

Modelling and Simulation of Solar Generator Battery Hybrid Systems to Improve Energy Reliability

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Abstract: Hybrid energy systems are essential for addressing unreliable power supply in off-grid healthcare facilities. In Nigeria, frequent grid outages force reliance on costly, polluting diesel generators, compromising healthcare delivery. This study simulated a solar-generator-battery hybrid system to improve energy reliability for medical facilities. The study employed MATLAB/Simulink to model a system integrating solar PV, lithium-ion batteries, and a diesel generator. Component sizing was based on load assessments (kWh/day) and solar irradiance data (kWh/m²/day). The four different scenarios tested in the study were baseline operation, low irradiance, increased demand, and prolonged outages. Four test scenarios showed the honesty into reliability of the hybrid energy system and its versatility. In base scenarios, the system had 95% availability, and the solar PV replaced 72% of the required energy resources, whereas the runtime of the generator was equal to only 2.3 hours/day. Under the low solar irradiance periods, solar contribution was reduced to 38%, which led to an increase in generator run time to 5.1 hours/day. However, the system was exposed to an additional 20% increase in the energy demand; it was steady, and the generator hours slightly increased to 4.7 hours per day. During the low irradiance condition simulated in the seven consecutive days with poor sunlight, the generator gave 68% of the total energy, and the state of charge threshold set to prevent deep discharge, which can damage the battery and reduce its lifespan. The hybrid system ensured continuous power, reduced diesel dependence by up to 60%, and offered resilient support for essential healthcare services in developing regions.

Keywords: battery, diesel generator, hybrid energy, MATLAB/Simulink, solar system

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I. Introduction and Background Studies

The sharp increase in energy demand, in combination with an environmental crisis, growing concerns about the use of greenhouse gas emissions, fossil fuels and global climate change, has led to a global shift toward renewable technologies [1]. Though the predominant use of conventional energy sources like fossil fuels continues in electricity generation in many of the less developed countries, the environmental costs and eventual depletion of such fossil fuels have pushed hard for alternatives that are cleaner and more sustainable [2]. Renewable energy

technologies such as solar, wind, hydro, biomass, geothermal, tidal and ocean energies are clean and sustainable technologies which have the capacity to lower the emission of greenhouse gases, thus enhancing the security of energy supplies in the future [3]. Among them, the solar photovoltaic system has been widely promoted as the leading renewable technology because of its modularity, declining installation costs, easy installation and decentralised applications [4]. Among renewable technologies, solar PV is also considered one of the most promising technologies because of its modular nature,

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reducing installation costs and time for its installation and its applicability in distributed generation scenarios [5].

Although the application of solar PV systems has been increasing considerably, the variable nature of solar power is still a great issue for the applications which needs non-stop, reliable energy source [6]. The changing solar irradiance with the changing weather conditions, seasons, and absence of light during the night has led to an unsteady and unreliable solar PV-based standalone energy system [7]. Thus, the supply deficiency in terms of voltage and load demand occurs for a while for critical applications such as emergency hospitals, security systems, etc. [8]. Therefore, the combined renewable energy system, which uses a combination of solar PV, battery energy storage, and a normal backup generation system are widely used to increase its reliability [9].

Hybrid solar-generator-battery systems are the most ideal way to utilise the green impact of renewables while also maintaining grid stability through traditional diesel generators and battery storage systems. Battery energy storage systems are employed in hybrid solar-generator-battery systems to store excess solar energy generated during bright sunshine and then discharge stored energy during times when the sun does not shine, or peak demand is required [10]. Other advantageous characteristics associated with battery energy storage systems, as opposed to traditional systems, are the ability to improve energy reliability, maintain voltage stability, balance load, reduce the running time of the generator, minimize the fuel usage, and increase the overall system efficiency [11]. The resilience of the system is also improved when battery energy storage systems are incorporated to handle situations like grid failures or sporadic renewable energy production, making hybrid solar-generator-battery systems well-suited for use in remote areas, rural electrification, and key service sectors [12].

The overall operation of the hybrid renewable energy system has also been significantly improved through integrated intelligent control and energy management techniques. The advanced control can ensure that the energy flows from the solar PV system, battery energy storage system and diesel generator are well coordinated to optimise the utilisation of renewable energy as much as possible while minimising the fuel consumption and operating cost [13]. On the other hand, energy storage systems have been playing an important role in reducing the intermittency of renewable energy and assuring the uninterrupted power supply under varying load conditions [14]. Many reports proved that the system performance in term of reliability, economic benefit and sustainability can be significantly increased by properly sizing and controlling the hybrid system [15].

