American Journal of Engineering Research (AJER)
e-ISSN: 2320-0847 p-ISSN: 2320-0936
Volume-15, Issue-6, pp-65-79
www.ajer.org
Research Paper Open Access

Integrated Load Audit and Hybrid Renewable Energy Optimization for a Space Science Research Facility Using Particle Swarm Optimization and Genetic Algorithm Techniques

Ezeugwu, Benneth Chijioke[1], Eze Ifedilichukwu Anthony[2], Ekeanyanwu Obinna Peter[3],Onyema Chidera Egbujor[4], Okala Paul Arome[5],AdemuUmarfaruq Seidu[6], Omeje Felix Nnaemeka[7], Obetta Nnamdi Tobias[8], Onwunzo Ndubuisi Chidozie[9], Enete Christian Oforbuike[10]
[1-10]Instrumentation Division, Centre for Basic Space Science (NASRDA) Nsukka, Enugu State, Nigeria

ABSTRACT: *This study presents a comprehensive load profiling, energy audit, and techno-economic optimization of the energy system of the Centre for Basic Space Science, Nsukka, Nigeria, with the aim of improving energy efficiency, operational reliability, and environmental sustainability. Detailed electrical load data were obtained from major facilities within the institution, including administrative offices, laboratories, workshops, and support units. The analysis revealed an annual electricity demand of approximately 306,712 kWh/year, with air-conditioning systems accounting for the largest share of energy consumption. The institution exhibited an Energy Use Intensity of 240.13 kWh per square meter per year, indicating significant energy inefficiencies and the need for optimization measures. A hybrid renewable energy system consisting of photovoltaic generation, battery storage, grid connection, and diesel backup was modeled and optimized using (HOMER Pro version 3.17.x). Five energy configurations were investigated based on net present cost, cost of energy, renewable energy penetration, fuel consumption, and system reliability. The optimal configuration comprised a 52.3 kW photovoltaic array integrated with battery storage and grid support, achieving a cost of energy of 47 ₦/kWh and a renewable energy fraction of 85.1 percent. The system maintained zero unmet load and eliminated diesel fuel dependency while significantly reducing greenhouse gas emissions. Sensitivity analysis further confirmed the economic robustness of the proposed configuration under varying inflation conditions. Validation using Particle Swarm Optimization and Genetic Algorithm demonstrated strong agreement with the optimization results, thereby confirming the reliability and global optimality of the proposed hybrid energy architecture for sustainable institutional electrification.*

KEYWORDS: *Techno-Economic Analysis, Energy Optimization, Photovoltaic Energy, Energy Audit, Hybrid Renewable Energy Systems, Battery Energy Storage*

Date of Submission: 08-06-2026 Date of acceptance: 18-06-2026

I. INTRODUCTION

The increasing global demand for electrical energy, rapid urbanization, industrial expansion, and growing environmental concerns associated with fossil-fuel-based electricity generation have intensified the need for sustainable and energy efficient power systems. Conventional electricity generation methods continue to contribute significantly to greenhouse gas emissions, environmental degradation, and climate change, thereby necessitating the transition toward cleaner and more sustainable energy technologies [1] - [9]. In recent years, renewable energy systems, particularly photovoltaic-based hybrid energy systems, have emerged as viable alternatives for improving energy reliability, reducing operational costs, and minimizing environmental impacts in both developed and developing economies [22]–[32].

Institutional and research facilities represent a major category of electricity consumers due to their extensive dependence on lighting systems, air-conditioning units, laboratory equipment, computing infrastructure, and other energy-intensive operational devices. The continuous operation of these facilities often results in high electricity demand and increased operational expenditure. Energy audits have therefore become essential tools for identifying inefficient energy consumption patterns, improving energy management practices, and enhancing sustainability in institutional buildings [10], [11], [12]–[21]. Studies have shown that detailed load profiling and energy audits provide valuable insights into electricity usage characteristics and assist in the development of cost-effective energy optimization strategies [4], [8], [12], [13].

In developing countries such as Nigeria, the challenge of unreliable grid electricity supply further complicates institutional energy management. Frequent power outages, rising diesel fuel costs, and dependence on backup generators significantly increase operational costs and negatively affect institutional productivity and sustainability [10]. Research-oriented institutions are particularly vulnerable to power instability due to the sensitive nature of scientific instrumentation, laboratory systems, and computational facilities that require uninterrupted electricity supply. Consequently, there is a growing need for reliable and economically viable hybrid renewable energy systems capable of ensuring stable power supply while reducing dependence on conventional fossil-fuel-based generation.

Several researchers have investigated the application of hybrid renewable energy systems for electrification and energy optimization in residential, industrial, and rural environments. [24], [29] examined the feasibility and optimization of standalone hybrid energy systems for rural electrification and demonstrated the economic viability of renewable-integrated configurations. [27] Analyzed the performance of photovoltaic-diesel-battery hybrid systems using Hybrid Optimization of Multiple Energy Resources software (HOMER) and reported significant reductions in operational costs and fuel consumption. Similarly, [25] conducted a techno-economic analysis of hybrid renewable systems for rural electrification and established the advantages of renewable-dominated architectures in minimizing lifecycle cost. [26] Further demonstrated the feasibility of photovoltaic-wind-diesel-battery systems for large facilities requiring reliable electricity supply.

In the area of institutional energy management, several studies have emphasized the importance of energy audits and intelligent building energy systems. [16] Investigated building energy information systems and demonstrated the significance of data-driven energy management strategies in improving operational efficiency. Dong and Lam [18] developed predictive control approaches for building heating and cooling systems based on occupancy behavior and weather forecasting. Similarly, [17] examined energy-related occupant behavior in buildings and established its impact on overall energy performance. Other studies have focused on organizational energy efficiency barriers [19], institutional legislation [7], and demand-side management strategies [9].

Despite the growing body of literature on hybrid renewable energy systems and institutional energy audits, limited studies have focused on research-oriented institutional facilities characterized by sensitive laboratory operations, variable daytime loads, and stringent reliability requirements. Furthermore, many existing studies primarily address either energy auditing or hybrid renewable optimization independently, with limited integration of comprehensive load profiling, techno-economic optimization, economic sensitivity analysis, and independent metaheuristic validation within a unified framework. In addition, the application of dual-validation techniques using Particle Swarm Optimization and Genetic Algorithm for institutional hybrid renewable energy systems remains insufficiently explored, particularly within the context of developing countries such as Nigeria.

Therefore, this study presents a comprehensive load audit, load profiling, and techno-economic optimization of the Centre for Basic Space Science, Nsukka, Nigeria, using a hybrid photovoltaic-battery-grid energy architecture. The study evaluates the electrical load characteristics of the institution and investigates multiple hybrid energy configurations using Hybrid Optimization of Multiple Energy Resources software to determine the most economically viable and environmentally sustainable system. In addition, economic sensitivity analysis was conducted to evaluate system robustness under varying inflation scenarios, while independent validation using Particle Swarm Optimization and Genetic Algorithm techniques was implemented in MATLAB to verify the consistency and global optimality of the obtained results.

The major contributions of this study include:

1. Comprehensive institutional load auditing and load profiling of a space science research facility in Nigeria.
2. Techno-economic optimization of hybrid photovoltaic-battery-grid energy configurations for improved energy reliability and sustainability.
3. Economic sensitivity analysis of the proposed hybrid system under varying inflation conditions.
4. Independent validation of optimization results using Particle Swarm Optimization and Genetic Algorithm techniques.
5. Development of a practical framework for sustainable institutional electrification and energy management in developing countries.

The findings of this study are expected to contribute to the growing body of knowledge on institutional renewable energy integration, hybrid energy optimization, and sustainable energy management while providing practical insights for policymakers, researchers, and institutional energy planners seeking to improve electricity reliability and reduce operational costs in research and educational facilities.

II. LITERATURE REVIEW

Energy audits have emerged as a critical instrument in modern energy management practices, especially within institutional, commercial, and industrial sectors. As global energy demand continues to rise due to population growth, urbanization, and technological advancement, the need for effective energy monitoring and optimization has become paramount. According to the International Energy Agency (IEA), energy demand is expected to grow by more than 25% by 2040 if current trends continue, emphasizing the urgency for demand-side efficiency measures [11].

