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Hybrid Electricity Generation System for Remote Areas: A Comparative Study of Design Configurations

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Abstract

This research paper centred on the comparative analysis of different hybrid electricity generating system configurations in rural communities of Iyi Ochioto and Ochi in Ebonyi State, Nigeria, with emphasis on the techno-economic viability of an optimal hybrid energy system. The community average daily electrical load demand was determined to be 451.32 kWh/day with a peak demand of 52.65 kW. Analytical methods were used for designing energy resources such as solar, wind, biomass, and diesel generator combined with battery storage for optimal sizing of system components. Hybrid Optimization of Multiple Electric Renewables Software (HOMER Pro) was used to carry out simulation and optimization to determine the system performance and techno-economic parameters like Net Present Cost (NPC), Cost of Energy (COE), CO2 emissions, etc. Five different system configurations were analyzed for technical feasibility and economic viability. The results obtained indicated that three of the selected optimal system configurations—Solar-PV/Diesel Generator/Biomass/Battery Bank (SDBiB), Diesel Generator/Biomass/Battery Bank (DBiB), and Solar-PV/Diesel Generator/Biomass/Wind Turbine/Battery Bank (SDBiWB)—had minimal CO2 emissions and were the most cost-effective, making them the preferred solutions. The SDBiB system had a net present cost of $503,451.30, a cost of energy of $0.2361/kWh, a renewable penetration factor (RPF) of 95.81%, and CO2 emissions of 6,946 kg/yr, the DBiB system had a total NPC of $514,287.00, a COE of $0.242/kWh, an RPF of 96.1%, and CO2 emissions of 5,613 kg/yr. and the SDBiWB system had a total NPC of $565,864.50, a COE of $0.266/kWh, an RPF of 96.1%, and CO2 emissions of 6,814 kg/yr were identified. The implication of this research serves as input to assist power system planners in intensifying efforts in electric power production through energy mix strategies, especially in remote locations in the country.

***Keywords**: Hybrid Electricity Generating System Configuration Power System Planners, HOMER Software, Net Present Cost, CO2Emission, Biomass, COE*

INTRODUCTION

In today's world, access to reliable electricity is paramount to the fulfillment of basic individual and communal needs in society [1]. For any country to achieve tangible progress in technological advancement and economic prosperity, stable and reliable power supply needs to be made available [2]. Adequate access to electrical energy is the lifeline of modern economies; it plays a cogent role in poverty alleviation, reduction in infant mortality, long life expectancy, and rapid urbanization in economically emerging countries [3].

The power system in Nigeria is characterized by a lot of problems ranging from insufficient generation capacity to meet growing loads, aged transmission and distribution lines, occasioned by the weak financial position of utilities, and the inability to recover revenue from low-income households. This has made demand for electricity much more than its supply, adversely affecting social, economic, and commercial activities in the country [4][5]. The 7th agenda of the 17 listed Sustainable Development Goals (SDGs) of the United Nations is the need for all to have access to affordable, reliable, sustainable, and modern energy [6]. Therefore, the provision of universal access to electricity is the ultimate agenda of many governments all over the world because, without access to electricity, the pathway out of poverty is narrow and long [7].

Nigeria's enormous and perennial electricity problems are hindering its development. Many citizens living in urban centers have gained access to the national grid, while access rates in rural and remote areas have been very slow, notwithstanding the availability of vast natural energy resources ranging from abundant gas to renewable energy sources [8][9].

In order to achieve stable, reliable, affordable, and eco-friendly electricity supply, especially in rural or remote communities, the abundant stock of untapped renewable energy resources, coupled with the availability of land in semi-urbanized and rural communities, can be harnessed and mixed with non-renewable resources in different configurations of hybrid electricity generating systems for community-level power supply [10]. This study intends to explore the potential for hybrid electricity generating systems with different configurations in the study area communities (Iyi Ochioto and Ochima) in Igbo-Etiti Local Government Area, Enugu State, integrating renewable energy resources with traditional fossil fuel sources to enhance energy security, reduce carbon emissions, and promote economic sustainability.

Statement of the Problem

With the steady increase in population in Nigeria, the demand for electric power has also increased. However, inadequate power supply from the national grid, as well as persistent transmission and distribution line faults, has resulted in Nigeria being ranked as having the lowest electricity per capita consumption in Africa [11]. Nigeria failed to achieve the Millennium Development Goals for water and sanitation in 2022, as only 61% of the citizens had access to basic water supply, while 39% of Nigerians do not have access to basic water supply services due to inadequate power supply [12].

