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Optimization and techno-economic analysis of hybrid renewable systems in Nigeria

Lambe Mutalub Adesina[1], Jamiu Lawal[1], Olalekan Ogunbiyi[1], Abdulwaheed Musa[1,3], Bilkisu Jimada Ojuolape[1], Monsurat Omolara Balogun[1], Bashiru Olalekan Ariyo[1,2]

[1]Department of Electrical and Computer Engineering, Faculty of Engineering and Technology, Kwara State University, Malete, Nigeria
[2]Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, University of Ilorin, Ilorin, Nigeria
[3]Institute for Intelligent Systems, University of Johannesburg, Johannesburg, South Africa

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ABSTRACT

Rising electricity demand, fossil fuel depletion, and environmental concerns highlight the need for sustainable rural electrification. The Elenjere community in Kwara State, Nigeria, depends on costly diesel generation and limited grid access, creating an urgent demand for reliable and affordable alternatives. This study designs and optimizes a hybrid renewable energy system (HRES) for the community using hybrid optimization model for electric renewables (HOMER) Pro simulation. The proposed system combines photovoltaic (PV), wind turbines (WT), battery storage (BAT), inverter (INV), and a diesel generator (DG) as backup. Field data on load demand, solar radiation, and wind speed were used for realistic modeling. System performance was evaluated using levelized cost of energy (LCOE), net present cost (NPC), and system capital cost (SCC). Results show the PV/WT/BAT/INV/GEN configuration achieved the lowest LCOE of USD 0.455/kWh, an NPC of USD 2.98 million, and 86.2% renewable penetration, significantly reducing diesel use. Sensitivity analysis revealed that reducing battery costs and increasing PV capacity could lower the LCOE to USD 0.227–0.325/kWh. The study demonstrates how modest wind resources (4.19 m/s at 10 m) complement PV in low-wind regions while addressing inflation realism (25.5% discount rate, foreign exchange (FX) volatility). Future work will include dynamic control simulation and lifecycle analysis to enhance scalability and sustainability.

Corresponding Author:

Jamiu Lawal
Department of Electrical and Computer Engineering, Faculty of Engineering and Technology
Kwara State University
Malete, Nigeria
Email: jamiulawal9557@gmail.com

1. INTRODUCTION

Access to reliable and sustainable electricity remains a major barrier to socioeconomic development, particularly in rural Sub-Saharan Africa (SSA), where electrification rates significantly lag behind urban areas [1]–[4]. Nigeria exemplifies this challenge, with only about 45% of the population having grid access in 2025. Even where grid connections exist, supply is notoriously unreliable, often limited to a few hours per day [5]–[7]. As a result, rural communities increasingly depend on diesel generator (DG), which are expensive, environmentally harmful, and detrimental to public health [8]–[10].

Hybrid renewable energy systems (HRES) that integrate renewable resources such as solar photovoltaic (PV), wind, and battery storage (BAT) with conventional DG are emerging as a sustainable solution to rural energy poverty [11]–[13]. These systems offer improved reliability, reduced emissions, and long-term cost savings compared to diesel-only options. Evidence across SSA, from countries such as Ghana, Kenya, Nigeria, Cameroon, Chad, and Mauritania, demonstrates the viability of hybrid configurations, with levelized cost of energy (LCOE) reductions to as low as USD 0.20–0.25 /kWh alongside significant emission cuts [14]–[17].

Despite these successes, most studies remain region-specific and fail to account for local climatic, economic, and social dynamics, limiting their real-world applicability. Many models also rely on generalized load assumptions and rarely address macroeconomic realities, such as high inflation and foreign exchange (FX) volatility, that strongly influence project economics in Nigeria and other SSA countries. This study addresses these gaps by developing a context-specific hybrid energy optimization model tailored for Elenjere, a rural community in Kwara State, Nigeria, providing both local insights and a replicable framework for similar rural settings.

Elenjere faces persistent energy poverty marked by unreliable grid supply, over-reliance on costly DGs, and the resulting environmental and health impacts. While Nigeria possesses abundant solar resources (average irradiance of ~7 kWh/m²/day), renewable adoption remains minimal due to infrastructural constraints, limited financing, and policy barriers [18], [19]. Therefore, a robust, hybridized energy system is urgently needed to balance cost, reliability, and environmental sustainability for rural electrification. This study aims to design and optimize a HRES for Elenjere, with the objectives of enhancing energy reliability, minimizing costs, and integrating local socioeconomic realities into system planning

Previous studies across SSA highlight the potential of hybrid systems but also reveal important limitations. For instance, studies in Mauritania demonstrated that optimized diesel-PV-battery configurations could halve electricity costs to USD 0.30/kWh [20]. Similar efforts in Nigeria's Jos and Benin regions achieved up to 90% carbon emission reductions compared to diesel-only systems, though outcomes were highly sensitive to inflation and financing structures [21], [22]. Research in Cameroon examined PV–wind–battery systems with electrochemical storage for reliability optimization [23], while broader reviews stressed the difficulty of balancing cost, emissions, and reliability in off-grid contexts [24], [25].

However, many of these studies lack localized data, particularly accurate rural load profiles, and do not sufficiently explore how macroeconomic instability affects system sustainability. To address these research gaps, this study introduces several novel contributions, including:

- Localized modeling – incorporates actual field-measured data for load, solar irradiance, and wind profiles, resulting in more realistic designs than those using generalized datasets.
- Inflation-aware simulations – integrates Nigeria's high inflation and FX volatility into HOMER Pro analysis, a rare feature in rural electrification research.
- Synergistic wind integration – demonstrates how modest wind speeds (4.19 m/s at 10 m hub height) can cost-effectively complement solar PV to enhance reliability in low-wind regimes.
- Policy-driven design – links engineering optimization with regulatory strategies, bridging the gap between technical performance and practical policy implementation for rural electrification.

By combining context-specific data, advanced simulation, and sensitivity analysis, this study creates a replicable methodological framework for SSA rural planners. It provides actionable insights into reducing energy costs, improving system reliability, and supporting decarbonization goals. Furthermore, the inclusion of policy-relevant outputs, such as loss of load probability (LOLP) metrics, cost-reflective tariffs, and grid-arrival compensation frameworks, makes the findings directly relevant to decision-makers.

The remainder of this paper is organized as follows: section 2 presents the methodology, including data collection, system modeling, hybrid optimization model for electric renewables (HOMER) Pro simulation setup, and sensitivity analysis. Section 3 discusses the results, covering configuration performance, economic outcomes, sensitivity scenarios, and policy implications. Section 4 concludes with a summary of key findings, limitations, and recommendations for future research.

2. METHOD

2.1. Case study description: Elenjere community

The Elenjere community, located in Asa Local Government Area of Kwara State, Nigeria (latitude 8°20′ N and longitude 4°54′ E), serves as the case study for this research. The community comprises approximately 125 buildings, including residential and small commercial structures with moderate daily load demands. Its semi-rural setting lacks grid connectivity, making it suitable for off-grid renewable hybrid energy system development. The local population depends on DGs and kerosene lamps for electricity, which are unsustainable and costly. This situation underscores the need for an optimal HRES to ensure reliable, clean, and cost-effective power supply.

To evaluate electricity consumption, a three-phase Fluke 432-II power quality and energy data logger Figure 1 was connected to the community's feeder pillar. Daily load demand was recorded over 30 consecutive days, including weekends. The collected data were transferred to a laptop via secure digital (SD) card for further analysis.

Figure 1. Three-phase data logger

The daily load profile Figure 2 shows three distinct patterns:
– Off-peak periods (00:00–08:00, 11:00–15:00): 8.5–9.5 kW
– Evening peak (16:00–21:00): Maximum ~15 kW at 19:00–20:00
– Average daily consumption: ~11.2 kW

These patterns reflect typical residential behavior and guide the optimal sizing of renewable generation and storage systems. Solar PV can meet daytime loads, while batteries and supplementary sources ensure evening peak supply.

