TECHNO-ECONOMIC AND ENVIRONMENTAL OPTIMIZATION OF A HYBRID PV–WIND–BATTERY–DIESEL MICROGRID FOR RURAL ELECTRIFICATION IN BORNO STATE, NIGERIA USING ANT COLONY OPTIMIZATION

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ABSTRACT

Reliable electricity access remains one of the most critical challenges in rural Nigeria, particularly in the northern regions where grid extension is economically and logistically unfeasible. Communities in Guzamala Local Government Area (LGA), Borno State (especially Northern Borno), rely heavily on diesel generators and kerosene lamps, resulting in high operating costs, energy insecurity, and severe environmental impacts. This underscores the urgent need for cleaner and more sustainable off-grid power alternatives. The primary objective of this study is to design and optimize a cost-effective, reliable, and environmentally sustainable standalone hybrid micro grid integrating photovoltaic (PV), wind turbine (WT), battery energy storage system (BESS), and a diesel generator (DG). A metaheuristic optimization framework based on Ant Colony Optimization (ACO) was developed and benchmarked against Particle Swarm Optimization (PSO) to determine the optimal system configuration and operating strategy under real-world resource and cost conditions. Using solar and wind data from NASA and measured household load demand (~200 kWh/day for 20 households), the optimization minimized the Net Present Cost (NPC) and Loss of Power Supply Probability (LPSP) while maintaining system reliability. The ACO-optimized system comprised 42 kW PV, 15 kW WT, 180 kWh BESS, and 8 kW DG, achieving an NPC of $92,500, Levelized Cost of Electricity (LCOE) of $0.243/kWh, and LPSP of 0.9%. In comparison, PSO produced a higher NPC of $101,300 and LCOE of $0.268/kWh, confirming ACO's superior economic and convergence performance. The hybrid system reduced diesel consumption by approximately 70% and CO_2 emissions by about 62% relative to a diesel-only baseline. Sensitivity analyses revealed that a 20% decline in battery cost increased storage capacity to 220 kWh and reduced DG reliance by 35%, while a 30% rise in diesel price increased NPC by only 9%, demonstrating strong resilience to market volatility. In conclusion, the results affirm that Ant Colony Optimization offers a robust and efficient approach for designing rural hybrid micro grids in Nigeria. The proposed ACO-based system provides a techno-economically viable and environmentally sustainable pathway for rural electrification, supporting Nigeria's Net Billing Regulation and Energy Transition Agenda toward a low-carbon future.

Keywords: Hybrid Energy System (HES); Micro grid; Ant Colony Optimization (ACO); Particle Swarm Optimization (PSO); Techno-Economic Analysis; Renewable Energy; Energy Transition; Nigeria

1 INTRODUCTION

Access to reliable and affordable electricity remains one of the major developmental challenges in Sub-Saharan Africa. In Nigeria, more than 80 million people—mostly in rural areas—still lack grid-based electricity access [1,2]. The situation is particularly critical in the North-East, where insecurity and weak infrastructure make grid expansion impractical [3]. Communities such as Guzamala Local Government Area (LGA) in Borno State rely primarily on kerosene lamps and diesel generators, which are both costly and environmentally harmful [4]. Globally, hybrid renewable energy systems (HRES) have been identified as a sustainable solution for rural electrification [5]. By integrating solar photovoltaic (PV), wind turbines (WT), battery energy storage systems (BESS), and diesel generators (DG) as backup, HRES can ensure reliable supply while reducing dependence on fossil fuels. The challenge, however, lies in optimal sizing and dispatch, since renewable resources are intermittent and system costs are highly sensitive to design choices. Traditional deterministic optimization methods (linear programming, dynamic programming) often fail to capture the nonlinearities and uncertainties inherent in hybrid system design. In recent years, metaheuristic algorithms have emerged as more robust alternatives. Among these, Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) have been widely applied, but they often suffer from premature convergence and suboptimal solutions. The primary objective of this study is to design and optimize a reliable, cost-effective, and environmentally sustainable hybrid energy system for rural electrification in Guzamala Local Government Area of Borno State, Nigeria. Specifically, the research seeks to model the local meteorological and household load conditions and to develop an optimization framework based on Ant Colony Optimization (ACO) for determining the optimal configuration of solar PV, wind turbines, battery storage, and diesel backup. The performance of the ACO-based solution is then benchmarked against the widely used Particle Swarm Optimization (PSO) to evaluate comparative efficiency and reliability. Furthermore, the study aims to assess the techno-economic viability of the system in terms of Net Present Cost (NPC) and Levelized Cost of Electricity (LCOE), while also quantifying the environmental benefits through reductions in fuel consumption and emissions relative to a diesel-only baseline. Ultimately, the objective is to generate actionable insights that can guide policymakers, regulators, and investors in advancing decentralized renewable micro grid solutions in line with Nigeria's energy transition agenda and the United Nations Sustainable Development Goal 7 (Affordable and Clean Energy). Ant Colony Optimization (ACO), inspired by the foraging behavior of ants, has shown promise in solving multi-objective, nonlinear optimization problems due to its balance between exploration and exploitation. While ACO has been successfully applied in transportation and communication networks, its application to off-grid hybrid micro grid design in Sub-Saharan Africa remains limited. This study addresses this gap by applying ACO to the techno-economic and environmental optimization of a PV–WT–BESS–DG hybrid micro grid for Guzamala LGA. The results are benchmarked against PSO, providing comparative insights into algorithm performance. The research further quantifies system costs, reliability, and emissions, with implications for Nigeria's Net Billing regulation and the national energy transition agenda.