In the rural communities of Iyi Ochioto and Ochima in Enugu State, Nigeria, most areas are not connected to the national grid. The Enugu Electricity Distribution Company, which supplies electricity to the community, only provides a maximum of three hours of electricity daily when there is supply, which is inadequate. Sometimes, electricity is not supplied to the community for months.

This inadequate power supply creates socio-economic challenges for the residents of these communities, despite the availability of several renewable energy resources yet to be harnessed in the area. In order to address the lack of access to or inadequate electricity supply in these communities, a study needs to be carried out to analyze different hybrid energy generating system configurations using the available energy mix resources (renewable and non-renewable) for an off-grid solution, which is the focus of this research.

LITERATURE REVIEW

The inefficiencies in generation, distribution, and human activities leading to the depletion of fossil fuel resources have made diversification into renewable energy and renewable energy mix inevitable [13]. The primary issue addressed in this research is the overreliance on fossil fuels for electricity production in rural communities. This overdependence is accompanied by shortcomings such as environmental degradation, greenhouse gas emissions, and economic vulnerabilities due to fluctuating oil prices. In addition, the existing energy infrastructure in most remote communities often struggles to meet the growing demand, leading to frequent power outages and an unreliable energy supply [14].

Transitioning to a more sustainable energy system is essential for the long-term economic and environmental health of the community. Nigeria is known to be the most populated country in Africa, with only 40% of the entire country's total population connected to the national power grid [15]. The remote and rural communities are often the worst victims, as they are rarely connected to the central electricity grid [16]. Due to the intermittent nature of renewable energy resources, penetration of renewable energy systems to replace some portion of energy produced by diesel generators is a good approach to consider. In order to achieve a better overall power supply pattern, the diesel generator can be used for operation when the renewable sources fail to satisfy the load and when battery storage is depleted [17].

The application of hybrid energy systems with different configurations is of increasing interest because a well-managed hybrid electricity generating system can achieve lifetime fuel savings while ensuring a reliable and cost-effective electricity supply [18].

Figure 1 and Figure 2 represent the block diagram of a Solar PV system and the schematic diagram of a wind turbine generator, respectively.