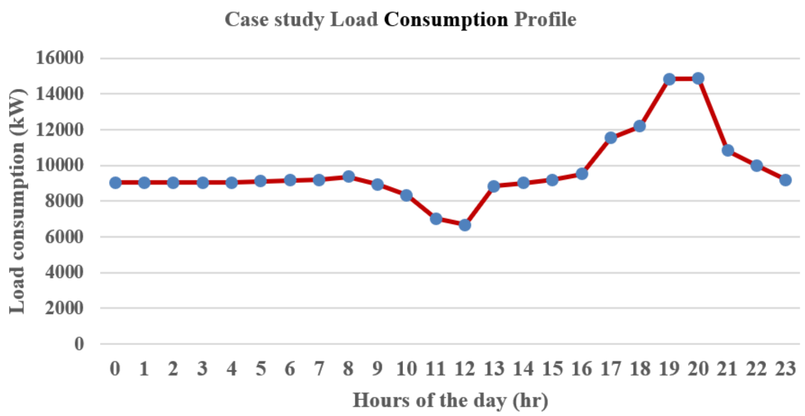

Figure 2. Case study daily load consumption profile

2.2. Renewable resource assessment

Renewable resource assessment was carried out using field measurements and secondary data sources to characterize the solar and wind energy potential of Elenjere. Solar irradiance data were collected through ground-based monitoring and validated against National Aeronautics and Space Administration – Surface Meteorology and Solar Energy (NASA-SSE) datasets, yielding an average global horizontal irradiance (GHI) between 3.95 kWh/m²/day (August) and 6.02 kWh/m²/day (March), indicating strong solar potential for HRES Figure 3.

Similarly, wind resource assessment using measured data and meteorological records revealed an average wind speed of 4.19 m/s at a 10-meter hub height Figure 4. Though moderate, this wind potential complements solar energy during low-sunlight or nighttime periods, making it suitable for hybrid integration. Together, these renewable resources form the foundation for a sustainable power generation mix for the community.

2.3. Proposed hybrid system's configuration

Figure 5 presents the schematic layout of the proposed hybrid energy system. The system is designed to comprise two renewable energy sources, a wind energy conversion system (WECS) and a solar photovoltaic system, supported by a DG and a battery energy storage system as backup, if the renewable sources are insufficient to meet the case study's total load demand.

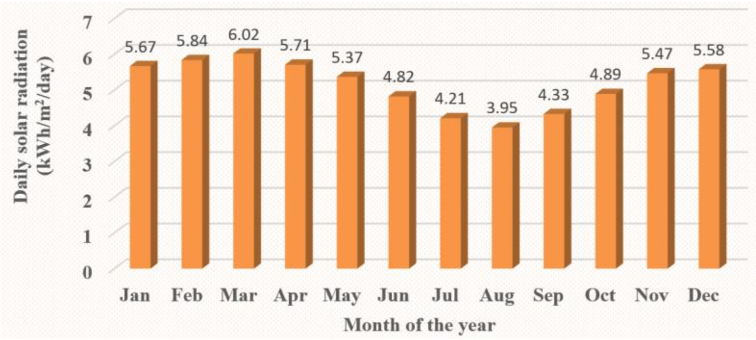

Figure 3. The case study's average solar radiation profile

Figure 4. The case study site's average wind speed

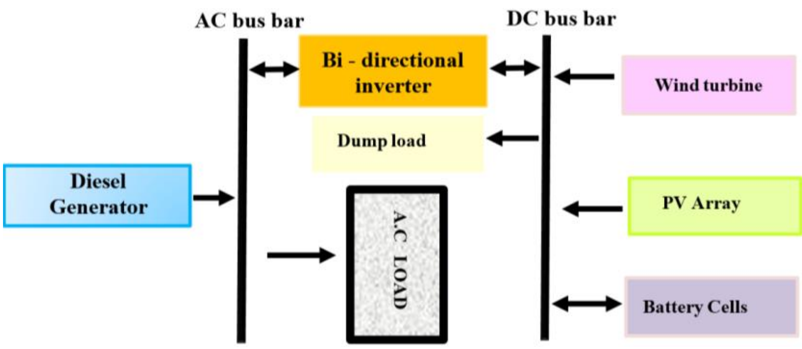

Figure 5. Schematic diagram of a renewable hybrid power system

The PV panels convert solar energy into electricity, complemented by wind turbines (WT) that capture wind power. Fuel cells provide dependable backup through electrochemical conversion, while batteries store excess renewable energy to enhance supply reliability. A direct current (DC) bus coordinates energy exchange among PV, wind, storage, and DC loads, with a dump load dissipating surplus energy to prevent overvoltage. Inverters convert DC into alternating current (AC), enabling use by household appliances, industries, and the grid. A power management unit supervises all operations, optimizing conversion efficiency, balancing demand and supply, and preserving stability. Collectively, these components ensure efficient, reliable, and sustainable power generation under diverse operating conditions.

2.4. Mathematical modeling of system components

Accurate modeling of HRES's components enables simulation of energy generation, storage, and cost, environmental trade-offs in HOMER Pro. Detailed mathematical formulations are provided in mathematical modeling and component integration.

Accurate modeling of HRES components is fundamental for evaluating system performance and reliability. Mathematical models describe the hybrid energy system components including solar PV, WT, BAT, and DG and provide the foundation for simulating energy generation, storage dynamics, and cost–environmental trade-offs in HOMER Pro.

2.4.1. Solar photovoltaic system

The PV system output is modeled based on solar irradiance, panel efficiency, and inverter (INV) performance. Full equations and parameters are presented in (1) [26], [27]. The power output of the PV array is calculated based on solar irradiance, panel efficiency, and derating factors. The hourly energy generation is modeled as presented in (1).

$$P_{PV}(t) = G_{POA}(t) \times A_{PV} \times \eta_{PV} \times \eta_{inv} \tag{1}$$

where:
$G_{POA}(t)$ = plane-of-array irradiance at hour t (kWh/m²/day)
A_{PV} = total PV surface area (1.08 m^2 number of panels1.08m2×number of panels)
η_{PV} = panel efficiency (90%, per manufacturer specification)
η_{inv} = inverter efficiency (95%)

2.4.2. Wind energy conversion system

Wind turbine power output is determined using hub-height wind speeds, rated power, and cut-in/out limits. Detailed formulation, including the piecewise power equation, is in. (2) [28], [29], (3) [30], and (4) [31], [32]. The WECS converts wind kinetic energy into electrical power through aerodynamic, mechanical, and electrical processes. Hourly power output from the wind energy system is as expressed in (2).

$$P^W = \left\{\begin{matrix} 0 & V_W < V_{ci} \; or \; V_w \geq V_{co} \\ P^R \frac{V_W - V_{Ci}}{V_r - V_{ci}} & V_{ci} \leq V_w \leq V_r \\ P^R & V_r \leq V_W < V_{co} \end{matrix}\right\} \tag{2}$$

where:
P^W = total power generated by the wind energy conversion systems
P^R = rated power of the wind turbine
V_W = wind speed of the wind turbine at hub height
V_{ci} = cut-in wind speed of the wind turbine
V_{co} = cut-out wind speed of the wind turbine
V_r = rated wind speed of the wind turbine

The wind speed at the turbine hub height, h, and reference height, hr, is determined using the power law equation as expressed in (3).

$$V_W = V_r \left(\frac{h}{h_r}\right)^{\propto} \tag{3}$$

where:
$\propto$ = shear coefficient, ranging from 0.10 – 0.40
The annual energy generated from the wind turbine is as expressed in (4).

$$J^{GW} = P^W \times 8760 \; (h/yr) \; kWh \tag{4}$$

2.4.3. Battery storage system

Battery dynamics, including state-of-charge evolution, charge/discharge efficiencies, and self-discharge, are modeled as described in (5) [33], [34]. The battery energy storage system stores electrical energy for later use, enhances HRES's stability, manages load fluctuations, and improves renewable energy integration efficiency. The state of charge (SOC) of the nickel-cadmium battery bank considered in this work's HOMER Pro simulation is governed by (5).

$$SOC(t) = SOC(t-1) \times (1-\sigma) + \left(P_{ch}(t) \times \eta_{ch} - \frac{P_{disch}(t)}{\eta_{disch}}\right) \times \Delta t \quad (5)$$

where:
σ = daily self-discharge rate (0.2%)
$(P_{ch}(t), P_{disch}(t)$ = charging / discharging power at hour t (kW)
η_{ch}, η_{disch} = charge/discharge efficiencies (85% and 90%, respectively)
Δt = time interval (1 hour)

2.4.4. Diesel energy generator

DG fuel consumption is modeled linearly with rated power and output. Local fuel pricing and availability are considered, with full equations given in (6) [35], [36]. All derivations, parameters, and assumptions are provided for clarity and reproducibility.

