 1 kWh and 3-4 kWh, although these points may vary based on the specific power profile.

Figure 3: Daily Loads and System Voltage

The changes over points are used in determining the actual voltage requirement of solar power systems. Since the Power Ratings for the Polytechnic Academic Areas has been determined and the battery system voltage, $B_{voltage}$ has been considered to be 48V using Figure 10, the electric current usage per day, I_{daily} for the Main campus A, B and C and the Polytechnic Annex has been determined using (1).

$$I_{daily} = \frac{P_{totalhr}}{B_{voltage}} \quad (1)$$

Using (1), the TOTAL electric current usage per day, I_{dailyT} was determined to be 110.722kAhr. Therefore, the total number of 200Ahr batteries that will meet the daily energy requirements will be approximately 555 number (taking into account all battery losses).

v. The Estimated Cost of the Solar PV System for the Academic Area

- i. Sub Total Cost of 200W Solar PV Panels = No. of Solar PV Panels × Cost of PV = 5,445 × \$100 = \$544,500
- ii. Sub Total Cost of Solar Batteries = No. of Batteries × Cost of Solar Battery = 555 × \$310 = \$172,050
- iii. Sub Total Cost of 2 number 450kVA Inverter = \$40,000
- iv. Sub Total Cost of Charge Controller = \$5,000
- v. Total Cost of the Solar PV Energy System = \$761,550

B. Design of the Wind Energy System

To ascertain the necessary size of the wind turbine required to fulfill the energy demand of the Polytechnic Academic Area (5,314,632Whr), the following assumptions were taken into account;

- a. Propeller type wind machine
- b. Coefficient of performance of 0.40 factor
- c. Average Wind speed of the test area using Figure 4.
- d. Density of air assumed to be 1 kg/m³
- e. Number of hours in a year 2,920hrs (365×8hrs).

i. Determination of the Power Density, P_d of the Wind

$$P_d = 0.5 \times \rho_{air} \times v^3 \quad (2)$$

Where;

ρ_{air} = Density of air (1kg/m³)

v = Average wind velocity of 5.0m/s (From Figure 4)

Using (2);

$$P_d = 0.5 \times 1 \times 5^3 = 62.5W/m$$

ii. Determination of the Actual Wind Power Density, P_{Actual}

$$P_{Actual} = P_d \times L_o \quad (3)$$

Where;

L_o = Overall loss factor given by;

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$$L_o = C_p \times L_T \times L_G \quad (4)$$

C_p = Coefficient of performance (0.40)
 L_T = Losses in transmission (0.90)
 L_G = Generator Losses (0.90)

Therefore;

$$L_o = 0.40 \times 0.90 \times 0.90 = 0.324$$

The Actual Power Density, P_{actual} from (3);

$$P_{Actual} = 62.5 \times 0.324 = 20.25 \text{W/m}^2$$

iii. Annual Wind Energy Density, E_{Annual} (Useful)

The annual energy density is given by;

$$E_{\text{Annual}} = P_d \times H_{\text{year}} \quad (5)$$

Where;

H_{year} = Number of hours per year

Therefore;

$$E_{\text{Annual}} = 20.25 \times 2,920 = 59,130 \text{Whr/m}^2$$

iv. The Wind Turbine Rotor Size

The Rotor size is obtained using the followings;

$$A_{\text{rotorl}} = \frac{P_{\text{totalhr}}}{E_{\text{Annual}}} = \frac{5,314,632}{59,130} = 89.88 \text{m}^2$$

Where;

A_{rotor} = Rotor Area, m^2

The radius of the rotor blade, R_{rotor} have been obtained using an expression for rotor area;

$$A_{\text{rotorl}} = \pi R_{\text{rotor}}^2 = 89.88 \text{m}^2$$

$$R_{\text{rotor}} = \sqrt{\frac{89.88}{\pi}} = 5.3 \text{m}$$

Therefore, the radius of the turbine rotor has been determined to be 5.3m.

v. The Wind Turbine Power Rating Estimation

The turbine power rating, P_{turbine} is given by;

$$P_{\text{turbine}} = P_{\text{Actual}} \times A_{\text{rotor}} = 20.25 \times 89.88 = 1,820 \text{W} = 1.82 \text{kW}$$

vi. Actual Rated Wind Power of the Turbine

Actual rated Power of the Turbine is given by;

$$P_{\text{turbactual}} = \frac{P_{\text{turbine}}}{\text{CapacityFactor}} = \frac{1.82 \text{kW}}{0.3} = 6,066 \text{W} = 6.066 \text{kW}$$

