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Techno-Economic Optimization of an Off-Grid Hybrid Solar–Diesel–Battery Energy System Using Genetic Algorithm for Institutional Electrification

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Abstract

Purpose: This study presents a techno-economic optimization of an off-grid Hybrid Renewable Energy System (HRES) comprising Solar Photovoltaic (PV), Battery Energy Storage System (BESS), and Diesel Generator (DG) for institutional electrification. The objective is to develop a reliability-constrained Genetic Algorithm (GA) model that minimizes the Levelized Cost of Energy (LCOE) while satisfying Loss of Power Supply Probability (LPSP) constraints for sustainable and cost-effective electricity supply.

Methodology: A mathematical optimization framework was developed for the hybrid PV–Battery–DG system using a Genetic Algorithm to determine the optimal sizing of system components under technical, operational, and reliability constraints. Four system configurations were evaluated, namely the GA-optimized PV–Battery–DG system, PV–Battery-only system, Diesel Generator-only system, and HOMER-optimized hybrid system. Simulations were implemented in MATLAB/Simulink, and the systems were assessed using techno-economic and environmental performance indicators including LCOE, Net Present Cost (NPC), LPSP, and CO_2 emissions.

Findings: The GA-optimized hybrid configuration achieved the best overall performance with an LCOE of $0.506/kWh, zero unmet load (LPSP = 0), and substantially lower CO_2 emissions than the diesel-only system. Although the PV–Battery-only configuration eliminated fuel consumption and emissions, it required significantly higher capital investment and exhibited slight load loss due to the absence of dispatchable backup. The diesel-only system provided high reliability but incurred the highest lifecycle cost and carbon emissions. The HOMER-optimized hybrid system confirmed the technical feasibility of hybridization but produced a higher energy cost than the proposed GA-based solution.

Unique Contribution to Theory, Practice and Policy: The study recommends the adoption of GA-based hybrid PV–Battery–DG energy systems for institutional off-grid electrification because they provide an optimal balance between economic viability, supply reliability, and environmental sustainability. Future studies should investigate multi-objective optimization techniques and incorporate demand-side management and other renewable energy resources to further improve system performance.

Keywords: *Hybrid Renewable Energy System, Genetic Algorithm, Techno-Economic Optimization, Loss of Power Supply Probability (LPSP), Levelized Cost of Energy (LCOE)*

JEL Classification: *C61, C63, O13, Q42, Q48*

INTRODUCTION

Reliable and affordable electricity supply remains a fundamental driver of socio-economic development, particularly in developing countries where energy poverty persists. In Nigeria, a significant proportion of the population and public institutions remain either unconnected to the national grid or experience severe supply unreliability (Bernal-Agustín *et al.*, 2006). Educational institutions are especially affected, as unstable power supply disrupts academic activities, laboratory operations, research productivity, and administrative efficiency. Grid extension to semi-urban and rural communities is often economically unviable due to high infrastructure costs, transmission losses, and operational challenges. Consequently, decentralized off-grid electrification has emerged as a viable alternative for ensuring reliable and sustainable power supply (Çelik, 2003; Suresh *et al*., 2020).

Renewable Energy Sources (RES), particularly solar photovoltaic (PV) systems, have received considerable attention for off-grid electrification because of Nigeria's abundant solar resource potential. Nevertheless, the intermittent nature of solar energy necessitates complementary technologies such as diesel generators and battery energy storage systems to guarantee uninterrupted electricity supply. Hybrid Renewable Energy Systems (HRESs) that integrate PV, diesel generators, and battery storage therefore provide a practical compromise between system reliability, economic performance, and environmental sustainability (Dawoud *et al.*, 2018; Chauhan and Saini, 2014). For institutional facilities such as colleges, universities, hospitals, and research centres, electricity demand typically follows a distinctive diurnal profile characterized by daytime operational loads, evening peaks resulting from residential and security activities, and occasional high-power laboratory or workshop operations. These varying and nonlinear demand characteristics present a complex optimization problem that cannot easily be solved using conventional deterministic approaches, thereby making metaheuristic algorithms such as the Genetic Algorithm (GA) particularly suitable for optimal system design and operation (Tezer *et al.*, 2017; Omar, 2025).

Several previous studies have investigated hybrid PV–diesel and PV–battery systems using commercial simulation platforms such as HOMER and other optimization tools (Ekren and Ekren, 2010; Dawoud *et al.*, 2018). Although these software packages provide valuable techno-economic assessments, they generally operate as proprietary "black-box" environments in which the internal optimization procedures, objective-function formulations, and constraint-handling mechanisms are not fully transparent or readily customizable. Consequently, researchers have limited flexibility to modify optimization objectives, incorporate application-specific reliability constraints, or develop customized operational strategies for unique load characteristics. Furthermore, many existing studies focus primarily on minimizing the Net Present Cost (NPC), which quantifies the total lifecycle investment of the system, without adequately considering the Cost of Electricity (COE)**,** which measures the lifecycle cost-efficiency of electricity production. Similarly, some investigations emphasize economic optimization while giving insufficient attention to reliability indices such as the Loss of Power Supply Probability (LPSP), resulting in economically attractive solutions that may not satisfy stringent reliability requirements for institutional applications (Dufo-López and Bernal-Agustín, 2008; Koholé *et al.*, 2024).

To address these limitations, this study develops a transparent and mathematically formulated Genetic Algorithm-based techno-economic optimization framework for an off-grid PV–Battery–Diesel hybrid energy system serving institutional electrification. Unlike software-only optimization approaches, the proposed framework explicitly integrates analytical models of photovoltaic generation, diesel generator operation, battery storage dynamics, and system power balance within a customized GA optimization process implemented in MATLAB. The optimization simultaneously minimizes the COE as a measure of lifecycle cost-efficiency while enforcing the Loss of Power Supply Probability (LPSP) as a reliability constraint to guarantee uninterrupted power supply. The performance of the proposed framework is subsequently validated through comparison with HOMER-based optimization, thereby demonstrating the effectiveness, transparency, and adaptability of the proposed methodology for institutional hybrid energy system design.

The main contributions of this study are summarized as follows:

i. Development of a comprehensive mathematical model for PV–DG–Battery hybrid energy systems suitable for institutional electrification.
ii. Formulation of a reliability-constrained techno-economic optimization problem using COE as the objective function and LPSP as a key constraint.
iii. Comparative validation and performance evaluation of the optimized configuration against conventional design approaches.

The remainder of this paper is structured as follows: Section 2 presents the system modeling and mathematical formulation of the hybrid components. Section 3 describes the optimization framework and Genetic Algorithm implementation. Section 4 discusses the simulation results and techno-economic analysis. Section 5 concludes the study and outlines future research directions.