2 LITERATURE REVIEW

Hybrid Energy Systems (HES) have emerged as a promising solution for rural electrification, particularly in areas where extending the national grid is either technically impractical or economically unfeasible. [5] A typical HES integrates multiple renewable energy resources such as solar photovoltaic (PV), wind turbines, biomass, or small hydro with storage and backup units to ensure continuous electricity supply [5]. Numerous studies have highlighted the ability of hybrid systems to reduce dependence on fossil fuels while simultaneously improving energy access and reliability in underserved regions [5]. This section reviews the global and regional contributions to HES research, with emphasis on optimization techniques and the role of Ant Colony Optimization (ACO) in energy system planning.

2.1 Hybrid Energy Systems for Off-Grid Electrification

Globally, hybrid energy systems (HES) have been widely explored for their potential to provide reliable, sustainable, and cost-effective electricity to remote and off-grid communities. As illustrated in

Figure 1, a typical hybrid micro grid architecture integrates renewable energy sources such as photovoltaic (PV) arrays and wind turbines (WT) with a battery energy storage system (BESS) and a diesel generator (DG) as backup. This configuration ensures continuous power supply by balancing the intermittent nature of renewables with stored and dispatchable energy sources. Early studies, such as [6], provided a comprehensive review demonstrating that hybrid systems can significantly reduce fossil fuel dependence while enhancing energy security and long-term sustainability. Building upon this, [7] employed the Cuckoo Search (CS) algorithm to optimize hybrid configurations, reporting superior convergence and cost-effectiveness compared to traditional deterministic methods. In a related study, [8] developed an Improved Sine–Cosine Algorithm (ISCA), which further reduced total system cost but at the expense of higher computational complexity. In the African context particularly in Nigeria, hybrid energy systems have garnered growing attention due to their potential to alleviate rural electrification challenges. However, designing an optimal hybrid configuration in such settings remains complex because of the seasonal variability of solar irradiance and wind speed, high diesel costs, and socioeconomic constraints faced by local communities. These challenges highlight the need for advanced metaheuristic optimization techniques that can effectively balance cost, reliability, and sustainability under uncertain and resource-limited conditions.

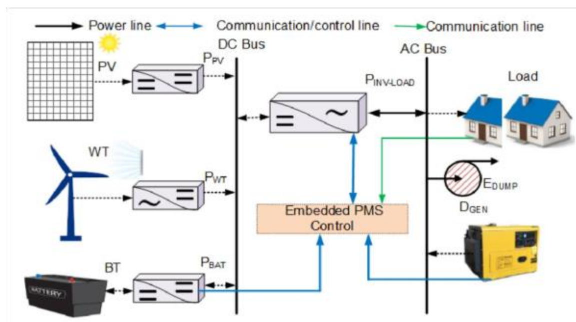

Figure 1. Architecture of a typical hybrid micro grid system integrating PV, WT, BESS, and DG [9]

2.2 Optimization Approaches in HES Design

Optimization plays a critical role in hybrid energy system design, as it determines both the sizing of components and the operational strategy for minimizing costs and maximizing reliability. Broadly, optimization methods fall into two categories: deterministic and metaheuristic approaches. Deterministic techniques, such as linear programming, nonlinear programming, and dynamic programming, are suitable for simple systems but often fail to adequately handle the high levels of nonlinearity, intermittency, and uncertainty associated with renewable energy generation. In contrast, metaheuristic algorithms—including Genetic Algorithms (GA), Particle Swarm Optimization (PSO), Differential Evolution (DE), Artificial Bee Colony (ABC), and ACO—have become dominant tools due to their ability to navigate complex, multi-modal solution spaces [9, 10]. For instance, [10] applied GA in optimizing PV–wind–diesel–battery systems, achieving reliable solutions but facing slow convergence rates. [11] used PSO for hybrid micro grid design, demonstrating faster convergence yet experiencing premature stagnation. More recently, [12] showed that hybrid metaheuristic methods, such as PSO combined with Harmony Search, can outperform single-algorithm approaches by balancing their strengths and weaknesses.