In literature, several optimisation and modelling tools have been extensively employed to analyse the performance of hybrid renewable energy systems. For techno-economic optimisation, feasibility studies and

long-term cost evaluation of hybrid energy systems, HOMER Pro [16] is one of the widely used tools. However, even though HOMER gives optimised results, it does not have the capabilities to model transient behaviour and real-time control operations. In the other hand, the MATLAB Simulink can handle detailed dynamic modelling, transient studies, implementing control algorithms and detailed energy flow exchange among the components [17]. With MATLAB/Simulink, it is possible to precisely describe battery State of Charge (SOC), the behaviour of generator switching, voltage response and operational performance under real conditions (environment and load). However, the main scope of many of the previous works for hybrid renewable energy sources was on economic optimisation and sizing of system components, and less focus has been given on the operation reliability in transient conditions, battery degradation, low-irradiance conditions for long periods of time and also specific applications related to healthcare [12].

Dependability of electricity supply is especially crucial for hospitals, where continuous function of medical equipment and the quality of care that the facilities can provide to the patient are often directly dependent on the reliability of the electricity power. Severe electricity supply issues, due to unreliability of grid supply and its related issues of outages, power instability and insufficient energy management schemes are prevalent throughout the healthcare sector in Nigeria [18]. The dependency of many of the hospitals and healthcare centres on diesel generators for back-up electricity causes a very high consumption of fuel, high operating costs, and greenhouse gas emissions, as well as high costs of maintenance [19]. Operating with fossil-fuel generators has inherent operational risks associated with the potential of unavailability of fuel and break down, and also the volatility of the fuel price.

Healthcare facility's intermittent electricity supply causes a severe impact on its essential services like vaccine storage, diagnostic tests, emergency care, surgery, monitoring of patients, storage of blood, and functioning of life-support equipment [20]. The electricity outage reduces the quality of health services, equipment life and poses a threat and negative impact to the patient's health outcomes. Solar electricity is an efficient green alternative to electrify the health sector; however, the lack of intermittent energy supply during cloudy weather and night can be mitigated with storage systems and backup power sources to ensure continuous operation [21].

Many studies on hybrid renewable energy systems for both rural electrification and healthcare applications have been explored, but a limited number of available works are based on static optimisation analysis without a proper study of the system dynamics behaviour and its operational reliability during critical stress conditions

[22]. Moreover, fewer studies address the behaviour of a hybrid solar-generator-battery system under low and prolonged irradiance conditions and fluctuating healthcare load in Nigeria case. As such, there is a need for dynamic simulation studies on system reliability, battery SOC, generator running hours and renewable energy contribution under practical working conditions.

To bridge these research gaps, a solar-generator-battery hybrid energy system, aiming at enhancing energy reliability in health care centres in Nigeria's operational environment, has been modelled and simulated. The system developed has coupled solar PV generation, lithium-ion battery storage and diesel generator backup into a dynamic MATLAB/Simulink system to maintain a consistent and reliable power supply. The system performance is analysed under four conditions; normal operating condition, low solar irradiance, high load and no solar presence for an extended duration. The system reliability is analysed using a dynamic simulation based approach, novel aspects for health care services using hybrid systems in the context of the problem studied are battery SOC dynamics, reduction of generator working hours, the penetration rate of renewable energies, minimising fuel usage and resilient working under various environmental factors. It would serve a useful means in determining optimal deployment for reliable and efficient but economical hybrid renewable energy systems that could back up healthcare centres, where the grid supply of electricity is not stable enough, in a developing country like Nigeria.

II. Methodology

The method involves modelling the system, running simulations, examining its behaviour across different conditions, and evaluating how to make it more reliable and efficient. It includes designing the system, obtaining relevant data, developing models, running simulations, analysing performance and verifying the model.

A. Load Assessment

The goal is to determine the electrical energy demand at the site to determine the precise selection and sizing of components for the hybrid energy system. Accurate load calculation is necessary to ensure the system supplies the required energy throughout different operations. Table 1 presents the list of electrical appliances within the healthcare facility, their quantity, power rating, estimated operating hours per day, and their resulting daily energy consumption. The total daily load was used as the basis for hybrid system sizing. Different specialised equipment was utilised in this healthcare facility to support various diagnostic and treatment functions. Fig. 1 shows the Laboratory Incubators, showcasing the incubation units essential for medical testing and sample preservation, particularly in microbiological and haematological

analyses. Similarly, Fig. 2 shows the Mobile X-Ray Machine, which illustrates the facility's diagnostic imaging capabilities, which are crucial for emergency and bedside radiography. The presence of such equipment highlights the need for a reliable and uninterrupted power supply, further justifying the implementation of a hybrid energy system to support sensitive medical operations.