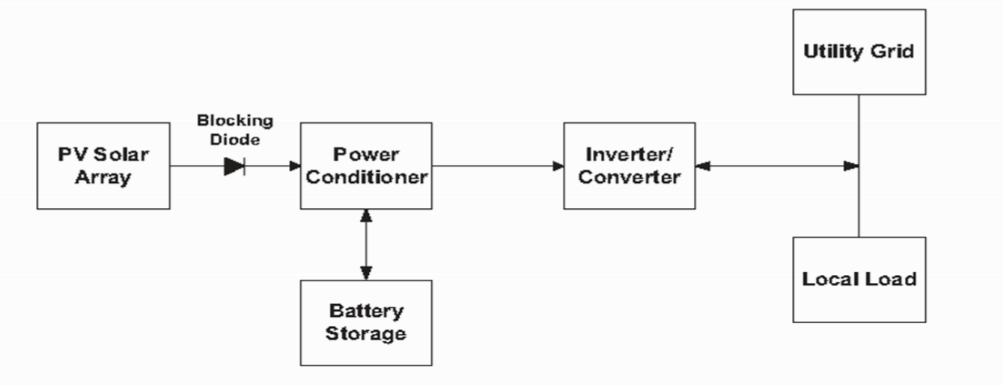


Figure 1: Block Diagram of Solar PV System Fundamentals

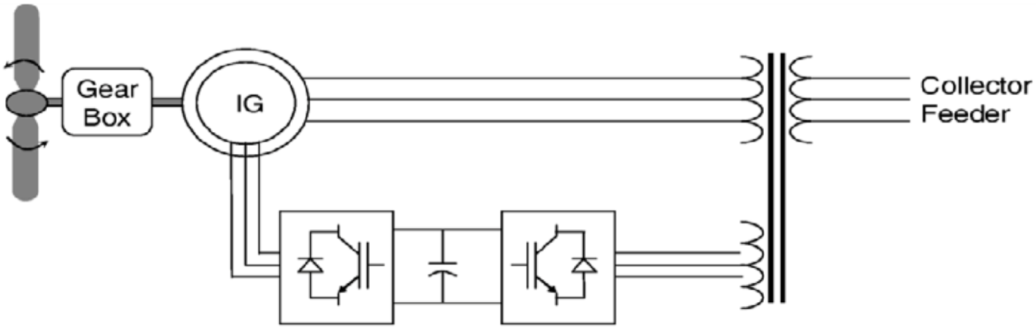
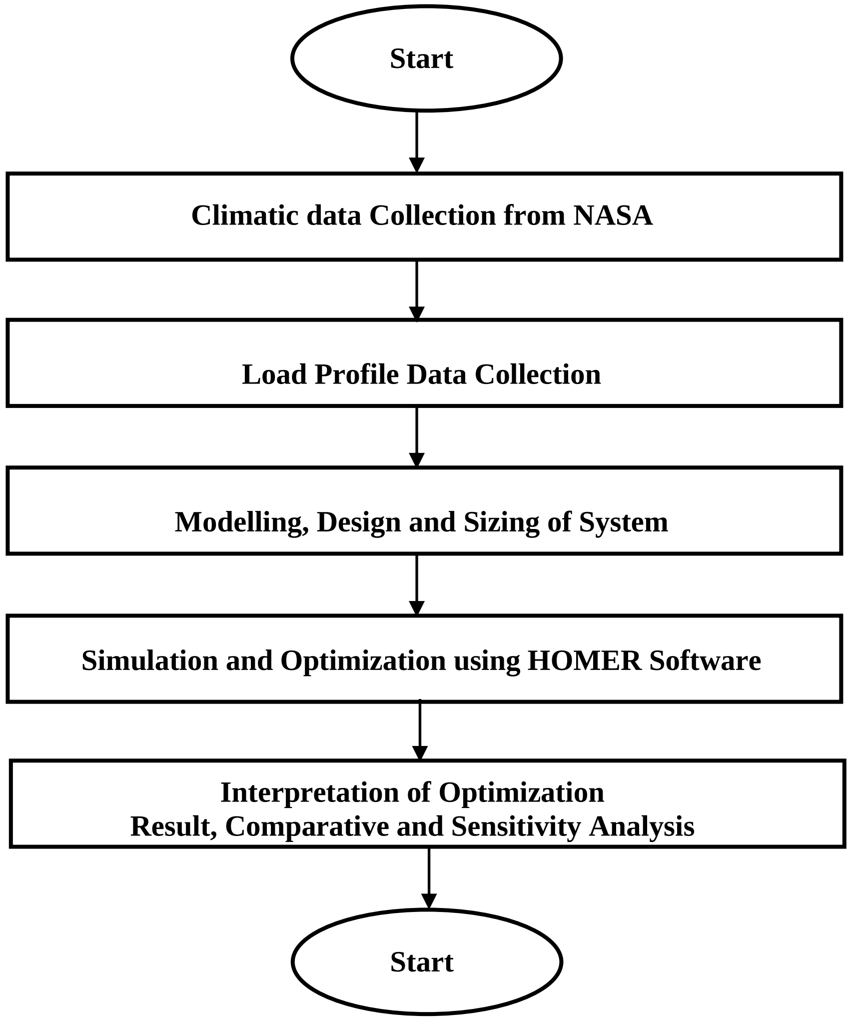


Figure 2: Schematic Diagram of Wind Turbine Generator

METHODOLOGY

This study is a comparative analysis of hybrid energy generating system configurations for typical rural communities. A deterministic method and mathematical modeling were employed for the design and optimal sizing of the systems. The simulation and optimization tool used is the Hybrid Optimization of Multiple Energy Resources (HOMER) software. Climatic condition data of the study community area was used to achieve the optimal system design. The research methodology steps used are summarized as shown in Figure 3.



- **StudyLocation**

Iyi Ochioto and Ochioma are communities in Igbo-Etiti LGA, Enugu State, Nigeria. The communities lie between latitude 6°48' N and 53°44' N, and longitude 7°25' E to 10°52' E. The major occupations of the inhabitants include farming, fishing, trading, and small- and medium-scale enterprises such as barbing and auto mechanics.

A field survey, conducted through formal interviews, was used to analyze the different electrical equipment currently owned by households, as well as those they estimate they would own in the future if there were an adequate supply of electricity. The study area is estimated to have a total of 144 households, 12 shops, one public primary school, one public secondary school, a community general hall, a community water project, streetlights, and other light loads. The average daily electricity demand for the study area is estimated to be 451.32 kWh/day, with a peak demand of 52.65 kW.

Study Area Solar Energy Potential

The solar radiation data used in this study is the monthly average global horizontal irradiance, measured at 10-minute intervals over a period of 10 years (July 1984 – June 1994) using the communities' coordinates, as depicted in Figure 4. This data was obtained from the National Aeronautics and Space Administration (NASA) database on November 14, 2024, and was considered in the HOMER Pro Software as the solar resource input.

The clearness index of the study area and its corresponding solar radiation values are shown in Table 1, with the clearness index varying from 0.373 to 0.538.