An energy audit is a systematic analysis of energy flows within a building or system, designed to understand current consumption patterns, identify areas of energy loss, and recommend interventions for improved efficiency. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) classifies audits into three levelswalk-through (Level I), energy survey and analysis (Level II), and detailed audit (Level III)each with increasing depth of investigation and data collection [12].

According to Thumann and Younger, energy audits should encompass technical, operational, and financial assessments to offer actionable insights that balance energy savings with investment costs [13]. This approach ensures that audit recommendations are both technically viable and economically justified.

Although industrial facilities have traditionally received the most attention for energy efficiency efforts, institutional buildingsincluding educational facilitieshave begun to garner interest due to their unique usage profiles and potential for cost-effective savings. Research indicates that non-residential buildings, including schools and universities, can achieve energy savings of 10–30% through audits and retrofits [14].

Educational institutions, in particular, are ideal candidates for energy audits due to their high energy loads associated with lighting, HVAC, laboratory equipment, and computing infrastructure. A study by Kats et al. found that green schoolsthose implementing audit-informed retrofits and sustainability practicesconsume 33% less energy and 32% less water than conventional schools [15].

Energy audits yield multiple benefits beyond just energy and cost savings. These include:

- Improved occupant comfort through optimized HVAC and lighting systems
- Reduced greenhouse gas emissions and environmental impact
- Data for informed policy-making and budgeting
- Enhanced reliability of power supply, especially in regions with unstable grids

A meta-analysis by Granderson et al. on commercial building energy audits revealed that lighting upgrades, HVAC optimization, and behavioral changes typically offer the highest return on investment [16]. Additionally, the introduction of real-time energy monitoring has enhanced the effectiveness of audits, allowing for continuous commissioning and adaptive control strategies [17].

Furthermore, the integration of Internet of Things (IoT) technologies and Building Management Systems (BMS) allows for dynamic monitoring and control, enabling facility managers to address inefficiencies in real time [18].

Despite their benefits, energy audits face several barriers: such as Initial investment costs for retrofits, Lack of awareness or technical expertise in interpreting audit results, Institutional inertia and delayed decision-making, Absence of regulatory enforcement or incentives in some regions.

A study by [19] highlighted that small and medium-sized institutions often lack internal capacity for energy management, relying instead on external consultants whose recommendations may not be fully implemented due to budgetary constraints.

Globally, energy audits have been promoted through frameworks such as the EU Energy Efficiency Directive, which mandates periodic audits for large enterprises [20]. In India, the Energy Conservation Act 2001 made audits compulsory for designated large consumers, spurring growth in the energy service industry [21]. Similarly, several African nations are incorporating energy audits into national energy efficiency policies, often supported by international organizations such as UNIDO and UNEP.

Despite the growing body of research on hybrid renewable energy systems, limited studies have focused on detailed energy auditing and techno-economic optimization of research-oriented institutional facilities in developing countries. Furthermore, previous studies rarely integrate multi-algorithm optimization validation and economic sensitivity analysis within a unified framework.

The literature emphasizes that energy audits are not only essential for reducing energy consumption and operational costs but also for advancing institutional sustainability. With advancements in digital technologies and supportive policy frameworks, the effectiveness and accessibility of energy audits continue to improve. However, for educational and research institutions, maximizing the benefits of energy audits requires overcoming institutional barriers, aligning energy strategies with core operations, and ensuring sustained stakeholder engagement. Therefore, Table 1 below summarizes the previous literature reviewed that is related to this study.

Table 1 : Comparative Summary of Reviewed Energy Audit Literature

Study / Source	Method / Scope	Tools / Technologies Used	Key Findings / Contributions
ASHRAE [12]	Classification of energy audits (Levels I–III)	Site walkthroughs, utility bill analysis, detailed surveys	Establishes standardized audit procedures with increasing complexity; Level III involves investment-grade audit.
Thumann & Younger [13]	Integrated technical & financial analysis	Audit templates, ROI calculators	Emphasizes coupling energy audit data with financial viability for implementation.
Kats [15]	Case study of U.S. green schools	Pre/post retrofit assessments	Green schools consume 33% less energy; savings justify initial investment.
Granderson et al. [16]	Meta-analysis of commercial building audits	Data loggers, meters, audit software	Lighting and HVAC upgrades yield highest ROI; behavior change also critical.
U.S. DOE [14]	Retrofit guide for commercial buildings	Audit checklists, DOE tools	Energy savings of 15–30% achievable with retrofits; lighting and HVAC are prime targets.
Hong et al. [17]	Occupant behavior in building performance	Surveys, sensors, behavior-based modeling	Occupant behavior significantly impacts energy use; models should account for it.
Dong & Lam [18]	Real-time predictive control systems	IoT sensors, MPC (Model Predictive Control)	Smart control systems optimize HVAC based on occupancy and weather, reducing consumption.
Trianni et al. [19]	Study of energy efficiency in SMEs	Surveys, structured interviews	Financial constraints and lack of internal expertise are key barriers to implementing audit recommendations.
European Directive [20]	Regulatory framework for EU nations	Legal audit mandates, compliance checks	Mandatory energy audits improve participation and performance in energy management across EU companies.
BEE – India [21]	National energy efficiency policy framework	Designated consumers, energy managers	Regulatory enforcement has led to broader implementation of audits in India, especially in large industries and institutions.
IEA [11]	Global energy demand forecast and context	Macroeconomic data modeling	Projected 25% increase in energy demand by 2040 necessitates proactive efficiency interventions like audits and retrofits globally.

III. MATERIALS & METHODS

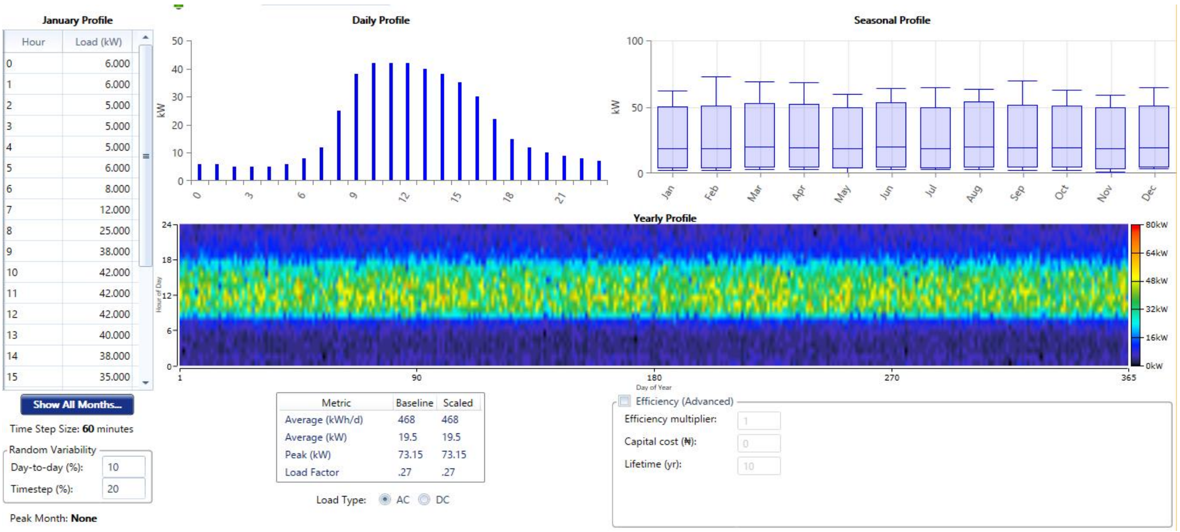
3.1 Load Data Acquisition

A comprehensive load audit was conducted across all functional buildings within CBSS. These included the Main Administrative Block, Science Building, Mechatronics Workshop, and Gate House. Power ratings of electrical appliances (lighting, air conditioning units, laboratory equipment, computers, and printers) were manually recorded using data sheets and verified with spot measurements using digital clamp meters and multimeters. Operating hours per device type were also documented to compute total energy consumption. The hourly and monthly load profile for the Centre Campus is illustrated in Figure 1. In reference to the estimated load profile of the Centre, it is evaluated that the annual electricity demand of the institute stood at 172.41kWh/day and the optimal demand is 21.32 kWp.

