Bulletin of Electrical Engineering and Informatics
Vol. 15, No. 4, August 2026, pp. 2888~2899
ISSN: 2302-9285, DOI: 10.11591/eei.v15i4.10778

Integrated-grid energy system for supplying reliable electricity to health sectors using grey wolf optimizer algorithms

Olumuyiwa Ajibola Awoniyi[1], Evans Chinemezu Ashigwuike[1], Timothy Oluwaseun Araoye[2]
[1]Department of Electrical and Electronics Engineering, University of Abuja, Abuja, Nigeria
[2]Department of Mechatronic Engineering, University of Nigeria, Nsukka, Nigeria

Article Info

Article history:

Received May 30, 2025
Revised Apr 12, 2026
Accepted Jun 19, 2026

Keywords:

Cost of energy
Gray wolf optimization algorithm
Health centre
Hybrid microgrid
Net present cost
Techno-economic modeling

ABSTRACT

This study evaluates the techno-economic and environmental performance of various hybrid renewable energy system (HRES) optimized using the gray wolf optimization (GWO) algorithm, aimed at supplying reliable and sustainable energy to a health centre. Multiple system configurations were analyzed, including combinations of photovoltaic (PV), wind, diesel generator (DG), battery storage, and the electrical grid. Key performance metrics assessed include the cost of energy (COE), net present cost (NPC), payback period, annual utility bill savings, carbon dioxide (CO_2) emissions, and annual fuel consumption. Results indicate that all hybrid systems significantly outperform the conventional grid-only base case across all evaluated parameters. The base case exhibits the highest COE ($0.159/kWh) and CO_2 emissions (8,549 tons/year), underscoring the economic and environmental drawbacks of sole grid dependency. In contrast, the PV/wind/diesel/grid configuration achieved the lowest COE ($0.013676/kWh) and substantial reductions in emissions (2,349 tons/year), with a favorable payback period of 4.5 years. The optimization results highlight the effectiveness of GWO in balancing economic viability with environmental sustainability. Among the configurations, the PV/wind/grid and PV/wind/diesel/grid systems emerged as the most cost-effective and environmentally beneficial solutions. These findings highlight the potential of intelligently optimized hybrid renewable systems to deliver reliable, low-cost, and low-emission energy to critical infrastructure, such as healthcare centers.

Corresponding Author:

Olumuyiwa Ajibola Awoniyi
Department of Electrical and Electronics Engineering, University of Abuja
Abuja, Federal Capital Territory, Nigeria
Email: awoniyi.olumuyiwa@yahoo.com

1. INTRODUCTION

The International Energy Agency (IEA) highlights that power generation remains the largest contributor to global carbon dioxide (CO_2) emissions. Nevertheless, it is also leading the global transition toward net-zero emissions, fueled by the rapid expansion of renewable energy technologies. A major challenge in this transition is ensuring the consistent delivery of reliable and affordable electricity to consumers while significantly lowering global CO_2 emissions [1]. Renewable energy sources offer environmentally sustainable alternatives to fossil fuels, playing a crucial role in reducing greenhouse gas emissions, strengthening energy security, driving economic growth, combating climate change, and improving electricity access, particularly in remote or underserved regions. Consequently, the development of renewable energy is vital for establishing energy systems that are not only sustainable and cost-effective but also dependable and efficient. However, the intermittent and variable nature of renewable energy sources presents significant challenges in maintaining system reliability, grid stability, and power quality [2]. Energy storage systems present an effective solution to the challenges associated with maintaining a stable and uninterrupted electricity supply [3], [4]. Numerous types of energy storage technologies have been examined in the literature to mitigate these issues [5]. However, no single storage technology can comprehensively fulfill all operational demands due to inherent limitations in areas such as power and energy density, cost, lifespan, response time, and other performance metrics [6]. To overcome these constraints and balance the trade-offs, hybrid energy storage systems (HESS), which integrate two or more storage technologies, have emerged as a promising approach [7], [8].

Among the various configurations studied, the combination of batteries and ultracapacitors has shown notable effectiveness, where batteries manage the steady energy supply, and ultracapacitors respond to rapid fluctuations in power demand [9], [10]. Recent research has extensively explored the feasibility and optimization of microgrids and hybrid renewable energy systems (HRESs) in various institutional and regional contexts, aiming to enhance sustainability and cost-efficiency in energy management. Alhawsawi *et al.* [11] analyzed university campus microgrids, focusing on the availability, efficiency, cost, and environmental impact of key renewable energy sources such as geothermal, wind, and photovoltaic (PV) systems. The findings indicate that hybrid configurations, particularly PV-grid-connected systems offer the highest energy output with minimal complexity. However, the study notes challenges related to the variability of weather conditions affecting renewable generation. To address this, HOMER Pro software was employed for system optimization. The proposed solutions emphasize aligning energy generation with demand through distributed generation and incorporating energy storage to improve microgrid efficiency and resilience. Similarly, AlKassem *et al.* [12] examined the optimal design of a university-based microgrid in Saudi Arabia for integrating renewable sources. The results show that PV systems can generate 2.68 GWh annually cost of 0.051 USD/kWh, while wind systems produce 2.71 GWh but at a higher cost. A hybrid system demonstrated superior performance, yielding 3.27 GWh annually.

Despite challenges such as high upfront costs and wind variability, the study recommends hybrid systems as an effective strategy to balance economic viability and system reliability, supported by optimization using HOMER Pro. Paspatis *et al.* [13] evaluated the feasibility of implementing a smart campus microgrid at the Hellenic Mediterranean University to advance sustainability objectives. Their study identified a PV and battery-based system as the most effective solution, yielding a net present value (NPV) of USD 752,562.80 and significantly lowering greenhouse gas emissions. Despite these benefits, the high cost of battery storage was noted as a major limitation. However, sensitivity analysis conducted using HOMER Pro indicated that future reductions in battery prices could significantly improve the system's economic viability. Similarly, Ahmed *et al.* [14] conducted a feasibility assessment of a hybrid grid-connected energy system for Bangladesh's health and education sectors. The optimal configuration, comprising PV, diesel generators (DGs), and battery storage, achieved a cost of energy (COE) of USD 0.0291/kWh and a net present cost (NPC) of USD 2.3 million. Challenges identified included high diesel fuel expenses and reliance on grid connectivity. Optimization through HOMER Pro proposed improved system configurations to reduce emissions and enhance economic performance.