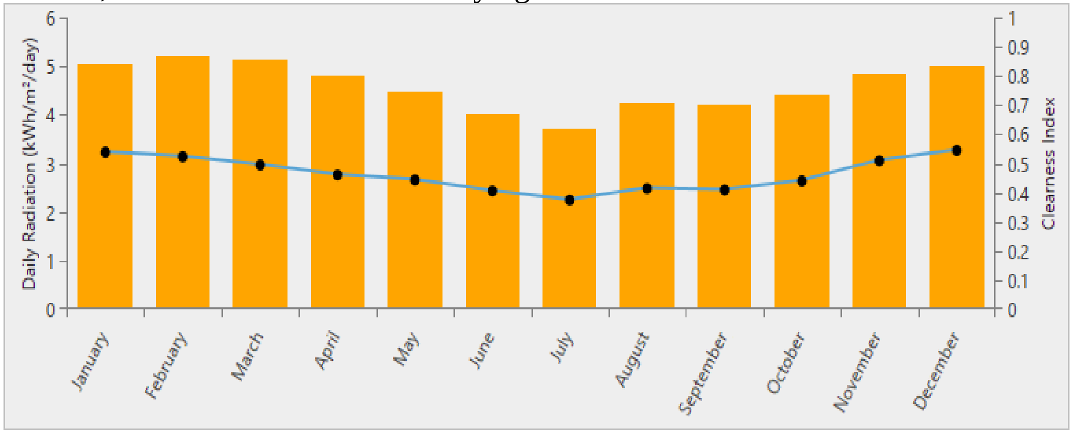


Figure 4: Monthly Solar Radiation and Clearness Index (HOMER Pro)

Table 1: 10-Year Average Monthly Irradiance and Clearness Index

Month	**AverageDailyRadiation(kWh/m^2/day)**	**ClearnessIndex**
January	5.055	0.538
February	5.194	0.523
March	5.130	0.494
April	4.797	0.460
May	4.491	0.443
June	4.009	0.405
July	3.724	0.373
August	4.240	0.414
September	4.222	0.409
October	4.400	0.439
November	4.825	0.509
December	4.998	0.544
Average	4.5904	0.463

Source: NASA Database

Study Area Wind Energy Potential

The wind speed data used in this study was recorded over a 24-hour period for 10 years (1984–1994) by NASA and downloaded from NASA's Surface Meteorology and Solar Energy Database.

The measurements were taken at 50 meters above the surface of the Earth and at a 50-meter anemometer height.

Table 2 presents the wind speed potential of the study area.

Table2:10–Year Average Monthly Wind Speed

Month	**Average Wind Speed m/s**
January	2.75
February	2.97
March	2.71
April	2.39
May	2.23
June	2.81
July	3.21
August	3.37
September	2.96
October	2.35
November	2.25
December	2.4
Average	**2.7**

Source: NASA Database

Study Area Biomass Resource

The primary biomass feedstock materials in the study area are rice husk and straw, which are residues from a rice processing plant located near the study area. One metric ton of rice husk can be supplied to the study area from nearby rice mills at a cost of 30,000 Naira (including labor and transportation), which is equivalent to $19.93 at the current exchange rate of 1,503.00 Naira per US dollar.

Modeling of Solar PV System

A generic flat-plate PV system was proposed. The HOMER Pro Software was used to optimize the required capacity. It is assumed that the solar PV modules have a maximum power point tracking (MPPT) system, with associated parameters and values as follows:

Capital cost: $4,000/kW
Replacement cost: $4,000/kW
Operation & maintenance cost: $50/year
Efficiency: 18%
Operating temperature: 46℃
Temperature coefficient: –0.5
Derating factor: 85%
Lifespan: 25 years

The output of the PV array for each time step will be calculated by HOMER Pro Software using Equation (1.1):

$$P_{PV} = Y_{PV} F_{PV} \left(\frac{G_T}{G_T S T_C}\right) [1 + \propto_P (T_C - T_G S T_C)] (1.1)$$

Where:

- **Y_PV**: Rated capacity of the PV array (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)
- **∝_P**: Temperature coefficient of power (%/°C)
- **T_C**: PV cell temperature (°C)
- **T_C,STC**: PV cell temperature under standard test conditions (25°C)

Modeling of Wind Power System

The instantaneous power output **of the** wind turbine generator **will be calculated by** HOMER Pro Software **using** Equation (1.2):
P=CsCPρπR2V3P = C_s C_P \rho \pi R^2 V^3P=CsCPρπR2V3

(Equation 1.2)

Where:

