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Techno-Economic Optimization of a Stand-Alone Hybrid PV-Diesel-Battery System for Rural Electrification Using Genetic Algorithm

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ABSTRACT

Extending the electricity grid to rural areas in sub-Saharan Africa is often cost-prohibitive, while Diesel Generators (DGs), though widely used, pose environmental and economic challenges. This study explores a more sustainable alternative by designing a stand-alone hybrid renewable energy system, combining Photovoltaic (PV), DG, and Battery Storage System (BSS), for rural electrification in Ayeoba, Olode, Osun State, Nigeria. Using local weather and load data from field surveys, a mathematical model of the system was developed. A Genetic Algorithm (GA) was applied to optimize system components, PV array, DG size, and battery capacity, with objectives to minimize the Cost of Energy (COE), achieve zero Loss of Power Supply Probability (LPSP), and reduce CO_2 emissions. The GA-based optimization gave a configuration with a COE of \$0.10/kWh, 0% LPSP, and daily CO_2 emissions of 84.2 kg, while the HOMER simulation yielded a COE of \$0.12/kWh, 2.4% LPSP, and 70 kg of CO_2 emissions. These results demonstrate the effectiveness of GA in designing reliable, affordable, and environmentally friendly off-grid systems. This work underscores the potential of AI-driven optimization for rural electrification in sub-Saharan Africa, advancing progress toward the United Nations Sustainable Development Goals (SDGs).

INTRODUCTION

Access to reliable electricity is critical for socio-economic development, especially in rural areas where poor infrastructure has long hindered progress in education, healthcare, and income-generating activities. Yet, over 600 million people in sub-Saharan Africa remain without electricity, most of them in remote, off-grid locations. In such areas, extending the national grid is often not feasible due to rough terrain, sparse populations, and high infrastructure costs (Konneh *et al*., 2019). Traditionally, Diesel Generators (DGs) have been the primary source of off-grid power. While dispatchable, DGs are costly to run, require frequent maintenance, and produce significant greenhouse gas emissions (Shezan *et al*., 2016; Alsharif, 2017).

To address these challenges and support the global shift to sustainable energy, Hybrid Renewable Energy Systems (HRES), which combine renewable and conventional energy sources, are gaining traction. Among these, PV–DG–Battery Energy Storage Systems (BESS) are especially promising due to their ability to offer clean, reliable, and cost-effective electricity (Bhandari *et al*., 2015).

In solar-rich countries like Nigeria, PV panels can harness abundant solar energy, while BESS ensures energy availability during periods of low sunlight (Bala *et al*., 2000). Diesel generators are retained only for backup, enhancing system reliability. However, optimizing the size and operation of each component remains a challenge, as it directly impacts system cost and environmental performance. Recent advances in computational intelligence, particularly the Genetic Algorithm (GA), offer powerful tools for addressing these complex optimization tasks. GA mimics the process of natural selection and has proven effective in solving nonlinear, multi-variable problems associated with hybrid systems (Bhandari *et al*., 2015; González *et al*., 2015). Unlike traditional methods, GA avoids getting stuck in local optima and works well even with limited data.

This study applies GA to design and optimize a stand-alone PV–DG–BESS system for rural electrification in Ayeoba, Olode (7°20′N, 4°37′E) in Osun State, Nigeria. The location was chosen due to its lack of access to electricity, which is essential for improving basic living conditions. The system aims to minimize the Cost of Energy (COE), achieve zero Loss of Power Supply (LPSP), and reduce CO_2 emissions. Results from the GA-based simulation in MATLAB are compared with those from HOMER Pro. The findings offer practical insights for planners and policymakers seeking to expand clean, affordable energy access in rural sub-Saharan Africa.

