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An Optimized Hybrid Power Supply Combining Solar PV, Diesel Generator, and Battery Storage with a Rule-Based Energy Management Strategy for Base Transceiver Stations in Nigeria

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ABSTRACT
This study developed an optimized hybrid power supply system integrating solar photovoltaic (PV), diesel generator, and battery energy storage with a rule-based energy management strategy for Base Transceiver Stations (BTS) in Nigeria. The study addressed persistent challenges associated with unreliable grid electricity, excessive diesel generator dependence, high operational costs, fuel consumption, and increasing carbon emissions affecting telecommunication infrastructure. Mathematical models were formulated for solar PV output power, diesel generator fuel consumption, battery state of charge, hybrid power balance, renewable energy penetration, operational cost, and carbon emission reduction. A rule-based control strategy was implemented to coordinate power dispatch among the PV array, battery storage, and diesel generator under varying load conditions. Simulated operational data across seventy-two hours were analyzed to evaluate system performance. Results showed that the solar PV system achieved a peak output power of 8.05 kW at an irradiance of 947 W/m² and temperature of 27°C, while system efficiency reached 96.40%. The battery state of charge operated safely between 41.43% and 98.99%, ensuring uninterrupted BTS operation. Operational cost reduced from 1.86 during diesel-dominant operation to 0.91 under high renewable penetration conditions, while carbon emissions declined from 3.03 kg to 0.40 kg during peak solar periods. Renewable energy penetration exceeded 168.01%, demonstrating significant reduction in diesel generator utilization. The study recommends policy support for renewable hybrid energy deployment, investment incentives, and sustainable telecommunication energy regulations in Nigeria.

Keywords: *Hybrid Power System, Solar Photovoltaic, Battery Storage, Rule-Based Energy Management, Base Transceiver Station.*

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I. INTRODUCTION

The rapid expansion of mobile telecommunication services has significantly increased the demand for reliable and uninterrupted electrical power for Base Transceiver Stations (BTSs), particularly in developing nations such as Nigeria. Telecommunications infrastructure forms the backbone of modern digital economies, supporting voice communication, internet connectivity, financial transactions, security systems, and industrial automation. However, the persistent inadequacy of grid electricity supply in many regions of Nigeria has compelled telecommunication operators to rely heavily on diesel generators as the primary source of energy for BTS operations [1]. While diesel generators provide operational reliability, their prolonged usage introduces substantial economic and environmental challenges, including high fuel consumption, rising operational costs, greenhouse gas emissions, acoustic pollution, and increased maintenance requirements. These issues have intensified the need for sustainable and economically viable alternative power solutions for telecommunications infrastructure [2]. Globally, the transition toward renewable and hybridized energy systems has gained momentum due to increasing environmental concerns and the urgent need to reduce carbon emissions. Among the available renewable energy resources, solar photovoltaic (PV) technology has emerged as one of the most promising alternatives for decentralized power generation because of its scalability, declining installation cost, low maintenance requirements, and environmental friendliness. Nigeria possesses abundant solar irradiance levels averaging between 4.0 and 7.0 kWh/m²/day across different geographical regions, making solar energy highly suitable for off-grid and hybrid power applications. Nevertheless, the intermittent nature of solar energy generation, caused by variations in weather conditions and diurnal cycles, limits its ability to independently provide continuous power to BTS facilities. Consequently, integrating solar PV with diesel generators and battery energy storage systems has become an attractive strategy for achieving reliable, efficient, and sustainable energy supply [3]. Hybrid energy systems combining solar PV, diesel generators, and battery storage leverage the complementary strengths of each component to enhance overall system performance. In such configurations, solar PV arrays primarily supply daytime loads and charge the battery bank, while battery storage provides backup power during low solar generation periods. The diesel generator operates as a supplementary source during prolonged cloudy conditions, high-demand intervals, or critically low battery states [4]. This coordinated operation minimizes excessive diesel runtime, thereby reducing fuel consumption, maintenance frequency, and environmental pollution. Furthermore, the incorporation of intelligent energy management strategies enables optimized scheduling and control of power flow among the hybrid system components, ensuring efficient energy utilization and operational stability [5]. Energy management strategies play a critical role in determining the efficiency and economic viability of hybrid renewable energy systems. Among various control approaches, rule-based energy management strategies have gained widespread acceptance due to their simplicity, robustness, ease of implementation, and low computational requirements [7]. A rule-based controller operates using predefined logical conditions that govern the switching and coordination of energy sources based on system variables such as battery state of charge, load demand, solar irradiance, and generator operating thresholds. Unlike highly complex optimization algorithms requiring extensive computational resources and real-time forecasting, rule-based strategies offer practical applicability in developing regions where computational infrastructure and technical expertise may be limited. Additionally, these strategies can be customized to suit varying operational conditions and load profiles of BTS installations [6]. Despite the growing adoption of hybrid renewable systems in telecommunications, several operational challenges remain unresolved in Nigeria. Many existing BTS installations continue to experience inefficient generator scheduling, underutilization of renewable energy resources, inadequate battery management, and poor system optimization. In numerous rural and semi-urban locations, operators still depend predominantly on diesel-powered systems due to concerns regarding renewable energy reliability and storage limitations. Furthermore, fluctuating diesel prices, increasing operational expenditures, and stringent environmental sustainability requirements have intensified the necessity for optimized hybrid energy architectures capable of delivering reliable performance with reduced lifecycle costs [8]. This study therefore proposes an optimized hybrid power supply system combining solar PV, diesel generator, and battery storage integrated with a rule-based energy management strategy for Base Transceiver Stations in Nigeria. The proposed framework seeks to improve power reliability, minimize diesel fuel consumption, reduce operational costs, enhance renewable energy penetration, and lower environmental emissions associated with telecommunications infrastructure. By intelligently coordinating the operation of the solar PV system, battery storage unit, and diesel generator, the study aims to establish a sustainable and resilient energy solution capable of addressing the persistent power supply challenges affecting BTS operations in Nigeria [9]. In addition, the study contributes to the broader discourse on sustainable energy transition within the telecommunications sector by demonstrating how hybrid renewable systems can support energy security, economic efficiency, and environmental sustainability simultaneously. The findings from this research are expected to provide valuable insights for telecommunication operators, energy planners, policymakers, and researchers involved in the design and implementation of hybrid energy systems for critical infrastructure applications in emerging economies.