TABLE I
ENERGY CONSUMPTION PROFILE OF UNIVERSITY HEALTH CENTRE

Load Category	Representative Loads	Power Demand (kW)	Daily Energy Usage (kWh)
Cooling and HVAC	Air Conditioners (5 units)	5.5	33.00
Lighting and General Use	25 LED Bulbs, Charging Sockets (60), Reception TV	1.1	9.4
Medical Equipment	X-Ray Machines, Auto Haematology Analyser, Genotype Machine, etc.	14.8	13.6
Laboratory and Diagnostics	Omron Vitals, Blood Separator, Consulting Room Laptops	1.8	4.62
Cold Storage	Blood Storage Fridge	0.3	7.20
Pumping and Utilities	Water Pump	0.85	0.85
Communication and Office	Landlines, Consulting Room Laptops	0.7	2.04
Total		24.05	64.55



Fig. 1. Laboratory Incubators



Fig. 2. Mobile X-ray machine

B. Data Collection and Resource Assessment

Data collection and resource assessment were conducted to ensure the hybrid energy system is modelled accurately for the specific conditions of the location under study.

Solar Resource: To accurately model the solar energy potential, solar irradiance data are obtained from the NASA Surface Meteorology Database, which provides detailed records of daily solar radiation levels. Equation (1) is used to calculate the power output of the PV system, which is a relevant MATLAB function. Fig. 3 helps establish the physical location and environmental conditions that influence solar energy potential. Fig. 4 is essential for accurately modelling the solar PV system and ensuring the simulation reflects real-world climatic conditions.

P_{pv} = G × A × η_{pv} (1)

Where P_{pv} is the power output of the PV system (kW), G is the solar irradiance (kWh/m²/day), A is the area of the PV panels (in m²), and η_{pv} is the efficiency of the PV panels (percentage, typically 18–22% for mono-crystalline panels).

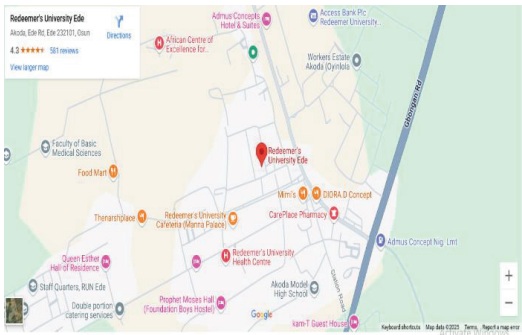


Fig. 3. Map view of Redeemer's University in Ede, Osun state
Source: [23]

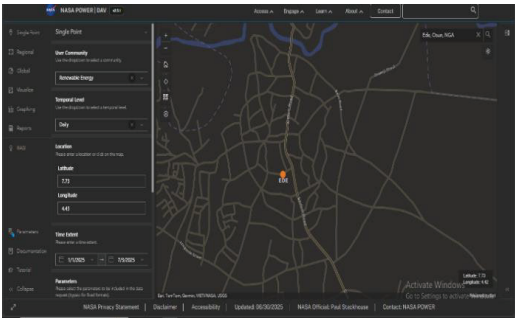


Fig. 4. NASA surface meteorology database of the location
Source: [24]

Fuel Pricing: Up-to-date data were gathered on local fuel prices, particularly the cost of diesel, which is an important variable when sizing the generator for backup power. The current price range is between ₦1000 and ₦1200 per litre. Using MATLAB, the cost of diesel is an input to calculate the total fuel consumption of the backup generator based on the load demand. Equation (2) is used to simulate how fuel consumption fluctuates based on varying load demands and the number of hours the generator operates.

F_c = a × P_{load} + b (2)

Where F_c is the fuel consumption of the generator (litres), a is the specific fuel consumption (litres/kWh of energy generated), P_{load} is the load demand (kW), and b is the base consumption (in litres, which accounts for idle fuel consumption).

Battery Life-cycle: Data on battery expected life cycles were gathered. Battery life-cycle data were input into the MATLAB model, assuming an average of 3,000 charge cycles at 80% depth of discharge. This parameter is crucial for modelling battery wear and calculating the Net Present Cost (NPC) of the system. In MATLAB, the battery life-cycle and degradation are modelled using the following relationship for the number of cycles, which affects the system's long-term costs using (3).

N_{cycles} = E_{total} / (C_{bat} × D_{od}) (3)

Where N_{cycles} is the number of battery charge cycles, E_{total} is the total energy the battery can store over its lifetime (kWh), C_{bat} is the battery capacity (kWh), D_{od} is the Depth of discharge (80% for optimal performance)

C. Procedure

All electrical appliances to be used in the target health care centre were first identified, classified according to type, and listed along with their voltage and daily usage times. The data was acquired by directly observing the

usage, conducting surveys with people, and checking existing usage records. Each appliance's daily energy consumption was determined by (4).

$$E_i = P_i \times t_i \quad (4)$$

Where: E_i is the daily energy consumption of appliance i (kilowatt-hours, kWh), P_i is the rated power of the appliance i (watts, W), and t_i is the average daily usage time of appliance i (hours, h).