In another study, Akindeji and Ewim [15] analyzed the economic and environmental impacts of a grid-connected hybrid power system for a university campus in South Africa. Their findings indicated annual utility savings of approximately USD 820,000, a 51% reduction in CO_2 emissions, and a 20% return on investment with a payback period of four years. Although the system's high initial capital cost posed a challenge, HOMER Pro optimization recommended integrating solar PV and wind turbines to maximize both cost-effectiveness and environmental benefits.

Almohaimeed [16] examined the carbon emission reduction potential of a microgrid energy system implemented at Qassim University. The researcher key findings revealed a significant decrease in CO_2 emissions from 615.8 metric tons to 147.4 metric tons, demonstrating the system's positive environmental impact. However, the study highlighted high upfront installation costs as a primary limitation. Optimization using HOMER Pro recommended increasing PV capacity and energy storage to further lower emissions and enhance system reliability. In a related study, Pérez *et al.* [17] conducted a comprehensive review of HRES applications across various sectors, with a particular focus on microgrid design using HOMER Pro. The review concluded that integrating solar, wind, and biomass energy sources in HRES significantly reduces reliance on fossil fuels. Nonetheless, the authors noted high capital investment and technological limitations as key challenges. HOMER Pro was identified as an effective tool for optimizing sustainable energy configurations across different geographic and sectoral contexts. Similarly, Molu *et al.* [18] investigated the viability of a HRES comprising solar, wind, and biogas for Manoka Island in Cameroon. The study found the system to be economically feasible, with a competitive energy cost of $0.1981/kWh and a NPV of $2,209,741, highlighting its potential to provide cost-effective and sustainable energy for remote island communities.

The research conducted by Nassar *et al.* [19] emphasized the substantial renewable energy potential in Palestine, including PV generation at 1700 kWh/kWp, wind energy reaching up to 600 W/m² in mountainous regions, and biomass resources estimated at 1717 GWh. Their findings suggest that an optimized hybrid energy system could supply up to 82% of the total energy demand, thereby decreasing dependency on the national grid, lowering energy costs, and contributing to the fight against global warming. Similarly, Ali *et al.* [20]

demonstrated that integrating pumped hydro storage (PHS) with renewable energy sources (RESs) greatly improves the reliability and continuity of electricity supply in Hurghada, Egypt.

Utilizing the system advisory model (SAM) software, their study optimized both the levelized cost of energy (LCOE) and NPC, revealing cost-effective outcomes comparable to conventional power sources. Furthermore, Almihat and Kahn [21] showed that implementing an integrated control strategy for hybrid renewable energy microgrids significantly enhances economic and operational performance. Their approach, which coordinates the management of solar, wind, diesel, and battery systems, effectively increases renewable energy penetration, reduces dependence on DG, and boosts overall system efficiency. El-Khozondar *et al.* [22] showed that replacing conventional lighting with LED lamps in a solar-powered system significantly reduced component requirements, cutting the number of batteries from 56 to 22 and solar panels from 20 to 8, resulting in substantial cost savings. The optimized configuration achieved a LCOE of $0.12 per kWh and a 30% reduction in NPC, thereby improving the system's overall efficiency and sustainability for street lighting applications.

In a separate study, Nassar *et al.* [23] proposed a HRES that integrates a parabolic dish solar concentrator with a biomass digester to deliver sustainable electricity, heating, and cooking gas in Brack City, Libya. The system demonstrated a payback period of 20.04 years, a capital investment of $12.37 million, and an annual CO_2 emission reduction of 7.8 kilotons, highlighting its environmental and economic viability. Additionally, the study by Hakizimana *et al.* [24] focused on the deployment of a grid-connected PV system at the SULFO Industry soap manufacturing facility. The system produces 502.2 MWh of electricity annually and achieves a 10-year payback period. It also significantly cuts energy expenses from $87,432.90 to $37,526.12 and reduces CO_2 emissions by 6,555.1 tons. These findings underscore the dual financial and environmental benefits of integrating solar PV technology into industrial operations.

Previous studies have explored HRESs for campuses, industries, and rural communities, often optimized using tools such as HOMER Pro or simulation-based analyses. While these works investigated economic feasibility, environmental impact, and technical performance, researchers did not explicitly address the unique reliability and sustainability needs of healthcare facilities in metropolitan regions. Moreover, most prior research emphasized cost minimization without integrating advanced metaheuristic optimization for balancing emissions reduction with resilience. This study bridges these gaps by applying the grey wolf optimization (GWO) algorithm to design hybrid systems that ensure affordable, sustainable, and uninterrupted electricity for critical health infrastructure. By integrating solar PV, wind, diesel, battery storage, and grid supply, the study evaluates multiple configurations using techno-economic and environmental metrics such as COE, NPC, payback period, fuel consumption, and CO_2 emissions. The GWO algorithm is applied to identify the most efficient system. The objective is to minimize costs and emissions while ensuring energy security, resilience, and sustainability for critical healthcare infrastructure.

2. METHOD

This study employs a techno-economic and environmental assessment of various HRES configurations for a health centre in Apo Community. The primary objective is to evaluate different system combinations involving solar PV, wind turbines, DG, and battery storage integrated with the grid, and to identify the most cost-effective and environmentally sustainable solution using GWO. Solar PV output was calculated using derating factor, rated array capacity, and incident solar radiation. Wind turbine output was derived from cut-in, rated, and cut-out wind speeds. DG output included lifetime, fuel curve coefficients, fuel price, and O&M costs. Battery storage was modeled with charging/discharging efficiencies, depth of discharge, and self-discharge rate. Inverter model accounted for efficiency, investment, replacement, and maintenance costs. Grid model balanced local demand with hybrid system output. The methodological framework is structured in three main phases: load assessment, system modelling and simulation, and optimization. The GWO algorithm was applied to minimize COE and CO_2 emissions, while maximizing savings and system reliability. The GWO was implemented in MATLAB, simulating the hunting and leadership behavior of wolves (Alpha, Beta, Delta) to search for optimal solutions.

2.1. Load profile and system requirements

The energy demand of the health centre is collected based on typical operational needs over 8,650 hours annually. This reflects a realistic scenario for healthcare facilities with continuous power demand. The load profile is collected for hourly variations throughout the year. The base case assumes a complete dependence on grid electricity, serving as a reference for comparative evaluation.