- **P**: Power derived from a wind turbine (W)
- **C_s**: Aerodynamic power coefficient (= 0.593)
- **C_P**: Coefficient of performance (efficiency factor in percentage)
- **ρ**: Air density (kg/m³)
- **R**: Blade length (m)
- **V**: Wind speed (m/s)

The **selected wind turbine model** has the following specifications:

- **Cut-in speed**: 2.5 m/s
- **Rated speed**: 12 m/s
- **Cut-out speed**: 30 m/s
- **Swept area**: 500 m²
- **Hub height**: 40 m
- **Installation cost**: $30,000 per unit
- **Lifespan**: 25 years

Modeling of Biomass System

A biomass generator with an input range of 0 to 50 kW was specified in this study, allowing HOMER Pro to optimize the required sizing and determine the most cost-effective operating sequence.

The biogas generator has the following specifications:

- Capital cost: \$1,500/kW
- Replacement cost: \$1,500/kW
- Operational & maintenance cost: \$0.18 per operating hour
- Lifetime: 25,000 hours

The fuel cost of the biogas generator is determined by HOMER Pro using the fuel curve equation (1.3):

$$F = F_0 Y_{gen} + F_1 P_{gen} \qquad (1.3)$$

Where:

Where:

- **F**: Fuel consumption (kg/hr)
- **F₀**: Fuel curve intercept coefficient (kg/hr/kWrated_{rated}rated) – defined as the no-load consumption of the generator divided by its rated capacity
- **F₁**: Fuel curve slope (kg/hr/kWoutput_{output}output) – defined as the marginal fuel consumption of the generator
- **Y_gen**: Rated capacity of the generator (kW)
- **P_gen**: Electrical output of the generator (kW)

Battery Model

For **energy storage**, a **generic 12V lead-acid solar battery** was selected for this design. The battery specifications are as follows:

- Rated capacity: 83.4 Ah
- Charge efficiency: 90%
- Depth of discharge: 40%
- Maximum charging current: 16.7 A
- Maximum discharge current: 24.3 A
- Installation cost: \$500/kW
- Operational & maintenance cost: \$40/year
- Lifetime: 10 years

The **autonomy** of the battery can be determined using **Equation (1.4).**

$$A_{batt} = \frac{N_{batt} V_{nom} Q_{nom} \left[\frac{1-q_{min}}{100}\right] \left({}^{24h}/_{d}\right)}{L_{prim.ave} (100Wh/kWh)} (1.4)$$

Where;
A_{batt}:is the storage battery bank autonomy (hrs)
N_{batt}:Is the number of batteries in the storage bank.
V_{nom}:Nominal voltage of a single storage (V)
Q_{nom}:is the nominal capacity of a single (Ah)
q_{min}:is the minimum state of charge of the storage bank (%).
$L_{prim.ave}$:is the average primary load (kWh/d)

Diesel–GeneratorModel

In the search for space for a **diesel generator**, combinations of **5 kW and 20 kW** in given intervals of **5 kW** were tested. The price of diesel was set at **$1.4 per liter**, which is the dollar equivalent of **₦1,400 per liter** based on Nigeria's present diesel price. The **initial capital cost** of the generator is **$5,500/kW**, with an **operation and maintenance cost** of **$0.04/hour** and a **lifespan of 25 years**.

Converter Model

For this study, a generic converter power model was selected with the following parameters:

- Capital cost: $400/kW
- Replacement cost: $400/kW
- Operation & maintenance cost: $0
- Lifetime: 15 years
- Inverter efficiency: 90%

Modeling of Different Hybrid Electricity Generating System Configurations

The modeling of different hybrid electricity generating system configurations consists of two or more system components, which include:

- Solar PV array
- Wind turbine
- Diesel generator
- Biomass generator
- Converter
- Battery banks

These components are used for the optimal sizing of the overall system, designed to meet the estimated load demand of 451.32 kWh per day for the study communities.

The chosen possible configurations in this research are as follows:

The chosen possible **hybrid electricity generating system configurations** in this research are as follows:

i. Solar PV / Diesel Generator / Biomass / Battery Bank (SDBiB)
ii. Diesel Generator / Biomass / Battery Bank (DBiB)
iii. Solar PV / Diesel Generator / Biomass / Wind Turbine / Battery Bank (SDBiWB)
iv. Diesel Generator / Biomass / Wind Turbine / Battery Bank (DBiWB)
v. Solar PV / Diesel Generator / Battery Bank (SDB)

Figure 5 depicts the schematic diagram of the different hybrid electricity generating system configurations when all the required components are combined.