LITERATURE REVIEW

Recent studies on HRES have explored different combinations of PV, DG, and battery storage as viable solutions for reliable and sustainable power in off-grid rural areas. Many of these works use various optimization and simulation tools to assess cost and environmental performance. However, gaps remain in addressing system reliability, optimal sizing, and local context. Jacobus (2010) compared Hybrid2 and HOMER software for cost analysis, but did not evaluate reliability or newer optimization methods. Faruk *et al*. (2012) simulated a PV/DG setup for rural health centers using HOMER, highlighting cost and pollution benefits but lacking detailed reliability or economic analysis. Anayochukwu and Nnene (2013) designed a hybrid PV/DG system for a GSM base station in Abuja with cost and emission benefits, but did not assess sensitivity or reliability. Similarly, Olatomiwa *et al*. (2015) used HOMER to optimize a solar-wind-diesel-BESS system for telecom applications, showing environmental and economic advantages, but without analyzing system performance under peak loads. Bhandari *et al*. (2015) reviewed AI-based optimization methods like GA but did not include validations for emissions or costs. Garcia-Hierro *et al*. (2016) found thermal benefits in solar thermal hybrid systems but did not extend the study to cost or environmental impact.

Adebanji *et al*. (2017) applied GA to optimize a hybrid PV/DG/BESS system for a Nigerian community, achieving a renewable fraction of 0.62 and a low LPSP of 0.0054. However, they did not benchmark their results against simulation tools like HOMER. Similarly, Anene *et al*. (2017) used HOMER to size a PV/DG system for the Dafara community in Nigeria, showing its suitability for rural needs, but without further optimization or emissions analysis. Fodhil *et al*. (2019) used PSO and ε-constraint methods to minimize COE and emissions in a PV-DG-BESS setup, though their study lacked reliability evaluation based on real-world data. In Sierra Leone, Konneh *et al*. (2019) optimized a PV-wind-biomass system using multi-objective PSO, focusing on cost and emissions but not reliability or site-specific validation. Olabode *et al*. (2021) gave a broad review of hybrid systems for off-grid use, stressing the need for reliability-based design and recommending AI-based tools like GA for planning in developing regions.

Despite their significant contributions, most of the literature on hybrid energy system configurations and optimization has some limitations. Also, most studies do not incorporate methods of advanced artificial intelligence that are able to find global optima in a complex solution space and rely exclusively on simulation software, for example, HOMER. When approaches such as GA have been utilized, community assembly is obtained, but either validations against known real-world communities or a comparison of results with commercial software are absent. Also, few analyze the technical, environmental, and economic performance of the solutions within a single optimization process. In particular, the application of GA to optimize PV–DG–BESS systems remains limited in underserved rural areas of Nigeria, including Ayeoba Olode community in Osun State. These gaps show the absence of a field-validated, robust, multi-objective optimization that realistically captures the complexities surrounding rural electrification in sub-Saharan Africa.

Among the contributions to knowledge are:

i. The application of GA to optimize a PV–Diesel–Battery hybrid system using local data, addressing the limited use of GA in rural communities in Sub-Saharan Africa.

ii. A comparative performance analysis demonstrating that the proposed system achieves lower cost and emissions than HOMER, highlighting its relevance for rural energy planning in Sub-Saharan Africa.

METHODOLOGY

Research Approach

The approach of this study is quantitative and simulation-oriented, focusing on the optimization of an existing stand-alone hybrid energy system for rural electrification using GA. The system, consisting of PV modules, a DG, and a BESS, was simulated for the rural community of Ayeoba Olode, an underserved area in Ife South Local Government Area of Osun State, Nigeria. The goal is to minimize COE while also achieving an LPSP of zero and maximizing carbon reductions. The research starts with a feasibility study in the specific site by assessing the available resources and profiling loads through the collection of field data. Based on this information, the performance of the components of the hybrid system and the operational dynamics of the system as a whole are modeled mathematically. The optimization process was carried out through the use of GA, which finds the best system configuration to achieve the given technical, economic, and environmental objectives. The modeling and optimization of the entire system were done on MATLAB R2021a.