DG provide reliable, high-availability power, ensuring continuous electricity in off-grid and hybrid systems, and complement intermittent renewable energy sources for a stable energy supply. The fuel consumption (D_f) of the diesel generator is modelled using a linear fuel curve as presented in (6).

$$D_f(t) = a \times P_{rated} + b \times P_{out}(t) \quad (6)$$

where:
a = no-load fuel consumption coefficient (0.00626 L/kWh) [36]
B = marginal fuel consumption coefficient (0.2831 L/kWh)
P_{rated} = rated capacity (100 kW)
$P_{out}(t)$ = generator output at hour t
Local diesel prices averaged ₦ 889 /L (≈ USD 0.52/L). Diesel supply reliability and price volatility justify its role as a backup power source rather than primary generation.

2.5. HOMER pro simulation setup

The PV–WT–diesel generator (GEN)–(BAT) hybrid configuration was modeled and optimized using the HOMER Pro interface Figure 6. The simulation incorporated site-specific inputs, including measured load profiles, solar irradiance, and wind speed data, along with the technical and cost parameters summarized in Tables 1 and 2. To ensure operational realism, optimization constraints such as the load-following strategy, battery priority rule, renewable energy fraction, LOLP, and battery depth of discharge (DoD) were applied. The DoD was restricted to 80% to extend battery lifespan, while the simulation time step was set to 10 minutes. A project lifespan of 25 years and an interest rate of 25.5% were adopted to reflect Nigeria's prevailing economic and inflation conditions. System performance was evaluated based on LCOE, NPC, and overall reliability, resulting in optimal component sizes and cost distributions for sustainable electrification in the Elenjere community.

Figure 6. Proposed hybrid system configuration for simulation in HOMER Pro

Table 1. HOMER Pro's simulation parameters

Simulation constraints	Specification
Simulation time step	10 minutes
Project lifespan	25 years
Interest rate	25.50%
Maximum renewable fraction	95%
Wind speed hub height	10 m/s
Maximum annual capacity shortage	5%
Dollar exchange rate	₦ 1,700 / $
Simulation time step	10 minutes
Project lifespan	25 years

Table 2. System component parameter and cost

Component	Capital cost ($)	Replacement cost ($)	Operation and maintenance cost ($)	Lifespan (yr)
Wind turbine (100 kW)	2500	1500	150	20
Solar PV System (100 kW)	3000	300	10	25
Inverter (150 kW)	2000	250	20	10
Diesel generator (100 kW)	1000	800	200	15
Battery (192 V, 600 Ah)	3500	3500	10	10

3. RESULTS AND DISCUSSION
3.1. Result:
3.1.1. Optimal system selection and economic assessment

The HOMER Pro simulations assessed hybrid renewable energy configurations based on LCOE, net present cost (NPC), and system capital cost (SCC) Figures 7–9. Among the configurations, the PV/WT/BAT/INV/GEN system performed best (LCOE = USD 0.455/kWh; Capital Cost = USD 706,836; NPC = USD 2.98M). A lower capital requirement not only eases the initial financial burden but also improves project feasibility for stakeholders operating under budgetary limitations, thereby strengthening overall return on investment (ROI) [37].

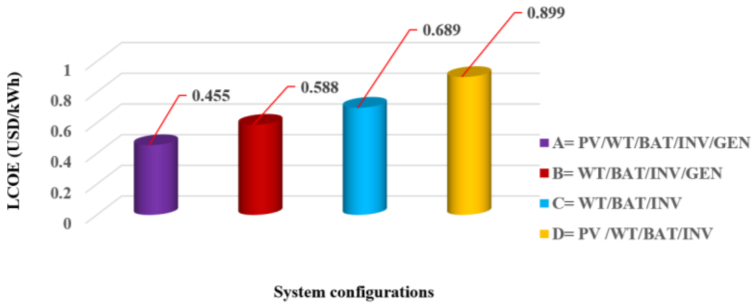

Figure 7. System configuration versus LCOE

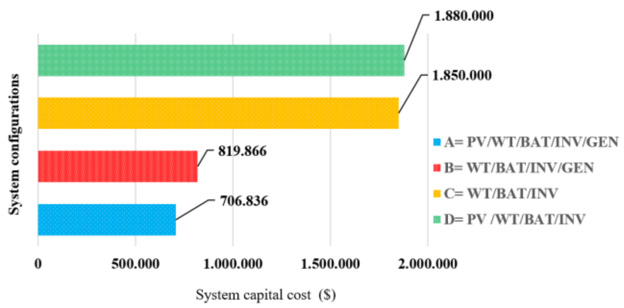

Figure 8. System configuration scenario vs SCC

Following identification of the PV/WT/BAT/INV/GEN setup as the most optimal, Scenario A's cost distribution Figure 10 shows batteries dominate total investment (~82%), followed by wind (~17%), with PV and inverter costs below 1%. This pattern reflects prevailing market prices, system design needs, and storage requirements for renewable stability.

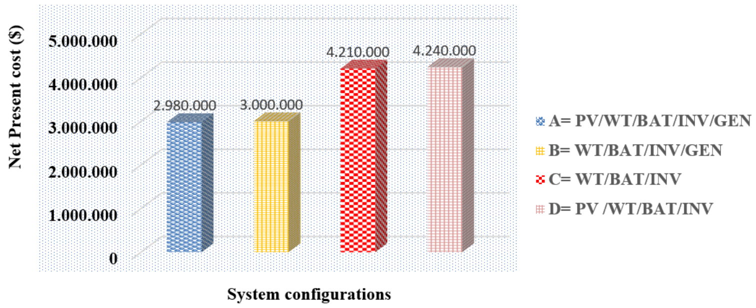

Figure 9. System configurations versus net present cost

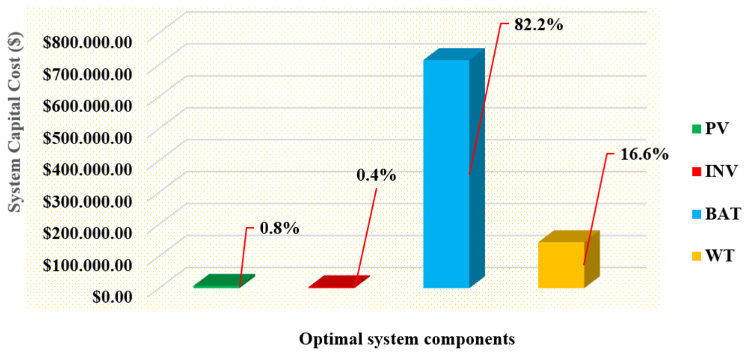

Figure 10. Optimal SCC summary

3.1.2. Sensitivity analysis

Sensitivity analysis Figure 11 shows LCOE is most sensitive to battery cost and PV capacity: lowering battery cost by 20% or increasing PV capacity by 20% substantially reduces LCOE, while higher discount rates raise it. Figure 11 for detailed scenario values. The renewable fraction illustrated in Figure 12 shows the optimal system provides 86.2% of annual energy from renewables, with the diesel generator covering 13.8%. Configurations without wind achieve lower renewable shares (80–82.5%) and higher diesel reliance, highlighting the importance of wind integration and adequate storage in enhancing renewable penetration and system reliability.