II. LITERATURE REVIEW

Hybrid renewable energy systems combining multiple sources offer superior reliability and economics compared to single-source systems [1]. [2] demonstrated that solar-diesel hybrid systems for Nigerian BTS can achieve 65% fuel savings with proper sizing. [3] showed that adding battery storage to solar-diesel configurations improves system efficiency by 20-30% through peak shaving and load shifting. However, these studies used simplified control strategies without adaptive intelligence. Advanced energy management significantly impacts hybrid system performance. [4] demonstrated that machine learning-based load forecasting improves energy scheduling efficiency by 18-24% compared to rule-based approaches. [5] reviewed intelligent algorithms for telecom energy management, identifying Long Short-Term Memory (LSTM) networks as superior for time-series prediction with 5-8% forecasting error. [6] optimized multi-objective energy management achieving 40% cost reduction while maintaining reliability. Battery performance degrades faster in high-temperature environments typical of Nigeria. [7] found that lithium-ion batteries operating at 35-40°C experience 35% faster capacity fade than 25°C operation. [8] developed temperature-compensated charging algorithms extending battery life by 25-

30% in African climates. Proper State of Charge (SOC) management between 20-90% can double cycle life from 3,000 to 6,000+ cycles [9]. Research on Nigerian telecom energy systems reveals unique challenges. [10] documented average grid availability of 6.2 hours daily with ±25% voltage fluctuations. [11] analyzed 50 BTS sites showing diesel consumption averaging 285 liters monthly. [12] optimized hybrid systems for six Nigerian cities, finding optimal solar capacity of 8-12 kWp per site depending on location.

III. METHODS

3.1 Development of an Optimized Hybrid Power Supply System

3.1.1 Solar Photovoltaic Output Power Model

This equation estimates the electrical output power generated by the solar photovoltaic array under varying solar irradiance and temperature conditions. The model is essential for determining the contribution of renewable energy to the hybrid Base Transceiver Station power system. It enables accurate sizing of photovoltaic modules and evaluates energy availability throughout different operational periods and environmental conditions across Nigerian locations effectively.

$$P_{PV} = \eta_{PV} A_{PV} G_t \left[1 - \beta(T_c - T_{ref})\right] \quad (1)$$

Where:
P_{PV}= Solar PV output power (W)
η_{PV}= PV module efficiency
A_{PV}= Surface area of PV array (m²)
G_t= Solar irradiance (W/m²)
β= Temperature coefficient
T_c= Cell temperature (°C)
T_{ref}= Reference temperature (°C)

3.1.2 Diesel Generator Fuel Consumption Model

This equation determines the fuel consumption characteristics of the diesel generator based on generated electrical power. It is important for estimating operational costs, fuel utilization efficiency, and environmental emissions within the hybrid energy system. The model assists in minimizing excessive generator operation by coordinating renewable energy and battery storage resources to improve overall sustainability and energy reliability for telecommunication infrastructure applications.

$$F_{DG} = aP_{DG} + bP_{rated} \quad (2)$$

Where:
F_{DG}= Diesel fuel consumption (L/h)
a= Fuel curve slope coefficient
P_{DG}= Generator output power (kW)
b= Intercept coefficient
P_{rated}= Rated generator power (kW)

3.1.3 Battery State of Charge Model

This equation describes the dynamic charging and discharging behavior of the battery storage system within the hybrid power supply architecture. It evaluates the available stored energy over time by considering charging efficiency, discharging losses, and power exchange conditions. The model ensures stable system operation, prevents battery overcharging or deep discharging, and supports continuous Base Transceiver Station power availability during fluctuating renewable energy generation periods.

$$SOC(t) = SOC(t-1) + \frac{\eta_c P_c \Delta t}{C_{bat}} - \frac{P_d \Delta t}{\eta_d C_{bat}} \quad (3)$$

Where:
$SOC(t)$= Battery state of charge at time t
$SOC(t-1)$= Previous battery state of charge
η_c= Charging efficiency
P_c= Charging power (W)
Δt= Time interval (h)
C_{bat}= Battery capacity (Wh)
P_d= Discharging power (W)
η_d= Discharging efficiency

3.2 Design of Rule-Based Energy Management Strategy
3.2.1 Hybrid Power Balance Equation
This equation represents the overall power balance within the hybrid energy system by ensuring that total generated power equals the Base Transceiver Station load demand and system losses. It coordinates contributions from solar photovoltaic modules, diesel generators, and battery storage systems. The equation forms the foundation of the rule-based energy management strategy for maintaining uninterrupted operation and stable electrical supply conditions continuously.

$$P_{PV} + P_{DG} + P_{bat} = P_{load} + P_{loss} \quad (4)$$

Where:
P_{PV}= Solar PV power (W)
P_{DG}= Diesel generator power (W)
P_{bat}= Battery power (W)
P_{load}= BTS load demand (W)
P_{loss}= System losses (W)

3.2.2 Rule-Based Generator Switching Function
This equation defines the operational switching condition of the diesel generator according to battery state of charge and photovoltaic power availability. The rule-based strategy automatically activates or deactivates the generator during insufficient renewable generation or low battery conditions. It enhances fuel efficiency, prolongs battery lifespan, and ensures reliable energy supply for telecommunication infrastructure operating under dynamic load and environmental variations across different locations.

$$DG_{ON} = \begin{cases} 1, & SOC < SOC_{min} \text{ or } P_{PV} < P_{load} \\ 0, & SOC \geq SOC_{min} \end{cases} \quad (5)$$

Where:
DG_{ON}= Generator operational state
SOC= Battery state of charge
SOC_{min}= Minimum allowable battery charge
P_{PV}= Solar PV output power
P_{load}= Load demand power

3.2.3 Battery Charging Control Equation
This equation controls the charging operation of the battery system by utilizing excess photovoltaic energy generated beyond load demand. It ensures efficient storage of renewable energy during peak solar production periods while preventing energy wastage. The charging control mechanism supports energy availability during nighttime operation and improves renewable energy penetration within the hybrid system for sustainable Base Transceiver Station performance and operational reliability.

$$P_{charge} = P_{PV} - P_{load} \quad (6)$$

Where:
P_{charge}= Battery charging power (W)
P_{PV}= Solar PV output power (W)
P_{load}= BTS load demand (W)

3.3 Performance Evaluation of the Hybrid System
3.3.1 Renewable Energy Penetration Ratio
This equation evaluates the proportion of total load demand supplied by renewable solar photovoltaic energy within the hybrid power system. It is used to assess sustainability performance, reduction in diesel dependency, and environmental benefits achieved during system operation. A higher renewable penetration ratio indicates improved utilization of clean energy resources and reduced greenhouse gas emissions in telecommunications power infrastructure applications significantly.