Therefore, a wind turbine with a rated power of 6.066 kW will generate the targeted annual energy output under the specified conditions. Given this 6.066 kW wind turbine, 100 units will need to be installed to supply the necessary power (664.329 kW) for the academic area. Considering a cost of approximately \$660 per kW for wind turbines, the capital outlay for the required number of turbines can be calculated as follows: 664.329 kW \times \$660 = \$438,457.

OPTIMIZATION OF THE HYBRID RENEWABLE ENERGY SYSTEM USING HOMER

Various simulation programs are utilized by researchers in the design of Hybrid Renewable Energy Systems (HRES), employing computer simulations to assess the effectiveness and cost of energy production across different system configurations. Among these programs, the Hybrid Optimization Model for Electric Renewable (HOMER) has emerged as a widely adopted tool for optimizing hybrid systems. HOMER facilitates the intricate optimization of operating strategies, offering economic feasibility, precision, and the capability to generate the lowest Total Net Present Cost (TNPC) for a given optimization scenario.

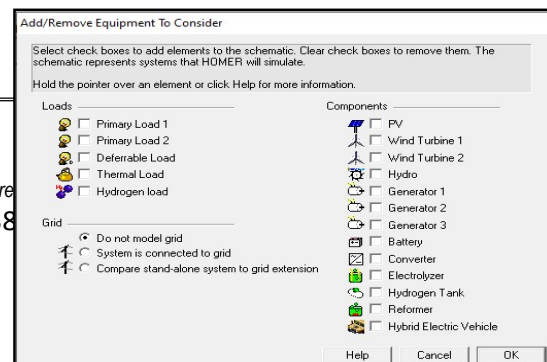
Abdullah et al. (2017) utilized HOMER in the design of a micro-Hydro-PV-Biogas based micro-grid, demonstrating its efficacy in system design and optimization. Similarly, (Sharma & Mishra, 2016) employed HOMER in crafting a hybrid renewable energy system for sustainable energy development in a village in Rajasthan,

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successfully meeting the area's load demands. HOMER software conducts comparative analyses of multiple technology options for power system designs, as illustrated in Figure 13.

Figure 4: Schematic Diagram of the HOMER Window

A. Hybrid System Configuration

This research explores Diesel generators 1 and 2, Power converter, PV panels, Wind turbine, and Battery systems. In the hybrid system configuration depicted in Figure 14, the diesel generators are linked to the AC side of the network, while the batteries, wind turbine, and solar panels are connected to its DC side. A conventional backup diesel generator (DG) is employed to complement the overall system during peak loads and in periods of insufficient renewable resources, ensuring system stability.

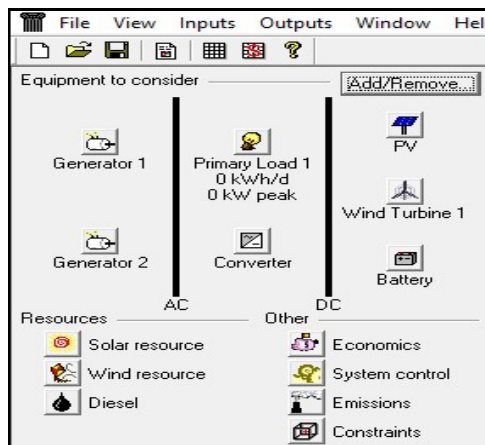


Figure 14: HOMER Diagram for the Hybrid System Set up

i. Primary Load Descriptions

In any power system, the primary load is a crucial factor to consider. HOMER optimizes system components based on these load profiles. In this study, load data details (kW) outlined in Figures 6, 7, 8, and 9 have been taken into account. The daily primary load profile

curve for the academic area, sourced from the HOMER tool library, is illustrated in Figure 15. Upon examination of the primary load inputs window, it was determined that the annual average load amounts to 4,466 kWh/day, the annual peak load reaches 1,166 kW, and the load factor is calculated to be 0.160.