The annual total energy demand as shown in (1) was computed using:

$$\boldsymbol{E_{annual}} = \sum(\boldsymbol{P_i} \times \boldsymbol{h_i} \times \boldsymbol{d_i}) \qquad 1$$

Where P_i is the power rating of device i (in kW), $h_i$is the average daily hours of operation, $d_i$is the number of operating days per year. This resulted in a total load demand of 306,712 kWh/year.



January Profile

Hour	Load (kW)
0	6.000
1	6.000
2	5.000
3	5.000
4	5.000
5	6.000
6	8.000
7	12.000
8	25.000
9	38.000
10	42.000
11	42.000
12	42.000
13	40.000
14	38.000
15	35.000

Time Step Size: **60** minutes

Random Variability
Day-to-day (%): 10
Timestep (%): 20

Peak Month: **None**

Metric	Baseline	Scaled
Average (kWh/d)	468	468
Average (kW)	19.5	19.5
Peak (kW)	73.15	73.15
Load Factor	.27	.27

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)
Efficiency multiplier: 1
Capital cost (₦): 0
Lifetime (yr): 10

Figure 1: CBSS Load Profile

3.2 Mathematical modeling of solar photovoltaic (PV) system

The equation for the power generated by the solar PV Panels applied in HOMER is shown in (2) [22].

$$P_{pv} = Y_o V_{pv} \frac{I_\tau}{I_s} \qquad (2)$$

Where Y_o is the PV derating factor, V_{pv} is the rated PV array capacity (kW), I_τ is the PV array global radiation solar incident (kW/m^2), I_s is the standard capacity of PV array radiation ($1kW/m^2$).

3.3. Mathematical modeling of diesel generator system

The diesel generator (Dg) power output equation as applied in HOMER is shown in (3) [22]. $F_{Gen} = C_{om} + \frac{C_r}{R_L} + F_n X_{Gen} C_{eff}$ (3)

Where $C_{om}$is the operational and maintenance cost (₦/hr), $C_r$is the replacement cost (₦), F_n is the intercept fuel curve coefficient (fuel/hr/kw), R_L is the generator lifetime (hrs.),X_{Gen} is capacity of generator (kw), and C_{eff} is the effective fuel price (₦/L)

3.4 Modeling and optimization with HOMER

HOMER software is an electrical renewable energy sources optimization tool developed by the National Renewable Energy Laboratory (NREL) for analyzing of energy generation and economics metric performances of the energy system architecture.With HOMER, we can design a hybrid model of different energy topology that evaluate the system performance and its corresponding system economic analysis [23].

This software computes and analysis various renewable energy sources including the power grid and diesel generator sets to determine the best system based on technical, economic, and eco-friendly benefits. HOMER as well can perform the modelled systems when varying the input parameters known as search space. Therefore, HOMER is doing three functions effectively: simulation, analysis and optimization.

During the analysis process, the software controls the outcome and proximity of change in the input parameter for future purposes. Thus, the input parameter is designed to have multiple optimizations in a specific range within the search space. The optimization process determines the visibility control of optimal variable value for the system, which includes the combination of the component in the system and evaluation of various energy that will specifically meet the desired objectives (technical, environmental, and economic) to minimal total net present cost (NPC). To analyze the levelized cost of energy (LCOE), HOMER evaluates the cost by dividing the annual cost of producing electricity (annual total cost divides by total load served and the energy from the grid) as shown in (4) [24].

$$Cost\ of\ Energy = \frac{C_{ann.tot}}{E_{prim}+E_{def}+E_{grid}} \qquad (4)$$

Where $C_{ann.tot}$the total is annualized cost of system (₦/year), E_{prim} is the primary load served by the system (kWh/year), E_{def} is the deferrable load served (kWh/year), and E_{grid} is the energy from the grid (kWh/year).

The profit made after the discount of an initial investment with a typical Net Present Cost (NPC) equations are shown in (5) and (6) [25]–[27]. Hence, the total net present cost (TNPC) is the currentcost of the system expenditures for a specific period minus the present value income generated at a specific period. This income is the cumulative operation costs, purchasing costs, cost of replacement, maintenance costs, and the fuel costs in a specific lifespan (N) [28]–[32].

$$Net\ Present\ Cost(NPC) = \frac{C_{at}}{R(i,N)} \qquad (5)$$

Where C_{at} is the total cost annually, N is the system lifespan, i is the annual interest rate, and $R(i,N)$ is the capital recovery factor.

$$R(i,N) = \frac{i(1+i)^N}{(1+i)^N-1} \qquad (6)$$

3.5 HOMER Validation with Particle Swarm Optimization and Genetic Algorithm

The validation was conducted using two metaheuristic algorithms implemented in MATLAB: Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). The canonical formulations of PSO and GA were adopted from [33][34]. These algorithms were chosen because they represent distinct optimization paradigms (Swarm intelligence and evolutionary computation) which provides a complementary perspective on the robustness of HOMER's solution. The PSO algorithm updates particle velocity and position according to equations (7) and (8).

Velocity Update

$$v_i^{t+1} = \omega . v_i^t + c_1 \cdot r_1 \cdot (pbest_i - x_i^t) + c_2 \cdot r_2 . (gbest - x_i^t) \qquad (7)$$

Position Update

$$x_i^{t+1} = x_i^t + v_i^{t+1} \qquad (8)$$

Where x_i^t is the position of the particle i at iteration$t$,$v_i^t$is the velocity of the particle$i$. While $pbest_i$is the personal best of particle i and $gbest$ is the global best solution found so far. $\omega$is the inertia weight, c_1, c_2 are the cognitive and social coefficients and r_1, r_2 are the random numbers $\{0,1\}$.

The Genetic Algorithm (GA) evolves candidate solutions through fitness evaluation, selection, crossover, and mutation as expressed in equations (9) – (12).

Fitness evaluation

$$f(x) = Objective\ Function\ Value \qquad (9)$$

Selection probability (roulette wheel)

$$P_i = \frac{f_i}{\sum_{j=1}^{N} f_j} \qquad (10)$$

Crossover (single –point)

$$child_1 = [p_1(1{:}k), p_2(k+1{:}n)], child_2 = [p_2(1{:}k), p_1(k+1{:}n)] \qquad (11)$$

Mutation

$$x_i' = x_i + \delta \qquad (12)$$

Where δ is a small random perturbation within the bounds.

IV. RESULTS AND DISCUSSION

This section presents the detailed findings obtained from the load audit, HOMER Pro optimization, and MATLAB/Simulink validation of the proposed hybrid energy system for the Centre for Basic Space Science (CBSS), Nsukka. The results provide insight into the existing energy consumption characteristics of the institution, the techno-economic performance of various hybrid configurations, renewable energy penetration, operational reliability, and power quality enhancement.

4.1 Load Audit and Energy Consumption Characteristics

The comprehensive energy audit conducted across the CBSS facilities revealed that the institution exhibits a relatively high and continuous electricity demand pattern due to the simultaneous operation of administrative offices, laboratories, research equipment, air-conditioning systems, ICT infrastructure, and workshop facilities. The measured annual electricity demand was estimated at approximately 306,712 kWh/year, corresponding to an average daily energy consumption of about 172.41 kWh/day.Figure 2 illustrates the hourly electrical load profile of CBSS, showing that the institution experiences peak electricity demand between 10:00 a.m. and 4:00 p.m. due to intensive laboratory operations, office activities, and air-conditioning usage. The figure further reveals that the daytime-dominated load profile closely aligns with periods of maximum solar irradiance, thereby making photovoltaic integration highly suitable for the facility.

In addition, the analysis showed in Figure 3that air-conditioning systems contributed the largest share of total electricity consumption, followed by office computing equipment and lighting systems. This trend is consistent with energy consumption patterns typically observed in tropical institutional environments where thermal comfort requirements significantly increase HVAC loads. The dominance of cooling loads also indicates that energy efficiency interventions targeted at HVAC systems could produce substantial reductions in overall electricity demand. The load profile analysis further demonstrated that electricity demand peaked during daytime operational hours, particularly between 10:00 a.m. and 4:00 p.m., coinciding with maximum occupancy and laboratory activities. This daytime-dominant load profile is advantageous for photovoltaic integration because it aligns closely with periods of maximum solar irradiance, thereby improving solar energy utilization efficiency.