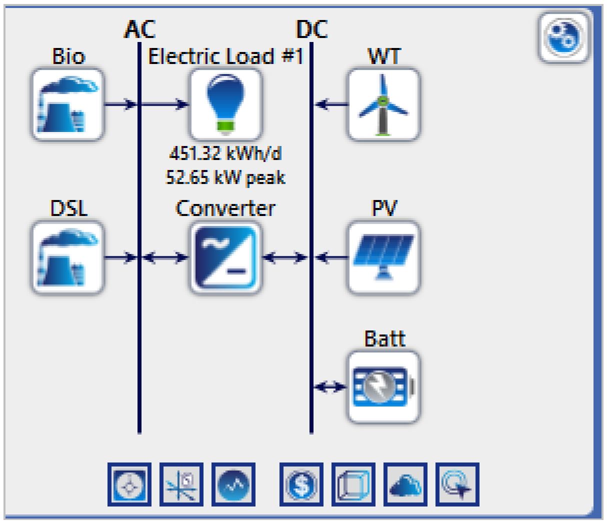


Figure5:Schematic Diagram of Hybrid Electricity Generating System Configurations (HomerPro)

Results of Selected Hybrid Electricity Generating System Configurations

Bar charts illustrating electrical energy production by each component of the optimal hybrid electricity generating system configurations for Cases 1, 2, and 3 are shown in Figures 6, 7, and 8, respectively. These three cases, which are the most cost-effective among the five chosen configurations, are analyzed and discussed in terms of their techno-economic parameters.

- Case 1: Solar PV / Diesel Generator / Biomass / Battery Bank (SDBiB)

The optimal system configuration of Case 1 (SDBiB) has reduced the Cost of Energy (COE) by 41.3% compared to Scenario 4 (Solar PV / Diesel Generator) if taken as the base case. Biomass generation in the study location is high, supplying 88% of the total load demand, which confirms the significant presence of biomass renewable energy resources in the study area.

- Case 2: Diesel Generator / Biomass / Battery Bank (DBiB)

Case 2 has a Renewable Penetration Factor (RPF) of 96.1%, compared to 95.81% in Case 1, indicating an improvement of 0.3%. It has an initial capital cost of $123,180, which is lower than the $125,903 obtained in Scenario 1. The CO_2 emissions for Case 2 are 5,613 kg/year, a 19.2% reduction from the 6,946 kg/year recorded in Case 1. Biomass generation in Case 2 contributes 96.1% of the total load demand (167,860 kWh/year) to the total energy production of 174,750 kWh/year, marking an 8.1% increase in biomass contribution compared to Case 1. Additionally, the diesel generator in Case 2 produces 6,890 kWh/year (3.94%), representing a 4.9% reduction from its contribution in Case 1, which remains the most cost-effective optimal HEGS configuration.

- Case 3: Solar PV / Diesel Generator / Biomass / Wind Turbine / Battery Bank (SDBiWB)

Case 3 follows Cases 1 and 2 in the order of cost-effectiveness. It has an RPF of 95.9%, slightly lower than 95.8% in Case 1, with an unmet load of 0.479 kWh/year and a capacity shortage of 32.8 kWh/year. The total annual energy production in Case 3 is 173,520 kWh, with biomass contributing 152,304 kWh/year (87.8%), wind turbines 650 kWh/year (0.374%), and the Solar PV array 13,495 kWh/year (7.78%). This highlights the strong solar and biomass energy potential in the study location. However, higher NPC and COE in Case 3, along with an excess electricity production of 159 kWh/year, pose a drawback compared to 138 kWh/year in Case 1 and 0 kWh/year in Case 2.

Using COE and NPC as comparison benchmarks, Case 1 is the most suitable for implementation.