2.2. System configuration and modelling

Six configurations were analyzed: i) PV/battery/grid, ii) PV/wind/diesel/grid, iii) PV/wind/battery/grid, iv) PV/wind/grid, v) wind/diesel/grid, and vi) the base case (grid only). Each configuration is modelled based on the integration of renewable and non-renewable energy sources and their corresponding storage systems. Key performance metrics include COE, NPC, annual utility bill savings, CO_2 emissions, and annual fuel consumption. The economic modelling incorporates capital costs, replacement costs, operational and maintenance costs, and fuel prices [22]. Figure 1 shows the health centre load profile, Figure 2 shows wind speed, and Figure 3 shows health centre temperature.

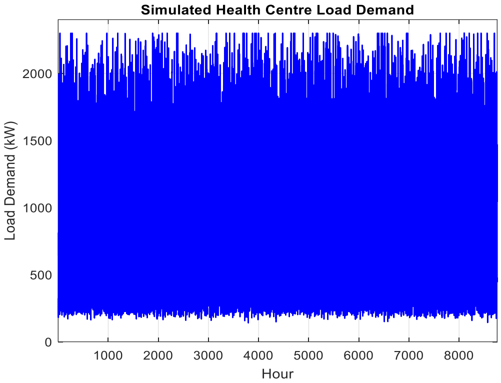


Figure 1. Health centre load profile

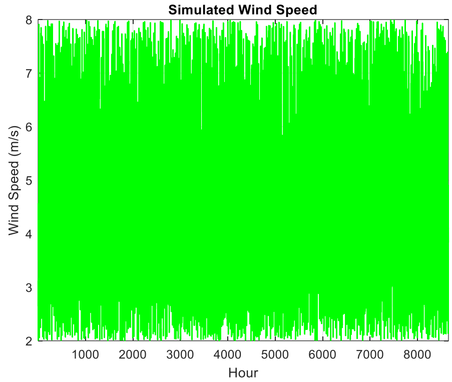


Figure 2. Wind speed

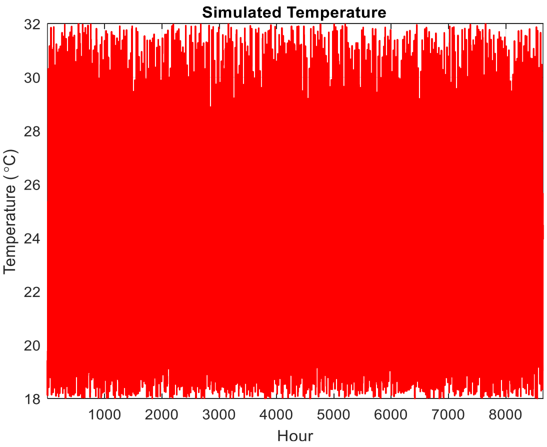


Figure 3. Health centre temperature

2.3. Inverter model

The inverter requires an upfront investment of $85 per kW. Operating and maintenance costs make up 1% of the investment cost, while replacement costs are anticipated to provide for 90% of the total cost [24]:

$$P_{opt} = P_i + \eta_{inv} \tag{1}$$

where P_{opt} is the power supply, P_i is the power input, and η_{inv} is the inverter performance.

2.4. Grid model

As shown in (2), it precisely expresses the balance between the load requirements of the grid-connected mode and the generator's energy generation:

$$Power\ Net\ equilibrium = P_{gen} - P_l \tag{2}$$

In the integrated-grid mode, P_l is the electrical power consumption or load, while P_{gen} is the electricity produced by the hybrid power configuration.

2.5. Mathematical modeling of solar photovoltaic system

The PV panels power output equation applied in HOMER is shown (3) [14]:

$$P_{pv} = Y_o V_{pv} \frac{I_T}{I_S} \quad (3)$$

where Y_o is the P.V. derating factor, V_{pv} is the rated P.V. array capacity (kw), $I_{.T.}$ is the P.V. array global radiation solar incident (kW/m^2), and I_s is the standard capacity of P.V. array radiation (1 kW/m^2).

2.6. Mathematical modeling of wind turbine system

The wind turbine power output equation applied in HOMER is shown (4) [15]:

$$P_w(t) = \begin{Bmatrix} 0,\ V(t) < V_d \\ qV(t^3) - wP_n, V_d < V(t) < V_n \\ P_n, V_n < V(t) < V_{dc} \\ 0, V(t) > V_{dc} \end{Bmatrix} \quad (4)$$

where P_n is the rated mean power, V_d is the wind speed cut-in, V_{dc} is the wind speed cut-out, and V_n is the estimated wind speed.

2.7. Mathematical modeling of diesel generator system

The DG power output equation applied in HOMER is shown (5) [14]:

$$F_{Gen} = C_{om} + \frac{C_r}{R_L} + F_n X_{Gen} C_{eff} \quad (4)$$

where C_{om} is the maintenance and operational 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 the capacity of the generator (kW), and C_{eff} is the effective fuel price ($/L).

2.8. Modeling of the battery storage system

The state of charge (S_oC) at a definite time (t) is determined considering the demand balance between the load and the P.V. hybrid system. It is expressed using (6) and (7) [16]:

$$E_{bb}(t+1) = E_{bb}(t)(1-\sigma) + surplus\ power * \eta_{BC} \quad \text{Charging mode} \quad (6)$$

$$E_{bb}(t+1) = E_{bb}(t)(1-\sigma) - \frac{deficit\ power}{\eta_{BD}} \quad \text{Discharging mode} \quad (7)$$

where, E_{bb} is the output energy of the battery bank, η_{BC} is the battery charging efficiency, and η_{BD} is the battery discharging efficiency. Finally, σ is the self-discharging rate of the battery; it is taken as 0.2% per day for most batteries.

The constraints on the system's battery bank at any time are represented using (8) and (9):

$$E_{bb,min} \le E_{bb}(t) \le E_{bb,max} \quad (8)$$

$$E_{bb}(t+1) = E_{bb}(t)(1-\sigma) \quad (9)$$

where, $E_{bb,max}$, is the maximum acceptable battery storage capacity, while $E_{bb,min}$ is the minimum acceptable battery storage capacity. $E_{bb,min}$ can be obtained with (10):

$$E_{bb,min} = D_o D \times E_{BR} \quad (10)$$

where, D_oD is the battery bank's maximum discharge depth, while $E_{.B.R.}$ is the battery bank's total nominal storage capacity.