METHODOLOGY

This study adopts a quantitative techno-economic optimization approach for the design and performance evaluation of an off-grid HRES comprising Solar PV, DG, and Battery Energy Storage System (BESS). The proposed framework integrates analytical system modeling, reliability-constrained optimization, and simulation-based validation. Detailed mathematical models of the PV array, DG, and BESS are first developed based on energy balance principles. Subsequently, a single-objective optimization problem is formulated to minimize the COE while satisfying technical, operational, and reliability constraints. System reliability is quantified using the LPSP, and a target value of LPSP = 0 is adopted as the design criterion. This zero-loss requirement ensures that the hybrid energy system is capable of supplying the institutional electrical load continuously without unmet demand throughout the simulation period, thereby guaranteeing 100% supply reliability. The optimization problem is solved using a GA, which determines the optimal sizes of the PV array, battery storage, and diesel generator. The optimized configuration is implemented in MATLAB/Simulink and evaluated using techno-economic performance indices, including COE, NPC, LPSP, and CO_2 emissions. Figure 1 illustrates the proposed PV–DG–BESS hybrid energy system.

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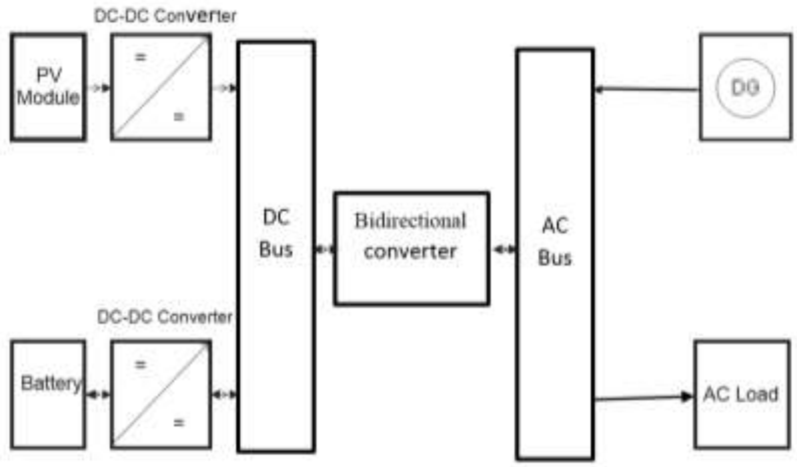

Figure 1: Block Diagram of Solar PV- DG-BATT System

Study Area and Load Assessment

The proposed system is designed for institutional electrification (Oyo State College of Education, Lanlate (OYSCOED) with a focus on meeting continuous and reliable power demand. The electrical load profile is determined based on hourly energy consumption patterns, incorporating academic facilities, administrative buildings, laboratories, lighting systems, and auxiliary services. The load demand $P_L(t)$ is evaluated on an hourly basis over a one-year period (8760 hours), ensuring seasonal and daily variability are captured. The annual energy demand E_{annual} is expressed as Equation 1 (Koutroulis *et al.*, 2006; Daud and Ismail, 2012)

$$E_{annual} = \sum_{t=1}^{8760} P_L(t) \qquad 1$$

Resource Data Collection

Solar radiation and ambient temperature data are obtained from reliable meteorological databases (NASA Surface Meteorology and Solar Energy database). The solar irradiance $G(t)$ and ambient temperature $T_a(t)$ are used as primary inputs to the PV model. Fuel cost, capital cost, replacement cost, operation and maintenance (O&M) cost, and technical specifications of PV modules, DG, and battery systems are sourced from manufacturer datasheets and market surveys.

System Components Modeling

Accurate modeling of individual system components is essential for reliable techno-economic optimization of the Hybrid Renewable Energy System (HRES). In this study, analytical mathematical models are developed for the Solar Photovoltaic (PV) array, Diesel Generator (DG), and Battery Energy Storage System (BESS) to capture their dynamic operational behavior under varying environmental and load conditions. The component models are formulated based on energy balance principles and hourly time-step simulation over an annual period (8760 hours). The

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PV model accounts for variations in solar irradiance and temperature; the DG model incorporates generator efficiency and fuel consumption characteristics; while the battery model represents charging–discharging dynamics, State of Charge (SOC) limits, and storage efficiency. These models are integrated within the optimization framework to evaluate system feasibility, compute power balance at each time step, estimate fuel usage, calculate energy deficits, and quantify reliability indices such as Loss of Power Supply Probability (LPSP).

A. Photovoltaic (PV) Model

The output power of the PV array at time t is expressed as Equation 2 (Muselli *et al.*, 2000; Sharafi and ElMekkawy, 2014):

$$P_{PV}(t) = f_d P_{rated} \frac{G(t)}{G_{STC}} \left(1 + \alpha\left(T_C(t) - T_{STC}\right)\right) \quad 2$$

where $P_{PV}(t)$ is PV output power at time t (kW), P_{rated} is rated capacity of PV array (kW), f_d is derating factor, $G(t)$ is solar irradiance at time t (kW/m²), G_{STC} is solar irradiance at Standard Test Condition, α is temperature coefficient, $T_C(t)$ is cell temperature at time t, and T_{STC} is Temperature at STC

B. Diesel Generator Model

The power generated by the diesel generator is expressed as Equation 3 (Shaahid and Elhadidy, 2003; Mahesh and Sandhu, 2015):

$$P_{DG}(t) = \eta_{DG} \cdot P_{rated} \quad 3$$

Fuel consumption is modeled as:

$$F(t) = a \cdot P_{DG}(t) + b \cdot P_{DG,rated} \quad 4$$

Where $P_{DG}(t)$ is DG output power at time t (kW), η_{DG} is DG efficiency, $P_{DG,rated}$ is rated DG capacity (kW), $F(t)$ is fuel consumption (liters/hour), a, b are fuel curve coefficients

C. Battery Energy Storage System (BESS) Model

The battery State of Charge (SOC) is expressed as Equation 5 (Elhadidy and Shaahid, 2000; Ghasemi *et al.*, 2013)

$$SOC(t) = SOC(t-1) + \frac{P_{ch}(t)\eta_{ch} - \frac{P_{dis}(t)}{\eta_{dis}}}{C_{best}} \quad 5$$

where $SOC(t)$ is state of Charge at time t, $P_{ch}(t)$ is charging power, $P_{dis}(t)$ is discharging power, η_{dis}, η_{dis} is charging/discharging efficiencies, and C_{bat} is battery capacity (kWh),

The SOC constraint is given as:

$$SOC_{\min} \leq SOC(t) \leq SOC_{\max}$$

D. Load Model

The community load demand is represented as an aggregated time-varying load as given in Equation 6 (Deshmukh and Deshmukh, 2008; Kashefi Kaviani *et al.*, 2009):

$$P_L(t) = P_{base}(t) + \Delta P(t) \qquad 6$$

where $P_L(t)$ is total load demand (kW), $P_{base}(t)$ is the typical daily demand profile, and $\Delta P(t)$ represents stochastic or disturbance variations (such as step load changes). For AC power flow and stability assessment, the load was represented as a ZIP model given in Equation 7

$$P_L(t) = P_0\left\{a_Z\left(\frac{V}{V_0}\right)^2 + a_I\left(\frac{V}{V_0}\right) + a_P\right\} \qquad 7$$

where P_0 is nominal power, V is bus voltage magnitude, V_0 is nominal voltage, and a_Z, a_I, a_P are the impedance, current, and constant power fractions satisfying $a_Z + a_I + a_P = 1$

The PV, DG, and battery components were integrated into a unified system model to meet the electric demand of the OYSCOED. The model was designed to ensure reliable supply to the institution load while maintaining acceptable voltage and frequency performance under high renewable energy penetration.