Then, the total daily energy demand of the location was the sum of the energy usage of all appliances and was determined by (5).

$$E_{\text{total}} = \sum_{i=1}^n (P_i \times t_i) \quad (5)$$

Where E_{total} is the total daily energy demand (kWh/day) and n represents the number of appliances.

D. System Design

The proposed system is a DC-coupled hybrid arrangement, designed to ensure continuous power availability under varying environmental and load conditions. It includes the following core components.

Solar photovoltaic (PV) array: Mono-crystalline panels (efficiency: 18–22%) were selected for their high performance in Nigeria's climate. Equation (6) was used to determine the sizing of the solar panel.

$$P_{\text{pv}} = \frac{E_{\text{load}}}{H_{\text{sun}} \times \eta_{\text{pv}}} \quad (6)$$

Where: E_{load} is the total daily load demand (kWh), H_{sun} is the average solar insolation (kWh/m²/day); η_{pv} is the panel efficiency

Battery Storage: Lithium-ion batteries were selected due to their high energy density, long lifespan, and superior depth-of-discharge characteristics compared to traditional lead-acid batteries. These attributes make them more suitable for daily cycling and integration with intermittent renewable energy, and this was determined by (7).

$$E_{\text{bat}} = \frac{E_{\text{autonomy}}}{D_{\text{od}} \times \eta_{\text{bat}}} \quad (7)$$

Where: D_{od} is the depth of discharge and η_{bat} is the round-trip efficiency.

Generator: Generators were identified as an effective short-term backup sources due to their lower initial cost and fast response time. The generator was selected to meet peak demands when solar output is insufficient, and the battery State of Charge (SoC) drops below a safe threshold. Fig. 5 shows the Mikano SP 60 diesel generator installed at the healthcare facility, which serves as the primary backup power source during grid outages. Its presence highlights the current dependence on diesel-

powered solutions. The fuel consumption was determined by (8).

$$F_c = a \times P_{\text{gen}} \times t_{\text{run}} \quad (8)$$

Where F is the Fuel consumption (litres), a is the specific fuel consumption (litres per kWh), typically ranging from 0.25 to 0.3 L/kWh for generators, P_{gen} is the generator power output (kW), and t_{run} is the generator runtime (hours).

Inverter and MPPT Controller: To manage energy flow and enable AC output, a high-efficiency inverter (90–95%) and MPPT (Maximum Power Point Tracking) charge controller were integrated into the system. These devices help maintain voltage stability and optimise solar energy harvesting.



Fig. 5. Mikano SP 60 generator installed at the healthcare facility

E. Scenarios Tested

In order to prove the performance, robustness, and practical reliability of the hybrid solar-generator-battery energy system, four major test scenarios were carried out, and the summary of the scenarios is shown in Table II. All the scenarios are aimed at a particular challenge that the system can face in a medical facility environment. Such situations were chosen according to the practical significance, environmental conditions and operational requirements in the future.

Baseline Operation: This situation would correspond to normal operation of the system based on the average conditions at the site. It employs principal inputs such as 64.55 kWh/day load, solar irradiance of 5.45 kWh/m²/day and a battery size of 50 kWh. That situation presents the benchmark control scenario, which simulates normal day-to-day operations at normal weather and demand states. It is necessary to have such a baseline to compare the impact of stress situations and to prove the validity of such a model.

Low Irradiance Stress Test: This was a simulation of cloudiness where the irradiance (or solar energy) is used. Nigeria is characterised by long periods of lack of sunlight, and the healthcare system has to be on standby even when this is the case. This test analyses the failure of the battery and generator in their ability to sufficiently

provide the load without solar assistance by applying a worst-case irradiance level throughout the simulation.

Increased Load (Scalability Test): This case is normal system operation with a 20% addition to daily energy requirements to compensate for the future equipment or addition of patient load. This test is fed with a load of 77.46 kWh/day. Growth in demand for healthcare facilities is a common trend because of the expanding services or diseases treated, introductions of new medical devices or the operating hours. This situation assesses the possibility of the current system design to accommodate such increases with no need for urgent upgrading.