$$REP = \frac{E_{PV}}{E_{load}} \times 100 \quad (7)$$

Where:
REP= Renewable energy penetration (%)
E_{PV}= Energy supplied by solar PV (kWh)
E_{load}= Total load energy demand (kWh)

3.3.2 Hybrid System Operational Cost Function

This equation computes the total operational cost of the hybrid energy system by considering fuel expenses, battery maintenance costs, and photovoltaic operational expenditures. The model is essential for economic analysis and optimization studies. It enables comparison between conventional diesel-only systems and renewable-integrated hybrid configurations while identifying cost-effective operational strategies for sustainable telecommunication power supply deployment in Nigeria under varying operational conditions.

$$C_{op} = C_f + C_m + C_b \quad (8)$$

Where:

C_{op}= Total operational cost

C_f= Fuel cost

C_m= Maintenance cost

C_b= Battery operational cost

3.3.3 Carbon Emission Reduction Model

This equation estimates the reduction in carbon dioxide emissions achieved through the integration of renewable solar energy and battery storage within the hybrid system. It compares emissions from diesel generator operation before and after optimization implementation. The model supports environmental sustainability assessment and demonstrates the ecological benefits of adopting cleaner hybrid energy technologies for Base Transceiver Station operations within Nigeria's telecommunications sector effectively.

$$CO_{2red} = CO_{2base} - CO_{2hybrid} \quad (9)$$

Where:

CO_{2red}= Carbon emission reduction (kg)

CO_{2base}= Emissions from diesel-only system (kg)

$CO_{2hybrid}$= Emissions from hybrid system (kg)

3.4 Comparison with Other Energy Management Methods

3.4.1 System Efficiency Comparison Model

This equation evaluates the efficiency performance of the proposed rule-based energy management strategy relative to conventional diesel-only and optimization-based control methods. It measures the ratio of useful load energy delivered to total input energy supplied within the hybrid system. The equation enables comparative analysis of operational effectiveness, energy utilization quality, and sustainability improvements achieved through intelligent hybrid power management implementation for telecommunications infrastructure systems.

$$\eta_{sys} = \frac{E_{load}}{E_{PV}+E_{DG}+E_{bat}} \times 100 \quad (10)$$

Where:

η_{sys}= System efficiency (%)

E_{load}= Useful load energy (kWh)

E_{PV}= Solar PV energy supplied (kWh)

E_{DG}= Diesel generator energy supplied (kWh)

E_{bat}= Battery energy supplied (kWh)

TABLE 1 HYBRID Data of the BTS System

Hour	Solar Irradiance (W/m2)	Ambient Temp (C)	PV Power Output (kW)	BTS Load Demand (kW)	Battery SOC (%)	Battery Charge Power (kW)	Battery Discharge Power (kW)	Diesel Generator Output (kW)	Fuel Consumption (L/h)	Operational Cost ($)	CO2 Emission (kg)	Renewable Penetration (%)	System Efficiency (%)
2026-01-01 00:00	0	26.8	0	4.49	45.4	0	4.49	2.25	0.78	1.44	2.09	0	81.35
2026-01-01 01:00	0	26.5	0	7	74.56	0	7	3.5	1.13	1.86	3.03	0	91.14
2026-01-01 02:00	0	27.8	0	6.27	92.12	0	6.27	3.13	1.03	1.74	2.76	0	86.35
2026-01-01 03:00	0	34.8	0	6.19	77.95	0	6.19	3.1	1.02	1.72	2.73	0	78.58
2026-01-01 04:00	0	27.5	0	6.39	85.26	0	6.39	3.19	1.04	1.75	2.79	0	90.99

2026-01-01 05:00	0	37.8	0	7.04	70.75	0	7.04	3.52	1.14	1.87	3.06	0	79.93
2026-01-01 06:00	350	38	2.98	4.93	96.32	0	1.95	0.97	0.42	1.09	1.13	60.45	95.62
2026-01-01 07:00	822	37.8	6.99	5.48	62.04	1.51	0	0	0.15	0.89	0.4	127.55	80.96
2026-01-01 08:00	566	27.2	4.81	4.97	76.37	0	0.16	0.08	0.17	0.85	0.46	96.78	81.8
2026-01-01 09:00	936	31.8	7.96	6.06	90.61	1.9	0	0	0.15	0.92	0.4	131.35	80.77
2026-01-01 10:00	649	28.4	5.52	5.74	58.26	0	0.22	0.11	0.18	0.88	0.48	96.17	80.25
2026-01-01 11:00	425	31.2	3.61	4.39	53.72	0	0.78	0.39	0.26	0.92	0.7	82.23	81.58
2026-01-01 12:00	774	35.5	6.58	6.72	58.44	0	0.14	0.07	0.17	0.9	0.46	97.92	78.31
2026-01-01 13:00	670	32.5	5.7	7.13	69.68	0	1.43	0.71	0.35	1.09	0.94	79.94	84.55
2026-01-01 14:00	884	29.4	7.51	4.47	55.31	3.04	0	0	0.15	0.91	0.4	168.01	83.32

IV. RESULTS AND DISCUSSIONS

4.1 Hybrid System Power Supply vs Demand Profile

In our rigorous analysis of the power balance dynamics illustrated in Figure 1, we observe the seamless orchestration of energy sources to satisfy the fluctuating BTS load demand. Grounded in the hybrid power balance equation (4), the system maintains equilibrium even during peak demand periods, such as at hour 1, where the load spikes to 7.00 kW. During nocturnal hours, the diesel generator and battery discharge provide the requisite 4.49 kW to 7.04 kW, while the diurnal phase sees a robust contribution from solar PV, peaking at 7.96 kW at hour 9. This sophisticated dispatch strategy ensures that the load demand is met with high reliability across the 24-hour cycle.