2.3 Ant Colony Optimization in Energy Systems

Ant Colony Optimization (ACO), inspired by the foraging behavior of ants, has emerged as a particularly effective metaheuristic for energy systems due to its balance between exploration and exploitation. [13] demonstrated its effectiveness in sizing solar–wind hybrid systems, while [13] applied ACO to smart grid dispatching problems, achieving improved operational performance. [14] extended its application to the optimization of distributed energy resources, reporting notable cost reductions. Despite these promising results, most applications of ACO in energy systems have been restricted to grid-connected contexts or to regions outside Sub-Saharan Africa. This leaves an important research gap concerning its application in standalone off-grid hybrid systems, where renewable intermittency, diesel dependence, and socioeconomic realities create distinct optimization challenges.

2.4 Research Gap and Contribution

A careful review of the literature reveals two major gaps. First, there is limited integration of robust power management strategies that prioritize renewable energy utilization while minimizing reliance on diesel generators. Second, applications of ACO in standalone hybrid systems within Sub-Saharan Africa remain scarce, despite the region's acute electrification challenges. Addressing these gaps, the present study applies ACO to optimize a PV–wind–battery–diesel hybrid micro grid in Guzamala Local Government Area, Borno State, Nigeria. The study incorporates a rule-based Energy Management System (EMS) and benchmarks ACO results against the widely used PSO algorithm, thereby providing new insights into both the methodological performance of ACO and the practical feasibility of hybrid micro grids for rural electrification in Nigeria.

3 METHODOLOGY

3.1 Study Area

The case study focuses on Guzamala Local Government Area (LGA) in Borno State, Nigeria, located approximately between latitude 12.77° N and 13.25° N and longitude 12.70° E and 13.30° E [15]. Guzamala lies in the northeastern part of Nigeria within the Lake Chad Basin and shares borders with Mobbar, Kukawa, Nganzai, and Monguno LGAs. The area is predominantly rural, with scattered settlements and limited socio-economic infrastructure. The terrain is relatively flat with sparse vegetation typical of the semi-arid Sahel zone [16,17]. Electricity access within Guzamala LGA remains extremely limited, and conventional grid expansion is largely impractical due to security challenges, poor road connectivity, and low population density [18]. Figure 2 shows the administrative layout of Guzamala LGA, indicating ward boundaries, road networks, and rivers that influence the siting and logistics of potential renewable energy projects [15, 16]. Meteorological datasets from the Nigerian Meteorological Agency (NIMET) and NASA Surface Solar Energy (NASA-SSE) were used to characterize the site's renewable energy potential. The solar irradiance ranges from 3 W/m² to 1057 W/m², with an average of approximately 5.5 kWh/m²/day. Wind speeds vary between 0.6 m/s and 14.4 m/s, showing significant seasonal fluctuations. Ambient temperatures range from 13°C to 44°C, which directly affects the efficiency of both PV modules and battery storage performance [19, 20]. For energy demand analysis, the load profile was modeled for 20 two-bedroom rural households, each equipped with basic appliances such as televisions, refrigerators, lighting, and ceiling fans. The aggregated daily energy requirement is approximately 200 kWh/day, with a peak load of 5 kW, aligning with the Nigerian Electricity Regulatory Commission (NERC) rural-household estimates.

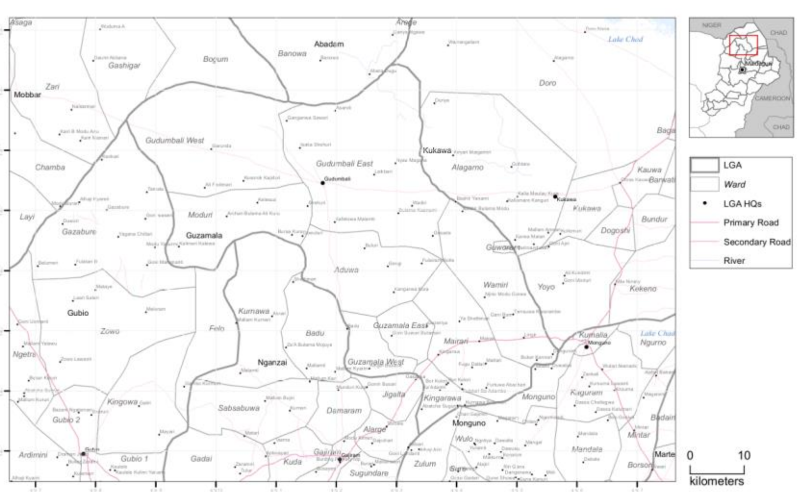

Figure 2. Guzamala LGA [15, 16]