2.9. Optimization using gray wolf optimization

GWO, a nature-inspired metaheuristic algorithm, is employed to identify the optimal configuration. GWO is particularly suitable for nonlinear, multi-objective problems involving system design and cost minimization [25]. The algorithm simulates the social hierarchy and hunting mechanism of gray wolves, including encircling, hunting, and attacking prey, which in this context translates to minimizing COE and emissions while maximizing utility bill savings. Simulation and optimization are executed using MATLAB, where the cost functions and system constraints are encoded. The performance of each configuration is evaluated across economic and environmental dimensions, and comparative results are tabulated for analysis.

Algorithm 1. Pseudocode for GWO

```
1. Initialize grey wolf population Xi (i = 1 to n)
- Load profile (hourly demand)
      - PV, wind, diesel, battery, grid cost data
      - Technical specifications (efficiency, lifetime, fuel price, etc.)
      - Emission factors.
2. Set maximum iterations (Max_iter)
- Minimize COE
      - Minimize CO₂ emissions
      - Maximize utility bill savings and reliability
3. Evaluate fitness of all wolves
      - Each wolf = vector of decision variables (PV size, wind size, diesel capacity, battery
   size)
4. Identify Alpha (best), Beta (second best), Delta (third best)
For t = 1 to Max_iter:
    For each wolf Xi:
        For each dimension j:
            Compute A and C (coefficient vectors)
            Update position using Alpha, Beta, and Delta:
                Xi_j = (X_alpha + X_beta + X_delta) / 3
5. Update a (linearly from 2 to 0)
6. Recalculate fitness
7. Update Alpha, Beta, and Delta based on new fitness
  - Optimal system configuration
      - Corresponding COE, NPC, payback, savings, CO₂ emissions
        Return Alpha as the best solution
```

3. RESULTS AND DISCUSSION

This section presents a comprehensive analysis of different HRES configurations simulated and optimized for powering a health centre. Table 1 presents the comparative techno-economic and environmental performance metrics of the different hybrid renewable energy configurations optimized using the GWO algorithm. The result summarizes key indicators including COE, NPC, payback period, annual utility bill savings, CO_2 emissions, and annual fuel consumption. These parameters provide a quantitative basis for evaluating the effectiveness of each configuration relative to the base case grid-only system. The results highlight the trade-offs between cost, sustainability, and reliability, thereby guiding the identification of the most optimal system for healthcare facilities.

Table 1. Results of economic and emission metrics for the health centre using GWO

Economic evaluation	(Grid)	PV/batt/grid	PV/wind/ diesel/grid	PV/wind/ battery/grid	PV/wind/ grid	Wind/diesel/ grid
COE ($/kWh)	0.159	0.013676	0.01673	0.013918	0.013846	0.014256
NPC ($)	7,142,582	4,868,420.63	5,955,544.43	4,954,506.84	4,929,267.29	5,130,784.16
Payback (years)	NA	4.5	5.1	4.5	4.2	4.7
Annual utility bill saving ($)	NA	795,625.92	801,714.63	798,734	797,543	799,429
CO_2 emission (ton/years)	8,549	2,349	2,997	2,474	2,425	2,745
Annual fuel consumption (L/year)	NA	NA	538	NA	NA	524

3.1. Base case: grid only

The base case represents complete reliance on the national electricity grid, without any renewable or backup power systems. This configuration incurred the highest COE at $0.159/kWh and the NPC of $7,142,582, which serves as a benchmark for comparative analysis. Additionally, this system produced 8,549 tons of CO_2 emissions annually, the highest among all configurations, indicating a heavy dependence on fossil-fuel-powered grid energy. No capital investment is required, but this model lacks resilience to outages and offers no savings or sustainability benefits. This underscores the necessity of incorporating renewable energy systems for long-term financial and environmental gains.

3.2. Photovoltaic/battery/grid system

This configuration combines PV panels, battery energy storage, and grid electricity. It was one of the most cost-effective systems, with a COE of $0.013676/kWh and an NPC of $4,868,420.63. The payback period is 4.5 years, and it achieves annual utility bill savings of $795,625.92. The carbon emissions are drastically reduced to 2,349 tons/year, which indicates a 72.5% improvement over the base case. This configuration is especially suitable for areas with high solar irradiance and moderate grid reliability. It minimizes fossil fuel use and operating costs while providing sustainable and reliable power for critical health centre operations.

3.3. Photovoltaic/wind/diesel/grid system

This system integrates four sources: PV panels, wind turbines, a DG, and the grid. It provides a COE of $0.01673/kWh and an NPC of $5,955,544.43, with a payback period of 5.1 years. It offers the highest utility savings ($801,714.63/year) among all configurations. Despite including a DG, the system consumes only 538 liters of fuel annually and emits 2,997 tons of CO_2/year, which is still a significant reduction (about 65%) compared to the base case. This configuration offers excellent reliability and resilience for off-grid or intermittently connected areas, with moderate environmental impact due to low diesel usage.

3.4. Photovoltaic/wind/battery/grid system

This four-component system substitutes the DG with a battery, making it a cleaner alternative. It achieves a COE of $0.013918/kWh, an NPC of $4,954,506.84, and a payback period of 4.5 years. The annual savings are $798,734, and emissions are 2,474 tons/year, slightly higher than the PV/battery/grid system but better than any diesel-inclusive design. This configuration is ideal for environmentally sensitive regions with favorable wind and solar resources. It balances sustainability, performance, and cost efficiency, making it a strong candidate for remote or semi-urban health facilities.

3.5. Photovoltaic/wind/grid system

This configuration excludes both battery and DG, relying on wind and solar systems supported by the grid. It results in a COE of $0.013846/kWh, an NPC of $4,929,267.29, and the shortest payback period of 4.2 years. Annual utility savings are approximately $797,543, while emissions are 2,425 tons/year, the second-lowest after the PV/battery/grid system. This system is financially efficient and environmentally sustainable, suitable for regions with stable grid infrastructure and favorable climate conditions. However, it may not provide sufficient resilience during grid failures.

3.6. Wind/diesel/grid system

This system combines wind turbines with a DG and grid connection, excluding solar PV. It results in a COE of $0.014256/kWh, an NPC of $5,130,784.16, and a payback period of 4.7 years. Annual savings are $799,429, and CO_2 emissions are 2,745 tons/year. It uses 524 liters of diesel per year, indicating efficient backup usage. This setup may be more viable in windy coastal or elevated areas but is less ideal than PV-inclusive designs in most cases due to higher emissions and fuel dependency. Figures 4 and 5 shows COE and NPC of the configuration respectively.