Model Implementation with Genetic Algorithm

To design a low cost and highly efficient HRES, Genetic Algorithm (GA) was applied. The GA iteratively adjusted the size of each HRES component (solar PV, DG and battery). This help in determined the better economic and cost effectiveness of the HRES for the OYSCOED. The developed optimized HRES model with GA was implemented and simulated in MATLAB R2023a.

The optimization objective is to minimize the Cost of Electricity (COE) as given in Equation 8:

$$\min COE = \frac{C_{total,annual}}{E_{served}} \qquad 8$$

where $C_{total,annual}$ is annualized total system cost, E_{served} is total energy supplied to load.. The total system cost includes: capital cost, replacement cost, operation & maintenance cost and fuel cost

The optimization objective is subjected to the following constraint.

i. Reliability Constraint: Reliability is quantified using the Loss of Power Supply Probability (LPSP) as given in Equation 9 (Omar, 2025):

$$LSPSP = \frac{\sum_{t=1}^{8760} P_{def}(t)}{\sum_{t=1}^{8760} P_L(t)} \qquad 9$$

Where P_{def} is power deficit at time t. The constraint is given as:

$$LPSP \le LPSP_{\max}$$

ii. Power balance constraint: This is given as Equation 10:

$$P_{PV}(t) + P_{DG}(t) + P_{dis}(t) = P_L(t) + P_{ch}(t) \quad (10)$$

iii. Capacity constraints: This is given as

$$0 \le P_{PV} \le P_{PV,\max}$$

$$0 \le P_{DG} \le P_{DG,\max}$$

The GA was implemented in MATLAB R2023a using the following steps:

1. Initialize population of candidate solutions (PV size, DG size, battery capacity).
2. Evaluate fitness function (COE) subject to LPSP constraint.
3. Apply selection operator (roulette wheel/tournament selection).
4. Perform crossover to generate offspring solutions.
5. Apply mutation to maintain diversity.
6. Replace worst-performing individuals.
7. Repeat until convergence criteria (maximum generation or tolerance) are reached.

The optimal configuration corresponds to the minimum COE satisfying reliability and operational constraints.

RESULTS AND DISCUSSION

The results of this study are presented in four comparative cases to comprehensively evaluate the techno-economic and reliability performance of different system configurations. The objective of this structured presentation is to assess the effectiveness of the proposed GA-based optimization framework relative to alternative design approaches and baseline scenarios.

The four cases considered in this study are:

Case 1: Hybrid PV–Battery–Diesel Generator system optimized using Genetic Algorithm.

Case 2: PV–Battery hybrid system (without Diesel Generator) optimized using Genetic Algorithm.

Case 3: Diesel Generator-only system (Conventional Baseline System).

Case 4: Hybrid PV–Battery–Diesel Generator system optimized using HOMER software (Benchmark Validation Model).

Table 1 presented the optimal configuration of the hybrid system. The GA selected a well-balanced hybrid configuration in which the PV system serves as the dominant energy generation source, while the battery system provides short-term energy storage to manage variability and ensure load continuity. The DG functions as a supplementary backup unit, operating only when renewable generation and stored energy are insufficient to meet demand. This allocation of roles reflects an optimized coordination among system components to achieve both economic and reliability objectives.

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The recorded DG operating time of 4,300 hours per year indicates that the generator does not operate continuously, but rather intermittently to compensate for renewable fluctuations. This operational pattern suggests a substantial level of renewable energy penetration within the overall energy mix. By limiting DG runtime, the system effectively reduces reliance on fossil-fuel-based generation, thereby demonstrating the benefits of hybridization in decreasing diesel dependency.

From a technical perspective, this configuration is desirable because it significantly reduces fuel consumption and associated operational costs. Moreover, lower diesel usage directly contributes to improved environmental performance through reduced carbon emissions. The integration of battery storage further enhances system stability by ensuring supply continuity during periods of low solar irradiance or peak demand, thereby maintaining power balance and supporting uninterrupted institutional operations.

Table 1: Optimal Configuration of the Hybrid System

Parameters	Value
PV Modules	298
BATT Modules	100
DG Capacity	107 kW
DG Operating Hours	4300 hrs/yr

Table 2 analyses economic and reliability performance of the hybrid system .The Levelized Cost of Energy (LCOE) obtained for the optimized hybrid configuration is $0.506/kWh, which represents the lowest cost among the renewable-integrated systems evaluated in this study. This indicates that the GA effectively identified an economically optimal balance between capital investment and operational expenditure. While compared to the diesel-only configuration, the fuel cost in this hybrid case is substantially lower, reflecting reduced generator runtime and improved renewable energy penetration. Although the capital cost is moderate due to the inclusion of PV modules and battery storage, the optimized sizing prevents excessive overinvestment, thereby maintaining overall economic efficiency.

The Net Present Cost (NPC) of the GA-optimized hybrid system is also significantly lower than that of the diesel-only case, further confirming the long-term economic advantage of hybridization. While the diesel-only configuration may exhibit lower initial capital cost, its high fuel consumption and maintenance requirements lead to substantially higher lifecycle cost. In contrast, the hybrid system distributes investment across renewable generation and storage, resulting in lower recurring operational expenses and improved cost stability over the project lifetime.

In terms of reliability performance, the Loss of Power Supply Probability (LPSP) is equal to 0.00000000, indicating that no load was lost during the entire simulation period. This demonstrates that the system achieved 100% supply reliability, fully satisfying the reliability constraint imposed in the optimization formulation. The ability of the GA to simultaneously minimize COE while maintaining zero energy deficit, validates the effectiveness of the reliability-constrained optimization framework. Such a combination of economic efficiency and perfect reliability performance significantly strengthens the technical contribution and publication potential of this study.

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The environmental performance of the GA-optimized hybrid system is reflected in its total annual CO_2 emission of 240,122 kg/year. This emission level is significantly influenced by the reduced operating hours of the diesel generator, as renewable energy sources contribute a substantial portion of the total energy supply. By allowing the photovoltaic system to function as the primary generation source and limiting diesel operation to backup support, the system effectively curtails fossil fuel combustion and associated greenhouse gas emissions.

Table 2: Metric Performance

Metric	Value
Capital Cost	$969,829
Replacement Cost	$452,257
O&M Cost	$585,588
Fuel Cost	$113,883
NPC	$1,932,462
LCOE	$0.506/kWh
LPSP	0.000000
CO_2 Emission	240,122 kg/yr

The convergence behaviour of the Genetic Algorithm (GA), illustrated in Figures 1 and 2, provides important insight into the optimization efficiency and stability of the proposed model. The single-run convergence curve demonstrates a rapid reduction in the objective function value during the early generations. This steep decline indicates that the GA effectively explores the solution space and quickly identifies promising regions with lower cost configurations. As the number of iterations increases, the curve gradually flattens, suggesting that the algorithm is refining candidate solutions and approaching an optimal or near-optimal point.