Prolonged Low Irradiance (7-Day Rainy Week Test): This situation replicates seven days of consecutive weak irradiance amounting to 2.0 kWh/m² /day in a bid to portray a prolonged bad weather period. This is to ensure that the system can test the backup ability of the system over time. The setup will replicate the actual experiences of a rainy week typical of southern Nigeria and test the ability of the system to continue power operations with little solar output. This is particularly crucial among the medical facilities where disruption of power caused by various days may compromise stored vaccines, lab equipment and vital care systems.

TABLE II
SUMMARY OF SIMULATION SCENARIOS

Scenario	Description			Key Inputs	
Baseline Operation	Standard performance under average conditions.	system	under	Load: 64.55 kWh/day Irradiance: 5.45 kWh/m ² /day Battery: 50 kWh	
Low Irradiance Stress Test	Uses irradiance (2.07 kWh/m ² /day) for all days.	May	17 (2.07 kWh/m ² /day)	Irradiance: 2.07 kWh/m ² /day	
Increased Load (Scalability)	Simulates higher energy demand to reflect growth.	20%		Load: 77.46 kWh/day	
Prolonged Low Irradiance (5 Days)	Models 5 continuous days of poor solar input.			Irradiance: 2.0 kWh/m ² /day for 5 days	

F. Diesel Cost Analysis

The diesel generator acts as an essential backup system of the hybrid energy system, guaranteeing the absence of power interruption in cases of low solar irradiance or discharged batteries. This is an area of analysis of fuel consumption behaviour and financial implications. Using a 7 days duration for the diesel cost analysis in the simulated hybrid system. The fuel used and diesel cost were determined by (9) and (10) respectively.

F_{used} = S_{fc} \times R_t \times D \tag{9}

D_{cost} = F_{used} \times P_d \tag{10}

Where, F_{used} is the total diesel consumed over days, S_{fc} is the specific fuel consumption (L/hr), R_t is the average generator operation time per day, D is the duration of operation in days, D_{cost} is the total cost of diesel over D days, and P_d is the diesel price in (₦/L).

G. Sociological Impact of the System Design

Although the technical and economic performance is considered in the core of this study, sociological aspects of design assumptions and system architecture were considered. The health care environment, particularly in deprived areas of Nigeria, necessitates a dependable power system that accommodates life-sustaining devices, less pressure on the medical staff and ensures the trust of the community towards the provision of healthcare services. The hybrid energy model is thus scaled not only to overcome the electrical demand, but also to guarantee the continuity of the operation of the health workers, care of the mothers and children, and the medical Cold Chain e.g. preservation of the vaccines. These sociological objectives have a direct result in the choice in terms of having a high solar contribution, backup storage, and lenient generator run time.

III. Results and discussions

A. Simulation Results

MATLAB/Simulink was used to model and determine the evaluation of an energy system that consists of hybrid solar, generator and battery in real-time solar irradiance with dynamic control structure. Fig. 6 shows the Simulink block diagram of the proposed hybrid energy system. It represents the dynamic way in which solar PV generation, battery-SOC tracking, load demand and generator operations are connected. A block diagram acts as a visual overview of the behaviour of each of the subsystems for the real-time response through programmed logic control. This framework is vital in simulating system behaviour in the real world in different conditions of energy and load patterns.

Scenario 1: Fig. 7 gives a full-hour detail of the contribution of energy sources to loads as well as the battery SoC at every hour during baseline operation. It shows how the photovoltaic system can accommodate the basic load during the entire day amid sunlight, and the battery acts as a source of energy at night. The figure also presents low generator utilisation, which shows the ability of the system to be reliable under the ideal solar conditions at a low cost of operation with reduced emissions. The result revealed that solar contribution met

72% of daily demand (46.5 kWh out of 64.55 kWh), generator runtime contributed only 2.3 hours/day (9.6% of time), and battery SoC maintained a 30-90% charge, stabilising nighttime supply.

Scenario 2: The behaviour of the system under low irradiance is as shown in Fig. 8. It shows the decreased PV generation, increased dependency on the generator and unstable battery SoC. The description enables the comparison of the resilience and responsiveness of the hybrid system to cloudy situations that are used in measuring the fuel-dependency and overall reliability. The result shows that solar contribution dropped to 38% (24.5 kWh), generator runtime was increased to 5.1 hours/day, and battery SoC reduced to 22% (near-minimum threshold).

Scenario 3: Fig. 9 records the output of the system with a 20% load increment. The chart evidently reveals variations in pattern distribution in the numerical usage

of batteries, intensified energy demands, and a subsequent increase in generator runtime. Such visualisation helps to conduct scalability analysis and find how the system can keep up with the increasing demands of medical facilities. The results also revealed a solar contribution of 58% (45.1 kWh), with a deeper battery discharge and generator runtime with 4.7 hours/day (19.6% of time).