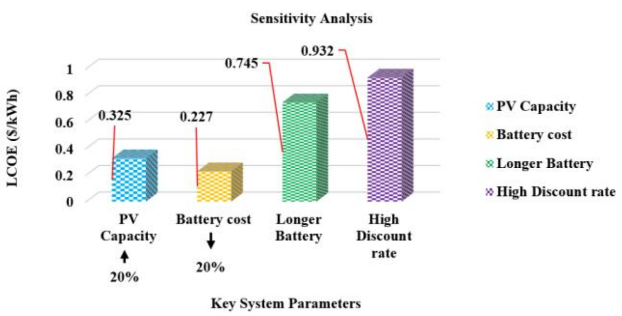

Figure 11 Impact of sensitivity analysis on LCOE

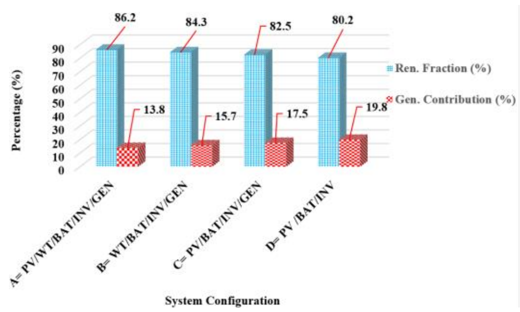

Figure 12. Renewable fraction vs generator contribution

3.1.3. Payback period estimation for the optimal system configuration

The payback period measures how quickly an investment recovers its capital cost through annual savings or revenues, such as energy sales, feed-in tariffs, or incentives [38], [39]. In renewable hybrid power systems optimization, it's a vital financial metric assessing investment attractiveness, risk, and economic resilience. A shorter payback enhances project appeal, supports financial planning, improves bankability, and informs policy and investment decisions [40]. Payback period is defined as presented in (7) [41], [42].

$$Payback\ Period\ = \frac{Capital\ Cost}{Annual\ revenue\ or\ saving} \quad (7)$$

$$Revenue\ per\ year\ \ = LCOE\ \times\ Annual\ Energy\ Production \quad (8)$$

Where, data from HOMER Pro optimal system configuration gives: LCOE = USD 0.455/kWh, annual energy production = 442,573 kWh, and optimal system capital cost: USD 706,836.

Therefore, using (7)–(8) and the optimal-system outputs (LCOE, annual energy production), the calculated payback is ≈ 3.5 years, a rapid capital recovery that indicates strong financial viability. The short payback period reinforces the project's financial attractiveness and scalability in resource-constrained communities.

3.1.4. Cash flow analysis

The cash flow distribution of the HRES in Figure 13 shows that capital costs are dominated by BAT, followed by WT and PV systems, reflecting the high initial investment required for reliable off-grid operation. Replacement costs are also primarily driven by batteries due to their limited lifespan, while PV and wind components require minimal replacements. Operation and maintenance costs are moderate, with WT and generators contributing most. Fuel costs are negligible, indicating the generator serves mainly as backup. Negative salvage values occur at the project's end, with batteries having the highest recovery value. Optimizing battery sizing and lifecycle management is crucial to reducing total costs and improving long-term system sustainability.

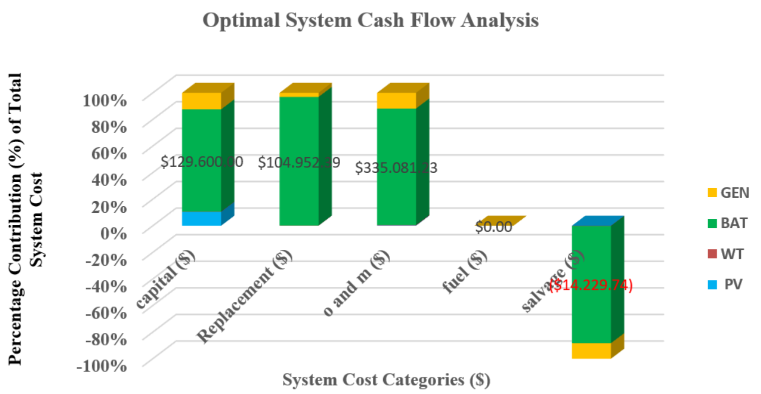

Figure 13. Cash flow distribution of HRES across lifecycle cost categories

3.2. Discussion

3.2.1. Interpretation of optimal system configuration results

The analysis confirms that the PV/WT/BAT/INV/GEN configuration is both technically and economically optimal, effectively balancing renewable penetration, investment cost, and operational reliability. BTS dominates capital expenditure (~82% of Capex), highlighting the potential of technological improvements and financing mechanisms to further lower LCOE. This dominance reflects the large storage capacity required for energy buffering, load smoothing, and backup during intermittency, alongside high lifecycle and replacement costs inherent to system design and operation.

Sensitivity analysis identifies battery cost and PV capacity as primary economic drivers, with discount rate (≈25.5%) and battery lifetime also influencing viability. A high renewable fraction (~86%) demonstrates that hybridization with modest wind speeds (~4.2 m/s) can substantially minimize diesel use and emissions.

Wind energy integration is justified by its complementary synergy with solar PV, providing generation during low-solar and nighttime periods while enhancing overall system stability. Moderate wind speeds (4–5 m/s) meaningfully supplement output, reducing battery cycling and operational costs. This integration also lowers system cost through shared infrastructure, mitigates greenhouse gas emissions, and strengthens renewable utilization efficiency, reliability, and resilience against resource intermittency.

3.2.2. System optimization and validation

The section compares HOMER and MATLAB Simulink for optimizing HRES. Ishraque *et al.* [43] presented a techno-economic and power system optimization study of a renewable-rich islanded microgrid for the Barishal and Chattogram regions in Bangladesh. HOMER was used to optimize component sizing and evaluate five dispatch strategies, generator order, cycle charging, load following, HOMER predictive dispatch, and combined dispatch, based on CO_2 emissions, NPC and LCOE. MATLAB Simulink was then employed to validate the system's dynamic performance and overall feasibility.

Results showed that the Load Following strategy achieved the best performance, delivering the lowest NPC, LCOE, operating cost, and CO_2 emissions, alongside a stable power system response. In contrast, the Combined Dispatch strategy performed the worst, with the highest costs and emissions. This integrated approach provides a comprehensive framework for designing, optimizing, and validating off-grid HRES under diverse operational conditions.

3.2.3. Environmental and socio-economic impacts

The optimized system reduces CO_2 emissions by ~68% (from 92,000 to 29,400 kg/year) [44] and particulate matter by 54% compared to diesel-only operation, aligning with SDG 7 and SDG 13. Economically, the high renewable fraction achieves competitive LCOE levels consistent with SSA mini-grid benchmarks. Mechanisms such as capital buy-downs, concessional debt, and blended financing can further improve affordability. Midday PV surplus can support productive-use electrification (cold chains, agro-processing, digital services), while tiered or seasonal tariffs enhance revenue streams and reduce reliance on diesel backup.

3.2.4. Comparison and contrast with existing literature

This section offers a comparative analysis of the present study against recent research on HRES's to validate this research findings, drawing from peer-reviewed publications in IEEE Xplore, Scopus, and Web of Science. Articles were selected using keywords such as "HRES," "Techno-Economic HRES," and "optimization techniques," focusing on contemporary studies from 2021–2025. Emphasis was placed on off-grid renewable hybrid power systems, innovative optimization approaches, and practical case studies assessing technical and economic performance.

Evidence across SSA and comparable low- and middle-income countries (LMIC) contexts highlight PV-battery hybrids as least-cost, lowest-emission solutions, with wind and limited diesel enhancing resilience. Table 3 presents comparative contrasts. LCOE is higher than "best-case" Gwadar, Pakistan / HOMER software, but sits squarely within SSA tariff bands observed for commercially viable mini-grids when FX, high discount rates (≈ 25.5%), and storage-heavy designs are modeled. Our renewable share (≈ 86%) exceeds many PV–DG systems that lack wind firming and aligns with studies that prioritize peak-shaving batteries over diesel runtime.

