Scholars Journal of Engineering and Technology
OPEN ACCESS
Abbreviated Key Title: Sch J Eng Tech
ISSN 2347-9523 (Print) | ISSN 2321-435X (Online)
Journal homepage: https://saspublishers.com

Analysis of Photovoltaic (PV) – Wind Hybrid Energy Systems for Office Building in Aliero, Nigeria

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DOI: https://doi.org/10.36347/sjet.2024.v12i09.001 | **Received:** 29.07.2024 | **Accepted:** 06.09.2024 | **Published:** 10.09.2024

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Abstract **Original Research Article**

The world energy demand rises due to population growth and other economic and political factors. The electrical energy generation source from renewable energy resources such as solar and wind energy can mitigate the problem. The technology of harnessing solar energy for electricity generation using PV is prominent. Integrating PV with wind turbine to form a hybrid system could be the best alternative. This work involved the use of improved Hybrid Optimization Model for Genetic Algorithm (iHOGA) for feasibility analysis of hybrid solar photovoltaic (PV)-wind energy system for power supply to office building in Aliero, Nigeria. The appliances required for office building includes: lighting points, standing fans, charging points and small scale portable refrigerator. The result from feasibility analysis revealed that, PV energy system generated 2,300 kWh energy and release 54.3% and 26.1% of it for serving the load and the auxiliary load. The wind energy system generated 420 kWh which is 68.2% less than the 1,320 kWh load demand. The hybrid PV-wind energy system generated 2,620 kWh and serves the load with only 46.6% and export 37.4% to auxiliary load, 4.2 % energy loss due to batteries and zero or negligible unmet load, while the remaining 11.8 % is losses through the inverter and charge controller. Therefore, 135 W PV module could be hybridize with 200 W wind turbine, two (2) pieces of 200 Ah batteries, 40 A charge controllers and 1600 VA inverter for portable power supply to the building. The net present cost (NPC), cost of energy (COE) and carbon dioxide (CO_2) emission for the optimal PV-wind hybrid energy system are $ 22,229.3, 0.9024 $/kWh and 104 kg/yr respectively. Therefore, based on this design, hybrid PV-wind energy system is more reliable and stable energy system.

Keywords: Solar Radiation, Photovoltaic, Wind turbine, Hybrid System, Charge Controller.

1.1 INTRODUCTION

Energy is one of the essential needs of every nation for its social and economic development. The world energy demands rises due to population growth and other political and economic factors (Aung, *et al.*, 2019). Electrical energy is mostly required for domestic and industrial application. Electrical energy plays a crucial role in powering modern society, and its efficient generation, transmission, and use are essential for meeting the energy needs of various sectors while minimizing environmental impacts. Energy sources are the various forms of energy that can be harnessed and converted into useful forms of power for human activities (Mergu and Raghuram, 2017). Electrical energy can be generated through conventional and renewable energy resources. The conventional are non-renewable energy sources such as oil and gas; that cannot be easily replenished and their utilization for electricity generation produces toxic emissions to the environment which results to global warming (Aryan *et al.*, 2022).

Renewable energy sources are forms of energy that can be sustainably and replenished naturally over time, environmentally friendly because they have a lower or no carbon footprint compared to fossil fuels and do not contribute significantly to climate change (Balaji, *et al.*, 2016). Solar energy can be converted into electricity through solar thermal and photovoltaic systems. The technology of utilizing solar energy for electricity through Photovoltaic (PV) is prominent; as such the PV modules are made available in the markets for domestic use (Shaffic, *et al.*, 2020). The widespread adoption of photovoltaic energy has been driven by declining costs, technological advancements, and increased awareness of the benefits of renewable energy. As a result, solar energy has become one of the fastest-growing sources of electricity generation worldwide (Kalli *et al.*, 2021).

The combination of solar PV and wind energy sources allows for improved energy reliability, cost-effectiveness, and reduced environmental impact (Aryan *et al.*, 2022). By combining these technologies, a hybrid photovoltaic-wind energy system is formed. These offers great advantages such as increasing energy production, enhancing reliability, improving system efficiency, and reducing dependency on non-renewable energy sources. The PV-Wind hybrid system contributes to a more sustainable and resilient energy infrastructure, supporting the transition to a cleaner and greener future (Kunle *et al.*, 2022).

Shezan *et al.*, (2016) worked on performance analysis of an off-grid wind-PV (photovoltaic)-diesel-battery hybrid energy system feasible for remote areas. Their findings confirmed that the optimize PV-wind hybrid system has NPC of 288,194 $ and cost of energy of 1.877 $/kWh and predicted that the hybrid energy system might be applicable to the other region of the world. Abdullahi, (2017) worked on investigation of prospect of hybrid renewable energy system in rural communities of Sokoto, where he found that the stand-alone PV-wind energy system is feasible in rural communities in Sokoto with 100% pollution free energy system. Ninet, *et al.*, (2017) conducted research on optimal sizing and economical analysis of PV-wind hybrid power system for water irrigation using genetic algorithm through iHOGA software for El-Arish. Their findings revealed that, PV-wind hybrid sytem was recognized the most economically feasible option with net present cost (NPC) of $37,433 compared to PV-alone which has NPC of $35,450.