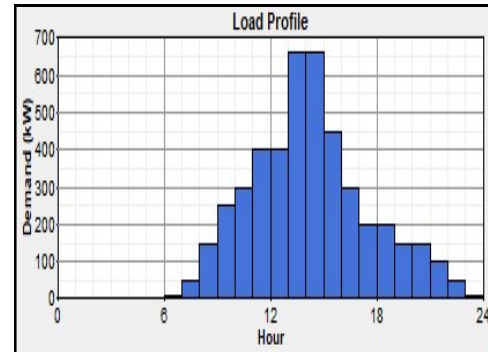
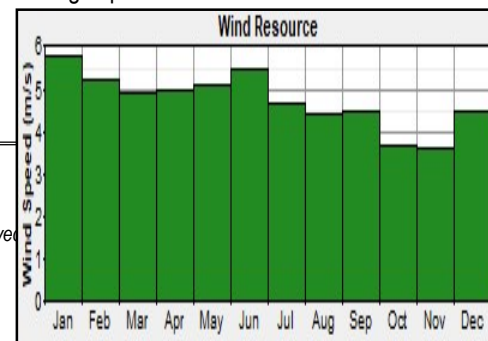


Figure 15: Daily Load Profile Curve of HAFED Poly Academic Area

ii. Solar and Wind Resource Data

In this research, a 2022 and 2023 wind speed and solar radiation data for the Academic Area of HAFED Poly Kazaure, Jigawa State (Latitude of 12°39'10"N and Longitude of 8°24'43"E) were collected from HAFED Poly Weather station Stationed at College of Agriculture. The data has been averaged to monthly values and imported into HOMER Solar Resource and Wind Resource Inputs window. The main essence is to evaluate the design of the hybrid systems so as to meet the load demand of the Academic Area. Figure 16 shows monthly average daily solar radiation for the Academic Area which ranges from 9.29kWh/m²/d in the month of May to 6.180kWh/m²/d in the month of January while the average was 7.65kWh/m²/d. Figure 17 shows monthly average daily wind speed which ranges from minimum speed of 3.6, maximum speed of 5.8m/s and the average speed determined to be 4.7m/s.



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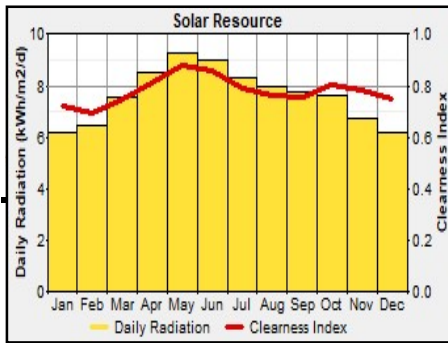


Figure 16: Daily Solar Radiation Data

Figure 17: Wind Speed Data

iii. Photovoltaic (PV) Panels

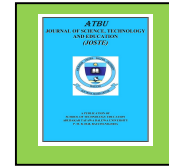
After conducting market survey, a 180-200W PV panel was chosen this is due to low cost and a considerable efficiency. The selected panel was poly-crystalline silicon with an efficiency of 15 %. The cost of each panel was estimated at \$100 and a total of 3320 panels have been considered to provide the academic area with 664kW of electrical power. The capital cost for this number has been determined to be \$330,000.

iv. Wind Turbine

WES 30 wind generator that can produce up to 14.9kW at 5m/s wind speed has been chosen from the HOMER tool library. An estimated number of 100 wind turbines with a capital cost of \$438,457, life time of 15years and hub height of 25m have been considered in this research.

v. Diesel Generator

The diesel generators 1 and 2 will be used to provide the required AC power during night time. Two generators each having capacity of 350kW has been considered in this research. The capital cost considered is \$55,000 for the two generators. Lifetime for generator 1 is



estimated at 2880 while that of generator 2 is 15000. However, the operating hours and price of the diesel was considered to be 0.5\$/litre.

vi. Converter

In the simulation model design, a converter with a capacity of 700 kW and a capital cost of \$40,000 was selected. This converter serves the dual function of rectification and inversion. It is estimated to have an efficiency of 90% and a lifespan of 15 years.

vii. Battery

For the battery component, the Vision 6FM 200D battery was chosen. It has a nominal capacity of 200 Ah, a life cycle of 4 years, a nominal voltage of 12V, and a round-trip efficiency of 80%. This battery was selected for its ability to provide necessary backup during emergencies such as load-shedding. A total of 555 batteries were considered, with assumed capital and replacement costs totaling \$172,000.