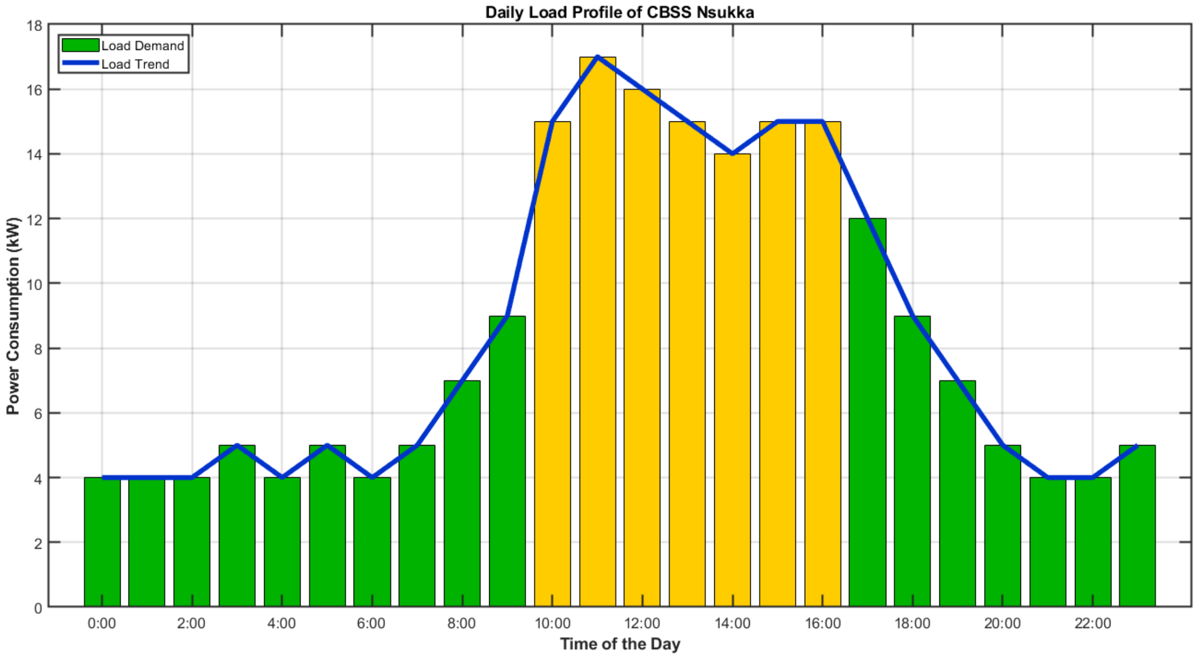


Figure 2: Hourly Load Profile of CBSS

Based on the total floor area of approximately 1,500 m² and the annual energy consumption, the Energy Use Intensity (EUI) of CBSS was estimated at 240.13 kWh/m²/year. This value significantly exceeds the recommended benchmark range of 100–150 kWh/m²/year for institutional buildings in developing countries, thereby confirming the presence of considerable energy inefficiencies within the facility. The elevated EUI further justifies the need for energy optimization and renewable energy integration.

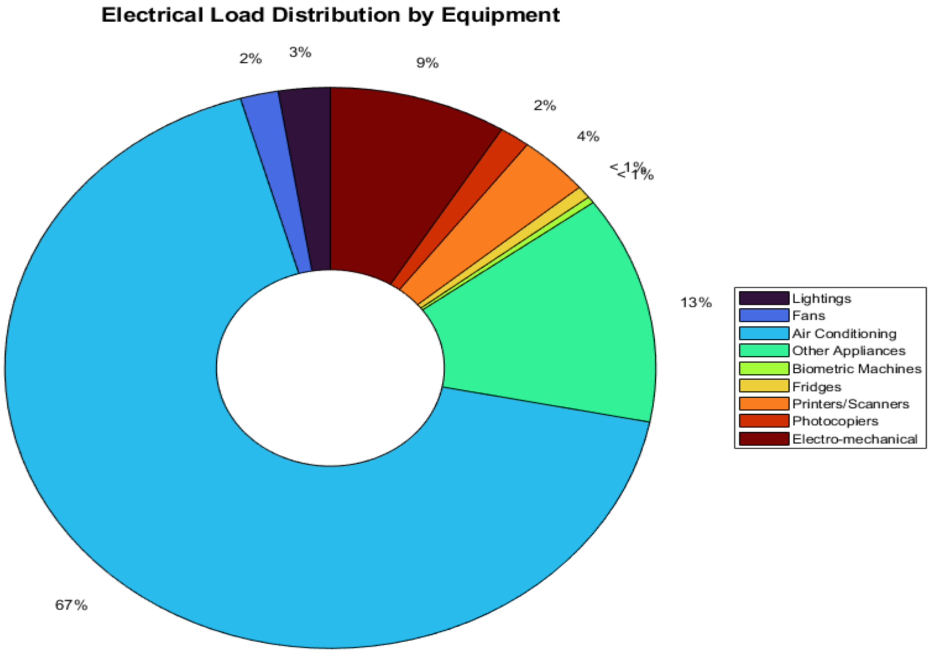


Figure 3 : Electrical Load distribution by Equipment Type

4.2 HOMER Pro Optimization Results

Five different hybrid system architectures were simulated and evaluated using HOMER Pro as shown in Figure 4. These configurations incorporated varying combinations of photovoltaic systems, diesel generators, battery storage systems, and grid connectivity. The primary optimization criteria included Net Present Cost (NPC), Cost of Energy (COE), operating cost, renewable energy fraction, and diesel fuel consumption.