The smooth stabilization of the convergence curve in later iterations reflects the attainment of a stable optimal solution. The absence of large oscillations near the final iterations suggests that the algorithm successfully avoided premature convergence and maintained a balanced exploration–exploitation mechanism throughout the search process. This behavior confirms the suitability of GA for solving the nonlinear and constrained optimization problem associated with hybrid energy system sizing.

In addition, the multiple-run convergence analysis (five independent runs) demonstrates similar convergence patterns and final objective values across different trials. This consistency confirms the robustness of the algorithm and indicates a strong tendency toward locating the global optimum rather than being trapped in local minimal. The low variance between runs further validates the reliability and repeatability of the proposed GA-based optimization framework, strengthening the credibility of the results for journal publication.

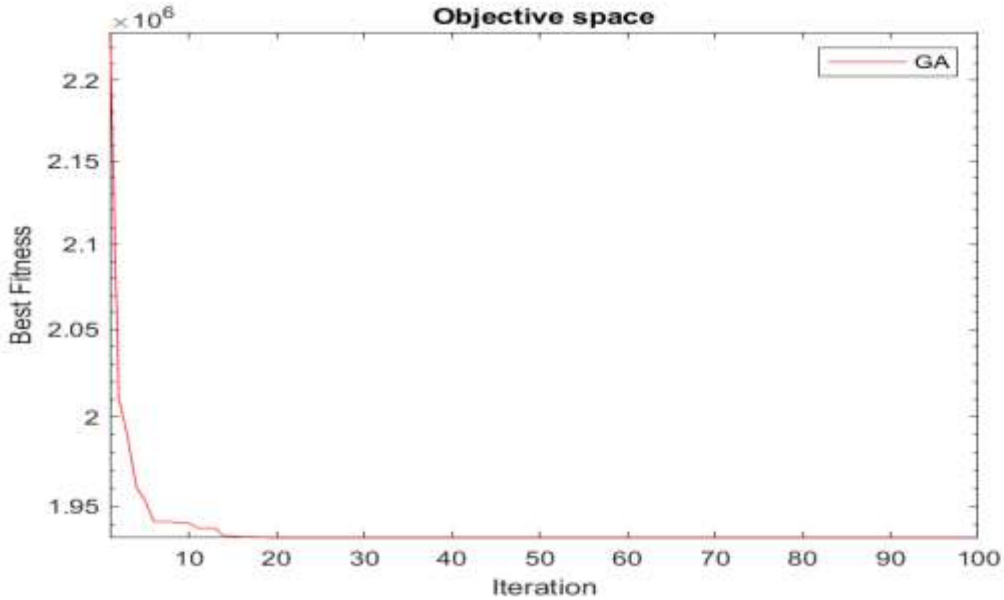

Figure 2: GA Convergence Characteristics for a Single Run

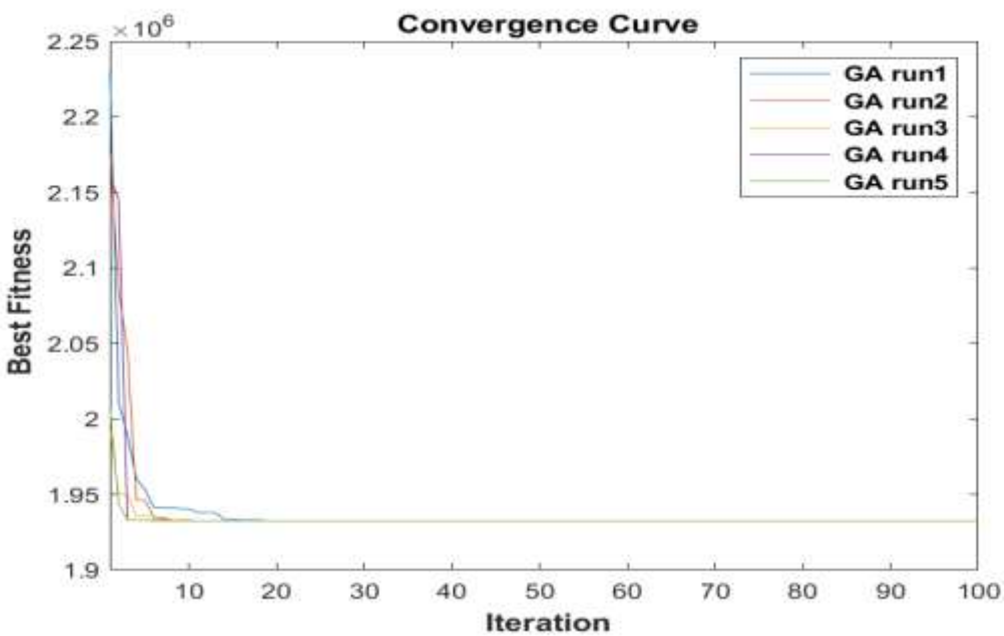

Figure 3: GA Convergence Characteristics for a Multiple Run (says 5 runs)

Figure 4 presents the system operational response of the optimized hybrid configuration, illustrating the interaction among load demand, PV generation, DG output, and battery energy storage behavior over the simulation period. The figure demonstrates the dynamic power-sharing mechanism within the Hybrid Renewable Energy System (HRES) and validates the effectiveness of the proposed energy management strategy. By plotting the contributions of each component against the load profile, the figure provides clear evidence of how energy balance is maintained under varying operating conditions.

During peak solar irradiance hours, the PV array supplies the majority of the load demand. In periods where PV generation exceeds instantaneous demand, the surplus energy is directed to charge the battery storage system, thereby increasing the State of Charge (SOC) and preserving energy for later use. This operational strategy enhances renewable utilization and minimizes unnecessary diesel operation.

Conversely, during periods of low solar irradiance—such as nighttime or cloudy conditions—the battery system initially discharges to support the load. When the stored energy becomes insufficient to meet demand or reaches its minimum SOC limit, the diesel generator is activated to supply the deficit power and, when necessary, recharge the battery. This coordinated control ensures uninterrupted energy supply while minimizing fuel consumption.

The system response confirms that the power balance constraint is satisfied at all time steps throughout the simulation period. At every hourly interval, the total generated and discharged power equals the load demand plus charging requirements, demonstrating that no energy deficit occurs. This dynamic interaction among PV, battery, and DG components validates the reliability-constrained optimization framework and confirms the technical feasibility of the proposed hybrid system design.