Muhammad, (2018) in his work spatial mapping of solar energy potentials in Kebbi State, Nigeria, revealed that Arewa-Dandi local government has the highest mean solar radiation energy at 5.53kWh/m^2/day compared to Birnin Kebbi and Ngaski whose values are 5.41 kWh/m^2/ day and 4.08 kWh/m^2/day respectively. Wind-solar PV hybrid energy system design and performance evaluation for Kola village at Birnin Kebbi, Nigeria was conducted by Maiyama *et al.*, (2018) by using HOMER. The result of their finding predicted 141,162 kWh/yr total generated power was enough to serve the load with net present cost (NPC) of 236,415 $ and levelised energy cost (LEC) of 0.413 $/kWh. Aung, *et al.*, (2019) in their work design and construction of a solar-wind hybrid system found that the energy conversion system is the core part of solar-wind hybrid power system. Kalli *et al.*, (2021) Nigeria is endowed with daily sunshine that is averagely 3.5 hours and 6.25 hours southern region and northern region of the nation respectively, with annual daily solar radiation average of about 3.5 KWm^2/day and 7.0 KWm^2/day in the coastal area in southern and northern part of the country respectively, Photovoltaic has the ability to generate electricity in a clean, eco-friendly, and reliable way. Stephen and Tariq (2021) have designed a hybrid power system using HOMER pro and iHOGA. They reported that, designing with iHOGA is more economics for hybrid system and a power production of 8,188.6 kWh/ yr which is 85.7% contribution by the wind turbine and 1,361.6 kWh/ yr by the solar PV which is 14.3% contribution to the total power production. They concluded that, the total energy contributed exceeded the total demand of the house.

Abdelmajid**,** *et al.*, (2022) worked on hybrid renewable energy system optimization using iHOGA. They concluded that, iHOGA is the most appropriate software for renewable energy system. Nishant *et al.*, (2022) In trying to meet the electricity demand more attention should be given to renewable energy source, as a result of his finding on energy efficient hybrid power system model base on solar and wind energy for integrated grids, which shows the effectiveness of using hybrid system in power generation. Umar *et al.*, (2023) conducted numerical design of off-grid wind energy systems for small scale residential power supply in Aliero. Their finding revealed that, BWC XL1 wind turbine was best which generated 1,782 kWh/ yr to serve a load of 1,595 kWh/ yr demand for the residential household. A research on Numerical design of an off-grid solar PV system for office shelter was conducted. The result of the finding confirmed that, the solar potential at Aliero reached a maximum of 6.321kWh/m^2/ day which enabled power production of 1.595 kWh/ day to serve a load of 0.850 kWh/ day (Umar, *et al.*, 2023).

The current electricity generation in Nigeria account to only 12.03% of the total energy demand. This resulted to about 45% of the population to lack access to national power grid (Jahnbosco, 2023). The residence of the isolated areas and offices in urban areas usually use fossil fuel portable generators as an alternative power supply which is costly and cause climatic changes. To mitigate the problems of power supply due to the shortfall of national grid, renewable energy could be the best alternative. Although, solar PV systems are economical and abundantly available, system faces challenges of unreliability. Therefore, solar PV-wind hybrid energy system is more desirable. If PV-wind system is effectively design, a stable and reliable power supply would be provided for an office building.

The energy imbalance between total power production and consumption is largely increasing in Nigeria due to some technical and economic challenges. Workers require continues power supply in their offices, however, the power from the national grid is interrupted by load shading. The use of renewable energy for power generation such as solar and wind and hybrid have been use to significantly mitigate the problems of power supply. Solar PV-wind hybrid energy systems for an off-grid application, plays an important roles for bridging the gap of power supply created by the load shading in an offices. Solar and wind energy resources are free and environmentally friendly and therefore, the electricity generated would be more economical and Zero hazardous to the environment. This could be enhanced by conducting feasibility analysis of Solar PV, Wind and PV-Wind hybrid energy systems by using iHOGA software.

1.2 Solar PV-Wind Hybrid Energy Systems

A photovoltaic-wind hybrid system combines both solar photovoltaic (PV) and wind energy technologies to generate electricity. By integrating these two renewable energy sources, the hybrid system can take advantage of their complementary characteristics and enhance overall energy production and system reliability (Bharat and Bal, 2018). The hybrid system utilizes both solar PV panels and wind turbines to generate electricity. Solar PV panels convert sunlight directly into electricity, while wind turbines harness the kinetic energy of the wind to generate rotational motion that is then converted into electricity. By combining these two technologies, the system can generate electricity from both solar and wind resources. Solar PV and wind energy have complementary characteristics regarding their energy generation patterns. Solar energy production is highest during the day when sunlight is available, while wind energy production can vary throughout the day and tends to be highest at night or during certain seasons. By combining solar and wind, the hybrid system can potentially provide a more consistent and balanced energy output (Aung *et al.*, 2019).