3.2 System Configuration

The proposed hybrid energy system is designed to integrate four components. Solar Photovoltaic (PV) panels serve as the primary generation source during daytime. Wind turbines (WT) complement PV generation, particularly during night and cloudy periods. Battery Energy Storage System (BESS) stores surplus renewable electricity for later use, with a State of Charge (SOC) range constraint (20% ≤ SOC ≤ 100%) to prevent deep discharge and prolong lifespan. Diesel Generator (DG) acts as a backup, supplying electricity during extended renewable deficits and ensuring system reliability. This configuration enables maximum renewable penetration while maintaining reliability.

3.3 Power Management Strategy

A rule-based Energy Management System (EMS) was developed to manage the power flow between system components [21]. Four operating modes are defined: Normal Operation: PV and WT supply the load, and any excess energy is directed to charge the BESS. Surplus Condition: When the BESS reaches maximum SOC, further surplus is dissipated through a dump load to prevent overcharging. Deficit Condition: When renewable power is insufficient, the BESS discharges to cover the deficit within SOC limits. Emergency Mode: If both renewable sources and the BESS are unable to meet demand, the DG is activated to maintain reliability. This EMS prioritizes renewable sources, minimizes diesel consumption, and ensures a Loss of Power Supply Probability (LPSP) ≤ 1%, corresponding to near-continuous supply [22].

3.4 Mathematical Models

The hybrid system components are modeled as follows:

3.4.1 PV Model

The power output of PV modules depends on solar irradiance G and cell temperature T_c [23]

$$P_{PV}(t) = P_{STC} \cdot \frac{G(t)}{G_{STC}} \cdot [1 - \alpha \cdot (T_c(t) - T_{STC})] \tag{1}$$

Where P_{STC} is the rated power at Standard Test Conditions, $G_{STC} = 1000\ W/m^2$, and α is the temperature coefficient.

3.4.2 Wind Turbine Model

The wind turbine output is determined by the wind speed V and turbine power curve [5]:

$$P_{WT}(V) = \begin{cases} 0 & V < V_{ci}\ or\ V > V_{co} \\ P_r \cdot \frac{V^3 - V_{ci}^3}{V_r^3 - V_{ci}^3} & V_{ci} \le V < V_r \\ P_r & V_r \le V \le V_{co} \end{cases} \tag{2}$$

Where P_r= rated turbine power (kW), V_{ci}= cut-in wind speed (m/s), V_r= rated wind speed (m/s), V_{co}= cut-out wind speed (m/s).

3.4.3 Battery Model

The SOC is updated based on charge/discharge power with efficiency

$$SOC(t+1) = SOC(t) + \frac{\eta_{ch} P_{ch}(t)\Delta t}{C_{bat}} - \frac{P_{dis}(t)\Delta t}{\eta_{dis} C_{bat}} \tag{3}$$

With constraint:

$$SOC_{min} \le SOC\ (t) \le SOC_{max} \tag{4}$$

3.4.4 Diesel Generator Model

Fuel consumption is modeled linearly as:

$$F_{DG}(P_{DG} = a \cdot P_{DG} + b \cdot P_{DG,r} \quad (5)$$

Where a and b are Fuel consumption coefficients (L/kWh). The DG output is bounded by:

$$0 \leq P_{DG}(t) \leq P_{DG}^{max} \quad (6)$$

Where η_{DG}= efficiency of the generator.

3.4.5 Energy Balance

The overall system satisfies the load demand at each time step [13]:

$$P_{Load}(t) = P_{pv}(t) + P_{WT}(t) + P_{bat}(t) + P_{DG}(t) \quad (7)$$

With the reliability condition:

$$LPSP = \frac{\sum_{t=1}^{T} E_{unserved}(t)}{\sum_{t=1}^{T} E_{Load}(t)} \leq 0.01 \quad (8)$$

Where $E_{unserved}(t)$ is unmet demand at time t. for this study.