Table 3. Comparative synthesis (selected 2021–2025 studies vs. this work)

Study	Context / tool	Optimal mix	LCOE (USD/kWh)	NPC / Capex (USD)	Ren. fraction	Key notes
[45]	Gwadar, Pakistan / HOMER software	PV – wind – grid – converter (model 2)	0.0347	—	73.3% (model 2)	Gwadar microgrid: model 2 optimal, reduces imports.
[46]	Kech village HOMER-Pro simulation	PV – wind – BAT – converter	0.137	127,345	100%	Reliable economical scalable rural electrification is achieved
[47]	HOMER + MCDM (32 scenarios)	PV – wind– battery	0.24	1.42 – 1.64 M	55.1%	Demonstrates trade-offs between economics and sustainability
[48]	Uttarakhand, India, HOMER-Pro simulation	PV – battery	0.143	43,738.53	Almost 100%	Cuts greenhouse gas (GHG) emissions by 21,545 kg/year
[49]	South Africa, HOMER grid	PV – wind– battery energy storage system (BESS)	0.23	9.3M	95%	Floating PV performance ratio 85.5%, with annual 15,835 MWh
[50]	South Coast, KZN, HOMER Pro 3.18.1.	Wind energy + converter + grid	—	13,000	74%	PV/grid is viable alternative but less cost-effective
[51]	Improved subtraction-average-based optimizer (ISABO)	PV – wind – fuel cell	—	1,357,018.15	—	Reliable operation with only 0.8% loss of power supply probability (LPSP) decline under PV failure
Present study (2025)	Nigeria/HOMER Pro	PV– WT – BAT – GEN	0.455	NPC 2.98 M; Capex 706,836	≈ 86%	Wind improves seasonal adequacy; storage dominates Capex

3.2.5. Modular framework for scaling

A modular framework is proposed to support replication across SSA, structuring the HRES into interchangeable PV, WT, BAT, INV, and GEN modules with standardized specifications, performance metrics (LCOE, NPC, SCC), and data-driven modeling procedures. Sensitivity analysis and scenario testing guide module sizing under varying financial and climatic conditions, enabling cost-effective deployment while accommodating advanced storage, demand-side management, and real-time control strategies.

3.2.6. Policy and practical implications

The study's findings have multiple practical and policy implications:
- Affordability and inclusive financing: competitive LCOE align with SSA mini-grid benchmarks. Mechanisms such as capital buy-downs, concessional debt, and blended finance can further lower tariffs and improve developer bankability [52], [53].
- Decarbonization and health co-benefits: diesel share (~14%) enables significant CO_2 and particulate matter reductions compared to diesel-only systems [54]–[56]. Policy frameworks that recognize carbon and health externalities can unlock climate financing and encourage low-carbon investments [57]–[59].
- Productive use and tariff design: midday PV surplus can support productive-use electrification (PUE) applications, including cold chains, agro-processing, and digital services. Tiered or seasonal tariffs enhance revenue streams and system utilization, reducing dependency on diesel backup.
- Institutional and regulatory support: sustainable operation requires grid-arrival compensation frameworks, standardized land/easement procedures, and FX-indexed cost pass-through rules, ensuring long-term bankability and quality of service [60].

3.2.7. Research contribution and novelty

The study advances HRES deployment in SSA through:
- Context-specific hybridization: demonstrates cost-effective wind integration in low-wind regions, complementing PV and minimizing diesel use.
- Financial realism: high discount rates and FX pass-through reveal battery-dominated Capex and LCOE sensitivity.
- Policy-ready quality of service (QoS) and tariff design: provides actionable instruments for mini-grid planning.
- Replicable workflow: combines validated local load data, site characterization, and HOMER modeling for other rural communities.
- High-inflation planning realism: incorporates market and finance considerations rarely embedded in rural HRES optimization [61], [62].

3.2.8. Challenges and limitations

Several factors constrain the study's findings, particularly in terms of economic accuracy, system risk, and seasonal representativeness, among which are:
- Currency and macro risk: with FX volatility and high discount rates, storage-heavy systems remain tariff-sensitive; concessional capital and FX- indexed contracts are pivotal [63], [64].
- Battery cost concentration: Capex is dominated by batteries (≈82%); supply-chain shocks and replacement timing materially swing LCOE, consistent with SSA benchmarking.
- Data horizons: thirty days of logging capture typical residential peaks but not agricultural/seasonal shocks; a full annual cycle would refine wind/solar complementarity and PUE sizing.
- Operation and maintenance (O&M) and governance: sustained QoS depends on local O&M capability, parts logistics, and clear grid-arrival rules; weak tenure and opaque buyout terms can strand assets.
- Social acceptance and demand risk: tariff shifts, metering trust, and appliance uptake shape revenue stability; PUE enablement (credit, devices) is necessary to realize modeled paybacks [65].

3.2.9. Future research directions

Future work should collaborate with hardware developers for field testing, integrate IoT-enabled monitoring, machine learning-based forecasting, and advanced real-time optimization beyond HOMER. This will enhance adaptive energy management, demand prediction, and scalable rural electrification with improved resilience and sustainability.

4. CONCLUSION

This study developed and optimized a HRES for rural electrification in Elenjere, Kwara State, Nigeria, using HOMER Pro. The PV–wind–battery–inverter–diesel configuration proved most technically and economically viable, achieving the lowest LCOE (USD 0.455 /kWh), NPC (USD 2.98 M), and capital cost (USD 706,836). With a renewable penetration of 86.2%, diesel use was minimized, operating mainly as backup during intermittency.

Sensitivity analysis indicated that lower battery costs and expanded PV capacity could further reduce LCOE to USD 0.227–0.325 /kWh. These findings align with SSA studies, underscoring the potential of renewable-dominated HRESs to deliver reliable, low-cost electrification while reducing emissions and enhancing energy security. The estimated 3.5-year payback period highlights strong investment appeal.

From a socio-economic perspective, the optimized system promotes inclusive rural development through affordable electricity that enhances livelihoods, supports productive-use enterprises, and reduces fuel costs and pollution-related health burdens, aligning with national electrification and sustainability goals.

While offering a replicable framework for similar regions, limitations include simulation assumptions and simplified intermittency representation. Future research should integrate demand-side management, advanced storage, and real-time control strategies to strengthen system resilience, scalability, and long-term sustainability.

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Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Lambe Mutalub Adesina				✓	✓	✓	✓		✓			✓	✓	✓
Jamiu Lawal	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Olalekan Ogunbiyi		✓	✓	✓	✓	✓				✓	✓	✓	✓	
Abdulwaheed Musa		✓	✓	✓	✓	✓				✓	✓	✓	✓	
Bilkisu Jimada Ojuolape		✓	✓	✓	✓	✓				✓	✓	✓	✓	
Monsurat Omolara Balogun		✓	✓	✓	✓	✓				✓	✓	✓	✓	
Bashiru Olalekan Ariyo		✓	✓	✓	✓	✓				✓	✓	✓	✓	

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

CONFLICT OF INTEREST STATEMENT

The authors declare that there is no conflict of interest in any form among the authors.

DATA AVAILABILITY

The data supporting the findings of this study are available from the corresponding author [J. Lawal], upon reasonable request. However, due to confidentiality concerns and the potential compromise of participant privacy, the data are not publicly available.

REFERENCES

[1] A. T. Mossisa and A. T. Han, "Transitioning to renewable electric energy in rapidly urbanizing Sub-Saharan Africa: Challenges and opportunities," *Energy Strategy Reviews*, vol. 61, Sep. 2025, doi: 10.1016/j.esr.2025.101842.

[2] P. Casati, M. Moner-Girona, S. I. Khaleel, S. Szabo, and G. Nhamo, "Clean energy access as an enabler for social development: A multidimensional analysis for Sub-Saharan Africa," *Energy for Sustainable Development*, vol. 72, pp. 114–126, Feb. 2023, doi: 10.1016/j.esd.2022.12.003.

[3] P. Gamette, N. M. Odhiambo, and S. A. Asongu, "Access to electricity and income inequality in sub-Saharan Africa: An exploratory review," *Sustainable Futures*, vol. 8, Dec. 2024, doi: 10.1016/j.sftr.2024.100361.

[4] E. A. Ehimen, P. Y. Sandula, T. Robin, and G. T. Gamula, "Improving energy access in low-income Sub-Saharan African Countries: A case study of Malawi," *Energies*, vol. 16, no. 7, Mar. 2023, doi: 10.3390/en16073106.