The hybrid system aims to maximize the utilization of available resources. During periods of high solar irradiation and low wind speeds, the solar PV panels can contribute a larger share of electricity generation. In contrast, during periods of low solar irradiation and high wind speeds, the wind turbines can compensate for the reduced solar energy production. Integrating solar and wind energy sources in a hybrid system improves overall system reliability. If one energy source experiences fluctuations or temporary unavailability, the other energy source can compensate and maintain a stable power supply. This redundancy and diversification of energy sources can enhance the reliability and resilience of the system. The block diagram of PV – wind hybrid system is shown in Figure 1.1

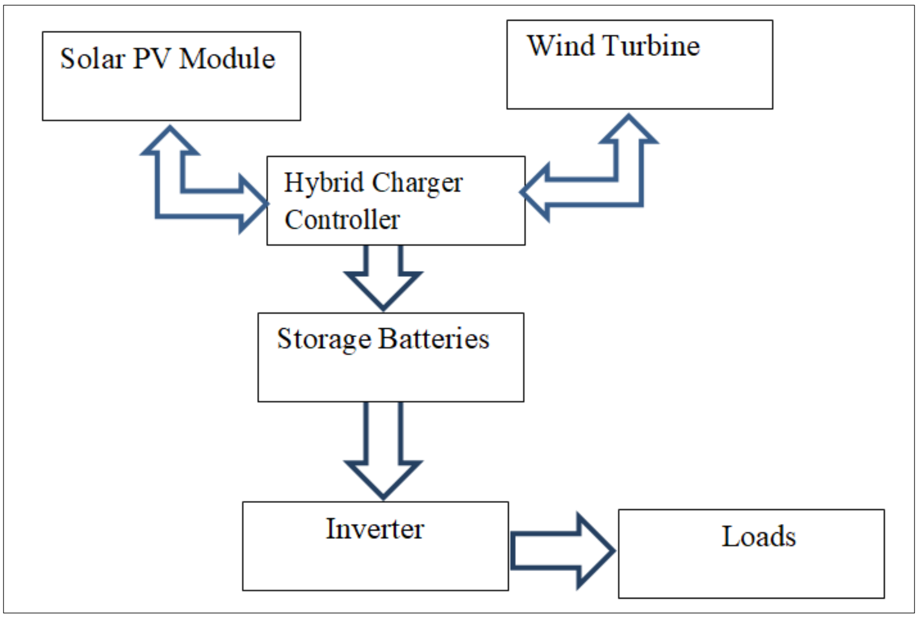

Figure1.1: Block Diagram of PV – Wind Hybrid System

2.1 MATERIAL AND METHODS

2.2 Simulation of Hybrid PV-Wind Energy Systems

The simulation of PV-Wind hybrid energy system was conducted by using iHOGA software based on the estimated system component sizes. The economics of the estimated system component sizes, and their constraints, the average monthly solar radiation, the average monthly wind speed and load demand were inputted into the iHOGA data sheet. The simulation was run by considering fifteen (15) years project lifetime and load following control strategy. The feasible configuration was determined by considering the most optimal from each system. The Technical parameters such as: total power production, excess electricity, total load, unmet load and battery charging, discharging and state of charge were considered. The economics figure of merits such as: total net present cost (NPC) and emissions were also considered.

a. Load Demand

The load demand was first parameter uploaded on to the iHOGA. Depending on the location, the software predicts the load demand when the coordinate was uploaded. The load demand uploaded from NASA was strategically scaled down to the load required by the office building. The iHOGA simulated the load demand data in to average daily and hourly data.

b. Solar Radiation

The Solar radiation of KSUST Aliero at coordinate 12.3°NS and 4.43°EW was uploaded (online) directly from NASA on iHOGA data base. The average monthly sun radiation at horizontal and tilted surfaces of the location was up loaded directly by using one (1) as scale factor.

c. PV Module

PV module is a significant component for electricity generation in solar energy system. Among the several PV modules being proposed by the iHOGA software for the simulation of PV energy system was the model aSi12-Schott: ASI100.

d. Inverter

Several models of inverter were available on the data base of iHOGA for the conduct of simulation. However, STECA: XPC 1600-48 model with power 1600 VA was chosen.

e. Charge Controller

The charge controller controls the charging of the battery. Several controllers are available but the model STECA: TAROM 440 was selected.

f. Wind Energy Resource

This is an energy resource and also an input parameter to the iHOGA for simulation. The wind speed data was collected from the metrological unit situated at Faculty of Agriculture Kebbi State University of Science and Technology Aliero. Average monthly wind speed was uploaded on to the iHOGA data base and the probability density function was instantly been simulated by the iHOGA. The data collected showed a better fitting and the wind speed was used by iHOGA for calculating the total power generation by the wind turbine.

g. Wind Turbine

The Wind turbine selected for the simulation was 1 kW, Southwest Whisper 100 Model. The power output profile of the selected wind turbine on the iHOGA simulation was conducted by using the average wind speed of the location. The wind turbine determines its starting, rated and cutup wind speeds with its related outputs

h. Simulation of PV-Wind Hybrid Energy System

This system comprises of the PV module, wind turbine, charge controller and storage batteries, inverter and load. These components were inter-connected on the iHOGA data base and the wind speed and sun radiation as the energy resources were inputted. The simulation of PV-Wind hybrid energy system was conducted and compared with the results obtained from conventional PV and wind energy systems. The schematic diagram of the PV-wind hybrid energy system is shown in Figure 3.4.