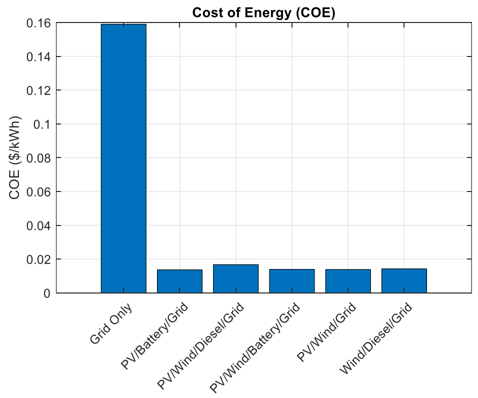


Figure 4. COE of the configuration

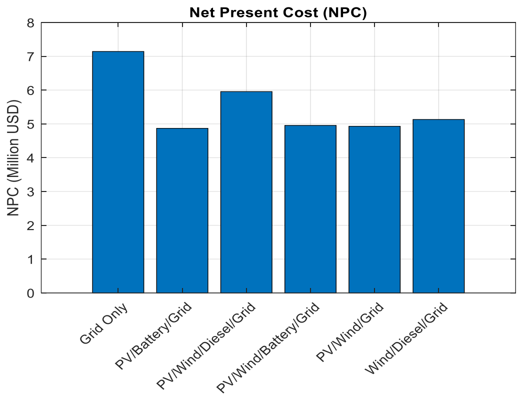


Figure 5. NPC of the configuration

The base case presents the highest COE, suggesting that relying solely on the conventional power grid is the most expensive option over time. This is consistent with literature indicating that grid electricity in regions with high fossil fuel dependency incurs higher long-term costs due to fluctuating fuel prices and infrastructure inefficiencies. All hybrid systems significantly reduce the COE. The lowest COE is observed in the PV/battery/grid system, closely followed by PV/wind/grid and PV/wind/battery/grid, indicating that systems with battery storage are economically favorable when well-optimized. The inclusion of diesel increases the COE slightly due to fuel costs and generator maintenance, though it remains much cheaper than the base case. This result demonstrates that hybrid systems, particularly those dominated by renewable sources with minimal reliance on fossil fuels, are more cost-effective in the long term. It also highlights the effectiveness of GWO in identifying optimal configurations that minimize lifecycle energy costs. Again, the base case results in the highest NPC, reinforcing the economic disadvantage of conventional grid reliance. The PV/battery/grid and PV/wind/grid systems achieve the lowest NPCs, showing that investment in renewables yields lower lifecycle costs. The slightly higher NPC for the PV/wind/battery/grid configuration is due to additional investment in both wind and storage technologies, which although increases capital cost, provide long-term stability and resilience. Figure 6 shows annual utility bill savings, Figure 7 shows CO_2 emissions, and Figure 8 shows annual fuel consumption.

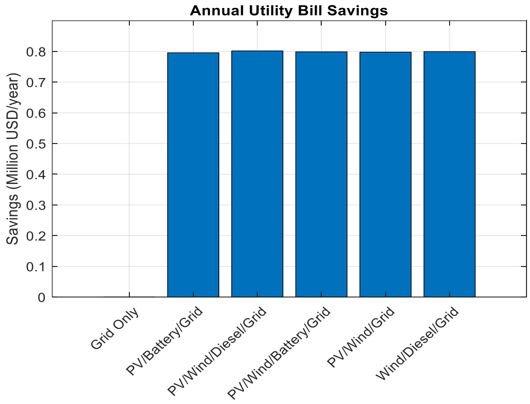


Figure 6. Annual utility bill savings

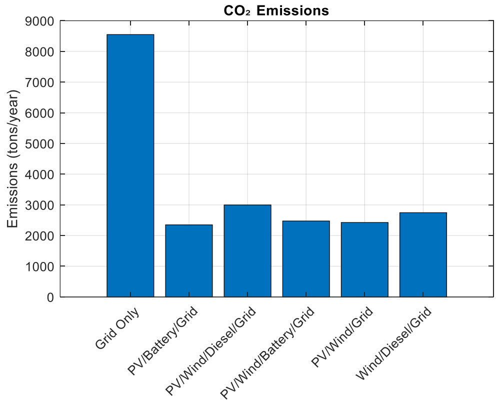


Figure 7. CO_2 emissions

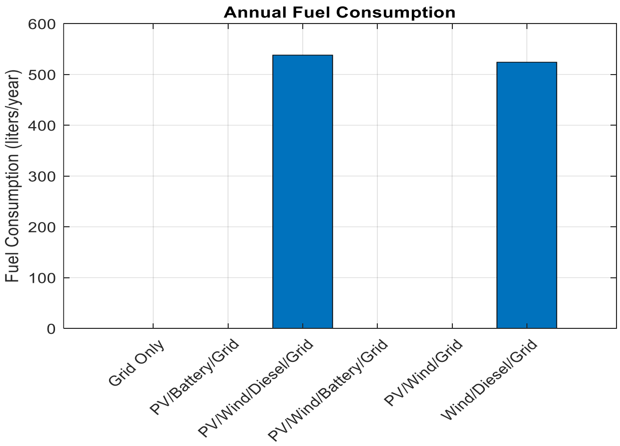


Figure 8. Annual fuel consumption

Interestingly, PV/wind/diesel/grid and wind/diesel/grid have higher NPCs than most PV-based systems despite diesel's lower upfront cost. This is attributable to recurring fuel expenditures and generator maintenance over time. Thus, while diesel offers operational flexibility, it imposes significant long-term financial burdens, validating global trends that discourage diesel reliance. All hybrid systems present short payback periods ranging between 4.2 and 5.1 years, which is highly favorable in institutional settings such as health centres. The PV/wind/grid configuration offers the shortest payback time, indicating the system's rapid cost recovery despite no diesel or battery backup. This also demonstrates the economic advantage of integrating wind energy in locations where wind potential is favorable. The PV/wind/diesel/grid system has the longest payback period due to fuel costs, although it still performs significantly better than the grid-only model. These results underscore the attractiveness of hybrid systems not only from a sustainability standpoint but also for financial planning and investment recovery. Utility bill savings represent recurring operational benefits from reduced grid reliance. All hybrid configurations yield significant annual utility bill savings, emphasizing the operational cost advantages of energy independence.