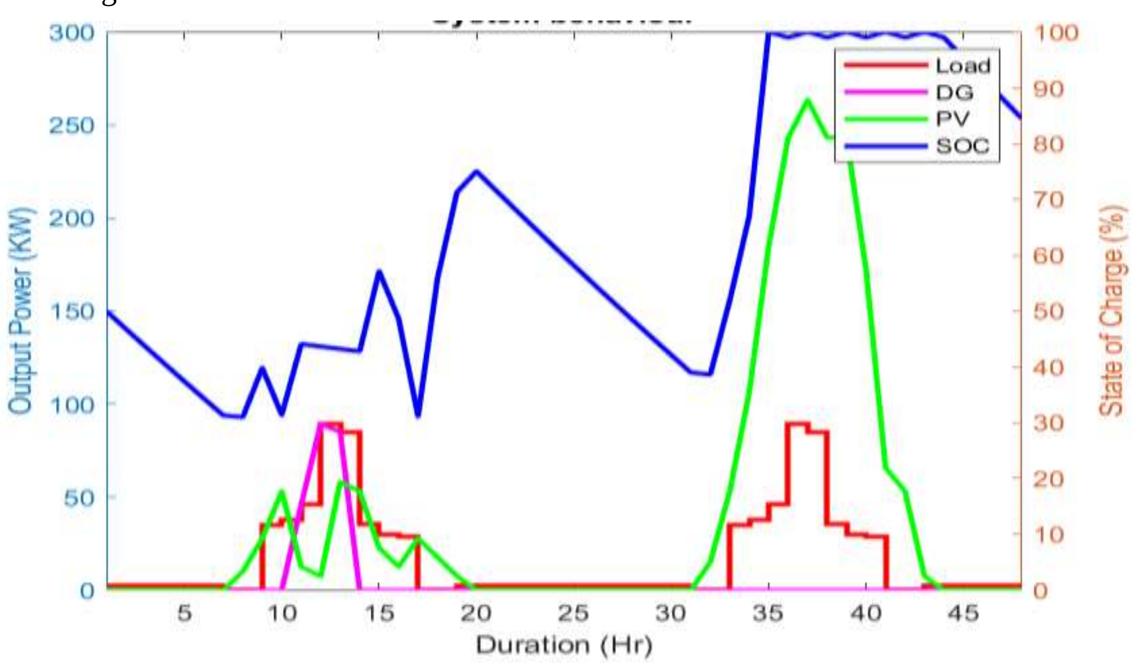

Figure 4: System Response

Table 3 presents the optimal component sizing obtained for Case 2, which represents a PV–Battery configuration without diesel generator integration. The Genetic Algorithm selected 687 PV modules and 265 battery modules, while the diesel generator capacity was 0 kW, with zero operating hours recorded annually. This configuration indicates that the optimization process fully eliminated fossil-fuel-based generation, thereby creating a 100% renewable energy-based system.

The large number of PV modules reflects the need to compensate for the absence of dispatchable diesel support, particularly during low irradiance periods. Similarly, the increased battery capacity is necessary to ensure sufficient energy storage for nighttime supply and cloudy conditions. The system therefore relies entirely on solar generation and storage buffering to maintain supply continuity. While environmentally attractive, this configuration inherently requires oversizing of renewable and storage components to meet reliability requirements.

Table 3: Optimal Configuration of the Hybrid System for Case 2

Parameters	Value
PV Modules	687
BATT Modules	265
DG Capacity	0 kW
DG Operating Hours	0 hrs/yr

Table 4 summarizes the economic, reliability, and environmental performance indicators for Case 2. The capital cost of the system is $2,170,650, which is significantly higher than the hybrid PV–Battery–DG configuration (Case 1). This increase is primarily attributed to the substantial PV and battery capacity required to achieve full renewable penetration. The replacement cost is also high at $1,198,481, reflecting the lifecycle replacement needs of battery components.

Although the fuel cost is $0.00, due to the complete elimination of diesel generation, the overall Net Present Cost (NPC) amounts to $3,765,390.44, which is considerably higher than Case 1. The Levelized Cost of Energy (LCOE) is $0.986/kWh, nearly double that of the GA-optimized hybrid system with diesel support. This indicates that while renewable-only operation eliminates fuel expenses, the high capital and storage investment significantly increases overall energy cost.

In terms of reliability, the Loss of Power Supply Probability (LPSP) is 0.00009899, which is slightly above zero. Although this value is very small, it indicates that minimal load loss occurs during certain periods of extreme low solar availability. This suggests that despite substantial oversizing, achieving absolute reliability without dispatchable backup remains technically challenging. However, the system achieves zero CO_2 emissions, demonstrating superior environmental performance compared to configurations that incorporate diesel generation.

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Table 4: Metric Performance for Case 2

Metric	Value
Capital Cost	$2,170,650
Replacement Cost	$1,198,481
O&M Cost	$7,547,149.20
Fuel Cost	$0.00
NPC	$3,765,390.44
LCOE	$0.986 kWh
LPSP	0.00009899
CO_2 Emission	0.00 kg/yr

Figures 5 and 6 illustrate the convergence behavior of the Genetic Algorithm for Case 2. The single-run convergence curve demonstrates rapid reduction in the objective function during early generations, followed by gradual stabilization as the algorithm approaches the optimal solution. This indicates effective exploration of the solution space and progressive refinement toward minimum cost configuration.

The multiple-run convergence analysis (five independent runs) shows similar convergence trends and closely aligned final objective values. This consistency confirms the robustness and repeatability of the GA optimization process, even under increased design complexity due to the absence of diesel backup. The low variability between runs further supports the reliability of the optimization framework.Figure 5: GA Convergence characteristics for case 2 for a single run

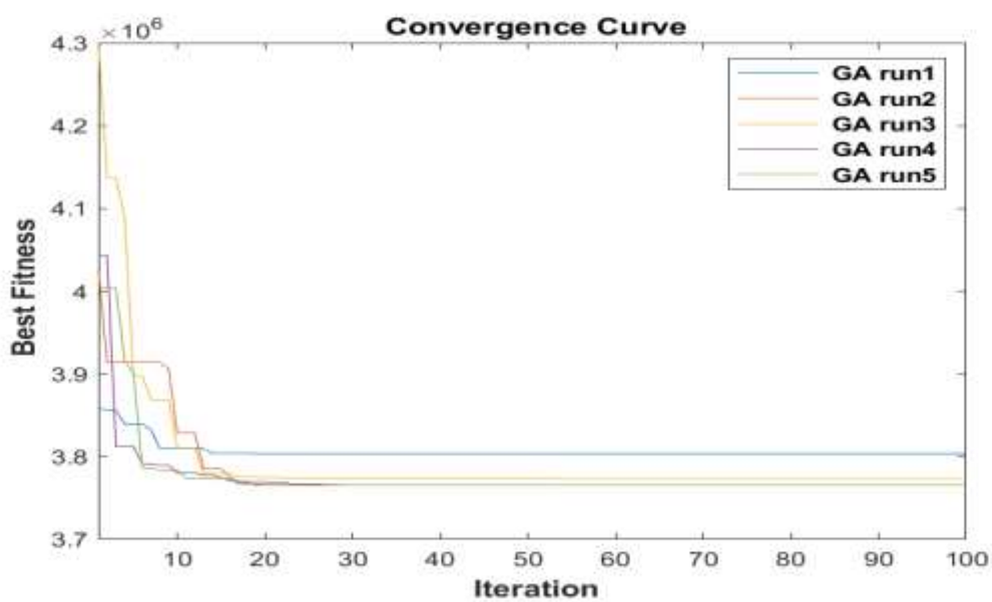

Figure 6: GA Convergence Characteristics for Case 2 for a Multiple Run (says 5 runs)

Figure 7 presents the system response for Case 2 illustrating the interaction between PV generation, battery charging/discharging, and load demand. During peak solar hours, PV generation supplies the load and charges the battery with surplus energy. During nighttime or low irradiance periods, the battery discharges to meet demand.