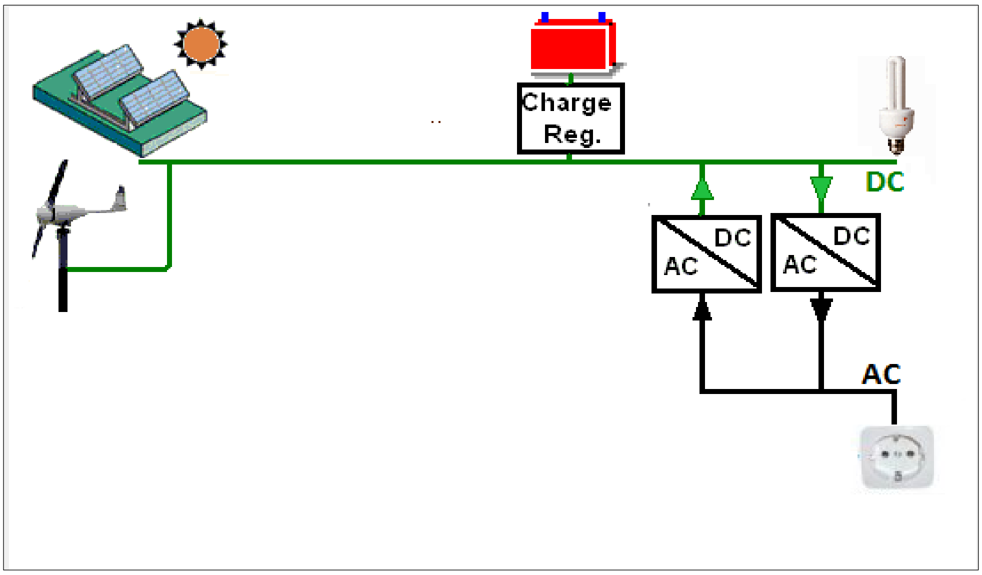

Figure 2.2: Schematic Diagram of PV-Wind Hybrid Energy System

3.1 RESULTS AND DISCUSSIONS

3.2 Result of Feasibility Analysis of PV-Wind Hybrid Energy

The Figure 3.1 Interprets variations of the project total Net Present Cost (NPC) ($) with carbon dioxide ($CO_2$) emission and power generation of the hybrid PV-wind energy system. It has been shown that at 1 kW power generation (NPC) was 22,528$, while the emission was 104 Kg/yr. As the power output rises to 2 KW then the NPC increases to 23,000$, while the emission of CO_2 has dropped to 0 Kg/yr. Both the power generation, the NPC and CO_2 emissions continuously rises until emission reach the peak at 140 Kg/yr, while the NPC was 25,600$ and the generation was 4 KW. However, at 7 KW power generation emission reduces to 116 Kg/yr, while the NPC was 27,000$. The maximum NPC was achieved when the generation was 10 kW with the emission of 132 Kg/yr. Figure 4.26 presents total monthly and annual average power productions by PV and wind turbine. The result shows that maximum monthly power productions were realized in the months of December, January and February with values 0.34 kW, 0.39 kW and 0.33 kW respectively. However, the minimum total monthly average power output was realized in the months of July and August with values 0.25 KW and 0.24 KW respectively. This shows that by hybridizing PV with wind, in December, January and February which are the winter months the system yield a better performance.