The PV/wind/diesel/grid system delivers the highest savings, possibly due to strategic optimization where diesel is used only when necessary, allowing the renewables to dominate the load. Even systems with higher NPCs, such as PV/wind/battery/grid, offer nearly equivalent annual savings, making them favorable in the long term. These results strongly advocate for renewable energy investment, as savings in operational expenditure can be redirected to essential healthcare services. The base case has the highest emissions, emphasizing the environmental cost of grid electricity in regions powered predominantly by fossil fuels. In contrast, all hybrid systems achieve substantial reductions in CO_2 emissions, with the best performance observed in the PV/battery/grid, PV/wind/grid, and PV/wind/battery/grid configurations. These systems cut emissions by over 70%, demonstrating their potential to contribute toward climate targets and improve air quality in surrounding communities. The wind/diesel/grid and PV/wind/diesel/grid systems, while higher in emissions than PV-only systems, still significantly outperform the base case. These results suggest that diesel can be retained as a minimal-use backup in hybrid systems, provided its operation is strictly optimized through algorithms such as GWO. All hybrid systems outperform the base grid-only system across economic and environmental parameters.

The PV/battery/grid and PV/wind/grid systems offer the lowest COE and NPC, making them the most economically attractive. The inclusion of batteries enhances resilience but slightly increases NPC, while DG introduce minor emissions but boost reliability in energy-deficient periods. Overall, the results validate that a properly optimized HRES can achieve significant cost reductions, reliability enhancements, and sustainability improvements for healthcare infrastructure. Health centres require highly reliable energy systems to support critical operations, diagnostics, and patient care. Frequent grid outages or cost volatility can severely impact service delivery. This analysis illustrates that GWO-optimized hybrid systems not only reduce costs but also drastically enhance sustainability and energy security. The results also indicate that health centres can transition away from sole grid dependency without compromising reliability. Moreover, the significant utility bill savings and short payback periods support reinvestment in healthcare resources. Institutions can thus align their operations with global climate goals while strengthening service resilience.

The study demonstrated that HRESs optimized with the GWO algorithm significantly outperform the grid-only base case. The PV/battery/grid system achieved the lowest COE ($0.013676/kWh) and CO_2 emissions (2,349 tons/year), while the PV/wind/grid configuration delivered the shortest payback period (4.2 years). All hybrid models reduced emissions by over 65%, with substantial annual utility savings exceeding $795,000. Although diesel-inclusive systems improved reliability, they contributed modest emissions and fuel use. The research findings offer definitive proof that optimized HRESs, particularly PV/battery/grid and PV/wind/grid configurations, drastically reduce COE and emissions while maintaining reliability. This improvement is linked to the intelligent system design enabled by the GWO algorithm, rather than being caused by increased fossil fuel use.

The results confirm that integrating solar and wind resources with minimal diesel reliance enhances sustainability, resilience, and economic viability for critical healthcare infrastructure. Overall, results confirm that optimized hybrid systems provide cost-effective, sustainable, and resilient power solutions for healthcare facilities. The comparison in Table 2 highlights the improvement of this study compare to literature studied. While previous works, such as in [11], [14], demonstrated the feasibility of hybrid renewable systems using HOMER Pro, the COE values (0.029–0.198 $/kWh) and payback periods were less favorable. In [15], [16] reported significant emission reductions (51–76%) but faced challenges of high upfront costs and longer recovery times. In contrast, the present study achieved the lowest COE (0.0137 $/kWh), substantial emission cuts (72.5%), and the shortest payback period (4.2–5.1 years) using GWO, ensuring healthcare resilience.

Table 2. Comparison of present study with recent literature

Study and year	Application context	Optimization/tool	COE ($/kWh)	CO_2 emissions	Payback period
Present study, 2025	Metropolitan healthcare facility	GWO	0.0137 (PV/batt/grid)	72.5% (2,349 t/yr)	4.2–5.1 yrs
[11] (2024)	University campus microgrid	HOMER Pro	~0.051 (PV)	Not stated	Not stated
[14] (2023)	Health and education sectors (Bangladesh)	HOMER Pro	0.0291 (PV/diesel/batt)	Not detailed	NPC $2.3M
[15] (2023)	University campus (South Africa)	HOMER Pro	Not stated	51% vs grid	4 yrs
[16] (2023)	University office complex (Saudi Arabia)	HOMER Pro	Not stated	76% (615.8 147.4 tCO_2)	Not stated
[17] (2024)	General HRES applications	HOMER Pro (surveyed)	~0.198 (off-grid cases)	Large reductions, context-dependent	Up to 20 yrs

4. CONCLUSION

The integration of renewable energy systems in healthcare facilities is becoming increasingly critical in light of growing energy demands, environmental concerns, and the need for a reliable, uninterrupted power supply. This study explored the techno-economic and environmental viability of various HRES configurations for a health centre, utilizing the GWO algorithm for system optimization. Six configurations were evaluated, including combinations of PV, wind, DG, battery storage, and the conventional electrical grid. Performance metrics such as COE, NPC, payback period, utility bill savings, CO_2 emissions, and annual fuel consumption were systematically assessed and compared with a conventional grid-only base case. The findings demonstrate unequivocally that all HRESs significantly outperformed the grid-only scenario in terms of both economic and environmental performance. The base case, dependent solely on grid electricity, recorded the highest COE ($0.159/kWh) and the highest carbon footprint, emitting 8,549 tons of CO_2 per year. These results reflect the inefficiency and unsustainability of continuing with grid dependency, particularly in healthcare settings where energy reliability and sustainability are paramount.

Among the hybrid systems, the PV/wind/diesel/grid configuration emerged as the most cost-effective option with the lowest COE ($0.013676/kWh) and a notably reduced NPC of $4.87 million. This configuration also demonstrated substantial environmental benefits, reducing CO_2 emissions by over 70% compared to the base case, while maintaining a moderate payback period of 4.5 years. The inclusion of a DG in this configuration, although traditionally viewed as environmentally detrimental, was optimized to operate minimally. This strategic deployment resulted in low annual fuel consumption (538 L/year), confirming the GWO algorithm's effectiveness in minimizing diesel reliance without compromising system reliability.

Among the evaluated configurations, PV/wind/grid and PV/wind/diesel/grid systems stand out for their excellent balance of low cost, high reliability, and minimal environmental impact. For health centres in remote or underserved areas with limited grid reliability, these systems offer a practical and scalable solution. While diesel-inclusive systems demonstrated strong economic performance, their carbon footprint, though significantly reduced compared to the base case, indicates that such systems should be considered transitional solutions. Policymakers and energy planners should focus on phasing out fossil fuel components over time as battery technologies improve and become more affordable. The findings mean that metropolitan health centres can improve energy security, cut operating costs, and contribute to climate goals simultaneously. Beyond healthcare, the approach can be extended to schools, industries, and rural electrification projects.