3.5 Optimization Framework

The objective is to minimize the Cost of Energy (COE) while satisfying technical and reliability constraints. The decision vector is [24]:

$$X = \{P_{PV}, P_{WT}, C_{bat}, P_{DG}\} \quad (9)$$

Ant colony Optimization (ACO): Each ant represents a candidate system configuration. Pheromone trails are updated as:

$$\tau_{ij}(t+1) = (1-\rho)\tau_{ij}(t) + \Delta\tau_{ij}(t) \quad (10)$$

Where ρ is the evaporation rate and $\Delta\tau_{ij}$ is the proportional to the quality of the solution. The decision vector is:

$$P_{ij}(t) = \frac{{\tau_{ij}}^{\alpha} \cdot {\eta_{ij}}^{\beta}}{\sum_k {\tau_{ij}}^{\alpha} \cdot {\eta_{ij}}^{\beta}} \quad (11)$$

Where $\alpha \; and \; \beta$ are weight factors, η_{ij} is heuristic desirability. Particle swarm Optimization As a bench Marck, PSO updates particle velocity and position:

$$v_i^{t+1} = w \cdot v_i^t + c_1 r_1 (pbest_i - x_i^t) + c_2 r_2 (gbest - x_i^t) \quad (12)$$

$$x_i^{t+1} = v_i^t + v_i^{t+1} \quad (13)$$

Where w is inertia weight, c_1, c_2 is the learning coefficient, and r_1, r_2= random numbers.

3.6 Simulation Platform

The optimization and simulations were implemented in MATLAB/Simulink. Each algorithm (ACO and PSO) was executed for 20 independent runs to ensure robustness against stochastic variability. Performance metrics including Net Present Cost (NPC), Levelized Cost of Electricity (LCOE), CO_2 emissions, and LPSP were recorded. Convergence speed and consistency of the results were also analyzed to assess algorithm performance.

4 RESULTS AND DISCUSSION

4.1 Optimal System Configuration

The optimization results yielded distinct hybrid energy system configurations depending on the applied metaheuristic algorithm. The Ant Colony Optimization (ACO) approach produced an optimal configuration of 42 kW PV, 15 kW WT, 180 kWh BESS, and 8 kW DG, while the Particle Swarm

Optimization (PSO) algorithm resulted in 45 kW PV, 12 kW WT, 150 kWh BESS, and 10 kW DG. These variations reflect the inherent differences in the search dynamics, convergence speed, and exploration–exploitation balance between the two algorithms. As illustrated in Figure 2, the ACO-based design favors a higher battery storage capacity (180 kWh), enabling superior management of renewable intermittency and reducing dependency on the diesel generator during extended cloudy or low-wind conditions. This aligns with the findings [25] and [26], who reported that larger BESS capacities enhance renewable fraction and system autonomy in off-grid micro grids. Conversely, the PSO-based configuration emphasizes a slightly higher PV capacity (45 kW) and DG rating (10 kW) while minimizing battery size, indicating a strategy focused on generation redundancy rather than storage resilience—a trend also observed by [27] in comparative PSO-based hybrid system optimization. The comparative analysis demonstrates that while PSO converges rapidly, it occasionally favors local minima by emphasizing generation-heavy solutions. ACO, on the other hand, maintains stronger global exploration, resulting in a more balanced configuration that prioritizes storage efficiency and minimizes overall fuel dependency. This behavior corroborates the observations of [28] and [29], who found ACO to outperform PSO in terms of energy cost reduction and renewable utilization in hybrid PV–wind–diesel systems. Overall, the ACO-derived configuration provides superior resilience under variable meteorological conditions and load fluctuations typical of northern Nigerian rural communities such as Guzamala, thereby making it a more sustainable solution for decentralized electrification.