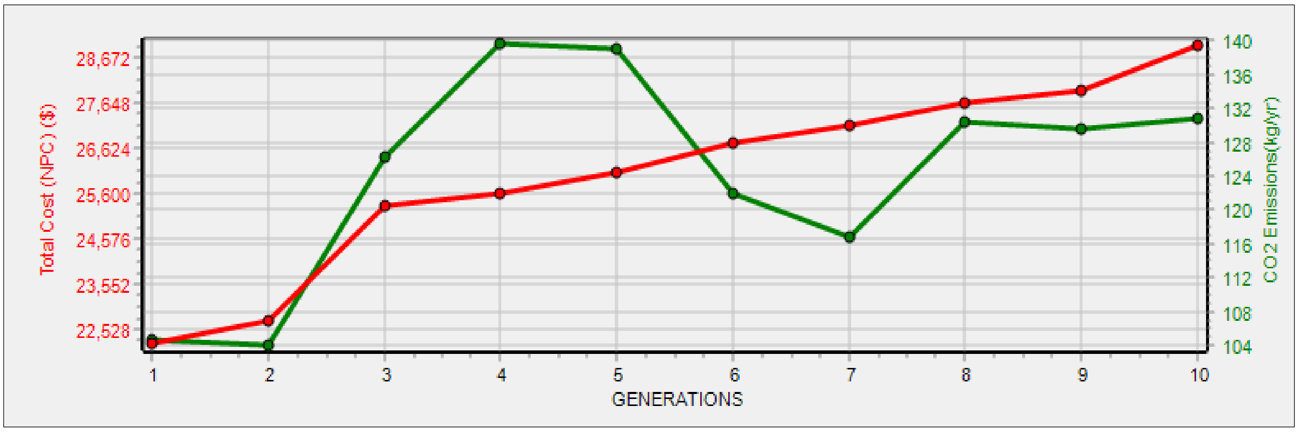

Figure 3.1: Graph of Generation, NPC total Cost and CO_2 Emissions

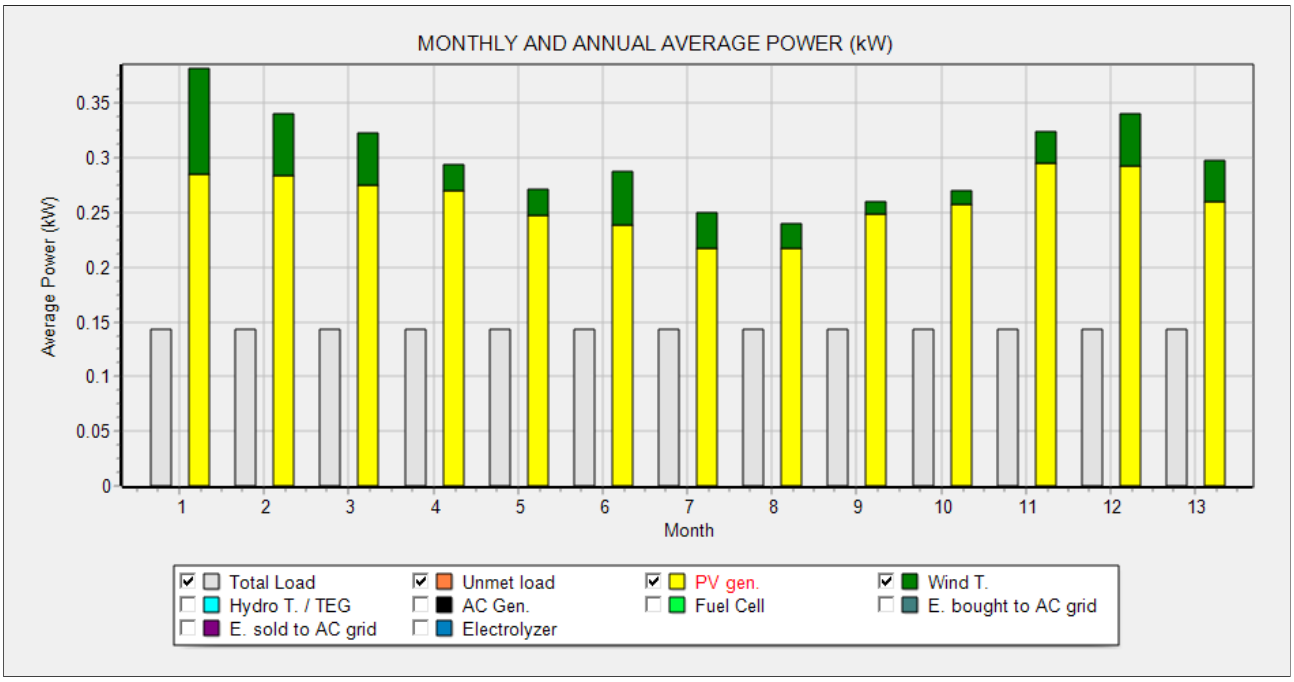

Figure 3.2: Graph of Monthly and Annual Average Power Production

Figure 3.3 presents total annual energy production by the PV generator and wind turbine, battery charging and discharging, export and total load power. It has been shown that, solar PV generator contribute a larger share of 2,300 KWh, while the wind turbine contribute 14.5 % (320 KWh) when it is compared with PV power production. However the battery was charged with 720 KWh and delivered 610 KWh to the load. This shows a loss of 110 KWh and the total load served by the hybrid system was 1,220 KWh, while 980 KWh was exported.

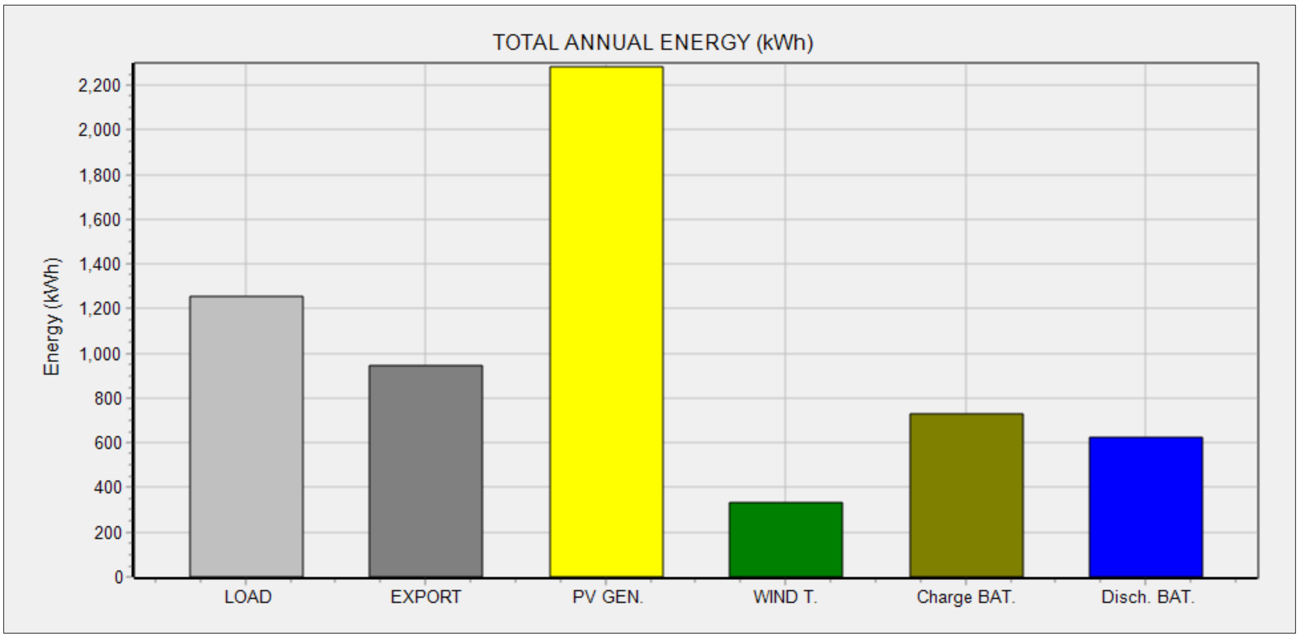

Figure 3.3: Graph of Total Annual Energy Production

3.3 Result of Optimal Hybrid PV-Wind Energy System

Base on the observation made from the simulation results of PV-wind hybrid system concerning the total power production, the optimum total production were noted in the months of December, January and February. Therefore, analysis of three days (1st December, 1st January and 1stFebrary) of the hybrid system were conducted and extracted directly from the iHOGA report sheet.