Future research should explore integration with smart grids, advanced storage technologies, and policy frameworks to ensure scalability, resilience, and long-term sustainability. Additionally, practical methods for combining GWO with other metaheuristic or artificial intelligence (AI)-driven controllers could be explored to improve system adaptability under uncertain demand and weather conditions. Field validation through pilot healthcare projects and integration with smart grid frameworks would provide deeper insights into scalability, long-term resilience, and real-world operational performance. Incorporating a sensitivity analysis by varying key parameters within ±10–20% would improve robustness and demonstrate how resilient the optimized solutions are under real-world uncertainties.

ACKNOWLEDGMENTS

The authors acknowledge the support received from the Department of Electrical and Electronic Engineering, University of Abuja.

FUNDING INFORMATION

This research has not received any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. The article processing charges and publication expenses are privately supported by the authors.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Olumuyiwa Ajibola Awoniyi	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓
Evans Chinemezu Ashigwuike				✓	✓	✓				✓	✓	✓	✓	
Timothy Oluwaseun Araoye			✓	✓	✓	✓				✓	✓		✓	

C : **C**onceptualization	I : **I**nvestigation	Vi : **Vi**sualization
M : **M**ethodology	R : **R**esources	Su : **Su**pervision
So : **So**ftware	D : **D**ata Curation	P : **P**roject administration
Va : **Va**lidation	O : Writing - **O**riginal Draft	Fu : **Fu**nding acquisition
Fo : **Fo**rmal analysis	E : Writing - Review & **E**diting	

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available upon request from the corresponding author.

REFERENCES

[1] C. D. Y. de L. E. Çam, Z. Hungerford, N. Schoch, and F. P. Miranda, "Electricity 2024: Analysis and forecast to 2026," IEA, 2024. [Online]. Available: https://www.iea.org/news/global-coal-demand-expected-to-decline-in-coming-years.

[2] T. Sutikno, W. Arsadiando, A. Wangsupphaphol, A. Yudhana, and M. Facta, "A review of recent advances on hybrid energy storage system for solar photovoltaics power generation," *IEEE Access*, vol. 10, pp. 42346–42364, 2022, doi: 10.1109/ACCESS.2022.3165798.

[3] S. Barakat, A. Emam, and M. M. Samy, "Investigating grid-connected green power systems' energy storage solutions in the event of frequent blackouts," *Energy Reports*, vol. 8, pp. 5177–5191, Nov. 2022, doi: 10.1016/j.egyr.2022.03.201.

[4] G. G. Farivar *et al.*, "Grid-connected energy storage systems: State-of-the-art and emerging technologies," in *Proceedings of the IEEE*, vol. 111, no. 4, pp. 397–420, Apr. 2023, doi: 10.1109/JPROC.2022.3183289.

[5] A. N. Abdalla *et al.*, "Integration of energy storage system and renewable energy sources based on artificial intelligence: An overview," *Journal of Energy Storage*, vol. 40, Aug. 2021, doi: 10.1016/j.est.2021.102811.

[6] A. F. Guven, A. Y. Abdelaziz, M. M. Samy, and S. Barakat, "Optimizing energy dynamics: A comprehensive analysis of hybrid energy storage systems integrating battery banks and supercapacitors," *Energy Conversion and Management*, vol. 312, Jul. 2024, doi: 10.1016/j.enconman.2024.118560.

[7] K. M. Tan, T. S. Babu, V. K. Ramachandaramurthy, P. Kasinathan, S. G. Solanki, and S. K. Raveendran, "Empowering smart grid: A comprehensive review of energy storage technology and application with renewable energy integration," *Journal of Energy Storage*, vol. 39, Jul. 2021, doi: 10.1016/j.est.2021.102591.

[8] J. I. Leon, E. Dominguez, L. Wu, A. M. Alcaide, M. Reyes, and J. Liu, "Hybrid energy storage systems: Concepts, advantages, and applications," *IEEE Industrial Electronics Magazine*, vol. 15, no. 1, pp. 74–88, Mar. 2021, doi: 10.1109/MIE.2020.3016914.

[9] M. S. Hassan, S. Hassan, M. R. M. Hassan, A.-H. M. El-Sayed, M. Shoyama, and G. M. Dousoky, "Performance improvement of a standalone PV system using supercapacitors: Modeling and energy management," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 15, no. 1, pp. 222–238, Mar. 2024, doi: 10.11591/ijpeds.v15.i1.pp222-238.

[10] M. E. Şahin and F. Blaabjerg, "A hybrid PV-battery/supercapacitor system and a basic active power control proposal in MATLAB/Simulink," *Electronics*, vol. 9, no. 1, pp. 1-17, Jan. 2020, doi: 10.3390/electronics9010129.

[11] E. Y. Alhawsawi, K. Salhein, and M. A. Zohdy, "A comprehensive review of existing and pending University campus microgrids," *Energies*, vol. 17, no. 10, pp. 1-29, May 2024, doi: 10.3390/en17102425.

[12] A. AlKassem, A. Draou, A. Alamri, and H. Alharbi, "Design analysis of an optimal microgrid system for the integration of renewable energy sources at a university campus," *Sustainability*, vol. 14, no. 7, pp. 1-20, Mar. 2022, doi: 10.3390/su14074175.

[13] A. Paspatis, K. Fiorentzis, Y. Katsigiannis, and E. Karapidakis, "Smart campus Microgrids towards a sustainable energy transition—the case study of the Hellenic Mediterranean university in Crete," *Mathematics*, vol. 10, no. 7, pp. 1-19, Mar. 2022, doi: 10.3390/math10071065.

[14] M. R. Ahmed, M. R. Hasan, S. Al Hasan, M. Aziz, and M. E. Hoque, "Feasibility study of the grid-connected hybrid energy system for supplying electricity to support the health and education sector in the metropolitan area," *Energies*, vol. 16, no. 4, pp. 1-23, Feb. 2023, doi: 10.3390/en16041571.

[15] K. T. Akindeji and D. R. E. Ewim, "Economic and environmental analysis of a grid-connected hybrid power system for a University Campus," *Bulletin of the National Research Centre*, vol. 47, no. 1, May 2023, doi: 10.1186/s42269-023-01053-6.

[16] S. A. Almohaimeed, "Techno-environmental analysis of a microgrid energy system in a university office complex," *Sustainability*, vol. 15, no. 16, pp. 1-27, Aug. 2023, doi: 10.3390/su151612506.