[5] N. Udoinyang, "Impacts of population trends, agricultural supply chains, and Environmental Decline in Otukpo LGA, Benue State, Nigeria," *International Journal of Environment, Engineering and Education*, vol. 6, no. 1, pp. 12–25, Apr. 2024, doi: 10.55151/ijeedu.v6i1.128.

[6] O. F. Orikpete, N. M. Gungura, E. Ehimare, and D. R. E. Ewim, "A critical review of energy consumption and optimization strategies in the Nigerian aviation sector: challenges and prospects," *Bulletin of the National Research Centre*, vol. 47, no. 1, Nov. 2023, doi: 10.1186/s42269-023-01146-2.

[7] K. S. Owoeye, K. Udofia, and N. Okpura, "Design and optimization of hybrid renewable energy system for rural electrification of an off-grid community," *European Journal of Engineering and Technology*, vol. 10, no. 1, pp. 28–42, 2022.

[8] F. Al Mubarak, R. Rezaee, and D. A. Wood, "Economic, societal, and environmental impacts of available energy sources: A review," *Eng*, vol. 5, no. 3, pp. 1232–1265, Jun. 2024, doi: 10.3390/eng5030067.

[9] C. Y. Wright *et al.*, "The impact of rolling blackouts on environmental health in South Africa," *Journal of Health and Pollution*, vol. 12, no. 1–4, Dec. 2024, doi: 10.1289/JHP1090.

[10] M. Farghali *et al.*, "Social, environmental, and economic consequences of integrating renewable energies in the electricity sector: A review," *Environmental Chemistry Letters*, vol. 21, no. 3, pp. 1381–1418, Jun. 2023, doi: 10.1007/s10311-023-01587-1.

[11] L. E. Natividad and P. Benalcazar, "Hybrid renewable energy systems for sustainable rural development: Perspectives and challenges in energy systems modeling," *Energies*, vol. 16, no. 3, Jan. 2023, doi: 10.3390/en16031328.

[12] S. A. Vincent, A. Tahiru, R. O. Lawal, C. E. Aralu, and A. Q. Okikiola, "Hybrid renewable energy systems for rural electrification in developing countries: Assessing feasibility, efficiency, and socioeconomic impact," *World Journal of Advanced Research and Reviews*, vol. 24, no. 2, pp. 2190–2204, Nov. 2024, doi: 10.30574/wjarr.2024.24.2.3515.

[13] P. H. Kumar, R. R. Gopi, R. Rajarajan, N. B. Vaishali, K. Vasavi, and S. Kumar P, "Prefeasibility techno-economic analysis of hybrid renewable energy system," *e-Prime - Advances in Electrical Engineering, Electronics and Energy*, vol. 7, Mar. 2024, doi: 10.1016/j.prime.2024.100443.

[14] K. Lammers, A. Linke, A. Andrade, and C. Cader, "Increasing electricity access for health facilities in Ghana through solar powered mini-grids—a GIS-based energy system modelling approach," *Environmental Research: Infrastructure and Sustainability*, vol. 4, no. 2, Jun. 2024, doi: 10.1088/2634-4505/ad4391.

[15] Y. Nurhikam, D. L. Hakim, N. T. Sugito, D. Zakaria, and A. G. Abdullah, "CRITIC-TOPSIS method: Design of hybrid renewable energy systems based on multi-criteria decision-making," *International Journal of Electrical and Computer Engineering Systems*, vol. 15, no. 8, pp. 705–718, Sep. 2024, doi: 10.32985/ijeces.15.8.8.

[16] I. Amoussou *et al.*, "Enhancing residential energy access with optimized stand-alone hybrid solar-diesel-battery systems in Buea, Cameroon," *Scientific Reports*, vol. 14, no. 1, Jul. 2024, doi: 10.1038/s41598-024-66582-0.

[17] B. Sawadogo, A. Benmouna, M. Becherif, S. Barakat, and M. Samy, "Integrated solar electrification and community empowerment in a Burkina Faso Village: A feasibility and design study," *Results in Engineering*, vol. 27, Sep. 2025, doi: 10.1016/j.rineng.2025.105686.

[18] G. Gbenga Ojo, O. A. Lottu, T. C. Ndiwe, U. Izuka, and N. N. -Ehiobu, "Solar energy adaptation and efficiency across diverse nigerian and global climates: A review of technological advancement," *Engineering Heritage Journal*, vol. 7, no. 1, pp. 99–107, Jan. 2023, doi: 10.26480/gwk.01.2023.99.107.

[19] P. P. Kumar *et al.*, "Optimal operation of an integrated hybrid renewable energy system with demand-side management in a Rural context," *Energies*, vol. 15, no. 14, Jul. 2022, doi: 10.3390/en15145176.

[20] C. S. Esobinenwu, "Optimization of hybrid solar PV and diesel generator system for an efficient electricity supply," *International Journal of Electrical and Electronics Engineering Studies*, vol. 9, no. 1, pp. 37–46, Jan. 2023, doi: 10.37745/ijeees.13/vol9n13746.

[21] M. He, H. F. Fard, K. Yahya, M. Mohamed, I. Alhamrouni, and L. J. Awalin, "Optimal design of hybrid renewable systems, including grid, PV, Bio generator, diesel generator, and battery," *Sustainability*, vol. 15, no. 4, Feb. 2023, doi: 10.3390/su15043297.

[22] 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, Jan. 2019, doi: 10.3390/su11030683.

[23] L. Kasprzyk *et al.*, "Optimization of a PV-wind hybrid power supply structure with electrochemical storage intended for supplying a load with known characteristics," *Energies*, vol. 13, no. 22, Nov. 2020, doi: 10.3390/en13226143.

[24] H. Kumba and O. A. Olanrewaju, "'Towards sustainable development: Analyzing the Viability and integration of Renewable energy solutions in South Africa'—A review," *Energies*, vol. 17, no. 6, Mar. 2024, doi: 10.3390/en17061418.

[25] S. De Nardi, C. Carnevale, S. Raccagni, and L. Sangiorgi, "Climate change impact on cereal production in Northern Africa: A comprehensive modeling and control approach," *IEEE Access*, vol. 13, pp. 5534–5550, 2025, doi: 10.1109/ACCESS.2024.3525146.

[26] L.-G. Hua *et al.*, "Comparative analysis of power output, fill factor, and efficiency at fixed and variable Tilt angles for polycrystalline and monocrystalline photovoltaic panels—the case of Sukkur IBA University," *Energies*, vol. 15, no. 11, May 2022, doi: 10.3390/en15113917.

[27] M. Tamoor, S. Habib, A. R. Bhatti, A. D. Butt, A. B. Awan, and E. M. Ahmed, "Designing and energy estimation of photovoltaic energy generation system and prediction of plant performance with the variation of Tilt angle and interrow spacing," *Sustainability*, vol. 14, no. 2, Jan. 2022, doi: 10.3390/su14020627.

[28] B. O. Ariyo, L. M. Adesina, A. Musa, O. Ogunbiyi, B. J. Ojuolape, and M. O. Balogun, "Optimization analysis of dual-mode renewable hybrid power systems: a review," *Nigerian Journal of Technological Development*, vol. 21, no. 4, pp. 48–58, Feb. 2025, doi: 10.4314/njtd.v21i4.2799.

[29] K. O. Roberts and N. Mahomed, "Hub height optimisation of commercial WTGs based on accurate wind resource analysis," *Wind Engineering*, vol. 46, no. 1, pp. 200–220, Feb. 2022, doi: 10.1177/0309524X211022727.

[30] B. Liu *et al.*, "Estimating hub-height wind speed based on a machine learning algorithm: implications for wind energy assessment," *Atmospheric Chemistry and Physics*, vol. 23, no. 5, pp. 3181–3193, Mar. 2023, doi: 10.5194/acp-23-3181-2023.