Load and Resource Assessment

The average load demand profile, daily and seasonal, of the Ayeoba Olode community was obtained through a field survey, with a total average load estimated at 40 kW. Daily energy demand was established according to appliance type and use, peak load times, and daily load profiles. Site daily solar radiation and temperature data were accessed through the NASA Surface Meteorology and Solar Energy database. The average solar irradiance in the community ranges between 4.8 to 5.5 kWh/m^2 daily, which is promising for PV's potential as the main energy source.

System Modeling

The hybrid system under analysis integrates a PV array, a DG, and a battery storage unit, all connected through a bi-directional converter. Each system component is modeled mathematically to represent its dynamic behavior during the optimization process. A schematic layout of the overall configuration is illustrated in Figure 1.

i. **PV Module:** The PV array output power is modeled based on solar irradiance and module efficiency as given in Equation (1).

$$P_{PV}(t) = N_{PV} \times \eta_{PV} \times A \times G(t) \quad (1)$$

where, $P_{PV}(t)$ = Output power of the PV array at time t (kW), N_{PV} = Number of PV modules, η_{PV} = Efficiency of a PV module, A = Area of one PV module (m²), $G(t)$ = Solar irradiance at time t (kW/m²)

ii. **Battery Bank:** The battery SOC is modeled by accounting for charging/discharging efficiencies as in Equation (2).

$$SOC(t) = SOC(t-1) + \frac{\eta_{ch} \times P_{ch}(t) \times \Delta t}{C_{bat}} - \frac{P_{dis}(t) \times \Delta t}{\eta_{dis} \times C_{bat}} \quad (2)$$

where, SOC(t) = State of charge at time t (%), $P_{ch}(t)$, $P_{dis}(t)$ = Charging and discharging power at time t (kW), η_{ch}, η_{dis} = Charging and discharging efficiencies, C_{bat} = Battery capacity (kWh), Δt = Time step (hr)

iii. **Diesel Generator:** The DG's fuel consumption is modeled as a linear function of output power as given in Equation (3).

$$F_{DG}(t) = a \times P_{DG}(t) + b \quad (3)$$

where, $P_{bat}(t)$ = Battery discharging power (can be negative during charging), $P_{load}(t)$ = Load demand at time t (kW)

Surplus PV energy is either stored in the battery or curtailed if the battery is full. Conversely, during deficit periods, the battery discharges or the DG is engaged.

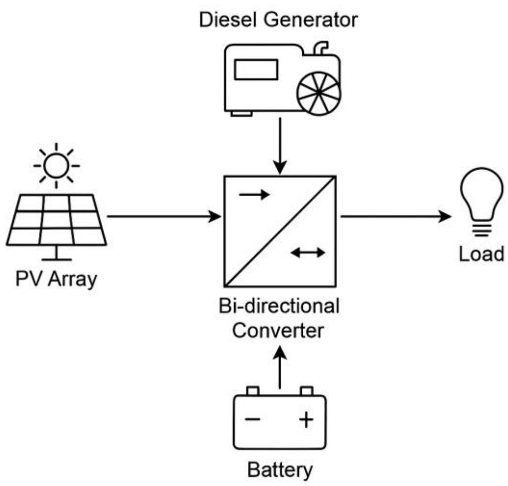

Figure 1: Schematic of the PV, DG, BESS Hybrid Energy System

Objective Function and Constraints

The system is designed to minimize the Annualized Cost of the System (ACS), which consists of capital cost, operation and maintenance cost, and replacement cost and is expressed as

$$\min ACS = C_{\text{cap}} + C_{\text{rep}} + C_{\text{om}} \quad (4)$$

where, C_{cap} = capital cost of PV, DG, and BESS, C_{rep} = replacement cost (assumed negligible for PV, C_{om} = annual operation and maintenance costs.

Minimizing ACS ensures that the system configuration chosen is economically efficient over its lifetime, making it affordable for rural electrification without compromising sustainability.