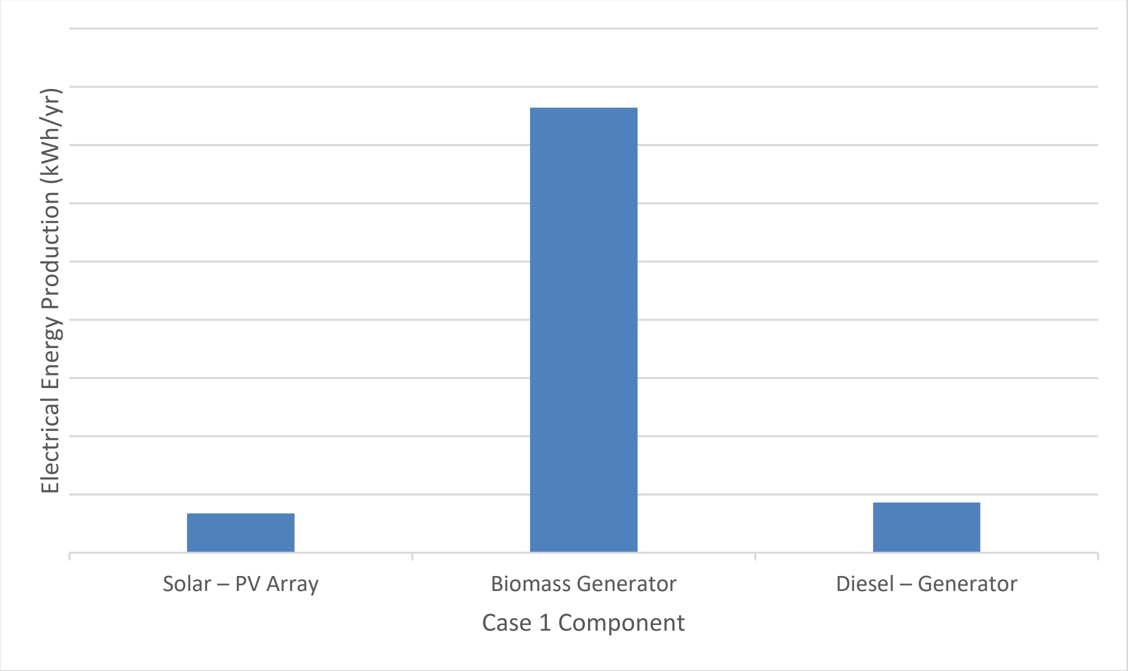


Figure6:ElectricalEnergyProductionbyEachComponentsoftheOptimalHEGSofCase1

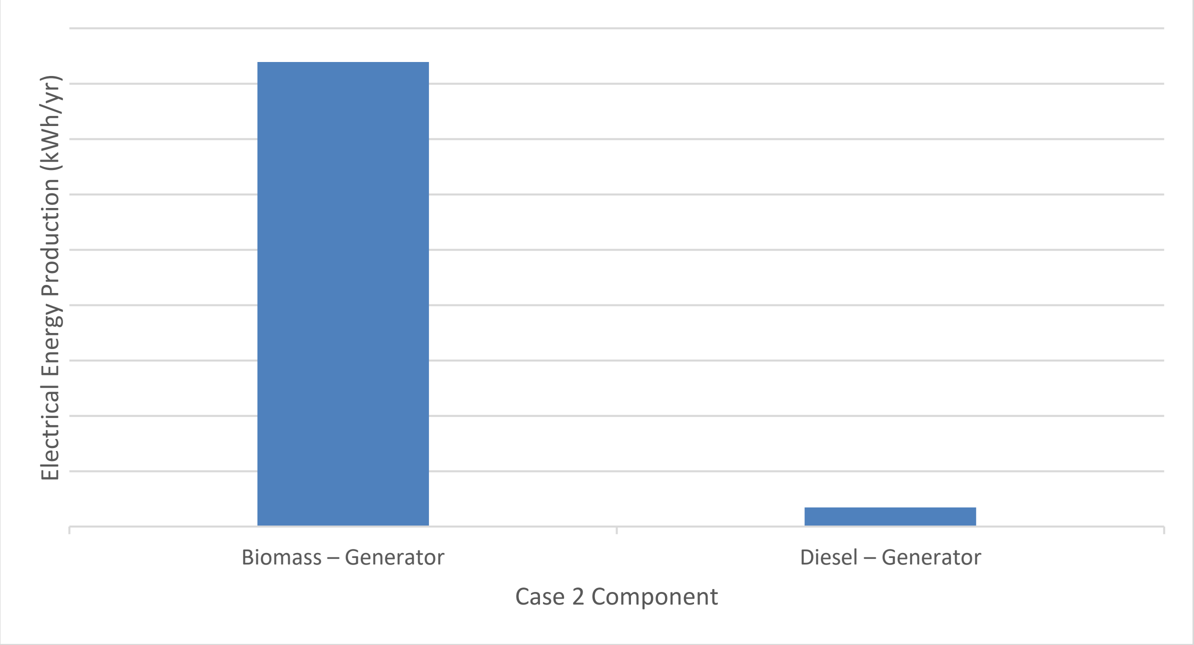


Figure7: Electrical Energy Production by Each Components of the Optimal HEG Sof Case2