[31] C. Swann, D. J. Sherman, and R. C. Ewing, "Experimentally derived thresholds for windblown sand on mars," *Geophysical*

Research Letters, vol. 47, no. 3, Feb. 2020, doi: 10.1029/2019GL084484.
[32] H. F. J. Katuuk, Syafaruddin, and Y. S. Akil, "Wind speed calculation utilizing the Hellmann coefficient method and roughness length for wind turbine application," in *2024 7th International Seminar on Research of Information Technology and Intelligent Systems (ISRITI)*, Dec. 2024, pp. 1030–1035. doi: 10.1109/ISRITI64779.2024.10963592.
[33] H. M. Hussein, A. Aghmadi, M. S. Abdelrahman, S. M. S. H. Rafin, and O. Mohammed, "A review of battery state of charge estimation and management systems: Models and future prospective," *WIREs Energy and Environment*, vol. 13, no. 1, Jan. 2024, doi: 10.1002/wene.507.
[34] S. Sun, Y. Wang, H. Wang, Y. Meng, and S. Liu, "Two-level optimal scheduling strategy of demand response-based microgrids based on renewable energy forecasting." *Research Square Platform LLC*, Jul. 05, 2023. doi: 10.21203/rs.3.rs-3074985/v1.
[35] A. Shateri, Z. Yang, and J. Xie, "Utilizing artificial intelligence to identify an optimal machine learning model for predicting fuel consumption in diesel engines," *Energy and AI*, vol. 16, May 2024, doi: 10.1016/j.egyai.2024.100360.
[36] B. O. Ariyo, M. F. Akorede, I. O. A. Omeiza, S. A. Y. Amuda, and S. A. Oladeji, "Optimisation analysis of a stand-alone hybrid energy system for the senate building, university of Ilorin, Nigeria," *Journal of Building Engineering*, vol. 19, pp. 285–294, Sep. 2018, doi: 10.1016/j.jobe.2018.05.015.
[37] S. Jin, "Integrating BIM to enhance stakeholder collaboration and economic efficiency in architecture and construction projects," *E3S Web of Conferences*, vol. 565, Sep. 2024, doi: 10.1051/e3sconf/202456503014.
[38] Ł. Augustowski and P. Kułyk, "The economic profitability of photovoltaic installations in households in Poland from a new policy perspective," *Energies*, vol. 16, no. 22, Nov. 2023, doi: 10.3390/en16227595.
[39] L. Otte, N. Schöne, A. Flessa, P. Fragkos, and B. Heinz, "Costs and benefits of citizen participation in the energy transition: investigating the economic viability of prosumers on Islands—the case of Mayotte," *Energies*, vol. 17, no. 12, Jun. 2024, doi: 10.3390/en17122904.
[40] C. D. Iweh, S. Gyamfi, E. Tanyi, and E. Effah-Donyina, "Economic viability and environmental sustainability of a grid-connected solar PV plant in Yaounde - Cameroon using RETScreen expert," *Cogent Engineering*, vol. 10, no. 1, Dec. 2023, doi: 10.1080/23311916.2023.2185946.
[41] P. G. Anselma *et al.*, "Economic payback time of battery pack replacement for hybrid and plug-in hybrid electric vehicles," *IEEE Transactions on Transportation Electrification*, vol. 9, no. 1, pp. 1021–1033, Mar. 2023, doi: 10.1109/TTE.2022.3202792.
[42] O. O. Babayomi *et al.*, "A review of renewable off-grid mini-grids in Sub-Saharan Africa," *Frontiers in Energy Research*, vol. 10, Jan. 2023, doi: 10.3389/fenrg.2022.1089025.
[43] M. F. Ishraque *et al.*, "Techno-economic and power system optimization of a renewable rich islanded microgrid considering different dispatch strategies," *IEEE Access*, vol. 9, pp. 77325–77340, 2021, doi: 10.1109/ACCESS.2021.3082538.
[44] I. Sorrenti, T. B. H. Rasmussen, Q. Wu, and S. You, "Carbon-emission reduction of hybrid renewable energy system stochastic day-ahead scheduling," *International Journal of Smart Grid and Clean Energy*, pp. 91–99, 2023, doi: 10.12720/sgce.12.4.91-99.
[45] M. S. Ali, S. U. Ali, S. M. Qaisar, A. Waqar, F. Haroon, and A. Alzahrani, "Techno-economic analysis of hybrid renewable energy-based electricity supply to Gwadar, Pakistan," *Sustainability*, vol. 14, no. 23, Dec. 2022, doi: 10.3390/su142316281.
[46] M. Sankoh, B. Diarra, R. Samikannu, and N. S. D. Ladu, "Techno-economic feasibility analysis of a solar photovoltaic hybrid system for rural electrification in Sierra Leone for Zero carbon emission," *International Transactions on Electrical Energy Systems*, vol. 2022, pp. 1–14, Aug. 2022, doi: 10.1155/2022/6349229.
[47] A. Xu, L. J. Awalin, A. Al-Khaykan, H. F. Fard, I. Alhamrouni, and M. Salem, "Techno-economic and environmental study of optimum hybrid renewable systems, including PV/Wind/Gen/Battery, with various components to find the best renewable combination for Ponorogo Regency, East Java, Indonesia," *Sustainability*, vol. 15, no. 3, Jan. 2023, doi: 10.3390/su15031802.
[48] A. Sharma, H. P. Singh, R. Viral, and N. Anwer, "Techno-economical planning of an off-grid integrated renewable energy system," *U.Porto Journal of Engineering*, vol. 8, no. 6, pp. 210–229, Nov. 2022, doi: 10.24840/2183-6493_008.006_0015.
[49] M. S. Nkambule, A. N. Hasan, and T. Shongwe, "Performance and techno-economic analysis of optimal hybrid renewable energy systems for the mining industry in South Africa," *Sustainability*, vol. 15, no. 24, Dec. 2023, doi: 10.3390/su152416766.
[50] D. Huo, M. Santos, I. Sarantakos, M. Resch, N. Wade, and D. Greenwood, "A reliability-aware chance-constrained battery sizing method for island microgrid," *Energy*, vol. 251, Jul. 2022, doi: 10.1016/j.energy.2022.123978.
[51] Y. Wang, X. He, Q. Liu, and S. Razmjooy, "Economic and technical analysis of an HRES (hybrid renewable energy system) comprising wind, PV, and fuel cells using an improved subtraction-average-based optimizer," *Heliyon*, vol. 10, no. 12, Jun. 2024, doi: 10.1016/j.heliyon.2024.e32712.
[52] A. A. Rathod and B. Subramanian, "Scrutiny of hybrid renewable energy systems for control, power management, optimization and sizing: Challenges and future possibilities," *Sustainability*, vol. 14, no. 24, Dec. 2022, doi: 10.3390/su142416814.
[53] A. A. Khan, A. F. Minai, R. K. Godi, V. Shankar Sharma, H. Malik, and A. Afthanorhan, "Optimal sizing, techno-economic feasibility and reliability analysis of hybrid renewable energy system: A systematic review of energy storage systems' integration," *IEEE Access*, vol. 13, pp. 59198–59226, 2025, doi: 10.1109/ACCESS.2025.3535520.
[54] T. J. Priyanka, S. Atre, M. M. Billal, and M. Arani, "Techno-economic analysis of a renewable-based hybrid energy system for utility and transportation facilities in a remote community of Northern Alberta," *Cleaner Energy Systems*, vol. 6, Dec. 2023, doi: 10.1016/j.cles.2023.100073.
[55] S. Mahmud, M. K. Kaihan, S. Salehin, M. T. Ferdaous, and M. Nasim, "Hybrid renewable energy systems for a remote community in a high mountain plateau," *International Journal of Energy and Environmental Engineering*, vol. 13, no. 4, pp. 1335–1348, Dec. 2022, doi: 10.1007/s40095-022-00494-5.
[56] M. S. Nkambule, A. N. Hasan, and T. Shongwe, "Analyzing the economic viability of microgrid solutions in the South African market," *IEEE Access*, vol. 13, pp. 29091–29121, 2025, doi: 10.1109/ACCESS.2025.3539691.
[57] P. Warren, M. Frazer, and N. Greenwood, "Role of climate finance beyond renewables: Hard-to-abate sectors," *Energy Reports*, vol. 10, pp. 3519–3531, Nov. 2023, doi: 10.1016/j.egyr.2023.10.021.
[58] G. Mandrini, C. M. Pittelkow, S. Archontoulis, D. Kanter, and N. F. Martin, "Exploring trade-offs between profit, yield, and the environmental footprint of potential nitrogen fertilizer regulations in the US Midwest," *Frontiers in Plant Science*, vol. 13, Apr. 2022, doi: 10.3389/fpls.2022.852116.
[59] A. Kusumawati, S. Suhanda, Darmawati, A. I. P. Natsir, and I. S. K. Juanda, "Bibliometric analysis of research trends and networks in carbon tax studies: Insights into environmental and economic policy implications," *Environmental Economics*, vol. 16, no. 1, pp. 43–58, Jan. 2025, doi: 10.21511/ee.16(1).2025.04.
[60] T. Kanyepi *et al.*, "Analyzing policy framework of agrivoltaics across the water energy and food (WEF) Nexus in The Gambia," *AgriVoltaics Conference Proceedings*, vol. 1, Feb. 2024, doi: 10.52825/agripv.v1i.696.
[61] N. Yimen, O. Hamandjoda, L. Meva'a, B. Ndzana, and J. Nganhou, "Analyzing of a photovoltaic/wind/biogas/pumped-hydro off-grid hybrid system for rural electrification in Sub-Saharan Africa - Case study of Djoundé in Northern Cameroon," *Energies*, vol.