However, in rare instances where solar generation is insufficient and battery State of Charge reaches its lower bound, slight energy deficits occur, which correspond to the non-zero LPSP observed. The absence of diesel backup removes the system's ability to compensate during prolonged low irradiance periods, thereby slightly compromising reliability.

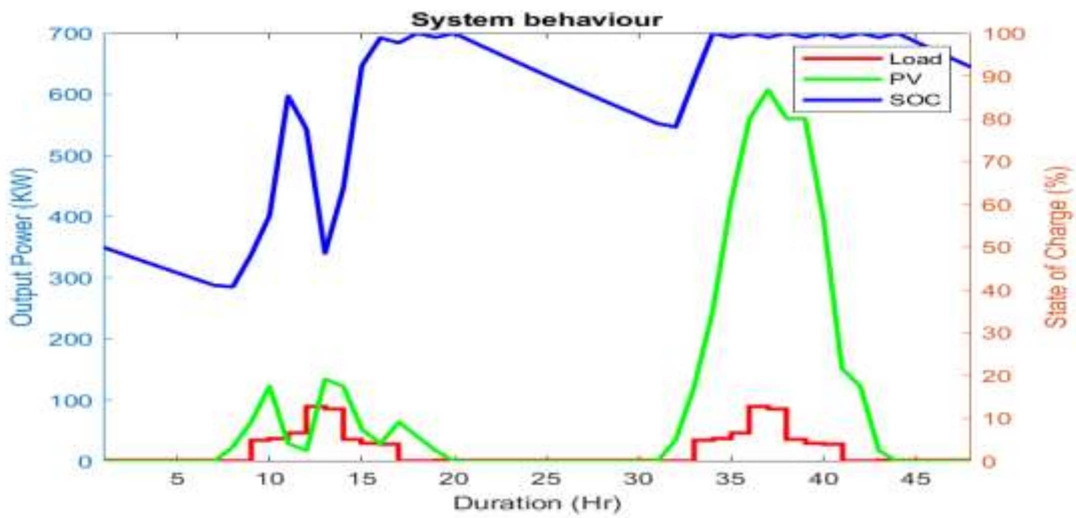

Figure 7: System Response for Case 2

Table 5 presents the configuration of Case 3, which represents a conventional diesel-only power supply system. In this scenario, no photovoltaic modules or battery storage units are included, while the diesel generator capacity is fixed at 107 kW. The recorded annual DG operating time is 219,000 hours/year (cumulative operation), indicating continuous reliance on diesel generation to meet the entire load demand.

The absence of renewable and storage components implies that the system depends exclusively on fuel-based generation. Although this simplifies system configuration and control strategy, it eliminates any contribution from renewable energy sources and removes the possibility of fuel displacement through hybridization. Consequently, the system operates as a purely conventional off-grid power solution.

Table 5: Optimal Configuration of the Hybrid System for Case 3

Parameters	Value
PV Modules	0
BATT Modules	0
DG Capacity	107 kW
DG Operating Hours	219000 hrs/yr

Table 6 summarizes the economic and performance metrics of the DG-only configuration The initial capital cost is relatively low at $53,829.56, which reflects the lower upfront investment required for a single generator system compared to hybrid alternatives. However, this apparent cost advantage is offset by extremely high operational expenditures.

The replacement cost amounts to $826,565.91, while the Operation and Maintenance (O&M) cost is exceptionally high at $15,003,380.56. In addition, the annual fuel cost is $1,837,810.94, reflecting continuous fuel consumption required to sustain full load supply. As a result, the Net Present Cost (NPC) escalates to $17,679,006.14, which is substantially higher than all hybrid configurations considered in this study.

The Levelized Cost of Energy (LCOE) is $4.638/kWh, representing the highest energy cost among all cases analyzed. This value clearly demonstrates the economic inefficiency of relying solely on diesel generation for long-term institutional electrification. While the system achieves LPSP = 0.00000000, indicating perfect reliability due to continuous generator availability, this reliability is achieved at an unsustainably high economic and environmental cost.

The total annual CO_2 emission for the DG-only system is 3,875,014.81 kg/year. This value is drastically higher than the hybrid configurations analyzed in previous cases. Since the generator operates continuously to meet load demand, fuel combustion occurs throughout the year, leading to significant greenhouse gas emissions.

Compared to Case 1 (GA-optimized hybrid system), the diesel-only configuration produces several times higher carbon emissions. This highlights the environmental drawback of conventional fossil-fuel-based off-grid electrification. Although technically reliable, the DG-only system contradicts global sustainability goals and carbon reduction strategies.

Table 6: Metric Performance for Case 3

Metric	Value
Capital Cost	$53,829.56
Replacement Cost	$826,565.91
O&M Cost	$15,003,380.56
Fuel Cost	$1,837,810.94
NPC	$17,679,006.14
LCOE	$4.638 kWh
LPSP	0.00000000
CO_2 Emission	3,875,014.81 kg/yr

Figure 8 illustrates the operational response of the diesel-only system. The system response likely shows a direct correspondence between generator output and load demand, since no renewable or storage buffering is available. The diesel generator dynamically adjusts its output to match hourly load variations.

Because there is no energy storage mechanism, all power balance adjustments occur through immediate generator output regulation. This ensures uninterrupted supply but results in continuous

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fuel consumption and mechanical stress on the generator. The lack of renewable contribution means that operational flexibility is minimal and economic efficiency is compromised.