B. HOMER Simulation Model

Having defined the required configurations for the energy systems which comprises of the load profile descriptions, solar and wind resources data, PV panels, Wind turbine selection, converter and battery, generator 1 and generator 2 selections, the HOMER model described in Figure 18 has been used to simulate a wide variety of the energy system configurations after which the best optimal system configuration which is suitable to provide the energy demand of HAFED Poly Academic Area was determined.

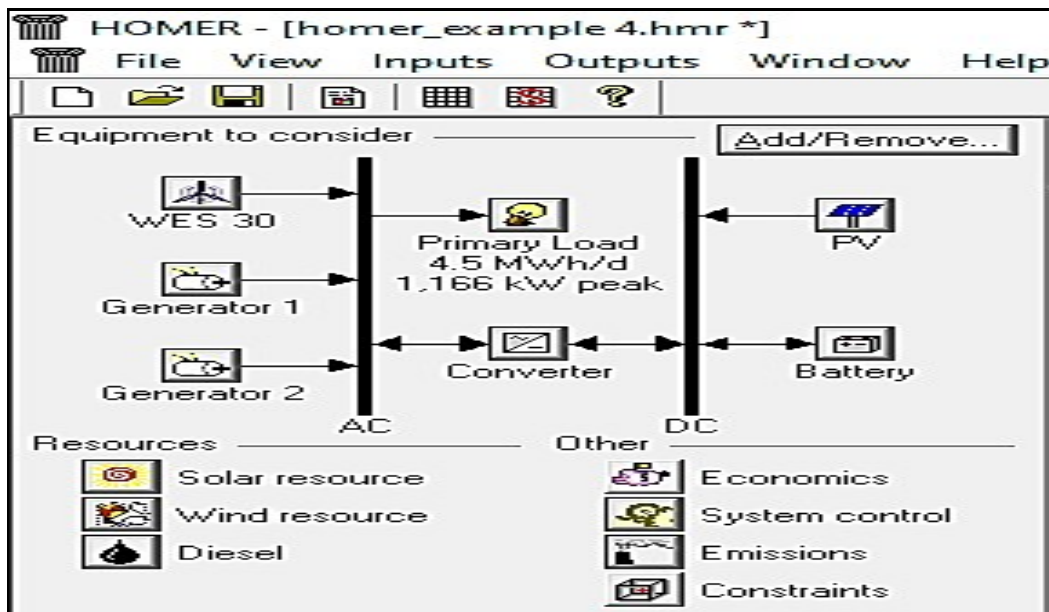


Figure 18: HOMER Simulation Model

RESULT AND DISCUSSION

A. Optimization Result

The simulation results for solar radiations of 7.65.07 kWh/m²/d and a wind speed

of 4.7 m/s revealed nine feasible system configurations as determined by HOMER, presented in Table 1.

Table 1: HOMER Optimization Result for the Different Configurations

	PV (kW)	WES30	Gen1 (kW)	Gen2 (kW)	Batt. (kW)	Conv. (kW)	Initial Capital	Total NPC	COE (\$/kWh)	Ren. Frac.	Diesel (L)	Gen1 (hrs)	Gen2 (hrs)
	664	100		350	555	900	\$ 1,007,957	\$ 1,640,462	0.079	1.00	36,144		478
	664	100	350		555	900	\$ 1,007,957	\$ 1,651,207	0.079	1.00	33,487	422	
	664	100	350	350	555	900	\$ 1,035,457	\$ 1,666,311	0.080	1.00	36,546	9	478
		100	350	350	555	900	\$ 705,457	\$ 1,772,352	0.085	0.99	96,608	152	943
	664	100	350	350		900	\$ 863,457	\$ 2,055,455	0.099	0.99	112,724	87	1,851
	664		350	350	555	900	\$ 597,000	\$ 2,878,564	0.138	0.71	245,344	116	3,000
	664		350	555	900		\$ 569,500	\$ 2,943,849	0.141	0.71	247,082		3,069
	664		350		555	900	\$ 569,500	\$ 3,217,613	0.154	0.71	240,726		2,916
			350	350	555	900	\$ 267,000	\$ 5,609,929	0.269	0.00	603,668	1,249	5,173

These configurations are arranged in descending order of cost-effectiveness, with the most cost-effective configuration listed first,

based on the total net present cost (TNPC). As depicted

in Figure 19, the first column showcases the most cost-effective configurations, with a minimal

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TNPC of \$1,604,462. This column encompasses five configurations: Solar PVs, WES30 wind turbines, Generator (GEN2), Battery, and Converter in a hybrid system.