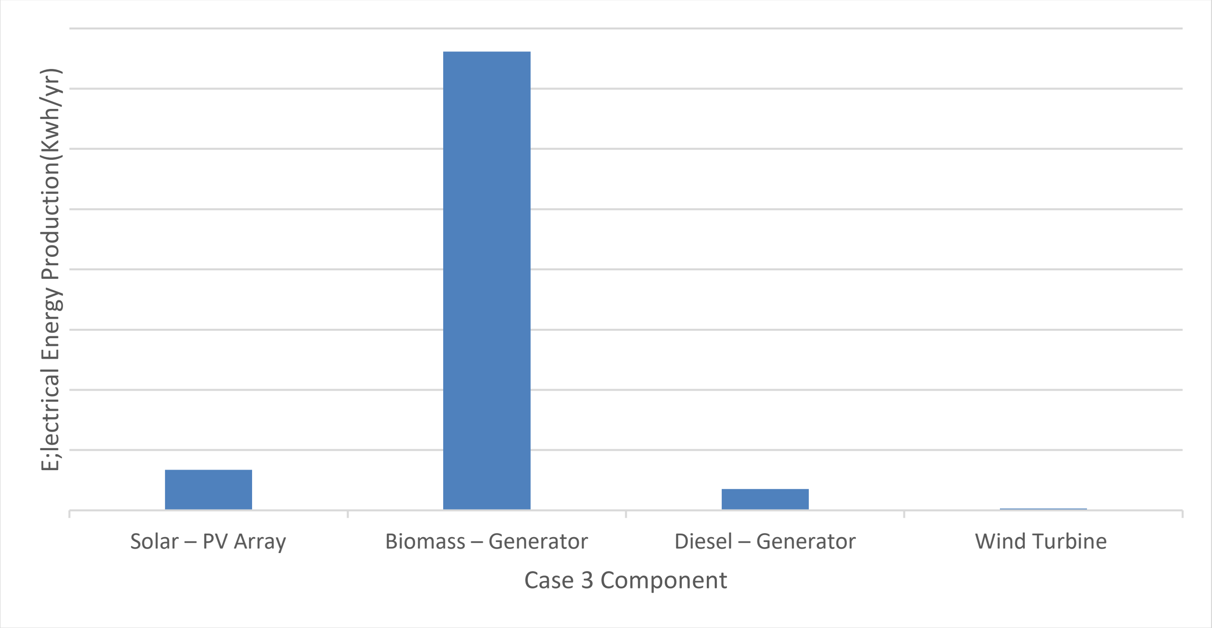


Figure8:Electrical Energy Production by Each Components of the Optimal HEG Sof Case 3

Results of Economic Terms for Cases 1, 2, and 3 Configurations

The economic results **of the** three top-ranked optimal Hybrid Electricity Generating System (HEGS) configurations **for the study area are presented in** Table 3**.**

Among the configurations, Case 2 **has the** highest Return on Investment (ROI) of 54.1% **and the** shortest payback period of 1.38 years**. If** ROI and payback time **are the primary considerations,** Case 2 is the most suitable for implementation**.**

Table3:EconomicsTermsoftheProposedHEGSOptimalSystemConfiguration

Metric	**Case1**	**Case2**	**Case3**
PresentWorth($)	352,723	341,867	290,290
AnnualWorth($/yr)	27,285	26,445	22,455
ReturnonInvestment(%)	53.1	54.1	25.1
InternalRateofReturn(%)	61.8	63.8	30.8
SimplePayback(yr)	1.44	1.38	3.35
Discountedpayback(yr)	1.54	1.48	3.69

VI. Conclusion

This study focused on the comparative analysis of different hybrid electricity generating systems in Iyi Ochioto and Ochioma communities in Enugu State, Nigeria. Data on community load demand, solar irradiation, wind speed, available biomass resources, and diesel generator specifications were collected, and the necessary calculations were performed. The HOMER Pro Software was used to model, simulate, and optimize the proposed hybrid electricity generating system configurations for the study area, evaluating their techno-economic parameters. The simulation results showed that the most cost-effective optimal system is Case 1: Solar-PV/Diesel–Generator/Biomass/Battery–Bank (SDBiB) configuration, with a total Net Present Cost (NPC) of $503,451.30, representing a 7.36% reduction compared to Case 2 (Diesel–Generator/Biomass/Battery–Bank - DBiB) and a 41.20% reduction from the base case (Scenario 5: Solar–PV/Diesel–Generator/Battery–Bank). The Cost of Energy (COE) for Case 1 is $0.236/kWh, which is 2.48% lower than Case 2 and 41.30% lower than the base case (Case 5).

Case 2 (Diesel–Generator/Biomass/Battery–Bank - DBiB) is also an attractive option for implementation. It remains cost-effective with a total NPC of $514,287.00 and a COE of $0.242/kWh. Additionally, Case 2 has the highest return on investment and the shortest payback period, making it a viable alternative.

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