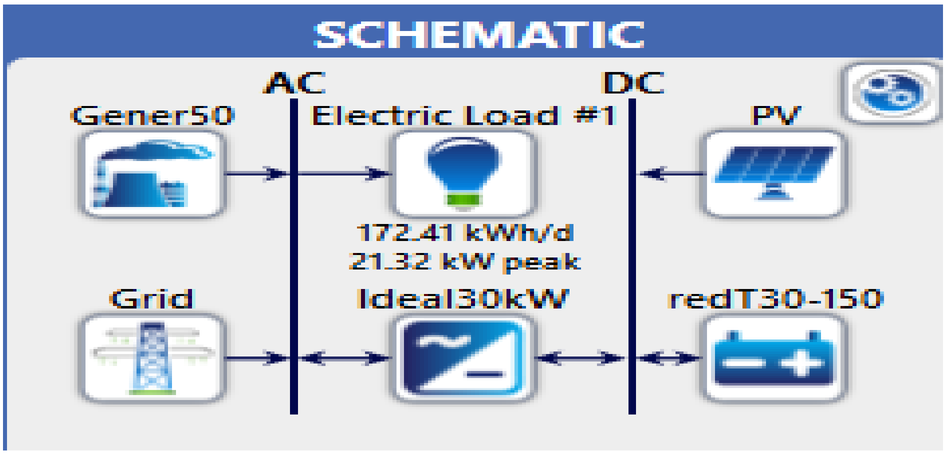


Figure 4 : Hybrid System Architecture

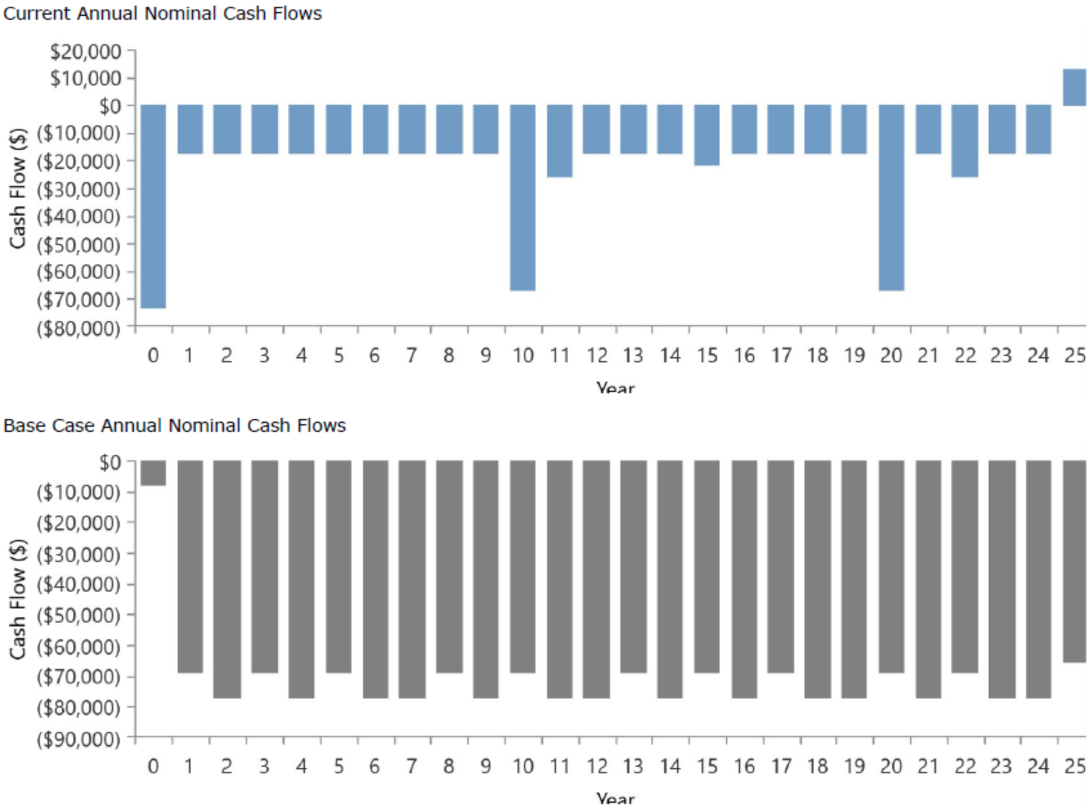


Figure 5 : Annual Nominal Cash Flow of the Simulated System

The optimization results revealed substantial performance differences among the proposed configurations. System A, representing the grid-only scenario, exhibited a relatively moderate COE of ₦54.8/kWh with no initial capital investment. However, its complete dependence on the unreliable national grid makes it operationally vulnerable, especially considering the persistent power instability experienced within Nigeria’s electricity sector.

System B, which integrated solar PV with grid supply but excluded battery storage, demonstrated improved renewable contribution during daytime operation. Nevertheless, the absence of storage limited its ability to provide uninterrupted supply during periods of low irradiance or grid outages. Consequently, the COE increased to ₦64.22/kWh despite reduced daytime grid consumption. System D combined photovoltaic generation, diesel backup, and grid support. Although this arrangement improved supply reliability, the operational burden associated with diesel fuel consumption significantly increased lifecycle costs. Annual diesel consumption reached approximately 2,410 liters/year, resulting in elevated operating expenses and carbon emissions.Figure 5shows the annual nominal cash flow characteristics of the proposed hybrid energy system. The figure indicates that although the renewable-integrated system requires higher initial capital investment, the operational savings obtained over time significantly reduce lifecycle expenditure.

System E, consisting primarily of diesel generation with grid support, produced the poorest economic and environmental performance among all evaluated configurations. The system recorded the highest COE of ₦98.77/kWh and annual fuel costs exceeding ₦7 million. The heavy reliance on fossil fuel generation also resulted in substantial greenhouse gas emissions, making the configuration unsuitable for sustainable institutional operation.

Among all configurations, System C emerged as the optimal solution. This configuration integrated a 52.3 kW photovoltaic array, battery storage system, and grid connectivity. The optimized system achieved a COE of ₦47/kWh, representing the lowest energy production cost among all simulated alternatives. Furthermore, the system attained a renewable energy fraction of 85.1%, indicating that the majority of the annual load demand could be supplied through renewable sources. The superiority of System C is attributed to the complementary interaction between photovoltaic generation, battery storage, and grid support. During daytime hours, the PV system supplied the primary load while simultaneously charging the battery bank. During nighttime operation or periods of reduced solar availability, the battery system discharged stored energy to support the load before supplemental power was drawn from the grid.Table 2compares the economic performance of the investigated hybrid system configurations. The results demonstrate that systems with higher renewable penetration achieved lower operating costs and reduced fuel dependency when compared to diesel-dominated systems.

The HOMER optimization also demonstrated that the proposed system maintained zero unmet electrical load and zero capacity shortage throughout the simulation period, confirming the reliability and adequacy of the selected hybrid architecture.

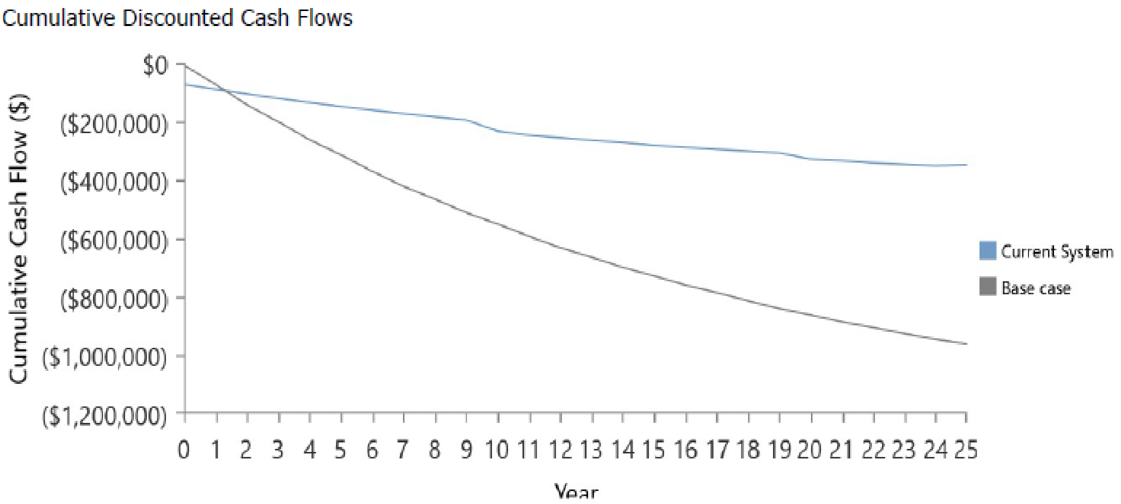


Figure 6 :Cumulative discounted Cash flows

Figure 6 illustrates the cumulative discounted cash flow of the optimized system over the project lifespan. The result demonstrates that the renewable-based configuration achieves positive economic returns within the projected operational period, thereby confirming the long-term financial viability of the proposed system.

Table 2: Comparative Economic Analysis Hybrid Stimulated System

System ID	PV (kW)	DG (kW)	Grid	Battery	Renewable Fraction (%)	Diesel Fuel (L/Yr.)	COE (₦/kWh)	NPC (₦M)	OPEX (₦M/yr.)	Capex (₦M)
A	0	0	Yes	No	0	0	54.8	44.6	3.45	0
B	50	0	Yes	No	0	0	64.22	52.2	3.27	10
C	52.3	0	Yes	Yes	85.1	0	47	78.3	1.88	31.3
D	43.3	50	Yes	No	77.4	2,410	76.28	63	1.95	39.5
E	0	50	Yes	No	0.19	6,930	98.77	80.4	3.87	30.3

4.3 Photovoltaic System Performance

Detailed analysis of the photovoltaic subsystem showed strong renewable generation capability throughout the simulation year. The HOMER results indicated that the PV array generated approximately 88,779 kWh/year, contributing about 83.2% of the total annual electricity production.

The PV system exhibited a rated capacity of 80.9 kW with a maximum instantaneous output of 53.9 kW and a capacity factor of 12.5%. The annual operating duration was approximately 4,380 hours/year, confirming the suitability of Nsukka's solar resource for large-scale photovoltaic deployment. The relatively high renewable penetration achieved in the study demonstrates that solar energy can effectively support institutional electrical infrastructure in Nigeria. The seasonal fluctuations in solar production observed during the simulation were adequately compensated through battery storage and supplemental grid support, thereby maintaining uninterrupted electricity supply.