Figure 3.4 presents analysis of 1st December for the total load, unmet load, battery charge and discharge power, wind and PV power production and state of charge with regard to daily hours. The result shows that from 1:00 am to 6:00 am there was no production by the PV and therefore, the battery charging was zero. During this period the wind turbine generate 220 W and charge battery with 400 Wh. The power generated from 3:00 am to 6:00 am by the wind turbine is larger than the load demand therefore, was enough to power the load. The energy stored in the battery between 1:00 am to 3:00 am was discharge to power the little load available since both wind and PV outputs were absent. Moreover, PV and wind turbine generates power from 6:00 am to 6:00 pm to serve the load and charge the battery simultaneously. The battery becomes fully charged at 10:30 am and reaches a peak of 13,000 Wh. The sun radiation was absent from 6:00 pm to 12:00 am and the total demand is higher than the total production by the wind turbine which causes the battery to discharge power in support of wind turbine to power the load.

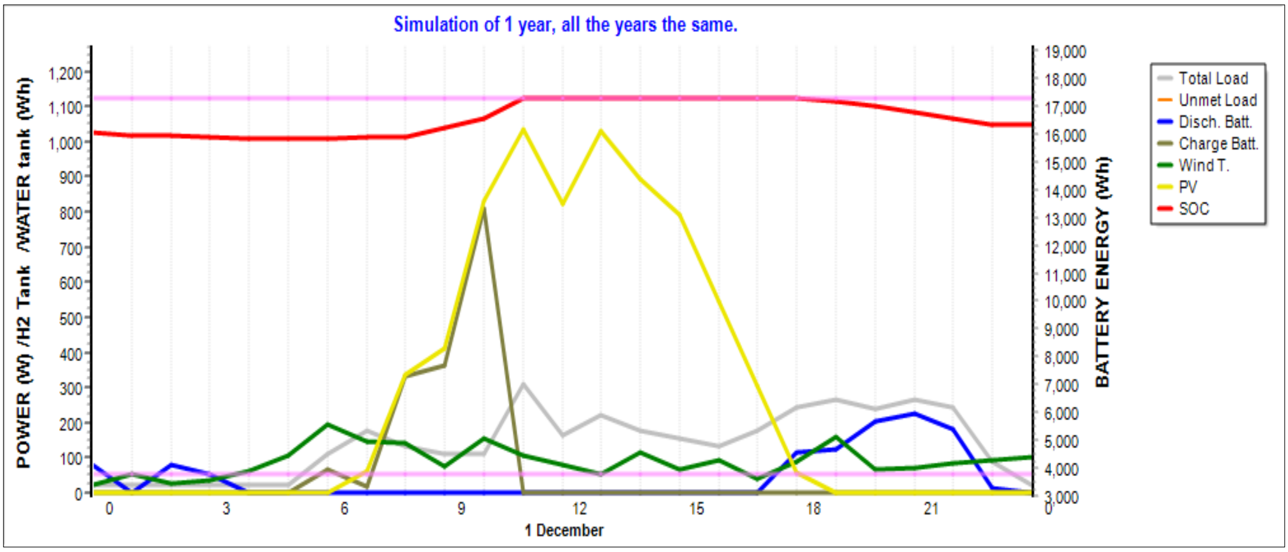

Figure 3.4: Graph of Hourly Simulation Power and Battery Energy for 1st December

Figure 3.5 present result analysis of PV-wind hybrid energy system under load flowing control strategy for 1st January. It shows that the wind turbine generate power above the load demand from 12:00 am to 5:30 am and serve the load. The battery discharge power from 5:30 am to 7:00 am as the wind turbine power output reduces and the PV module start generation to charge the battery and serve the load simultaneously. It has been observed that from 7:00 am to 4:30 pm the battery was fully charged and the wind turbine generation was adequate to serve the available load demand, by 4:30 pm the battery discharge power to serve the load as the load demand was greater than the wind turbine and PV module generation.