Under normal operation, the PV and WES30 systems meet the daytime load demand, with any surplus energy stored in the battery until

it reaches full capacity. The 900kVA converter converts DC power from the PV and WES systems into AC power for use in the academic area. The diesel generator (GEN 2) serves as a backup in scenarios where supply from PV and wind (WES30) is unavailable.

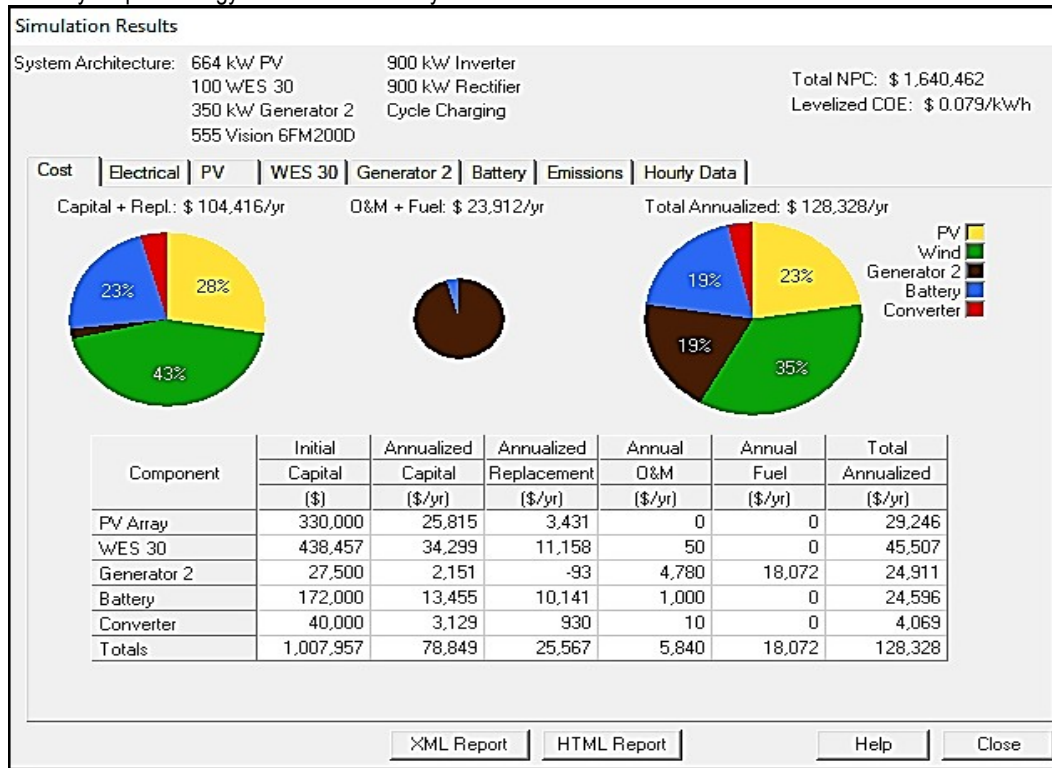


Figure 19: Simulation Result for the Most Cost-Effective Configuration

CONCLUSION

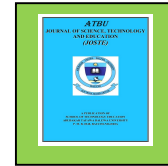
In this research, a Solar PV Power system, Wind Energy Power System, and Diesel Generator were designed for implementation in the Academic Area of Hussaini Adamu Federal Polytechnic Kazaure, utilizing data acquired from an Energy Audit conducted on the area's electrical power demand. The Hybrid Optimization Model for Electric Renewable Energy (HOMER) simulation software was employed to optimize the designed renewable energy systems, including PV-wind-battery and diesel hybrid systems. Throughout the

optimization process, HOMER software simulated various system configurations within the search space, selecting the system with the lowest total Net Present Cost (NPC) as the optimal solution. Based on the findings, it can be concluded that a standalone Hybrid Renewable Energy System is feasible for the Academic Area of Hussaini Adamu Federal Polytechnic Kazaure.

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