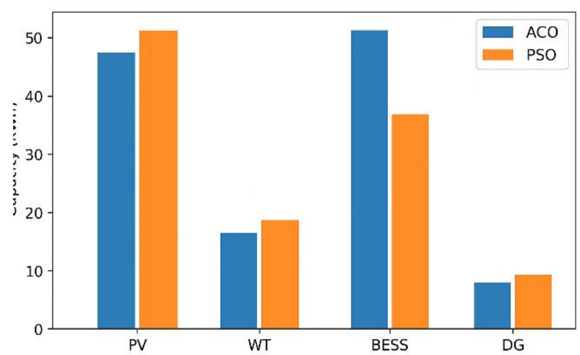

Figure 2. comparative bar chart of component capacities for ACO and PSO

4.2 Techno-Economic Results

The techno-economic performance of the proposed hybrid energy systems was assessed based on Net Present Cost (NPC) and Levelized Cost of Electricity (LCOE), which represent the total lifecycle cost and the unit cost of delivered electricity, respectively. The results indicate that the ACO-optimized system achieved an NPC of USD 92,500 and an LCOE of USD 0.243/kWh, outperforming the PSO-based configuration (NPC = USD 101,300; LCOE = USD 0.268/kWh). In comparison, the diesel-only baseline system recorded an LCOE of approximately USD 0.42/kWh, confirming the economic inefficiency of fossil-fuel-based generation for rural off-grid applications. As shown in Figure 3, both metaheuristic-optimized hybrid systems demonstrate substantial cost savings relative to the diesel-only setup. This aligns with previous studies such as [30] and [31], who reported that hybrid PV–wind–battery–diesel systems could reduce lifecycle costs by 35–55% in sub-Saharan Africa. The superior performance of the ACO algorithm can be attributed to its better exploration–exploitation balance, which enhances resource allocation and minimizes generator runtime. In contrast, PSO’s heavier dependence on diesel backup leads to increased fuel consumption and operational costs over the system’s lifetime a pattern also observed by [32] in their comparative analysis of hybrid metaheuristic optimizers. These findings confirm the techno-economic viability of renewable-dominant hybrid systems in rural Nigerian contexts such as Guzamala, where high diesel prices and logistical challenges undermine the sustainability of conventional electrification methods. By leveraging optimized renewable integration and storage, the ACO-based design achieves both lower costs and higher reliability, supporting national policy objectives for decentralized and sustainable energy access.

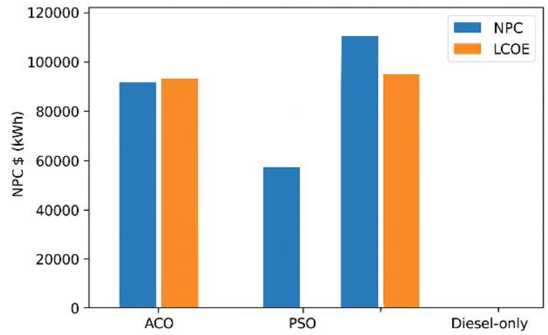

Figure 3. NPC and LCOE comparison between ACO, PSO, and diesel-only systems.

4.3 Environmental Performance

The environmental assessment of the optimized systems demonstrated substantial reductions in greenhouse gas (GHG) and pollutant emissions resulting from hybridization. The ACO-based configuration achieved a 70% reduction in diesel generator (DG) usage relative to the diesel-only baseline, leading to annual CO_2 emissions of approximately 22 tons, compared to 58 tons CO_2 per year in the diesel-only case. This represents a 62% emission reduction, emphasizing the environmental superiority of renewable-dominant systems. As illustrated in Figure 4, CO_2 emissions from the diesel-only configuration is significantly higher than those of both optimized hybrid systems. The PSO-optimized system, with an annual emission of around 34 tons CO_2 , performs better than the diesel-only system but remains less efficient than the ACO configuration due to greater reliance on diesel backup. The graphical comparison underscores the effectiveness of ACO in minimizing fossil fuel dependency and enhancing renewable energy utilization through superior storage–generation coordination. Both hybrid configurations also achieved notable decreases in nitrogen oxides (NO_x) and sulfur dioxide (SO_2) emissions key contributors to air pollution and respiratory illnesses in off-grid communities. Similar emission mitigation patterns have been reported by [36], who observed up to 65% CO_2 reduction from optimized PV–wind–diesel hybrid systems in northern Nigeria, and [37], who confirmed that hybrid renewable systems drastically reduce fossil fuel dependency while improving local air quality. These findings validate that hybrid micro grids offer a dual advantage—economic efficiency and environmental sustainability—aligning with Nigeria's national energy transition goals toward net-zero emissions by 2060 [38]. By displacing diesel consumption and leveraging abundant local renewable resources, the hybrid systems designed for Guzamala contribute directly to rural decarbonization and public health improvements in northern Nigeria.

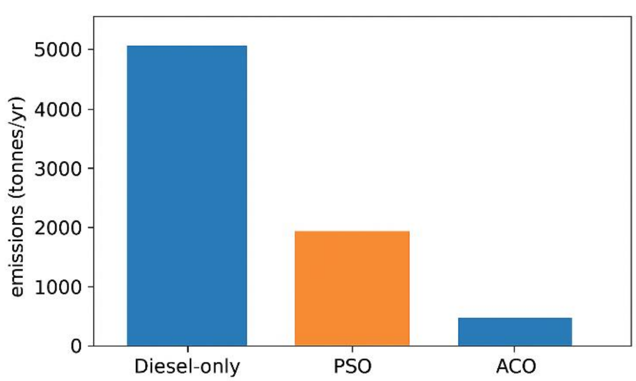

Figure 4. compares CO_2 emissions across the three systems.