In general, the photovoltaic generators have a service life that is comparable to the lifetime of the hybrid system, resulting in a replacement cost of zero. The capital cost of the system is determined by Equation (5).

$$C_{cap} = CRF * (C_{PV_{tot}} + C_{bat_{tot}} + C_{dg_{tot}}) \quad (5)$$

where:

$$C_{PV_{tot}} = N_{PV} * C_{PV} \quad (6)$$

$$C_{bat_{tot}} = \left(\frac{n}{LS_{bat}}\right) N_{bat} * C_{bat} \quad (7)$$

$$C_{gen_{tot}} = \left(\frac{n}{LS_{DG}}\right) N_{DG} * C_{DG} \quad (8)$$

where, C_{PV}, C_{bat}, C_{DG}. are the capital costs respectively of photovoltaic panels, batteries and diesel generator, respectively, N_{PV}, N_{bat}, N_{DG}. are the number of photovoltaic panels, batteries and diesel generator, respectively.

The CRF is the capital recovery factor, which is defined as Equation (9)

$$CRF = \frac{i(1+1)^n}{(1+i)^n - 1} \quad (9)$$

where i is the rate, n is the life span of the hybrid system

The maintenance cost (C_{om}) of a hybrid system is described in Equation (10).

$$C_{om} = \left(C_{PV} * \sum_{t=1}^{T} P_{PV}(t) * \Delta t \right) + \left(C_{DG} * \sum_{t=1}^{T} P_{DG}(t) * \Delta t \right) * 365 \quad (10)$$

where P_{PV}, P_{DG} are photovoltaic panels and a diesel generator, respectively

Since the simulation in this study was conducted over a period of 20 years, which exceeds the lifespan of the panels, the replacement cost (C_{rep}) for these components was considered to be zero.

The optimization is subject to the following constraints:

$$LPSP = 0 \quad (11)$$

This constraint enforces an LPSP of zero, signifying that the hybrid system must continuously satisfy the entire electrical load without interruption. In practical terms, this ensures full load coverage at all times—a critical requirement for rural communities like Ayeoba, where access to reliable electricity underpins socioeconomic activities and public services.

$$SOC_{\min} \leq SOC_t \leq SOC_{\max} \quad (12)$$

This constraint maintains the battery's SOC within predefined operational bounds at any time t, typically between a minimum (e.g., 20%) and maximum (100%) threshold. By enforcing these limits, the system prevents overcharging and deep discharging, thereby preserving battery health, extending lifespan, and ensuring reliable energy support during periods of low solar generation or diesel unavailability.

$$P_{\mathrm{PV}} + P_{\mathrm{DG}} + P_{\mathrm{BESS}} \geq P_{\mathrm{load}} \quad (13)$$

This constraint ensures that the total power supplied by the PV array, DG, and BESS at any time is sufficient to meet or exceed the load demand. It guarantees continuous load satisfaction by coordinating generation and storage resources, thereby reinforcing the zero-LPSP reliability requirement established earlier and maintaining uninterrupted power delivery throughout the system's operation.

Genetic Algorithm Optimization

To determine the optimal configuration of the hybrid PV–Diesel–BESS system, GA is employed due to its robustness in solving complex, non-linear optimization problems. The objective is to minimize the ACS, as defined in Equation (1), subject to the constraints in Equations (11) – (13).

The GA operates on a population of candidate solutions (chromosomes), where each chromosome encodes a unique combination of PV capacity, DG size, and battery storage capacity. The optimization process follows the steps outlined below:

The GA-based Optimization algorithm is as follows:

Step 1: Initialization: Generate an initial population of candidate system configurations, each represented by a chromosome encoding PV capacity, DG size, and BESS capacity.

Step 2: Fitness Evaluation: Evaluate each candidate using a fitness function based on Equations (11) – (13).

Step 3: Selection: Select the fittest individuals using a selection method (e.g., tournament or roulette wheel) based on their fitness values.

Step 4: Crossover: Perform crossover operations on selected individuals to produce new offspring, exchanging parameter values between parent chromosomes.

Step 5: Mutation: Apply random mutations to some chromosomes to introduce diversity and avoid local minima.