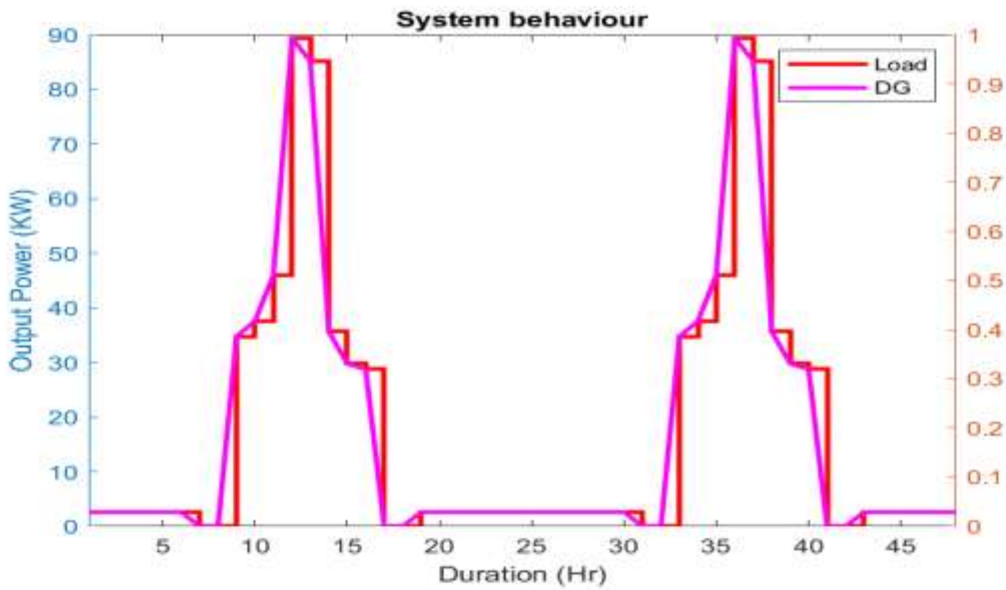

Figure 8: System Response for Case 3

Table 7 presents the optimal component sizing for Case 4, where the hybrid PV–Battery–DG system is optimized using HOMER software as a benchmark validation model. The optimal configuration consists of 505 PV modules and 189 battery modules, with a diesel generator capacity of 110 kW. The diesel generator operates for only 725 hours per year, indicating that the system is designed to rely predominantly on solar generation and battery storage, with the DG functioning strictly as a limited backup source.

The low DG operating hours suggests that HOMER prioritizes high renewable penetration and storage buffering to reduce fuel usage. Compared to the GA-based hybrid configuration (Case 1), the PV and battery sizes are larger, but the DG runtime is significantly lower, reflecting a design preference that minimizes generator dispatch. This configuration implies that, under HOMER's optimal dispatch strategy, PV generation satisfies most daytime demand while the battery provides energy support during non-solar periods, thereby reducing reliance on diesel generation.

Table 7: Optimal Configuration of the Hybrid System for Case 4

Parameters	Value
PV Modules	505
BATT Modules	189
DG Capacity	110 kW
DG Operating Hours	725 hrs/yr

Table 8 summarizes the economic and reliability performance of the HOMER-optimized hybrid system. The capital cost is $1,641,028.80, which is higher than the GA-optimized hybrid case, consistent with the increased PV and battery component sizes. The replacement cost is

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$854,765.70, reflecting lifecycle replacements, particularly for storage components, while the O&M cost is $591,734.92, which remains within a moderate range relative to other cases.

The fuel cost is relatively low at $20,702.21, which aligns with the very limited DG operating hours and indicates substantial fuel displacement achieved through PV and battery dominance. The reported LCOE is $0.7323/kWh, which is higher than Case 1 but significantly lower than the PV–Battery-only case and the DG-only baseline. This result demonstrates that HOMER achieves cost-effective supply through increased renewable penetration, though at a higher cost than the GA-based optimum.

The reliability index for Case 4 is LPSP = 0.00000000, confirming that no load was lost throughout the simulated period. This indicates that the HOMER-optimized configuration satisfies full supply reliability, likely due to sufficient storage capacity combined with backup DG availability. In this sense, Case 4 provides a strong benchmark that validates the feasibility of achieving zero unmet load in the hybrid architecture.

The annual CO_2 emission for Case 4 is 43,650.77 kg/year. This value is substantially lower than the GA hybrid Case 1 and dramatically lower than the DG-only baseline. The large emission reduction is directly linked to the minimal generator runtime (725 hours/year), implying that diesel combustion is infrequent and limited to periods of low renewable availability or battery constraint.

This outcome demonstrates that HOMER's dispatch strategy achieves strong environmental performance by prioritizing renewable generation and storage utilization. For journal discussion, this case is particularly important because it shows that hybrid systems can deliver both high reliability and very low emissions, provided adequate PV and storage capacity are installed and the diesel generator is used sparingly.

Table 8: Metric Performance for Case 4

Metric	Value
Capital Cost	$1.641,028.80
Replacement Cost	$854,765.70
O&M Cost	$591,734.92
Fuel Cost	$20,702.21
NPC	$27,797,239.77
LCOE	$0.7323 kWh
LPSP	0.00000000
CO_2 Emission	43,650.77 kg/yr

Figure 9 presents the system response for Case 4. The operational behavior likely demonstrates PV dominance during high irradiance hours, with battery charging occurring under surplus PV generation. During non-solar hours, battery discharge supports the load, and the diesel generator is engaged only intermittently when PV generation is low and battery State of Charge approaches its minimum threshold.

The system response therefore confirms an effective power balance strategy in which energy supply is continuously matched to demand through coordinated dispatch among PV, battery storage, and limited diesel support. The zero LPSP further supports that the power balance constraint is satisfied throughout the simulation horizon.

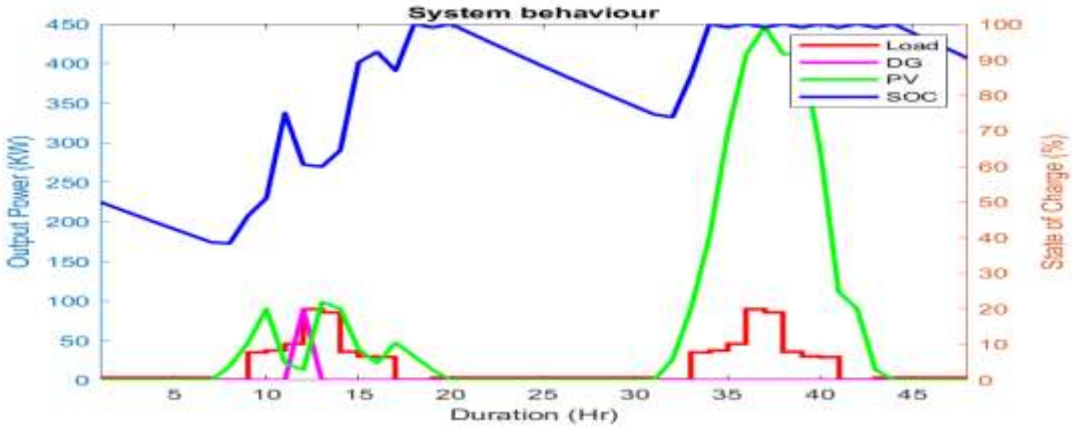

Figure 9: System Response for Case 4

Conclusion

This study presented a comprehensive techno-economic and reliability assessment of four off-grid power system configurations, including a GA-optimized Hybrid PV–Battery–DG system, a PV–Battery-only system, a DG-only baseline system, and a HOMER-optimized hybrid configuration The comparative analysis demonstrates that relying solely on diesel generation, although highly reliable, results in extremely high lifecycle cost and excessive carbon emissions, making it economically and environmentally unsustainable. Conversely, the PV–Battery-only configuration eliminates fuel consumption and emissions but requires substantial capital investment and exhibits slightly reduced reliability due to the absence of dispatchable backup support. Among all configurations, the GA-optimized hybrid system achieves the most balanced performance, combining moderate capital investment, low Levelized Cost of Energy (LCOE), zero Loss of Power Supply Probability (LPSP), and significantly reduced carbon emissions. While the HOMER-optimized hybrid system exhibits very low generator operating hours and reduced emissions, its cost performance is comparatively higher than the GA-based solution. Overall, the results confirm that integrating renewable energy sources with battery storage and limited diesel backup, optimized through a reliability-constrained Genetic Algorithm framework, provides a technically feasible, economically viable, and environmentally sustainable solution for institutional off-grid electrification.