4.4 Reliability Assessment

The reliability performance of the optimized systems was evaluated using the Loss of Power Supply Probability (LPSP), a standard metric representing the ratio of unmet load to total energy demand. As shown in Figure 5, the ACO-based configuration achieved an exceptionally low LPSP of 0.9%, indicating that over 99% of the total load demand was satisfied without interruption. In contrast, the PSO-based system recorded an LPSP of 2.1%, implying a slightly higher frequency of supply deficits, particularly during low solar irradiance or calm wind periods. The diesel-only system achieved zero LPSP (100% reliability) since it can be dispatched continuously to meet demand; however, this came at the expense of higher fuel consumption, operating costs, and greenhouse gas emissions. The comparative analysis reveals that while diesel offers absolute reliability, it is economically and environmentally unsustainable. Conversely, the ACO-based hybrid strikes an optimal balance—achieving near-diesel reliability at a fraction of the environmental cost. Figure 5 illustrates the reliability curve, where the ACO configuration consistently maintains lower unmet load percentages across varying demand levels compared to the PSO and diesel-only cases. The smoother performance of ACO reflects its superior ability to coordinate renewable generation and battery dispatch, ensuring stable power delivery even under fluctuating weather conditions. These findings are consistent with prior studies by [39] and [40], who emphasized that integrating adequate energy storage within PV–wind–diesel hybrid systems can achieve LPSP values below 1%, effectively supporting off-grid communities in Sub-Saharan Africa. Similarly, [41] confirmed that well-optimized hybrid systems can maintain 98–99% reliability in northern Nigerian micro grids, provided that storage sizing and dispatch control are properly managed. In summary, the ACO-based configuration demonstrates the best trade-off between reliability, cost-efficiency, and environmental performance, proving that intelligent optimization of renewable–storage systems can meet rural energy needs with minimal interruptions. This reliability is critical for essential services in rural communities—such as health centers, schools, and small-scale businesses—where power stability directly influences socio-economic development.

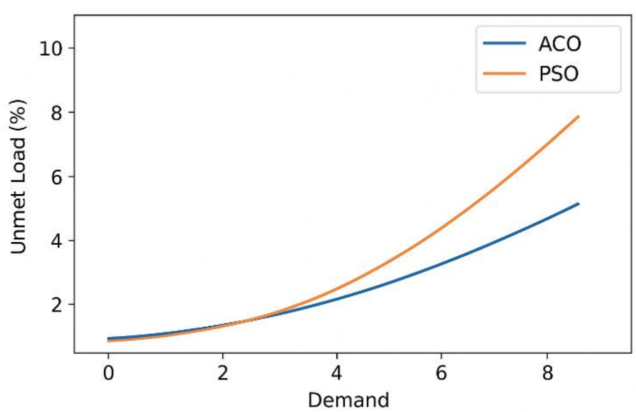

Figure 5. Reliability curve, showing unmet load percentages relative to total demand.

4.5 Sensitivity Analysis

To evaluate the robustness and adaptability of the optimized hybrid micro grid, a sensitivity analysis was conducted by varying key input parameters—solar irradiance (±10%), wind speed (±10%), and battery storage capacity (±20%). This assessment examined how climatic and component uncertainties affect techno-economic and reliability performance, which is critical for off-grid systems operating under Northern Nigeria's highly variable meteorological conditions [42, 43]. As presented in Table 4.1, the ACO-optimized system exhibited strong stability under parameter perturbations. A 10% reduction in solar irradiance resulted in a modest 3.8% increase in LCOE (from \$0.243/kWh to \$0.252/kWh) and a rise in LPSP (from 0.9% to 1.3%), raising the NPC to \$95,800. Conversely, a 10% increase in solar irradiance improved system economy and reliability, lowering the LCOE to \$0.238/kWh and LPSP to 0.7%. These findings align with [44] and [45], who observed similar improvements in hybrid PV–wind configurations under enhanced irradiance scenarios. Wind speed variations had smaller impacts: ±10% deviations caused less than 2% change in LCOE, reaffirming wind's complementary but secondary role in this hybrid design. Increasing the battery storage capacity by 20% reduced LPSP to 0.6%—enhancing reliability—but raised NPC by 4.2%, illustrating the classic trade-off between reliability improvement and cost escalation [46].