Step 6: Replacement: Replace the less fit individuals with the newly generated offspring to form the next generation.

Step 7: Convergence Check: Repeat Steps 2–6 until a stopping condition is reached (e.g., no significant improvement in ACS or a set number of generations).

Step 8: Output: Return the best-performing configuration that meets all constraints as the optimal system solution.

Benchmarking with HOMER

In order to ensure the GA-optimized outputs are reliable, the identical system is modeled in a more traditional manner using HOMER Pro, a conventional hybrid system optimization software. Performance indicators such as the Cost of Energy (COE), Net Present Cost (NPC), fuel consumption, and CO_2 emissions were evaluated and compared with the results obtained from the GA-based optimization implemented in MATLAB. This comparison exposes the utility of a GA to find less expensive and greener solutions to this problem.

RESULTS AND DISCUSSION

Feasibility Assessment of Ayeoba, Olode Community

The study area from where data is collected, Ayeoba, Olode in Ife South Local Government Area of Osun State, has good potential for solar energy, with the average daily solar irradiance between 4.8 and 5.5 kWh/m². According to the NASA Surface Meteorology and Solar Energy database, the ambient temperatures were around 25°C to 34°C, ideal for PV performance. A community energy audit established an average daily load demand of approximately 8.2 kWh/day and a peak power requirement of 1.9 kW. These parameters make the location ideal for deploying a standalone PV-diesel-battery hybrid system, considering both energy access needs and renewable resource availability.

GA-based Optimization Results in MATLAB and Comparative Analysis with HOMER

The system was modeled in MATLAB R2021a, where GA was implemented to evaluate different configurations of PV array size, battery bank capacity, and DG rating. The objective was to minimize the ACS, achieve zero LPSP, and reduce CO_2 emissions while ensuring technical feasibility and reliability. To validate the GA results, the same system configuration parameters and load profile were simulated using HOMER Pro, a widely used hybrid energy system optimization tool.