The renewable summary generated by HOMER further revealed that renewable generation exceeded the annual load demand during certain periods as shown in Table 3, resulting in renewable production equivalent to 119% of the load requirement. This indicates the possibility of future system expansion, net metering opportunities, or integration of additional research facilities without substantial increases in generation capacity.

Table 3 : Electrical Summary of the System

Production Summary		
Components	**Value**	**Units**
Generated Energy from PV System	88,779	kWh/yr
Generated Enegry from Diesel Generator Set	17,869	kWh/yr
Consumption Summary		
AC Primary Load	74,460	kWh/yr
DC Primary Load	0	kWh/yr
Excess and Unmet		
Excess Electricity	27,070	kWh/yr
Unmet Electric Load	0	kWh/yr
Capacity Shortage	0	kWh/yr

4.4 Battery Storage System Performance

The battery subsystem played a critical role in enhancing energy reliability and renewable energy utilization. The selected battery storage system provided an autonomy period of approximately 7.25 hours, thereby enabling sustained operation during nighttime periods and transient grid outages. The storage system recorded annual energy input and output values of 25,580 kWh/year and 24,298 kWh/year respectively, with minimal energy losses of approximately 1,279 kWh/year as shown in Table 4. The expected battery lifespan was estimated at 10 years, indicating acceptable long-term operational durability.

The integration of battery storage significantly improved the self-consumption rate of solar energy while reducing dependence on external energy sources. Without battery support, excess daytime solar generation would have been curtailed or wasted during low-load periods. The storage system therefore enhanced renewable energy utilization efficiency and improved overall system economics.

Table 4 : Simulated Battery Storage Result Data

Description	**Value**	**Units**
String Size	48	Batteries
Strings in parallel	6	Strings
Bus voltage	96	Vdc
Energy In	25,580	kWh/yr
Energy Out	24,298	kWh/yr
Storage Depletion	-2.62	kWh/yr
Losses	1,279	kWh/yr
Annual Throughput	24,929	kWh/yr
Autonomy	7.25	Hr
Storage Wear Cost	125.15	₦/kWh
Lifetime Throughput	249,292	kWh
Expected Life	10	Yr

4.5 Diesel Generator Operational Characteristics

Although the optimal system excluded diesel generation, simulations involving diesel-supported configurations provided useful insights into the operational limitations of fossil-fuel-dependent systems. The diesel generator subsystem produced approximately 17,869 kWh/year with annual fuel consumption of about 7,234 liters. Table 5illustrates the diesel fuel consumption profile of the generator subsystem.

The generator operated for approximately 1,428 hours/year and exhibited a relatively low capacity factor of 4.08%, indicating underutilization during most operational periods. Despite its contribution to supply reliability, the generator introduced substantial fuel costs, maintenance requirements, and environmental pollution. Emission analysis revealed annual carbon dioxide emissions of approximately 18,939 kg/year alongside additional pollutants including sulfur dioxide, nitrogen oxides, particulate matter, and unburned hydrocarbons.Table 6 shows the emission characteristics associated with diesel generator operation. These findings reinforce the environmental disadvantages associated with diesel-based backup systems and further justify the transition toward renewable-dominated hybrid architectures.

Table 5: *Diesel Consumption Statistics of CBSS*

Quantity	**Value**	**Units**
Total fuel consumed	7,234	L
Avg fuel per day	19.8	L/day
Avg fuel per hour	0.826	L/hour

Table 6: *Emission Analysis of Diesel Generator*

Pollutant	**Quantity**	**Units**
Carbon Dioxide	18,939	kg/yr
Carbon Monoxide	118	kg/yr
Unburned Hydrocarbons	5.21	kg/yr
Particulate Matter	0.709	kg/yr
Sulphur Dioxide	46.4	kg/yr
Nitrogen Oxides	111	kg/yr

4.6 Economic Sensitivity Analysis

Sensitivity analysis was performed to evaluate the resilience of the optimal hybrid system under varying inflation conditions and economic uncertainties. The analysis considered inflation rates of 2%, 5%, and

8%. The results as shown in Figure 7 indicated that although both NPC and COE increased moderately with rising inflation, the proposed PV-battery-grid configuration remained economically viable under all evaluated scenarios. Specifically, the COE increased from ₦47/kWh at 2% inflation to ₦52.11/kWh at 8% inflation, while NPC increased from ₦78.3 million to ₦87.4 million.

Despite these increases, the hybrid renewable system still outperformed diesel-dominated alternatives in terms of lifecycle cost and operational sustainability. This demonstrates the robustness of the proposed solution against future economic fluctuations and fuel price volatility.

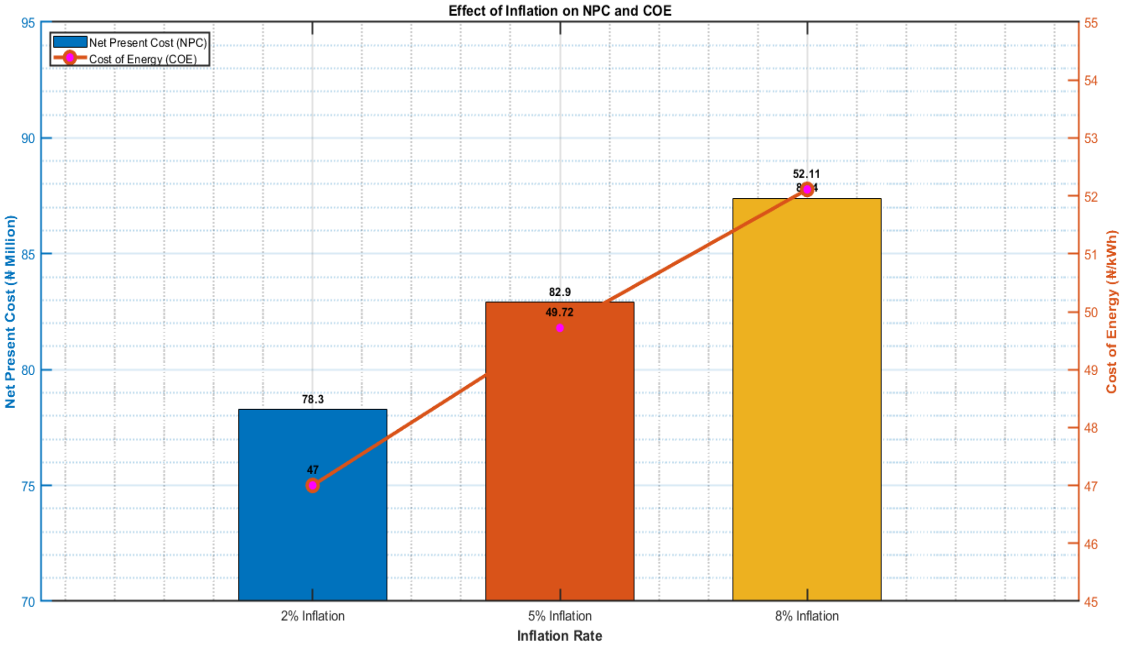
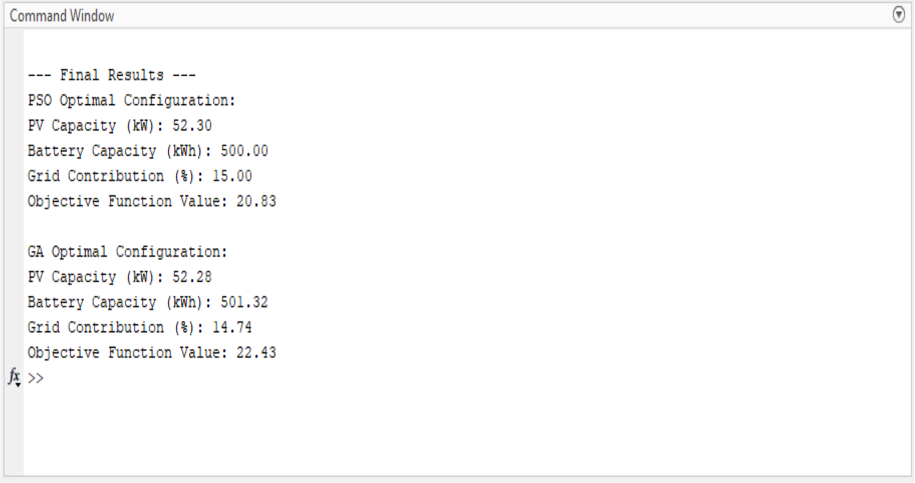