Implications of the Study

The findings of this study have significant practical, economic, environmental, and policy implications for off-grid institutional electrification. The GA-based optimization framework provides a transparent and flexible alternative to proprietary software for the optimal sizing of hybrid renewable energy systems, enabling designers to incorporate application-specific objectives and reliability constraints. The demonstrated ability of the optimized PV–Battery–DG system to achieve a low COE, zero LPSP, and reduced carbon emissions indicates that the approach can support the deployment of reliable and sustainable energy systems in educational institutions, healthcare facilities, and other public establishments located in underserved or remote areas. From a policy perspective, the study provides evidence that integrating renewable energy with battery storage and limited diesel backup can significantly reduce dependence on fossil fuels while ensuring uninterrupted electricity supply. Furthermore, the developed optimization framework can serve as a decision-support tool for engineers, energy planners, policymakers, and investors involved in the design and implementation of hybrid renewable energy projects, and it provides a foundation for future research on multi-objective optimization, smart energy management, demand response, and the integration of additional renewable energy technologies.

Author Contributions

K. O. Oladeji: Supervision, Investigation, Validation, Writing – review and editing.

R. A. Adetutu: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, MATLAB/Simulink modeling and simulation, Visualization, Writing – original draft.

S. O. Okeniyi: Software, Data curation, Validation, Formal analysis.

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REFERENCES

Bernal-Agustín, J. L., Dufo-López, R., and Rivas-Ascaso, D. M. (2006). Design of isolated hybrid systems minimizing costs and pollutant emissions. *Renewable Energy*, *31*(14), 2227–2244. https://doi.org/10.1016/j.renene.2005.11.008

Çelik, A. N. (2003). Techno-economic analysis of autonomous PV-wind hybrid energy systems using different sizing methods. *Energy Conversion and Management*, *44*(12), 1951–1968. https://doi.org/10.1016/S0196-8904(02)00233-X

Chauhan, A., and Saini, R. P. (2014). A review on integrated renewable energy system based power generation for stand-alone applications: Configurations, storage options, sizing methodologies and control. *Renewable and Sustainable Energy Reviews*, *38*, 99–120. . https://doi.org/10.1016/j.rser.2014.05.079

Daud, A. K., and Ismail, M. S. (2012). Design of isolated hybrid systems minimizing costs and pollutant emissions. *Renewable Energy*, *44*, 215–224.

Dawoud, S. M., Lin, X., and Okba, M. I. (2018). Hybrid renewable microgrid optimization techniques: A review. *Renewable and Sustainable Energy Reviews, 82*(Part 3), 2039–2052. https://doi.org/10.1016/j.rser.2017.08.007

Deshmukh, M. K., and Deshmukh, S. S. (2008). Modeling of hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews*, *12*(1), 235–249. https://doi.org/10.1016/j.rser.2006.07.011

Dufo-López, R., and Bernal-Agustín, J. L. (2008). Multi-objective design of PV–wind–diesel–hydrogen–battery systems. *Renewable Energy*, *33*(12), 2559–2572. https://doi.org/10.1016/j.renene.2008.02.012

Ekren, O., and Ekren, B. Y. (2010). Size optimization of a PV/wind hybrid energy conversion system with battery storage using simulated annealing. *Applied Energy*, *87(*2), 592–598. https://doi.org/10.1016/j.apenergy.2009.05.022

Elhadidy, M. A., and Shaahid, S. M. (2000). Parametric study of hybrid (wind + solar + diesel) power generating systems. *Renewable Energy*, *21*(2), 129–139.

Ghasemi, A., Asrari, A., Zarif, M., and Abdelwahed, S. (2013). Techno-economic analysis of stand-alone hybrid photovoltaic–diesel–battery systems for rural electrification in eastern part of Iran A step toward sustainable rural development. Renewable and Sustainable Energy Reviews, 28, 456–462.

Kashefi Kaviani, A., Riahy, G. H., and Kouhsari, S. M. (2009). Optimal design of a reliable hydrogen-based stand-alone wind/PV generating system, considering component outages. *Renewable Energy, 34*(11), 2380–2390.

Koholé, Y. W., Ngouleu, C. A. W., Fohagui, F. C. V., and Tchuen, G. (2024). Optimization and comparative analysis of hybrid renewable energy systems for sustainable and clean energy production in rural Cameroon considering the loss of power supply probability concept. *Energy Conversion and Management: X*, *23*, 100829.

Koutroulis, E., Kolokotsa, D., Potirakis, A., and Kalaitzakis, K. (2006). Methodology for optimal sizing of stand-alone photovoltaic/wind-generator systems using genetic algorithms. *Solar Energy, 80*(9), 1072–1088. https://doi.org/10.1016/j.rser.2006..011

Mahesh, A., and Sandhu, K. S. (2015). Hybrid wind/photovoltaic energy system developments: Critical review and findings. Renewable and Sustainable *Energy Reviews, 52*, 1135–1147. https://doi.org/10.1016/j.rser.2006.07.011

Muselli, M., Notton, G., and Louche, A. (2000). PV-hybrid power systems sizing incorporating battery storage: An analysis via simulation calculations. *Renewable Energy, 20*(1), 1–7.

Omar, M. A. (2025). Techno-economic analysis of PV/diesel/battery hybrid system for rural community electrification: A case study in the Northern West Bank. *Energy, 317*, 134770

Shaahid, S. M., and Elhadidy, M. A. (2003). Opportunities for utilization of stand-alone hybrid (photovoltaic + diesel + battery) power systems in hot climates. *Renewable Energy, 28*(11), 1741–1753.

Sharafi, M., and ElMekkawy, T. Y. (2014). Multi-objective optimal design of hybrid renewable energy systems using PSO-simulation based approach. *Renewable Energy, 68*, 67–79.

Suresh, V., Muralidhar, M., and Kiranmayi, R. (2020). Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas. *Energy Reports, 6*, 594–604. https://doi.org/10.1016/e.report.2020.12.038

Tezer, T., Yaman, R., and Yaman, G. (2017). Evaluation of approaches used for optimization of stand-alone hybrid renewable energy systems. Renewable and Sustainable *Energy Reviews, 73,* 840–853. https://doi.org/10.1114/e,er.2