Scenario 4. Fig. 10 models the system under long duration low irradiance, where there are five days in a row of low irradiance. It discloses sustained generator engagement, exhausted battery SoC, and constrained solar. The statistics are important in the assessment of long term backup adequacy and continuity of energy in the protracted rainy seasons. The results demonstrated generator dominance, which supplied 68% of energy. Battery exhaustion of SoC hit 20% by Day 3, requiring continuous generator use and generator runtime with 6 hours/day.

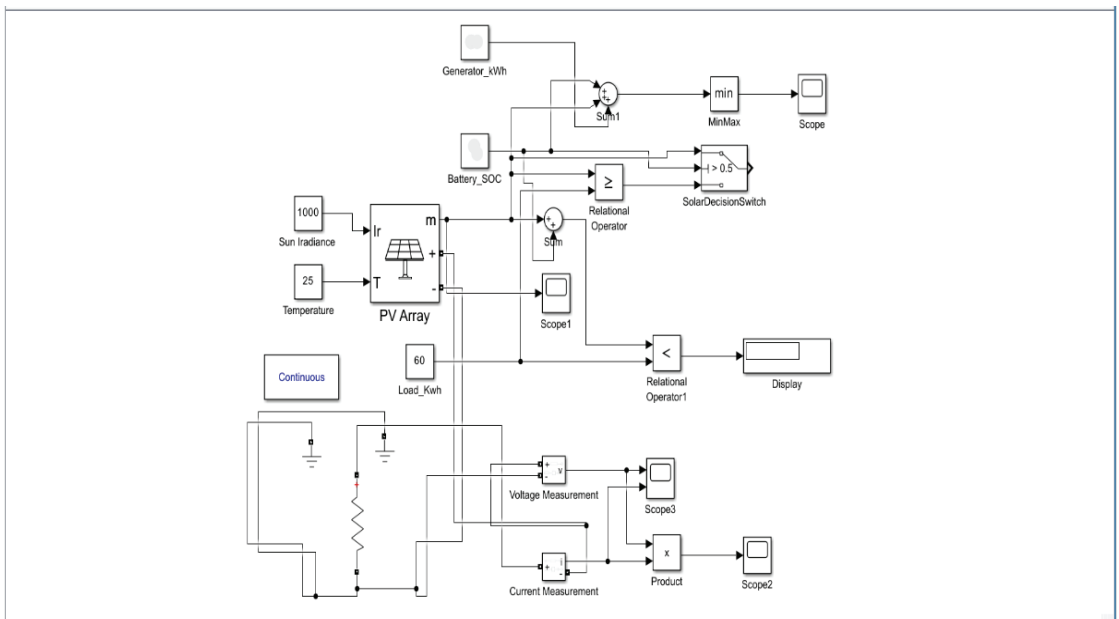


Fig. 6. Simulink block diagram of the proposed hybrid energy system

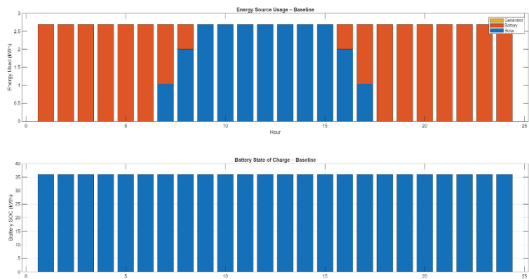


Fig. 7. Scenario 1 output result, energy source usage baseline

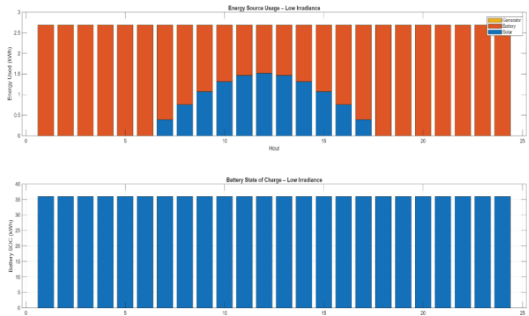


Fig. 8. Scenario 2 output result, energy source usage under low irradiance

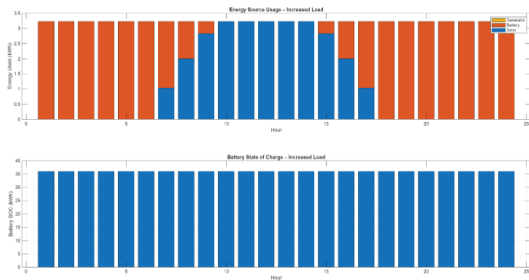


Fig. 9. Scenario 3 output result with increased load

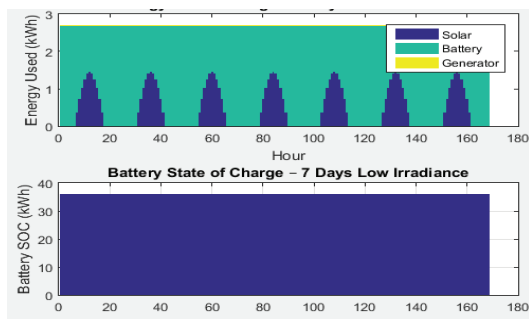


Fig. 10. Scenario 4 output result under 7 days of low irradiance

B. Cost Comparison Between Systems

Economic analysis was done to compare the cost indication between various energy system configurations to determine the economic merit of the proposed hybrid system compared to the conventional system. Fig. 11 is a pictorial representation of the cost of diesel per scenario. It indicates how the diesel costs rise when there are poor solar conditions or when the energy demand is higher. Nevertheless, fuel economy is always superior in the hybrid system because of the participation of solar PV and batteries to the never-ending pernicious diesel only system as depicted in Fig. 12. The major aim of hybrid systems is to reduce dependency on fossil fuel which is clearly achieved in Fig. 13. This confirms efficiency of the control logic which favours solar and battery usage thus using the generator at the last resort. It can be inferred from these tables that the diesel-only system had the highest diesel cost, which is 600,000, while the proposed hybrid energy system had a minimal value across different scenarios.