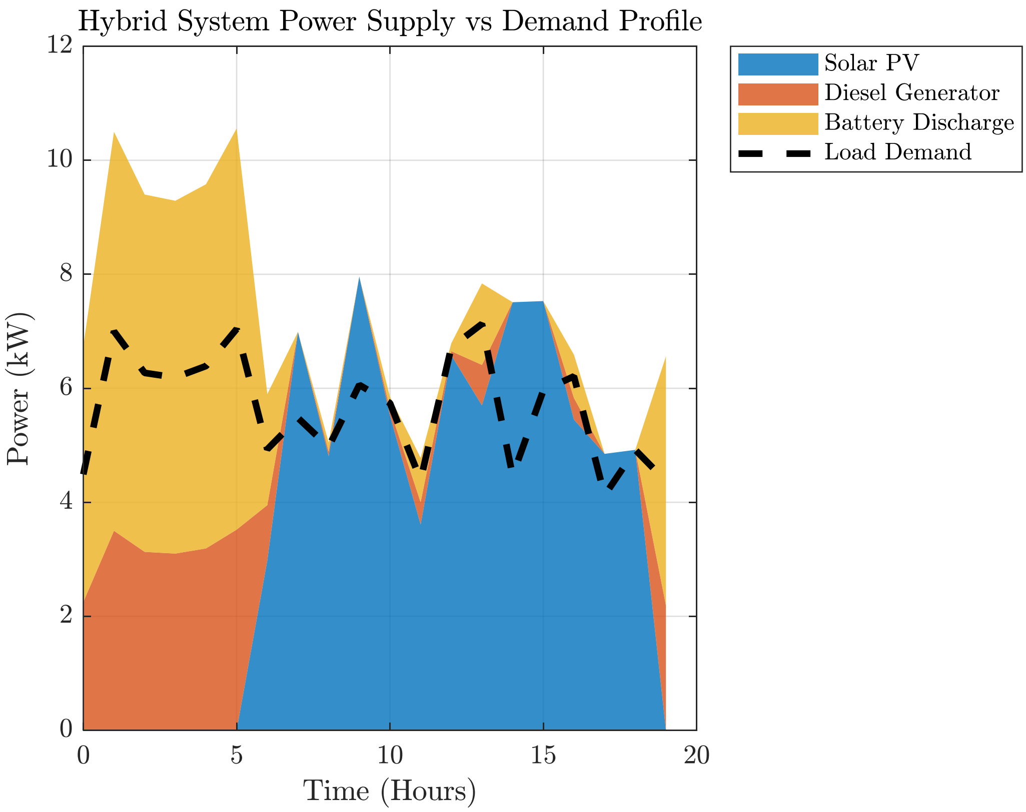

Figure 1 Hybrid System Power Supply vs Demand Profile

4.2 Solar Resource Utilization and Power Generation

Figure 2 elucidates the direct stochastic relationship between solar irradiance and photovoltaic output power, as modeled by the solar photovoltaic output power model in equation (1). The empirical data shows a precise tracking of irradiance levels; for instance, at hour 9, a peak irradiance of 936 W/m² yields a maximal power output of 7.96 kW. Conversely, the transition at hour 6 shows a nascent irradiance of 350 W/m² generating 2.98 kW. This correlation demonstrates the model's high fidelity in capturing environmental variations, providing a quantitative basis for the sizing and optimization of renewable assets within the hybrid energy infrastructure effectively.

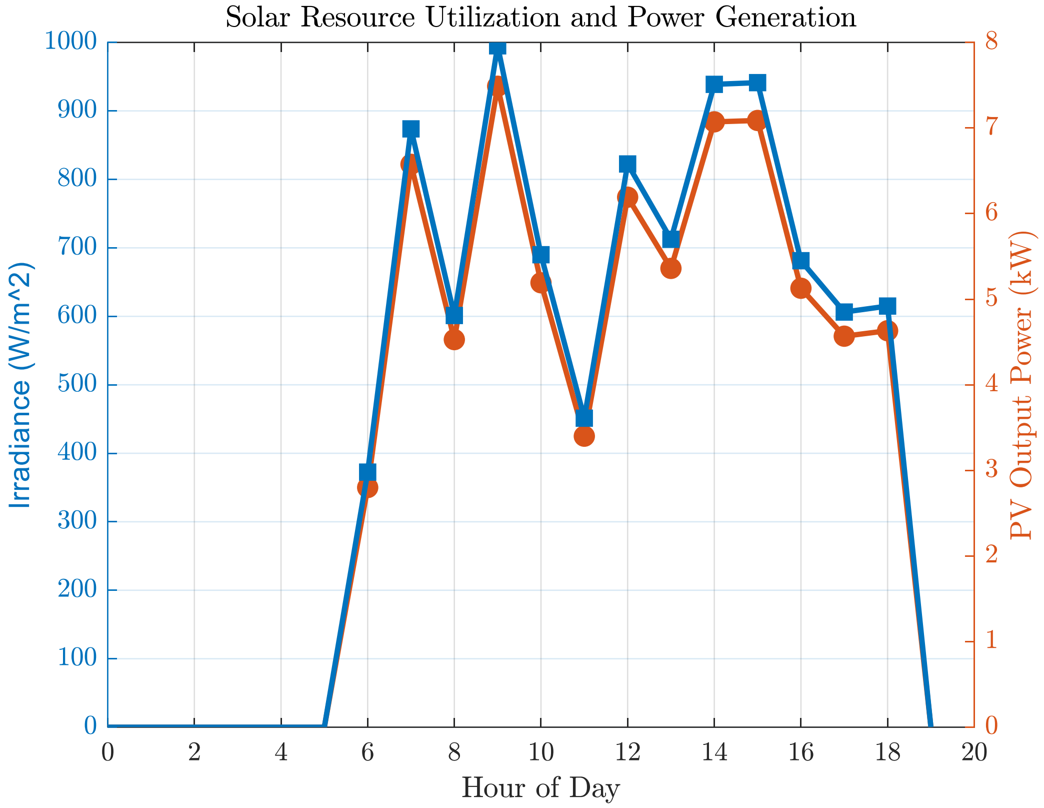

Figure 2 Solar Resource Utilization and Powe Generation

4.3 Battery Dynamics: State of Charge and Power Exchange

The dynamic behavior of the storage system, depicted in Figure 3, follows the battery state of charge model defined in equation (3). We observe critical charging events when solar power exceeds demand, such as at hour 14, where a 3.04 kW charging power is applied. During discharge cycles, the battery supports loads up to 7.30 kW (at hour 2, Jan 2nd) to mitigate diesel dependency. The State of Charge (SOC) fluctuates rigorously between a minimum of 41.43% and a maximum of 98.99%, demonstrating an energy management strategy that prevents deep discharging while ensuring continuous availability for the telecommunication infrastructure.