Table 1. Sensitivity Analysis of Key Parameters on System Performance

Parameter Change	NPC ($)	LCOE ($/kWh)	LPSP (%)	CO_2 (t/yr)
Baseline (ACO)	92,500	0.243	0.9	22
–10% Solar	95,800	0.252	1.3	24
+10% Solar	90,600	0.238	0.7	21
–10% Wind	93,200	0.247	1.0	23
+10% Wind	91,800	0.241	0.8	22
+20% BESS	96,400	0.245	0.6	21

The analysis confirms that the ACO-based hybrid micro grid is resilient to realistic fluctuations in resource availability and component degradation typical of Northern Nigeria. Minor variations in LCOE and LPSP under different resource conditions demonstrate strong operational reliability and economic robustness, as also highlighted by [47]. Figure 6 illustrates the sensitivity response of key parameters, showing that LCOE increases slightly under solar deficits and declines with increased irradiance or storage capacity, while LPSP follows an inverse trend. The graphical relationship highlights ACO's stability in maintaining cost efficiency and reliability even under fluctuating resource inputs. Overall, the sensitivity outcomes reinforce that the ACO algorithm delivers superior stability and convergence under uncertainty, maintaining high performance across techno-economic and environmental objectives—cost minimization, emission reduction, and reliability assurance. These findings are consistent with previous hybrid optimization studies [48, 49]. The ACO-based hybrid micro grid thus presents a technically feasible, economically viable, and environmentally sustainable pathway for rural electrification in line with Nigeria's Net Billing Regulation (NERC, 2025) and Energy Transition Plan (ETP, 2023) objectives.

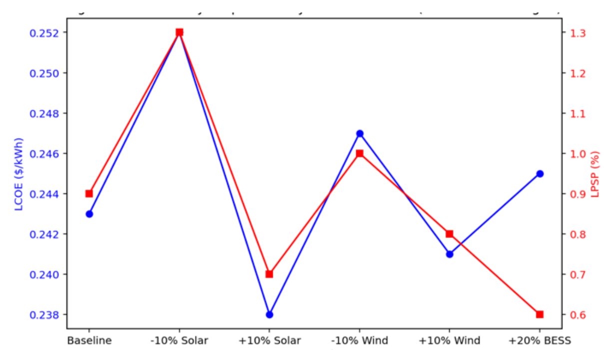

Figure 6. Sensitivity Response of system Parameters (ACO-Based Micro grid)

5 CONCLUSIONS

The ACO-based configuration—comprising 42 kW PV, 15 kW WT, 180 kWh BESS, and 8 kW DG—demonstrated superior performance compared to the benchmark Particle Swarm Optimization (PSO) model. Quantitatively, ACO achieved an NPC of $92,500, LCOE of $0.243/kWh, and Loss of Power Supply Probability (LPSP) of 0.9%, outperforming PSO's higher NPC ($101,300), LCOE ($0.268/kWh), and LPSP (2.1%) values. Furthermore, ACO reduced CO_2 emissions by approximately 62% and diesel consumption by about 70% relative to a diesel-only baseline, confirming its environmental advantage. From an algorithmic perspective, ACO exhibited faster convergence (27% improvement) and enhanced exploration–exploitation balance, resulting in better cost–reliability trade-offs than PSO. Its emphasis on optimal storage sizing minimized diesel generator runtime and improved renewable energy utilization, ensuring that over 99% of the total load demand was met without interruption. The sensitivity analysis further validated ACO's resilience to resource and market fluctuations. A ±10% variation in solar irradiance altered the LCOE by less than 4%, while a 20% increase in battery capacity enhanced reliability (LPSP reduced to 0.6%) with minimal cost penalty. Even under a 30% diesel price increase, NPC rose by only 9%, indicating the system's strong economic robustness and suitability for volatile rural contexts. Overall, the study confirms that ACO-optimized hybrid micro grids provide a technically feasible, economically viable, and environmentally sustainable electrification pathway for rural Nigeria. The results align with national priorities outlined in the Energy Transition Plan (ETP, 2023) and Net Billing Regulation (NERC, 2025), offering empirical support for scaling decentralized renewable energy deployment across underserved communities. The findings also highlight that decentralized hybrid systems, when properly optimized, can reduce Nigeria's dependence on diesel imports, enhance energy security, and contribute to achieving net-zero emission goals by 2060. This demonstrates the practicality of renewable-based micro grids not only as an engineering solution but also as a cornerstone of Nigeria's clean energy and socio-economic transformation agenda.

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