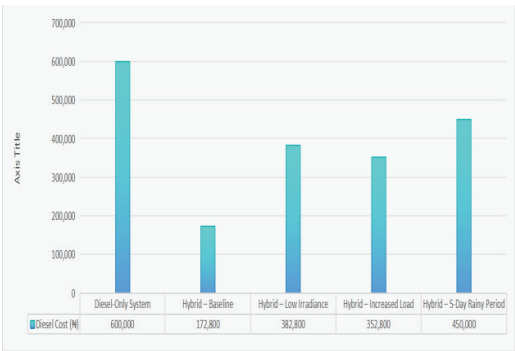


Fig. 11. Diesel cost analysis

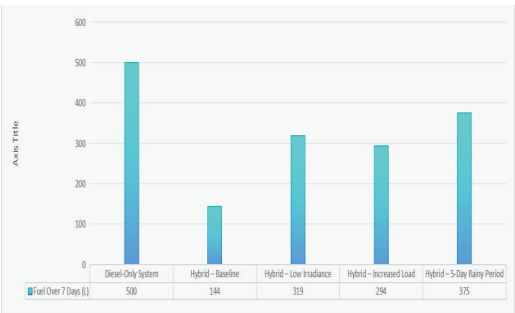


Fig. 12. Fuel consumption over 7 days

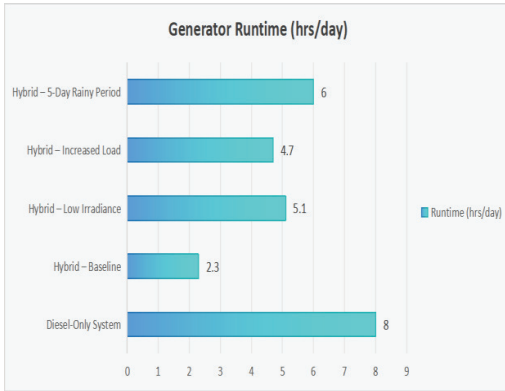


Fig. 13. Generator run time

C. Sociological Impact of Hybrid System Deployment

Simulation results indicated that the hybrid solar-generator-battery system offers technical, economic, and sociological advantages by ensuring patient safety, maintaining vaccine storage, and supporting staff access to essential medical equipment and records. There was a sustained provision of energy that promoted the use of local health services, enhancing equity among the vulnerable populations, such as women, children, and the elderly. Monetarily, the system allowed saving of ₦427,200 in a week to allocate the funds more correctly to the wage payments, equipment, and medications. Also, the solution is in line with SDG 3rd (Good Health), 7th (Clean Energy), 10th (Reduced Inequality) and 13th (Climate Action), which makes it both an enabler of energy and a development facilitator in underdeveloped areas.

D. Cost comparison between systems

The data provided in the cost comparison analysis has further emphasized the cost benefit of this hybrid energy system when compared with the diesel only power system. The diesel only power system incurred the highest generator running hours of 8 hours/day, thus consuming 500L of diesel fuel over 7 days with corresponding cost of ₦600,000. This implies a high operating and fuel dependency cost of operating a pure diesel system.

With the optimum scenario (Hybrid baseline) however, the generator running hours was greatly reduced to 2.3 hours/day consuming only 144L of diesel fuel for the same period with an approximate cost of ₦172,800 and a cost savings of approximately 71.2% when compared to the diesel only system. This also clearly shows the effectiveness of incorporating solar energy and battery storage system in minimizing fuel consumption and operating costs.