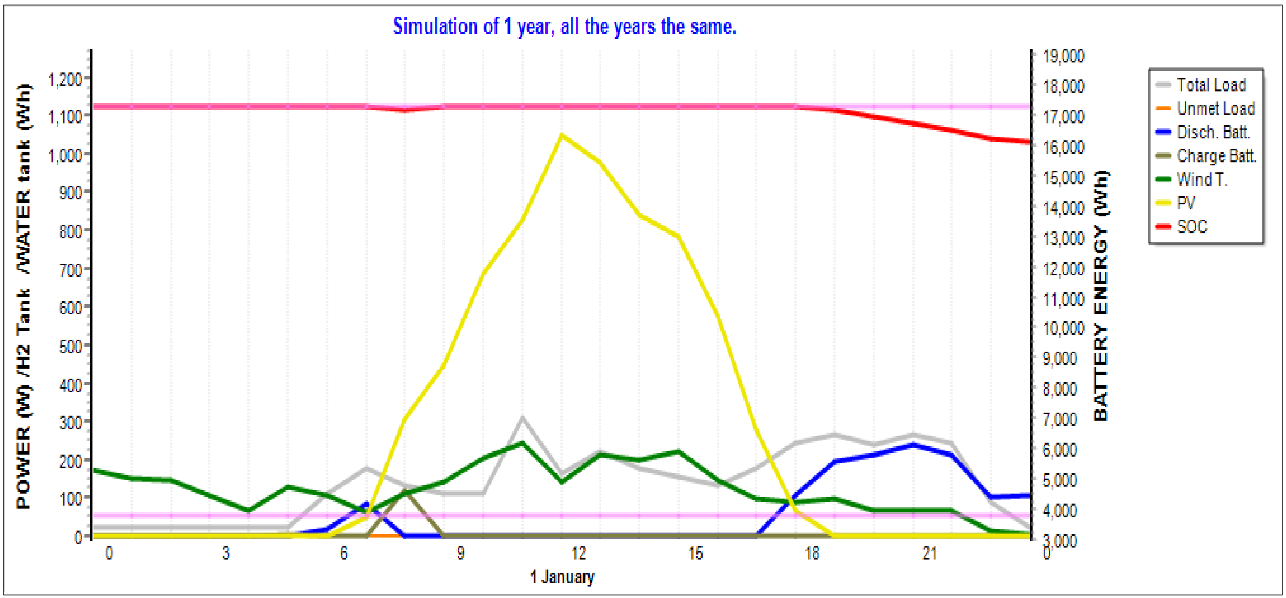

Figure 3.5: Graph of Hourly Simulation Power and Battery Energy for 1st January

Figure 3.6 present PV-wind simulation result by using iHOGA. The result shows that wind turbine generate power from 12:00 am to 2:00 am in order to serve the load. As the wind turbine output decreases to a minimal value, the battery discharges power to serve the load from 3:00 am to 7:00 am. The PV power output was greater than the load demand by 7:00 am which causes the load tobe served simultaneously with battery charging and the battery becomes fully charged by 11:00 am. Although, wind turbine is generating power less than the demand from 12:00 pm to 6:00 pm, but the difference between the total power production by the wind and PV and the load determine the excess energy production. The battery discharge power to serve the load by 5:30 pm. Though, wind turbine is still generating power to settle the load demand efficiently until at 12:00 am when load demand reduces to zero, then the discharge energy reduces also to zero level.

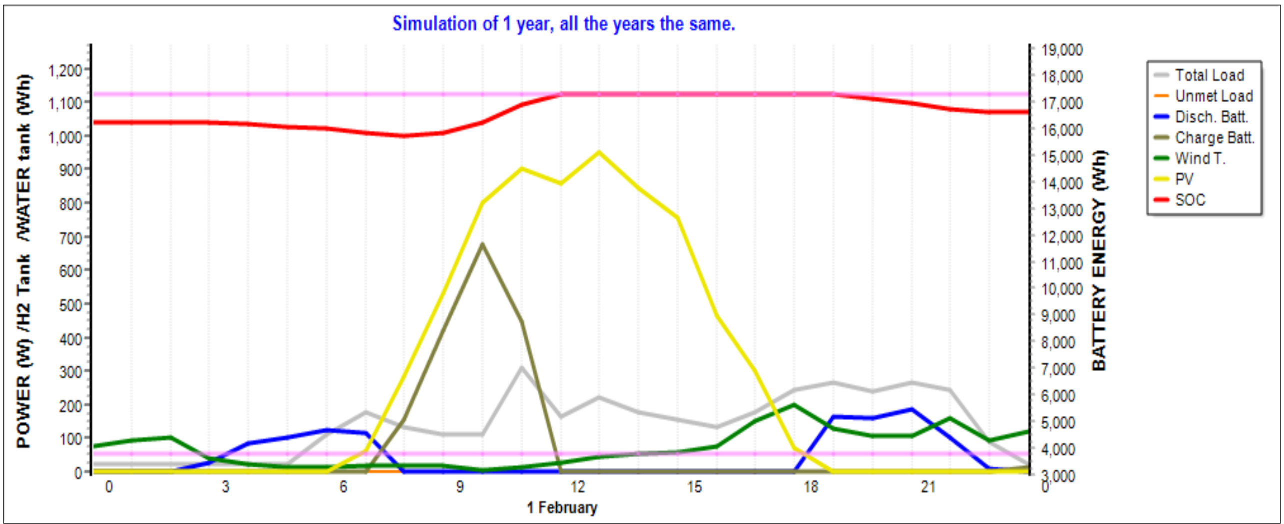

Figure 3.6: Graph of Hourly Simulation Power and Battery Energy for 1st February

3.4 Comparison between the PV, Wind and Hybrid PV-Wind Energy Systems

Table 3.1: Comparison of Technical Parameters between PV, Wind and PV-Wind Energy Systems

Systems Technical Parameters	PV Energy System	Wind Turbine Energy System	PV-Wind Hybrid Energy System
Total Energy Production (kWh)	2,300	420	2,620
Load (kWh)	1,250	1,320	1,220
Export (kWh)	600	-	980
Unmet Load (kWh)	-	1,040	-
Charge Battery (kWh)	950	80	720
Discharge Battery (kWh)	800	80	610
Energy Loss (kWh)	450	-	110