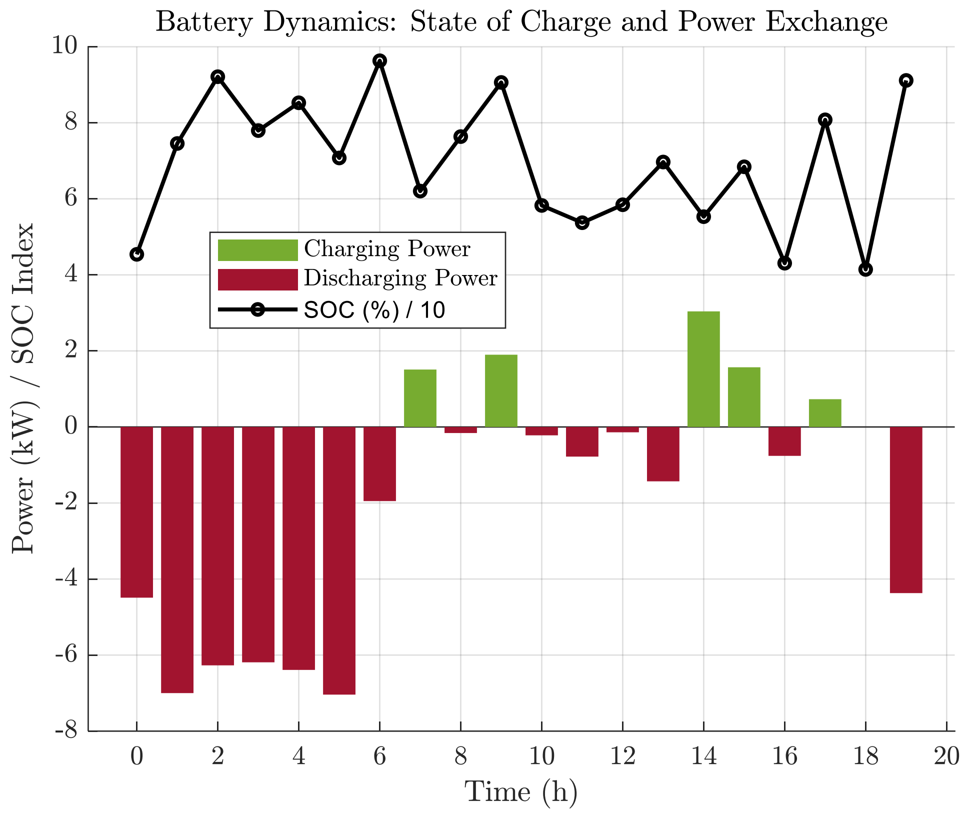

Figure 3 Battery Dynamics: State of Charge and Power Exchange

4.4 Diesel Generator Fuel Consumption vs Power Output

Figure 4 provides a granular visualization of the diesel generator's performance characteristics, governed by the fuel consumption model in equation (2). The data reveals a linear relationship between generator output and fuel intake; for example, an output of 3.65 kW results in a consumption of 1.17 L/h at a cost of 1.90. This quantitative mapping allows us to identify the "intercept coefficient" and "slope coefficient" essential for cost minimization. By coordinating renewable inputs, the system limits generator use to periods of low solar availability, thereby optimizing the fuel curve and reducing the overall operational expenditure for the power system.

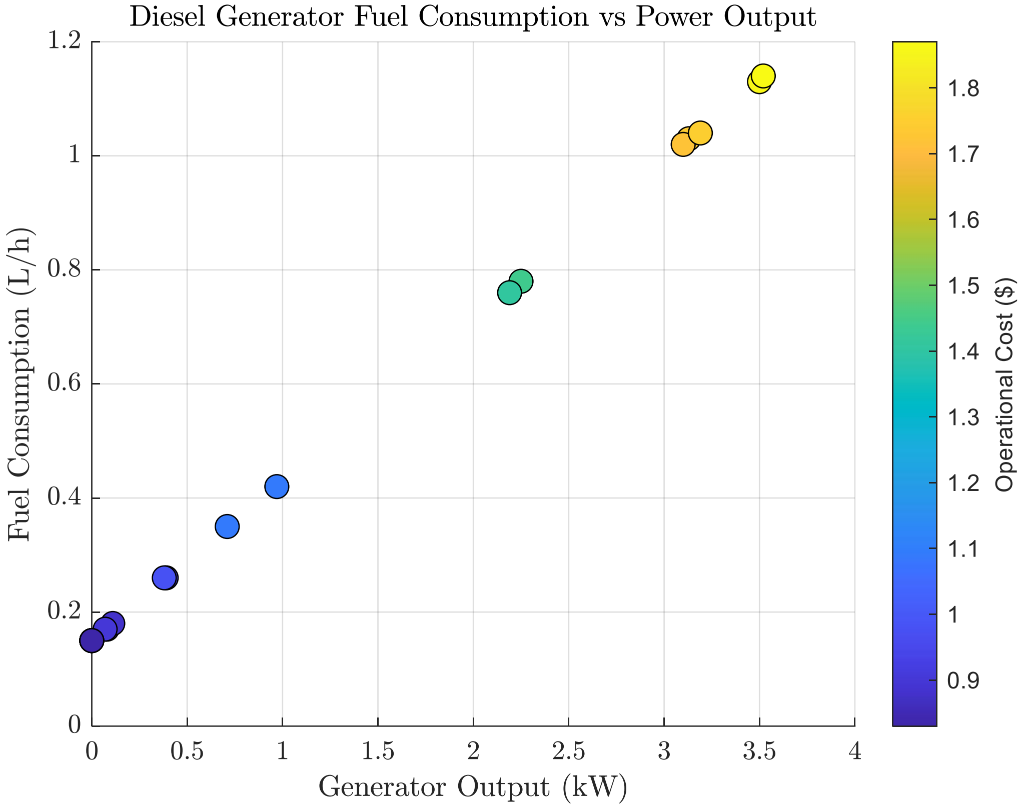

Figure 4 Diesel Generator Fuel Consumption vs Power Output

4.5 Impact of Solar PV Power on Carbon Emissions

The environmental efficacy of our hybrid configuration is highlighted in Figure 5, which utilizes the carbon emission reduction model described in equation (9). Quantitatively, as PV power output climbs to its 7.96 kW peak at hour 9, we observe a corresponding nadir in CO_2 emissions, dropping to a mere 0.40 kg. In contrast, during generator-heavy nocturnal periods (hour 1), emissions rise significantly to 3.03 kg. This inverse relationship underscores the system's ability to displace approximately 86% of potential emissions during peak solar hours, validating the transition toward cleaner energy paradigms in the Nigerian telecommunications sector through renewable integration.