Figure 7: Economic Sensitivity Analysis Plot

4.7 Validation Result of PSO and GA

To ensure robustness of the optimization, HOMER results were validated using two metaheuristic algorithms: Particle Swarm Optimization (PSO) and Genetic Algorithm (GA). Both algorithms independently converged to nearly identical configurations as HOMER's System C (PV ≈ 52 kW, Battery ≈ 500 kWh, Grid ≈ 15%). The MATLAB simulation output results as seen in Figure 8confirms this consistency, with PSO achieving rapid stabilization and GA exploring the solution space more broadly before settling near the same optimum. The convergence curves of the simulation shown in Figure 9 illustrate that PSO reached the minimum objective value faster, while GA demonstrated a more gradual descent, reflecting its evolutionary search characteristics.



```
--- Final Results ---
PSO Optimal Configuration:
PV Capacity (kW): 52.30
Battery Capacity (kWh): 500.00
Grid Contribution (%): 15.00
Objective Function Value: 20.83

GA Optimal Configuration:
PV Capacity (kW): 52.28
Battery Capacity (kWh): 501.32
Grid Contribution (%): 14.74
Objective Function Value: 22.43
>>
```

Figure 8: *PSO AND GA Validation Results*

The close agreement among HOMER, PSO, and GA validates the global optimality of the techno-economic model and strengthens confidence in the proposed hybrid energy system design for CBSS Nsukka. This dual-algorithm validation demonstrates that the optimal configuration is not algorithm-dependent but rather a true global solution under the defined constraints. The Particle Swarm Optimization (PSO) and Genetic algorithm (GA) validation was conducted independently using a Matlab-based script implementation we developed. All parameter bounds, constraints, and objective functions were derived directly from the HOMER Pro simulation parameters, without manual adjustment or data manipulation. The algorithms was executed under identical techno-economic conditions to ensure methodological consistency. Convergence results were obtained through iterative computation, as shown in the PSO vs GA convergence curve in Figure 9, confirming that the algorithms naturally approached HOMER's optimal configuration. The full PSO and GA scripts and input parameters are available upon request to enable reproducibility and independent verification of the findings.

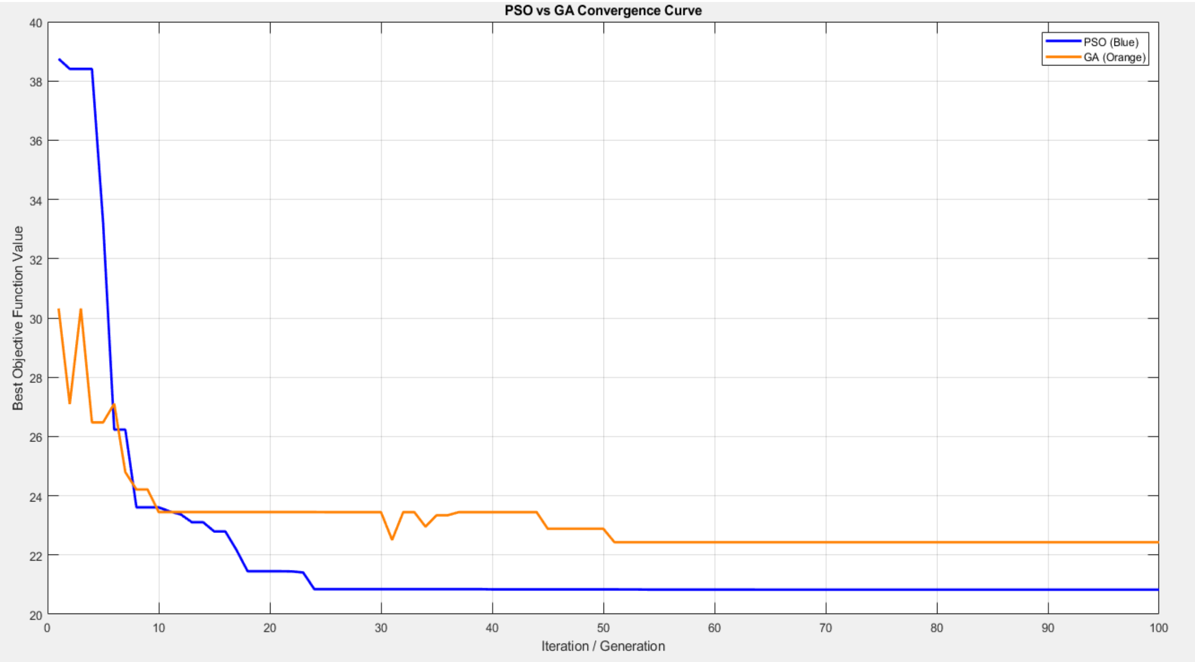


Figure 9: PSO VS GA Convergence Curve

V. CONCLUSION

This study successfully carried out a detailed load profiling and energy optimization audit of the Centre for Basic Space Science, Nsukka, Nigeria, with the objective of developing a reliable, economically viable, and environmentally sustainable energy solution for the research institution. The findings showed that the Centre possesses a relatively high peak electrical demand primarily driven by air-conditioning systems, laboratory equipment, office computing infrastructure, and lighting loads which attributed to the Nsukka's Climate. The evaluated Energy Use Intensity significantly exceeded recommended benchmarks for institutional buildings, thereby confirming the presence of substantial energy inefficiencies and the urgent need for energy optimization interventions in the Centre.

The techno-economic analysis conducted using Hybrid Optimization of Multiple Energy Resources software (HOMER) demonstrated that renewable integrated hybrid systems significantly outperform conventional diesel-dependent configurations in terms of operational cost, energy reliability, and environmental sustainability. Among the investigated alternatives, the system with the photovoltaic-battery-grid configuration emerged as the most optimal solution, achieving the lowest cost of energy (COE), high renewable energy penetration, zero unmet load, and complete elimination of diesel fuel consumption during normal operation. The integration of battery storage further enhanced energy reliability by ensuring uninterrupted supply during grid outages and periods of low solar irradiance.

The study also established that the proposed hybrid renewable system possesses strong long-term economic viability despite higher initial capital investment. Sensitivity analysis confirmed that the system remains financially attractive under varying inflation scenarios, while validation using Particle Swarm Optimization and Genetic Algorithm verified the robustness and global optimality of the obtained solution.

Furthermore, the significant reduction in greenhouse gas emissions highlights the environmental benefits of transitioning institutional facilities toward renewable-dominated energy architectures.

Overall, this research demonstrates that the integration of photovoltaic generation, battery storage, and intelligent energy optimization strategies can substantially improve energy efficiency, reduce operational expenditure, enhance supply reliability, and support sustainable development within research and educational institutions in Nigeria and other developing countries. The study therefore provides a practical framework for future institutional renewable energy deployment and energy management policy formulation.

REFERENCES:

[1]. Timothy OluwaseunAraoye, Evans ChinemezuAshigwuike, Sadiq Abubakar Umar, Taiwo Felix Adebayo , Sochima Vincent Egoigwe, Matthew Chinedu Odo , Chikammadu Emmanuel Opata , Ohagwu Walter Akachukwu, "Modeling and optimization of hybrid microgrid energy system: a case study of University of Abuja, Nigeria," International Journal of Power Electronics and Drive Systems (IJPEDS) Vol. 14, No. 2, June 2023, pp. 1201~1209 ISSN: 2088-8694, DOI:10.11591/ijpeds.v14.i2.pp1201-1209

[2]. O. E. Atiba, U. K. Efemwenkiekie, R. O. Olatunji, O. S. Ohunakin, D. S. Adelekan, and O. A. Oyeleke, "Walk-Through Energy Audit of An Institutional Building," *J. Phys.: Conf. Ser.*, vol. 1378, no. 3, p. 032051, 2019.

[3]. R. Hari Baskar, H. Mittal, M. S. Narkhede, and S. Chatterji, "Energy Audit – A Case Study," *Int. J. Emerg. Technol. Adv. Eng.*, vol. 4, Special Issue 1, pp. 73–77, 2014.