[17] D. A. P. Uc, S. E. de L. Aldaco, and J. A. Alquicira, "Trends in hybrid renewable energy system (HRES) applications: A review," *Energies*, vol. 17, no. 11, pp.1-34, May 2024, doi: 10.3390/en17112578.

[18] R. J. J. Molu *et al.*, "Optimizing technical and economic aspects of off-grid hybrid renewable systems: A case study of Manoka Island, Cameroon," *IEEE Access*, vol. 11, pp. 130909–130930, 2023, doi: 10.1109/ACCESS.2023.3332693.

[19] Y. F. Nassar, H. J. El-Khozondar, M. Elnaggar, F. F. El-batta, R. J. El-Khozondar, and S. Y. Alsadi, "Renewable energy potential in the State of Palestine: Proposals for sustainability," *Renewable Energy Focus*, vol. 49, Jun. 2024, doi: 10.1016/j.ref.2024.100576.

[20] A. F. M. Ali, E. M. H. Karram, Y. F. Nassar, and A. A. Hafez, "Reliable and economic isolated renewable hybrid power system with pumped hydropower storage," in *2021 22nd International Middle East Power Systems Conference (MEPCON)*, Dec. 2021, pp. 515–520, doi: 10.1109/MEPCON50283.2021.9686233.

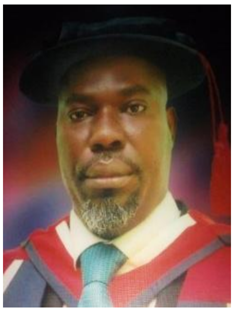
[21] M. M. G. Almihat and M. M. T. E. Kahn, "Design and implementation of hybrid renewable energy (PV/wind/diesel/battery) microgrids for rural areas," *Solar Energy and Sustainable Development Journal*, vol. 12, no. 1, pp. 71–95, Aug. 2023, doi: 10.51646/jsesd.v12i1.151.

[22] H. J. El-Khozondar *et al.*, "Photovoltaic solar energy for street lighting: A case study at Kuwaiti roundabout, Gaza strip, Palestine," *Power Engineering and Engineering Thermophysics*, vol. 3, no. 2, pp. 77–91, Jun. 2024, doi: 10.56578/peet030201.

[23] Y. F. Nassar, H. J. El-khozondar, A. A. Ahmed, A. Alsharif, M. M. Khaleel, and R. J. El-Khozondar, "A new design for a built-in hybrid energy system, parabolic dish solar concentrator and bioenergy (PDSC/BG): A case study – Libya," *Journal of Cleaner Production*, vol. 441, Feb. 2024, doi: 10.1016/j.jclepro.2024.140944.
[24] E. Hakizimana, H. Umuhoza, E. Manishimwe, and V. Kayibanda, "Economic optimization of grid-connected photovoltaic solar systems in industrial energy," *Solar Energy and Sustainable Development Journal*, vol. 13, no. 2, pp. 204–229, Aug. 2024, doi: 10.51646/jsesd.v13i2.242.
[25] S. Mirjalili, S. M. Mirjalili, and A. Lewis, "Grey Wolf Optimizer," *Advances in Engineering Software*, vol. 69, pp. 46-61, 2014, doi: 10.1016/j.advengsoft.2013.12.007.

BIOGRAPHIES OF AUTHORS

Engr. Olumuyiwa Ajibola Awoniyi is a seasoned power industry expert with over 20 years of experience. He holds a Postgraduate Diploma and Master's degree in Electrical Engineering from the University of Agriculture, Makurdi, and is currently pursuing a Doctorate in Power System Engineering at the University of Abuja. He holds a Global fellowship award with RMI on renewable energy transition. DISCO representative to the UK Infrastructure Advisory Facility (UKNIAF) on the Integrated Resource Plan working group to meet the nation's commitment to the Nationally Determined Contribution (NDCs), and realization of the Net-Zero goal of the Energy Transition Plan. He has undergone local and international training in Distribution network planning, PSS SINCAL with Siemens International. He is a Member of the Council for the Regulation of Engineering in Nigeria (COREN), a Member of the Nigeria Institute of Electrical and Electronics Engineers (IEEE), and a Fellow of the Institute of Corporate Administration of Nigeria (FCAI). He has made a few publications in local and international journals. Throughout his career, he has held various leadership positions, and currently the Head of Network Planning and Investment at Abuja Electricity Distribution Company. He is a renewable energy expert with several projects executed in Nigeria and sub–Sarah African countries. He can be contacted at email: awoniyi.olumuyiwa@yahoo.com.



Prof. Evans Chinemezu Ashigwuike received a B.Eng. (Hons) in Power Systems Engineering and M.Eng. in Instrumentation Engineering from Nnamdi Azikiwe University, Awka, in 1999 and 2005, respectively. He received a Ph.D. in Electronic and Computer Engineering with a specialization in Electromagnetic Non-Destructive Testing and Structural Health Monitoring, from Brunel University, London, in 2015. His main research interests include industrial instrumentation, precision measurement, sensor technologies, electromagnetic nondestructive testing techniques, structural health monitoring, wireless sensor networks, power system automation, and artificial intelligence. He is a registered member of several professional bodies, including the Council for the Regulation of Engineering in Nigeria (COREN), the Nigerian Society of Engineers (NSE), Nigerian Computer Society (NCS), the Institute of Electrical/Electronic Engineering (IEEE), Canadian Institute of Non-Destructive Testing, British Institute of Non-Destructive Testing. He has published in several peer-reviewed and indexed journals both locally and internationally. He can be contacted at email: ecashigwuike@ymail.com.

Dr. Timothy Oluwaseun Araoye received a Bachelor degree of Technology (B.Tech.) in Electrical and Electronics Engineering from Ladoke Akintola University of Technology (LAUTECH), Ogbomoso, Oyo State, Master's Degree (M.Eng.) from Enugu State University of Science and Technology (ESUT), Agbani, Enugu State, and a Ph.D. degree at the University of Abuja, Nigeria, in the same course with a specialization in Electrical Machine and Power System. He is a registered member of the Nigeria Society of Engineers (NSE) and Council for the Regulation of Engineering in Nigeria (COREN). His research interest includes artificial intelligence, machine learning, power systems and machines, renewable energy, power system reliability, microgrid optimization and control, robotics, IoT, modeling and simulation, distributed generation, control system, and power electronics. He has attended many conferences where he presented papers. He can be contacted at email: timothy.araoye@unn.edu.ng.