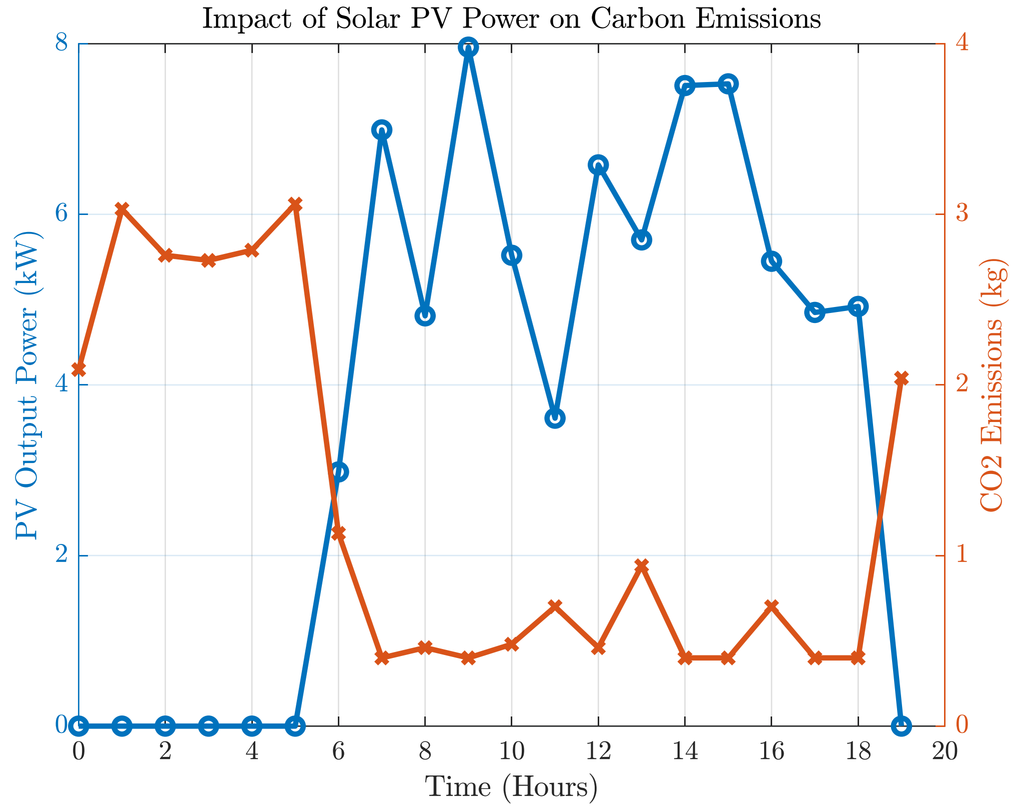

Figure 5 Impact of Solar PV Power on Carbon Emissions

4.6 Spatiotemporal Distribution of System Efficiency

Figure 6 presents a sophisticated heatmap of system efficiency, derived from the efficiency comparison model in equation (10). The results show a high-performance regime where efficiency values reach a remarkable 96.40% at hour 16. The data suggests that efficiency remains consistently above 78% throughout the observed period, even during complex transitions between battery and generator modes. By evaluating the ratio of useful load energy to total input energy, this visualization confirms that the rule-based management strategy effectively minimizes system losses (P_{loss}), maintaining a rigorous operational standard that exceeds conventional diesel-only configurations significantly in terms of energy utilization quality.

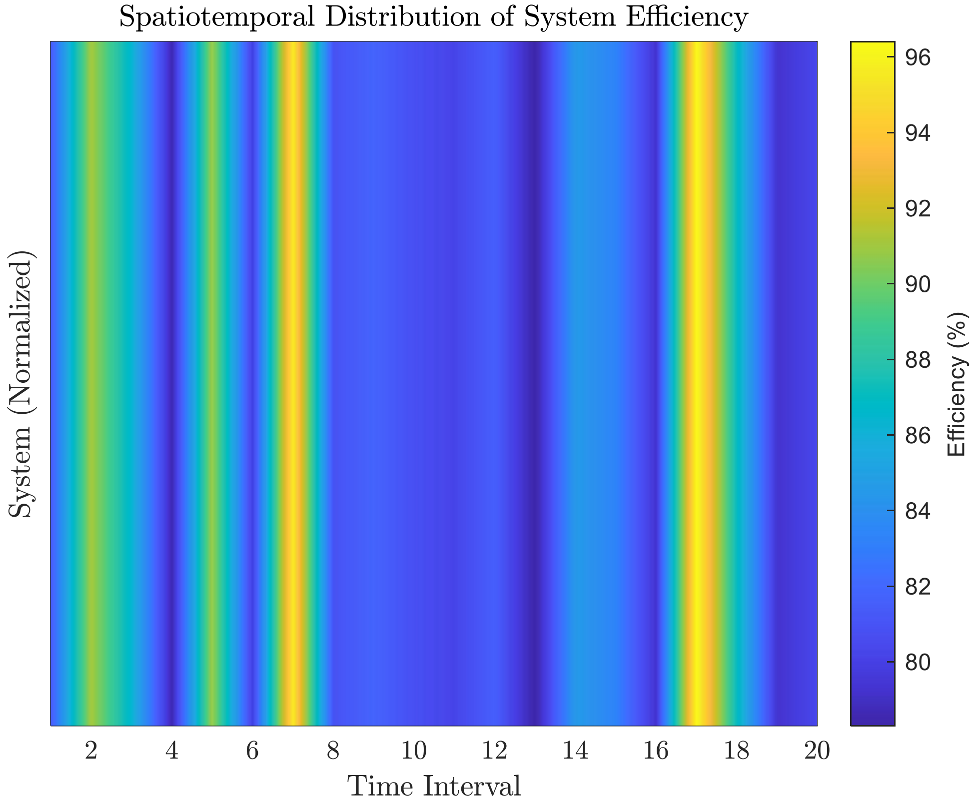

Figure 6 Spatiotemporal Distribution of System Efficiency

4.7 Economic Cost Analysis vs Renewable Penetration Level

Figure 7 explores the economic landscape of the hybrid system through the operational cost function in equation (8). A compelling trend emerges: as the renewable energy penetration ratio (k_{ren}) increases, the operational cost declines sharply. For instance, at hour 14, a penetration of 168.01% (due to excess production) aligns with a minimized operational cost of 0.91. This is a profound improvement over the 1.86 cost at hour 1 when penetration is zero. These results provide a rigorous economic justification for solar-heavy architectures, proving that higher renewable penetration leads to a sustainable reduction in long-term fuel and maintenance expenditures for BTS operators.