Result from Table 3.1 presents comparison of technical figure of merits between the PV, Wind and hybrid PV-Wind energy systems. It has been observed that in PV systems 54.3% of 2,300 kWh energy productions was used for serving the load. The system after serving the load has opportunity of releasing 26.1 % to an auxiliary load and has zero unmet loads. However, two major disadvantages associated with PV system were the higher percentages loss of 19.6 % and inability to generate energy during night period when sun radiation was absent. In addition, increasing number of batteries to store the excess energy render its uneconomical. The conventional wind-alone energy systems has very low capacity, therefore, the energy generated could not power the load alone as a result, it experiences a higher percentage 78.8% unmet load. Moreover, considering the hybrid PV-wind energy systems, 46.6 % of 2,620 kWh total energy production was used to serve the load demand of 1,220 kWh. This system has great advantages over PV and wind energy systems because it has been reported with 4.2 % energy loss due to batteries and zero or negligible unmet load. In addition, higher percentage of 37.4 % has been exported for auxiliary load and the remaining 11.8 % is losses through the inverter and charge controller. In view these, hybrid PV-Wind energy system is recommended for office shelter.

3.5: Summary of Components Specification

Table 3.2: Summary of Components for PV-Wind Hybrid Energy Systems

Component	Specification	Quantity
PV Module	135 W	1
Wind Turbine	200 W	1
Storage Battery	390 Ah	1
Charge Controller	40 A, 48V	1
Inverter	1600 VA, 24V DC, 240V AC	1

Table 3.2 presents the components, specifications and quantities required for hybrid PV-Wind energy system. It has been noted that, 135 W PV module could be hybridize with 200 W wind turbine. The total energy produce could be stored in 390 Ah, which means two (2) pieces of 200 Ah batteries. The battery charges could be controlled by using 40 A charge controllers, while the stored DC energy could be converted to AC for AC load appliances using 1600 VA inverter.

Table 3.3: Economic Parameters of the Optimal PV-Wind Hybrid Energy System

Parameter	Cost
Net Present Cost (NPC)	$ 22,229.3
Levelized Cost of Energy (LCO)	$ 0.9024/kWh
Cost of Operation and Maintenance (C.O & M)	1.43 $/yr
Carbon dioxide (CO_2) Emission	104 kg/yr

From the analysis, it has been reported that, the optimal PV-wind hybrid energy system has economic parameters presented in Table 3.3. The result shows that, the NPC for the optimal system of PV-wind energy system is $ 22,229.3 with CO&M and COE 1.43 $/yr and $ 0.9024/kWh respectively. The emission reported for optimal PV-wind hybrid energy system is 104 kg/yr.

The results of the optimal PV-wind hybrid energy system which predicted higher values of total power production in the months of December, January and February which were analyzed by chosen first days from each month were presented in Figures (3.4, 3.5 and 3.6). These Figures explained the strategy of load flowing control system upon which the simulation of PV-wind hybrid energy system has operated. It has been found that, wind turbine power production depends on the intensity of wind speed and that of PV depend on the intensity of sun radiation. When the total power production exceeded the load demand, the batteries were charged. When power productions turns to zero, due to the absence of wind speed or and sun radiation, the batteries delivered the energy been stored to provide alternative power supply. However, it could be understood that, when the load exceeded the power production, the difference between the two could be the unmet load. Also, when the total power production exceeded the load as the batteries were fully charged, the balance between the two could be an excess energy. This excess energy can either be exported to auxiliary load or wasted through the dump-load as excess heat which is delivered to the environment. Moreover, considering the result of optimal hybrid PV-wind energy system, presented from Table 4.2, it has been reported that, PV contributed 87.8 % (2,300 kWh) and wind turbine contributed 12.21 % (320 kWh) to the total power production which served a load of 1,220 kWh. This meant that, the system has reported a loss of 4.2 % due to batteries, zero or negligible unmet load, 37.4 % energy exported for auxiliary load and the remaining 11.8 % was losses through the inverter and charge controller. The result of the economic figure of merits presented from Table 3.3 depicted that, the NPC and COE for the optimal PV-wind hybrid energy system were $ 22,229.3 and $ 0.9024/kWh respectively. While, reported 104 kg/yr as carbon dioxide (CO_2) emission.

4.1 CONCLUSIONS

The feasibility analysis of hybrid PV-wind energy system for office building has been conducted by using iHOGA software. The results of the finding depicted that Aliero has good solar and wind energy potentials of powering solar PV module and wind turbines for stable electrical power supply to office building. The feasibility analysis confirmed that, hybrid PV-wind energy system was the best configuration which is economically and technically feasible compared to conventional wind and PV-alone systems. The hybrid PV-wind energy system could serve the desired office building load demand with stable and reliable power supply and provides excess power for auxiliary consumption. The components sizes required for PV-wind hybrid energy system are: 135 W PV module, 200 W wind turbine, two (2) pieces of 200 Ah batteries, 40 A charge controllers and 1600 VA inverter.

Acknowledgements

The Authors wishes to acknowledge the Department of Physics, Faculty of Physical Sciences, Kebbi State University of Science and Technology Aliero, Waziri Umaru, Federal Polytechnics Birnin Kebbi and Tertiary Education Trust (TETFund) Nigeria, for their support and contributions.

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