[4]. G. Sultana and H. H. U., "Electrical Energy Audit: A Case Study," *IOSR J. Electr. Electron. Eng.*, vol. 10, no. 3, pp. 1–6, 2015.

[5]. A. Rodriguez, ST. Smith, and B. Potter, "Sensitivity analysis for building energy audit calculation methods : Handling the uncertainties in small power load estimation", *Energy*, vol. 238, 121511, Jan. 2022

[6]. J. Woo and T. Moore, "An End-User-Focused Building Energy Audit: A High-Density Multi-residential Development in Melbourne, Australia," in *Energy Performance in the Australian Built Environment*, pp. 75–90, 2019.

[7]. S. Gamtessa and H. Guliani, "Are Households with Pro-environmental Behaviours More Likely to Undertake Residential Energy Efficiency Audits? Evidence from Canada," *Energy Efficiency*, vol. 12, no. 3, pp. 735–748, 2019.

[8]. C. Roberts, Y. Bobrova, and L. Marjanovic-Halburd, "Impacts of Energy Legislation on Organizational Motivation: A Case Study," *Build. Res. Inf.*, vol. 47, no. 2, pp. 234–244, 2019.

[9]. K. Cho and S. Kim, "Energy Performance Assessment According to Data Acquisition Levels of Existing Buildings," *Energies*, vol. 12, no. 6, p. 1149, 2019.

[10]. K. Wohlfarth, M. Klobasa, and A. Eßer, "Setting Course for Demand Response in the Service Sector," *Energy Efficiency*, vol. 12, no. 2, pp. 327–341, 2019.

[11]. J.-F. Akinbami and A. Lawal, "Opportunities and Challenges to Electrical Energy Conservation and CO_2 Emissions Reduction in Nigeria's Building Sector," *Fifth Urban Research Symposium, Cities and Climate Change*, pp. 28–30, 2009.

[12]. International Energy Agency, "World Energy Outlook 2021," Paris, France: IEA, 2021. [Online]. Available: https://www.iea.org/reports/world-energy-outlook-2021

[13]. ASHRAE, "Procedures for Commercial Building Energy Audits," 2nd ed., American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA, 2011.

[14]. A. Thumann and W. J. Younger, *Handbook of Energy Audits*, 9th ed. Lilburn, GA: Fairmont Press, 2012.

[15]. U.S. Department of Energy, "Advanced Energy Retrofit Guide: Practical Ways to Improve Energy Performance," DOE/EE-0826, 2014.

[16]. G. Kats, "Greening America's Schools: Costs and Benefits," Capital E, Washington D.C., 2006.

[17]. J. Granderson, M. A. Piette, G. Ghatikar, and P. Price, "Building energy information systems: User case studies," *Energy Efficiency*, vol. 4, no. 1, pp. 17–30, 2011.

[18]. T. Hong, S. C. Taylor-Lange, S. D'Oca, D. Yan, and S. P. Corgnati, "Advances in research and applications of energy-related occupant behavior in buildings," *Energy and Buildings*, vol. 116, pp. 694–702, 2016.

[19]. B. Dong and K. P. Lam, "A real-time model predictive control for building heating and cooling systems based on the occupancy behavior pattern detection and local weather forecasting," *Build. Simulation*, vol. 7, no. 1, pp. 89–106, 2014.

[20]. A. Trianni, E. Cagno, and S. Farné, "Barriers, drivers and decision-making process for industrial energy efficiency: A broad study among manufacturing small and medium-sized enterprises," *Applied Energy*, vol. 162, pp. 1537–1551, 2016.

[21]. European Parliament, "Directive 2012/27/EU on Energy Efficiency," Official Journal of the European Union, 2012.

[22]. Bureau of Energy Efficiency, "Energy Conservation Act, 2001 (Amended 2010)," Ministry of Power, Government of India.

[23]. T. Lambert, P. Gilman, and P. Lilienthal, "Micropower system modeling with Homer," in Integration of Alternative Sources of Energy, Hoboken, NJ, USA: John Wiley & Sons, Inc., 2006, pp. 379–418.

[24]. A. K. Yadav, H. Malik, S. S. Chandel, I. A. Khan, S. Al Otaibi, and H. I. Alkhammash, "Novel approach to investigate the influence of optimum tilt angle on minimum cost of energy-based maximum power generation and sizing of PV systems: a case study of diverse climatic zones in India," IEEE Access, vol. 9, pp. 110103–110115, 2021, doi: 10.1109/ACCESS.2021.3102153.

[25]. A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, M. F. Mohammed, and M. A. M. Ramli, "Feasibility analysis of grid-connected and islanded operation of a solar PV microgrid system: a case study of Iraq," Energy, vol. 191, p. 116591, Jan. 2020, doi: 10.1016/j.energy.2019.116591

[26]. K. Murugaperumal and P. Ajay D Vimal Raj, "Feasibility design and techno-economic analysis of hybrid renewable energy system for rural electrification," Solar Energy, vol. 188, pp. 1068–1083, Aug. 2019, doi: 10.1016/j.solener.2019.07.008.

[27]. M. Hossain, S. Mekhilef, and L. Olatomiwa, "Performance evaluation of a stand-alone PV-wind-diesel-battery hybrid system feasible for a large resort center in South China Sea, Malaysia," Sustainable Cities and Society, vol. 28, pp. 358–366, Jan. 2017, doi: 10.1016/j.scs.2016.10.008.

[28]. L. M. Halabi, S. Mekhilef, L. Olatomiwa, and J. Hazelton, "Performance analysis of hybrid PV/diesel/battery system using HOMER: a case study Sabah, Malaysia," Energy Conversion and Management, vol. 144, pp. 322–339, Jul. 2017, doi: 10.1016/j.enconman.2017.04.070.

[29]. T. M. Azerefegn, R. Bhandari, and A. V. Ramayya, "Techno-economic analysis of grid-integrated PV/wind systems for electricity reliability enhancement in Ethiopian industrial park," Sustainable Cities and Society, vol. 53, p. 101915, Feb. 2020, doi: 10.1016/j.scs.2019.101915. [29] A. S. Aziz, M. F. N. Tajuddin, M. R. Adzman, A. Azmi, and M. A. M. Ramli, "Optimization and

sensitivity analysis of standalone hybrid energy systems for ruralelectrification: a case study of Iraq," Renewable Energy, vol. 138, pp. 775–792, Aug. 2019, doi: 10.1016/j.renene.2019.02.004.

[30]. A. Aziz, M. Tajuddin, M. Adzman, M. Ramli, and S. Mekhilef, "Energy management and optimization of a PV/diesel/battery hybrid energy system using a combined dispatch strategy," Sustainability, vol. 11, no. 3, p. 683, Jan. 2019, doi: 10.3390/su11030683.

[31]. A. Nosrat and J. M. Pearce, "Dispatch strategy and model for hybrid photovoltaic and trigeneration power systems," Applied Energy, vol. 88, no. 9, pp. 3270–3276, Sep. 2011, doi: 10.1016/j.apenergy.2011.02.044.

[32]. T. O. Araoye, E. C. Ashigwuike, S. V. Egoigwe, F. U. Ilo, A. C. Adeyemi, and R. S. Lawal, "Modeling, simulation, and optimization of biogas-diesel hybrid microgrid renewable energy system for electrification in rural area," IET Renewable Power Generation, vol. 15, no. 10, pp. 2302–2314, Jul. 2021, doi: 10.1049/rpg2.12164.

[33]. Biskas, P.N.; Ziogos, N.; Tellidou, A.; Zoumas, C.; Bakirtzis, A.; Petridis, V.; Tsakoumis, A.L. Comparison of Two Metaheuristics with Mathematical Programming Methods for the Solution of OPF. In Proceedings of the 13th International Conference on Intelligent Systems Application to Power Systems, Arlington, VA, USA, 6–10 November 2005; pp. 510–515.

[34]. Timothy OluwaseunAraoye, C. A. Mgbachi, OlusholaAdebiyiOmosebi, Oluwaseun Damilola Ajayi and AdeleyeQasimOlaniyan, "Development of a Genetic Algorithm Optimization Model for Biogas Power Electrical Generation" EJERS, European Journal of Engineering Research and Science, Vol. 4, No. 2, February 2019