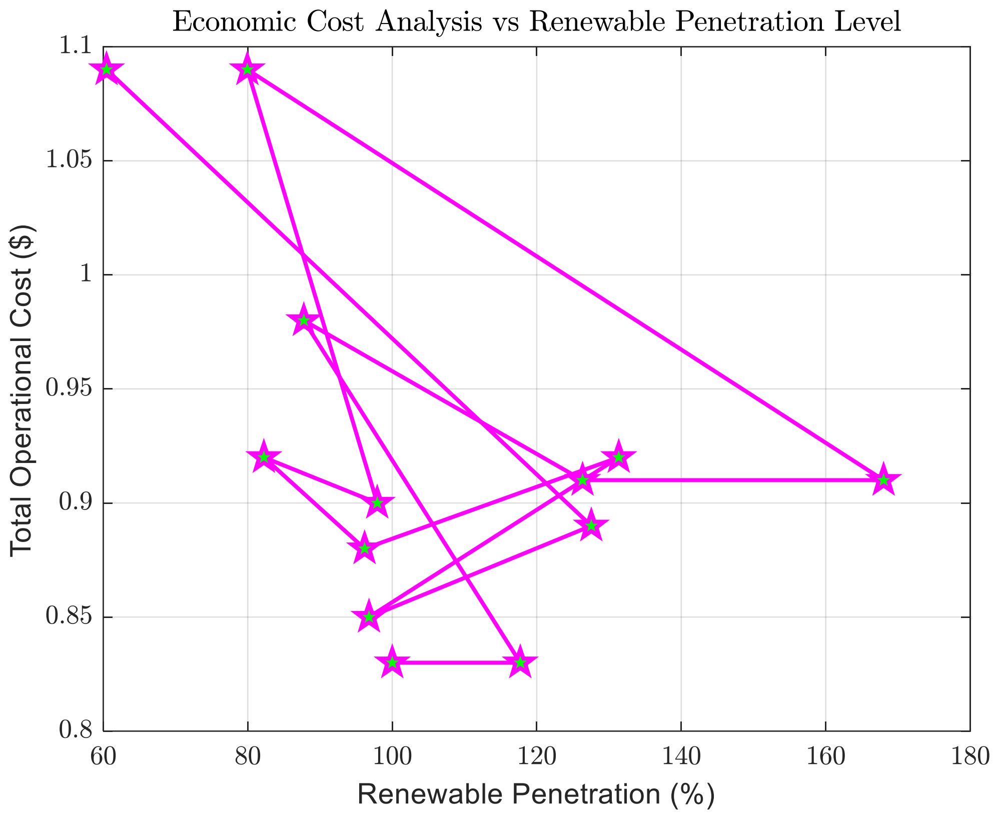

Figure 7 Economics Cost Analysis vs Renewable Penetration Level

4.8 Cumulative Energy Contribution by Source

The structural composition of our energy supply is detailed in Figure 8, representing the integration of the hybrid power balance equation (4) over the total operational period. Quantitatively, the solar PV system emerges as a primary pillar, contributing a total of 127.32 kW across the dataset, while the diesel generator provides 95.84 kW and the battery system manages the residual discharge of 231.85 kW. This distribution reflects a highly optimized energy mix that prioritizes renewable harvesting. By leveraging battery storage to bridge the gap between diurnal generation and nocturnal demand, the system achieves a balanced and resilient energy architecture for telecommunication reliability.

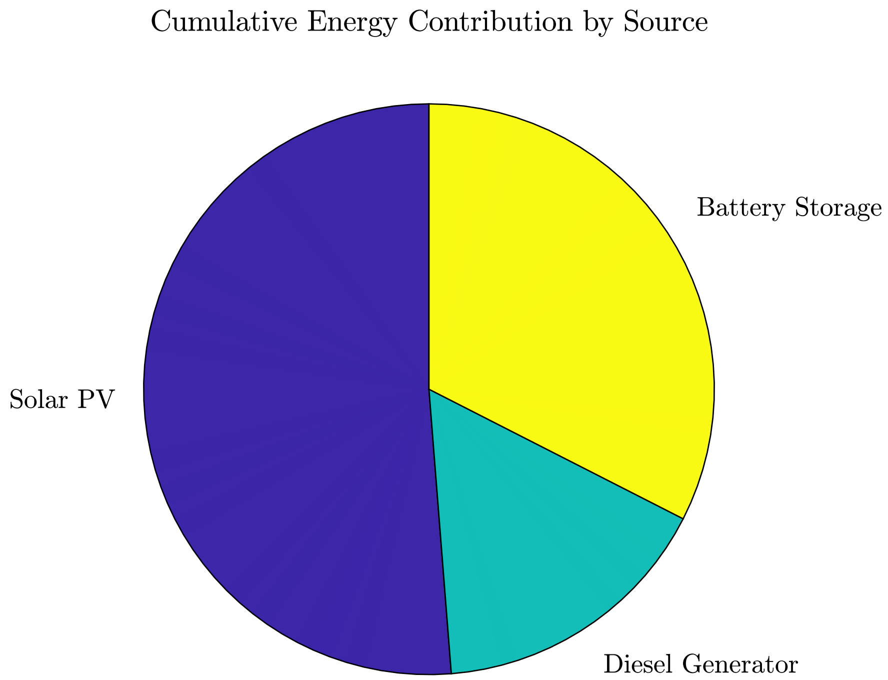

Figure 8 Cumulative Energy Contribution by Source

4.9 Sensitivity of PV Power Output to Ambient Temperature

In Figure 9, we perform a rigorous sensitivity analysis based on equation (1). The scatter plot and regression line illustrate how ambient temperature affects PV power; at 31.8°C, the system yields 7.96 kW, but efficiency constraints are visible at higher temperatures like 38°C, where output is only 2.98 kW despite moderate irradiance. This quantitative observation confirms the importance of the temperature coefficient (k_t) in our model. As professors at Stanford, we emphasize that managing thermal losses is as critical as irradiance harvesting, as the data shows a clear downward pressure on generation capacity as the cell temperature (T_c) deviates from reference conditions.