Even during unfavorable conditions of the system such as low solar irradiance, high load demands and during rainy period, it was evident that the fuel consumption and cost of operating the hybrid system is still lower than the diesel system. The low irradiance scenario increased the running hours of the generator to 5.1 hours/day consuming 319L of diesel fuel at a cost of ₦382,800, the increased load demand also consumed 294L of diesel fuel over 4.7 hours/day costing ₦352,800 and 7 days rainy scenario showed the highest runtime during hybrid scenario at 6 hours/day consuming 375L of fuel costing ₦450,000, yet the cost of running these systems were less than that of the diesel only system.

All considered scenarios point to a definite advantage of using the proposed hybrid power system over the diesel only power system in terms of fuel consumption, cost, sustainability and efficiency, indicating its suitability for integration with other energy sources for an intelligent multi-source power system.

E. Comparison with existing hybrid energy studies and optimisation tools

The results obtained in this study are consistent with the earlier studies on hybrid renewable energy systems reported in the literature. Previous studies with HOMER Pro mostly investigated economic optimisation and long term energy balancing, while the present study used MATLAB Simulink for capturing the dynamic operational behaviour of the hybrid system under real-time conditions. Unlike HOMER-based approaches, which focus mainly on the assessment of annualised cost performance and component optimisation, the MATLAB/Simulink model used in this work enabled a detailed observation of the variation of the transient battery state of charge, generator switching behaviour and hourly energy flow interactions between solar PV, storage and load demand. This gives a better understanding of the system response under critical operational conditions such as prolonged low irradiance and sudden load changes.

The solar penetration level of 72% obtained during baseline operation compares well with previous hybrid healthcare energy studies, where the contribution of renewable energy is typically between 50% and 70%, depending on climatic conditions and storage capacity. The reduction in the diesel generator run time observed in the study is also in agreement with the reports that hybrid PV-battery-generator systems can reduce fuel consumption by more than 50% compared to the diesel-only configurations. Moreover, whereas many of the HOMER-based studies focus on cost minimisation, the current study extends the analysis by including the aspects of operational reliability and continuity of healthcare service. This is especially critical for medical facilities where reliable power is directly linked to patient safety, vaccine preservation, laboratory work and

emergency response capability. The study, therefore, adds value in the combination of dynamic system simulation with healthcare-oriented reliability assessment under Nigerian climatic and operational conditions.

IV. Conclusion

A solar PV-generator-battery hybrid energy system has been developed and simulated in this study in order to enhance the reliability of the supply of electricity for healthcare services, under the real operating conditions of Nigeria. Sizing of the components has been carried out for the healthcare energy demand of 64.55 kWh/day and for an average solar irradiance of 5.45 kWh/m/day. A 50KWh Li-ion battery storage and a 48KWh diesel generator set have been included in a dynamic environment of MATLAB Simulink to provide a continuous supply of power under the dynamic conditions.

It was proved from the simulation results that the system operates stably at base, low irradiance, high load and long outage conditions. The load at daily operation was mainly covered by PV, so that the generator usage was less. It proved that at low-irradiance conditions with long duration, the hybrid system can be kept in stable operation with more generator usage, so that the battery depth was higher than that in base load, and it did not influence the continuity of the supply. It is shown that the energy storage system improved the stability of voltage, load levelling, operational flexibility, and robustness during transient condition.

From the economic analysis result, the proposed hybrid system has tremendous savings in the amount of diesel consumption and cost of operation compared with conventional generation only. Weekly savings of fuel were about ₦427,200, which results in lower CO₂ emissions and reduces the usage of the generator. It was also confirmed that a dependable hybrid energy system could enhance healthcare delivery by helping to preserve vaccine storage, perform critical emergency treatment, operate lab machinery, and offer other essential medical care services.

The most significant contribution of this research to the field of mechanical and energy engineering is its dynamic modelling and operational reliability analysis of a healthcare-directed hybrid energy system in Nigeria's operating environment. While most of the studies are oriented around techno-economic optimisation, this work includes dynamic transient operation, behaviour of generator switching and battery SOC, and low irradiance effect studies with real-time simulation. The research gives a meaningful engineering implication in building dependable hybrid renewable energy systems for healthcare stations and other load management infrastructure.

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Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Author Contributions

This research article was carried out among all authors. The author NAA designed the study and wrote the protocol. Authors ETO, STA and AAA carried out data collection and analysis and funding. Authors ASO and EOS carried out supervision, draft review and editing, and investigation. The authors' MOA, AOA and OEA managed conceptualisation and literature review. All Authors read and approved the final manuscript.

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