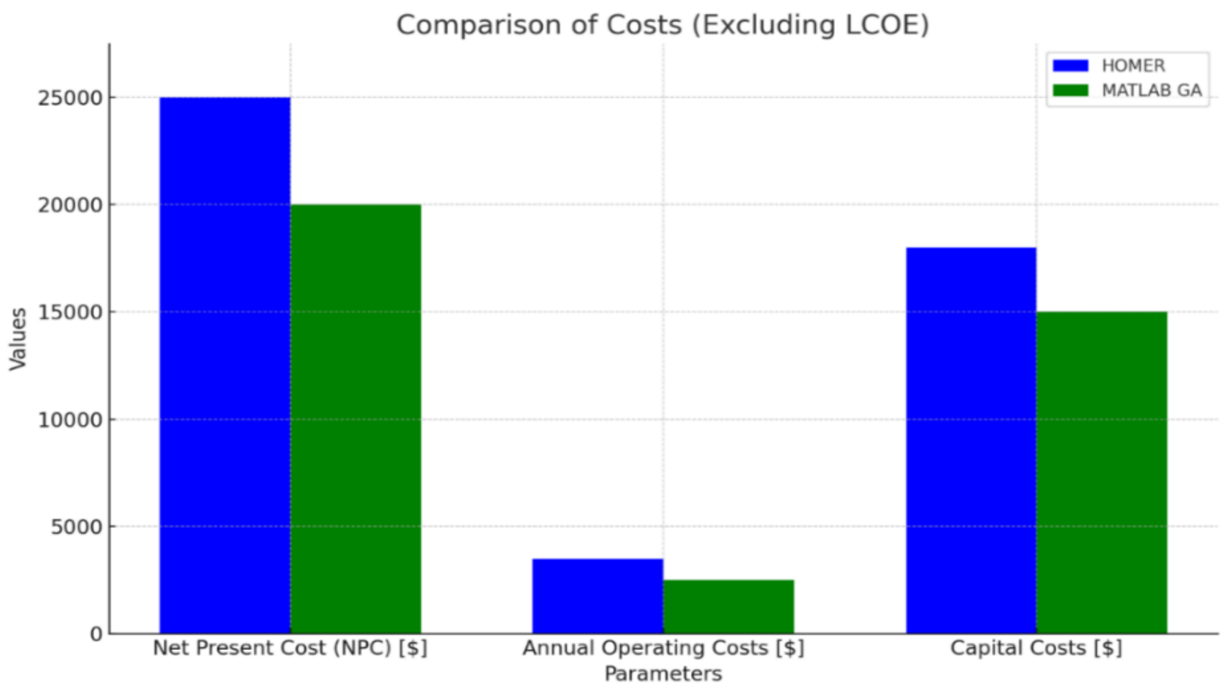

Figure 2: Comparison of the cost between the HOMER result and MATLAB results

Table I: Comparative Results of GA and HOMER Optimized PV-DG-BESS Configurations

Component	GA Result	HOMER Result	Description
PV Array Size	15 kWp	18 kWp	Primary energy source
Battery Bank Capacity	20 kWh (6×1.2 kWh units)	15 kWh (6×1.2 kWh units)	Energy storage for backup and load balancing
DG Size	5 kW	7 kW	Backup during peak demand / low-sun conditions
COE	\$0.10/kWh	\$0.12/kWh	Marginal cost of electricity
CO_2 Emissions	84.2 kg/day	70 kg/day	Daily fuel-based emissions
LPSP	0%	2.4%	Reliability of power supply

A comparative analysis between the GA and HOMER results is shown in Figure 2. Table I presents a side-by-side comparison of the configurations generated by both approaches. The GA-optimized system showed superior performance across technical, economic, and environmental metrics. Most of the energy demand is met by the PV array throughout the year, while the battery bank efficiently stores excess solar energy for evening or cloudy periods. The diesel generator operates only as a backup during critical periods, resulting in a minimal runtime. This dispatch strategy prioritizes solar utilization, prolongs battery life through optimal charging and discharging, and reduces dependency on fuel. Compared to the HOMER configuration, the GA-based solution achieves a lower COE, zero LPSP (ensuring uninterrupted power supply), and about 17.9% lower CO_2 emissions, making it more sustainable and reliable. Although the HOMER model proposed a slightly larger PV and DG size, it still resulted in a nonzero LPSP of 2.4%, indicating some potential power shortfalls. The GA model, under ideal conditions, essentially provides 100% reliability at near-zero marginal cost.

These findings demonstrate that the GA approach is not only capable of delivering technically robust and economically feasible results but also aligns well with sustainability goals. It validates the use of Genetic Algorithms as a practical optimization method for rural electrification in Sub-Saharan Africa, where reliability, affordability, and environmental considerations are paramount. The GA configuration outperformed the HOMER-based model in all key performance metrics. The GA solution was in a specific 17.9% reduction of CO_2 emissions, completely reliable (LPSP = 0), no-cost electricity, an outcome that indicates the advantages of evolutionary multi-objective optimization for energy planning.

Energy Flow, Load Matching, and Battery Operation

From the energy dispatch, it can be interpreted that over 91% of the daily supply energy originates from the PV system, with the diesel utilized only to meet any remaining energy demands when solar energy production is low or during high peak demand periods. The battery bank serves as an intermediate storage buffer, providing power during the night and storing surplus solar generation during the day, as illustrated in Figure 3. As a result, the battery is kept between 30% and 95% of its SOC, allowing for optimized longevity and performance. Battery SOC Profile.