11, no. 10, Oct. 2018, doi: 10.3390/en11102644.
[62] A. M. Eltamaly and Z. A. Almutairi, "Nested optimization algorithms for accurately sizing a clean energy smart grid system, considering uncertainties and demand response," *Sustainability*, vol. 17, no. 6, Mar. 2025, doi: 10.3390/su17062744.
[63] T. F. Agajie *et al.*, "A comprehensive review on techno-economic analysis and optimal sizing of hybrid renewable energy sources with energy storage systems," *Energies*, vol. 16, no. 2, Jan. 2023, doi: 10.3390/en16020642.
[64] H. M. Abdullah, S. Park, K. Seong, and S. Lee, "Hybrid renewable energy system design: A machine learning approach for optimal sizing with net-metering costs," *Sustainability*, vol. 15, no. 11, May 2023, doi: 10.3390/su15118538.
[65] V. Sharma, S. M. Aziz, M. H. Haque, and T. Kauschke, "Energy economy of households with photovoltaic system and battery storage under time of use tariff with demand charge," *IEEE Access*, vol. 10, pp. 33069–33082, 2022, doi: 10.1109/ACCESS.2022.3158677.

BIOGRAPHIES OF AUTHORS

Lambe Mutalub Adesina received the B.Eng. degree in Electrical Engineering from the University of Ilorin, Nigeria, in 1988, the M.Eng. degree from Bayero University Kano, Nigeria, in 1995, and the Ph.D. degree in Power Systems Quality from the University of Ibadan, Nigeria, in 2016. He served as a lecturer at Kaduna Polytechnic, Kaduna, for seven years before joining the Power Holding Company of Nigeria (PHCN) in December 1997 as Manager (Electrical), where he rose to the position of District Manager. In 2018, he joined the Department of Electrical and Computer Engineering, Kwara State University (KWASU), as a senior lecturer, became Head of Department in 2019, and was promoted to Associate Professor in 2022. He has published 57 academic papers in both local and international journals and has received both national and university-based research grants in 2025. Currently, he serves as the Director of the Centre for Sustainable Energy, KWASU, and as an external examiner for postgraduate programs in several Nigerian universities. His research interests include power quality, renewable energy integration, and power system stability. He is a member of recognized professional bodies. He can be contacted at email: lambe.adesina@kwasu.edu.ng.

Jamiu Lawal received the B.Eng. degree in Electrical and Electronics Engineering from the Federal University of Technology, Akure, Nigeria, in 2017, and the National Diploma from the Federal Polytechnic, Offa, Nigeria, in 2011. He is completing the M.Sc. degree in Electrical and Electronics Engineering at Kwara State University, Malete, Nigeria, with the dissertation "Optimization and Techno-Economic Analysis of Hybrid Renewable Systems in Nigeria." He is a COREN-certified Engineer and a registered member of the Nigerian Society of Engineers (NSE). He has over five years of professional experience in metering systems, power distribution, and technical operations, currently serving as Meter Standards Officer with Ibadan Electricity Distribution Company (IBEDC), Ilorin. His experience includes teaching power system engineering and industrial training at the Transmission Company of Nigeria (TCN). His research interests include renewable hybrid power systems, energy optimization, power system reliability, metering technologies, and smart grid integration. He can be contacted at email: jamiulawal9557@gmail.com.

Olalekan Ogunbiyi earned his Ph.D. degree in Electrical Engineering from the University of Ilorin in 2018. Earlier, he obtained his Bachelor's and Master's degrees in Electrical and Electronics Engineering from the same university in 2009 and 2013, respectively. His research interests include automatic control systems, embedded systems, and power system control and stability. He has published over 30 academic papers in the areas of control systems, computer networks, and power systems. He is currently a senior lecturer in the Department of Electrical and Computer Engineering at Kwara State University, Malete, Nigeria. He can be contacted at email: Olalekan.ogunbiyi@kwasu.edu.ng.

Abdulwaheed Musa received the Doctor of Engineering degree with specialization in Wireless Communication Systems. He is currently the Head of the Department of Electrical and Computer Engineering and the Founding Director of the Centre for Artificial Intelligence and Machine Learning Systems (CAMS) at Kwara State University (KWASU), Malete, Nigeria. He previously served as a Postdoctoral Research Fellow and Senior Research Associate at the Institute for Intelligent Systems, University of Johannesburg, South Africa. His research interests include wireless communications, artificial intelligence, renewable energy systems, and emerging technologies. He is a senior member of the Institute of Electrical and Electronics Engineers (IEEE), a member of the Institution of Engineering and Technology (IET), and a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN). He can be contacted at email: abdulwaheed.musa@kwasu.edu.ng.

Bilkisu Jimada Ojuolape received the B.Sc. degree in Electrical/Electronic Engineering from Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, in 2011, the M.Sc. degree in Systems Engineering from Loughborough University, Loughborough, U.K., in 2013, and the Ph.D. degree in Electrical Engineering from Universiti Sains Malaysia, Penang, Malaysia, in 2022. She is currently a Lecturer I in the Department of Electrical and Computer Engineering at Kwara State University, Malete, Nigeria. Her research interests include cyber-physical power systems, dynamic thermal rating (DTR) systems, renewable energy, smart grid reliability, and the application of ICTs in smart grids. She has published 23 articles in reputable journals and is a member of recognized professional bodies, including the Association of Practicing Women Engineers in Nigeria (APWEN). She can be contacted at email: bilkisu.jimada@kwasu.edu.ng.

Monsurat Omolara Balogun received the Ph.D. degree in Computer Engineering. She is currently a senior lecturer in the Department of Electrical and Computer Engineering, Faculty of Engineering and Technology, Kwara State University, Malete, Ilorin, Kwara State, Nigeria. Her research interests include artificial intelligence, biometric systems, and image processing, with a current focus on AI-based soil humidity monitoring systems to improve crop yield in Nigeria. She has published articles in reputable journals and has supervised numerous undergraduate projects and M.Eng. theses. She is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN), and a member of the Nigerian Society of Engineers (NSE), the Nigerian Institute of Management (Chartered), and the Artificial Intelligence for Sustainable Agriculture and Rural Development (AI4SARD) research team. Her extracurricular interests include reading and listening to music. She can be contacted at email: monsurat.balogun@kwasu.edu.ng.

Bashiru Olalekan Ariyo received his Master's degree in Computer and Control Engineering and is presently at the completion stage of his Ph.D. degree at Kwara State University, Malete, Nigeria. He is currently a Chief Laboratory Technologist in the Department of Electrical and Electronics Engineering, Faculty of Engineering and Technology, University of Ilorin, Nigeria. His research interests include power system engineering, renewable hybrid power systems, and microgrid system optimization. He has published articles in reputable journals and serves as a reviewer for notable publications. He is a registered engineer with the Council for the Regulation of Engineering in Nigeria (COREN) and a member of the Nigerian Society of Engineers (NSE). He can be contacted at email: ariy@unilorin.edu.ng.