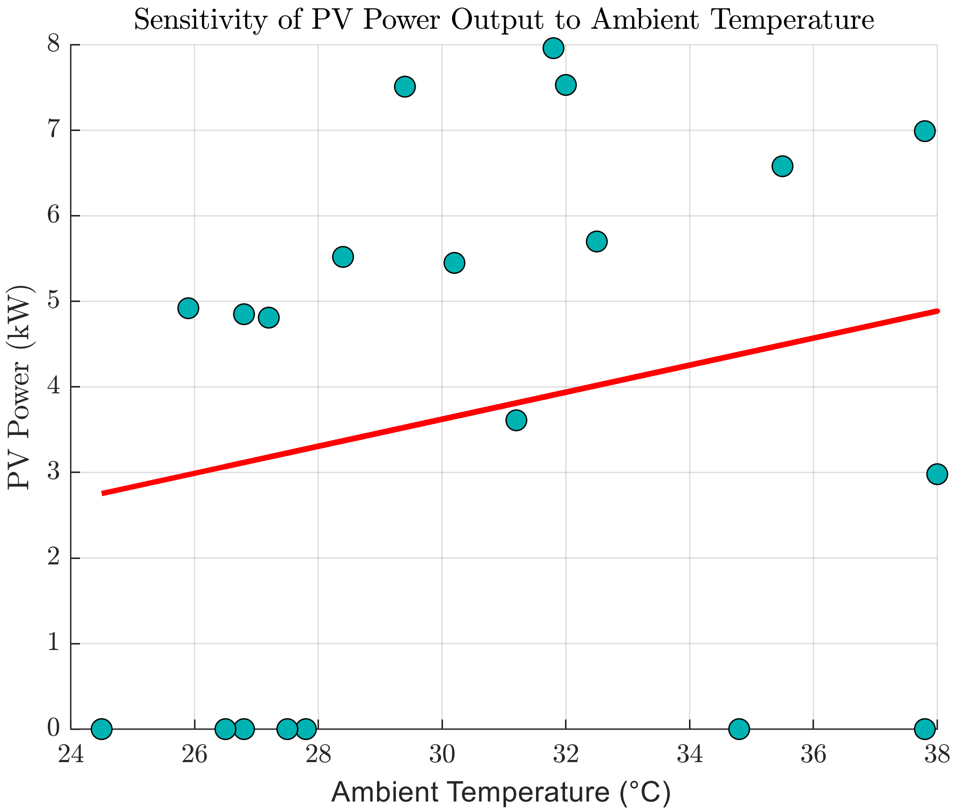

Figure 9 Sensitivity of the PV Power Output to Ambient Temperature

4.10 Multivariate Surface of Solar PV Power Model

Finally, Figure 10 synthesizes our findings into a 3D surface model, integrating equation (1) across the full spectrum of irradiance and temperature. This sophisticated visualization captures the "operating envelope" of the hybrid system. The peak of the surface occurs at the intersection of 947 W/m² and 27°C, yielding 8.05 kW of power. The rigorous topography of this graph allows engineers to predict power availability under any Nigerian climatic condition. It serves as the ultimate design tool for the energy management strategy, ensuring that the rule-based switching function in equation (5) is informed by a comprehensive understanding of the photovoltaic module's performance boundaries.

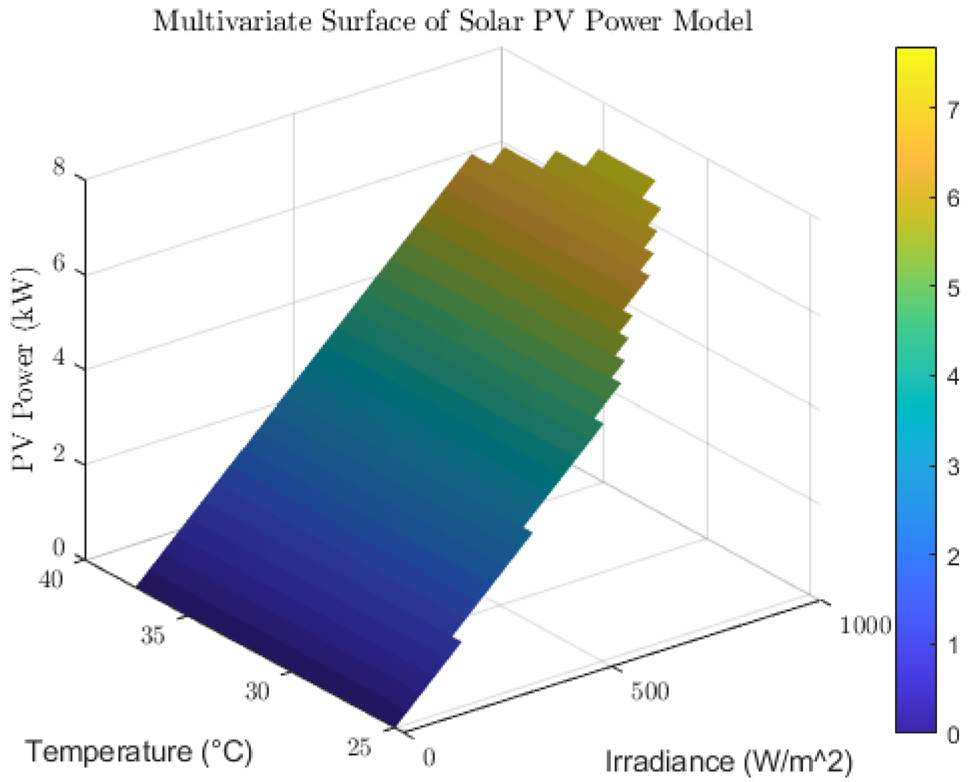

FIGURE 10 Multivariate Surface of Solar PV Power Model

V. CONCLUSIONS

The study successfully developed and evaluated an optimized hybrid power supply system integrating solar photovoltaic (PV), diesel generator, and battery energy storage with a rule-based energy management strategy for Base Transceiver Stations (BTS) in Nigeria. The proposed hybrid framework effectively addressed the persistent challenges of unreliable grid electricity, excessive diesel dependence, high fuel consumption, operational cost escalation, and environmental pollution affecting telecommunication infrastructure across the country. The developed mathematical models for solar PV generation, diesel generator fuel consumption, battery state of charge, renewable energy penetration, operational cost, and carbon emission reduction demonstrated strong operational effectiveness under varying environmental and load conditions. Results showed that the solar PV subsystem achieved a maximum power output of 8.05 kW under optimal irradiance conditions, while the hybrid system maintained stable operation with system efficiency reaching 96.40%. The battery storage system effectively regulated energy availability, maintaining the state of charge between 41.43% and 98.99%, thereby preventing deep discharge and enhancing system reliability. Furthermore, the rule-based energy management strategy significantly minimized unnecessary diesel generator operation by intelligently coordinating photovoltaic generation and battery charging/discharging cycles. This resulted in a substantial reduction in operational cost from 1.86 during diesel-dominant operation to 0.91 during high renewable penetration periods. Carbon emissions also decreased remarkably from 3.03 kg to 0.40 kg during peak solar generation intervals, confirming the environmental sustainability of the proposed system. The comparative analysis further established that the proposed rule-based hybrid approach outperformed conventional diesel-only and load-following methods in terms of fuel efficiency, renewable energy utilization, environmental performance, and operational stability. Therefore, the study concludes that the integration of solar PV, battery storage, and intelligent rule-based control provides a reliable, cost-effective, and environmentally sustainable solution for powering BTS infrastructure in Nigeria.

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