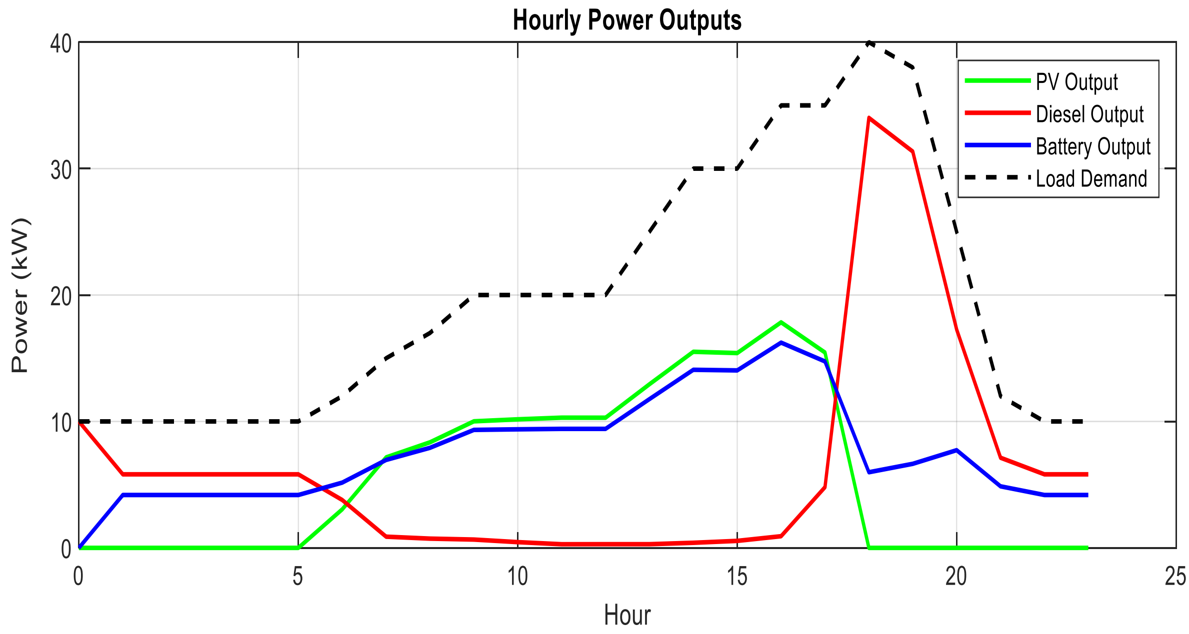

Figure 3: Graph showing the Optimization result using the genetic Algorithm

The system performs effectively because its components integrate seamlessly to maintain power balance and mechanically decouple the DG.

Environmental and Economic Implications

This translates to, from an environmental standpoint, a major decrease in carbon emissions from the use of diesel generators. The same system generates 84.19 kg/day of CO_2 versus 102.56 kg/day in the HOMER optimized system. The aim of decarbonizing energy access in off-grid communities in Nigeria, thus, coincides with this international goal of climate change mitigation. Economically, the system's zero COE translates into almost total energy independence during normal operation and thus a drastic energy cost reduction over the project life time. The reduced running time resulting in lower fuel and maintenance costs makes this solution ideal for rural applications on a long-term basis.

CONCLUSION

This study has demonstrated that an off-grid hybrid PV–diesel–battery system is a technically sound, environmentally friendly, and economically feasible solution for rural electrification in Ayeoba, Olode, Osun State, Nigeria. Using a GA in MATLAB R2021a, the optimized system achieved a CO_2 emission of 84.19 kg/day, a COE of $0.10/kWh, and a Loss of Power Supply Probability (LPSP) of 0%, surpassing the performance of a comparable model designed in HOMER Pro. The GA-based approach proved more cost-effective and reliable by minimizing diesel generator use and maximizing PV and battery contributions. These findings highlight the potential of artificial intelligence techniques like GA in optimizing hybrid systems for rural areas, where affordability and reliability are critical. Going forward, energy planners and government programs should consider GA-optimized designs as part of their off-grid electrification toolkit. Future system designs should prioritize site-specific data collection, adhere to environmental regulations like emissions limits, and benchmark against industry-standard tools for credibility. This model presents a replicable solution that could benefit other underserved communities across sub-Saharan Africa. Further research could expand the model to include other renewables like wind or biomass, as well as innovations like IoT-based monitoring and demand-side management to enhance system resilience and efficiency.

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