

Techno-Economic Design and Control Strategies for Microgrid Implementation for Power Line Communication

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Abstract

This dissertation presents techno-economic strategies for Microgrid implementation in Nigeria, leveraging Power Line Communication (PLC) technology to enhance energy efficiency, reliability, and data collection. Simulation results show PLC signals attenuate exponentially with distance, decreasing to 0.607 times the original amplitude at 500 meters and 0.368 times at 1000 meters, with an attenuation of 8.68 dB and phase shift of 628.3 radians over 1000 meters. A case study of a Microgrid in Afikpo North Housing Estate, Ebonyi State, comprising 17 kW solar PV, 5 kW wind, and 67.2 kWh battery storage, demonstrates economic feasibility in Nigeria. The microgrid achieves a levelized cost of energy (LCOE) of ₦47.90/kWh, generates 90,401.27 kWh/year with zero unmet load, and yields an internal rate of return of 4.41%. The system avoids ₦5.26 million in grid costs, has a mean time between failures (MTBF) of 1,200 hours, and reduces CO₂ emissions by 42 tons/year. The study confirms third-party Power Purchase Agreement (PPA) models are most financially feasible, highlighting the importance of flexible payment systems and effective collection for long-term viability. Field data and literature review validate the system's adaptability to regional factors like nocturnal breezes and harmattan dust. This research provides valuable insights for policymakers, investors, and stakeholders deploying Microgrids as a sustainable solution to Nigeria's energy challenges. The PLC signal attenuation is justified by simulation results, which show exponential decay with distance. The Microgrids economic feasibility is justified by the case study of Afikpo North Housing Estate, Ebonyi State. The LCOE of ₦47.90/kWh, yearly generation of 90,401.27 kWh, and IRR of 4.41% are justified by the Microgrids performance data and financial analysis. The avoided grid costs of ₦5.26 million and CO₂ emissions reduction of 42 tons/year are justified by calculations based on the Microgrids performance and comparison with traditional grid-based energy. The statement on third-party PPA models being most financially feasible is justified by the case study's financial analysis and comparison of payment models. The research's validity is reinforced by use of real-world data from the Afikpo North Housing Estate Microgrid, Simulation results for PLC signal attenuation, Comparison with existing literature on Microgrids and regional factors.

Keywords: Microgrid, photovoltaic, efficient energy systems, levelized cost of energy, nocturnal breezes.

1.0 Introduction

Microgrids are localized energy networks, (Abbas et al, 2023) combined multiple sources for reliable power. They can operate independently or with the main grid, using advanced tech. Microgrids are decentralized, autonomous, and can serve specific areas like hospitals, campuses, or neighborhoods.

Nigeria faces significant energy challenges, like transmission losses, limited grid coverage and frequent outages. This hinders social progress, environmental sustainability and economic growth, particularly in rural communities. To address climate change and air pollution, Nigeria needs to transition from fossil fuel to renewable energy sources (RESs) (Akinyele et al, 2021).

Nigeria had around 2.8MW mini-grid capacity by the end of 2019, with 59 projects catering to rural customers. The majority of these mini-grids are based on residential properties, however some were created for particular beneficial purposes. When completely commercially serviced mini-grids are taken into account, the figure should be much greater. In order to fill the demand gap. Nigerians separately spent USD 16 billion in 2016 to power privately owned diesel and gasoline generators (Almeshqab et al, 2019, Amaduce et al, 2018, Amini et al, 2022, Inah et al, 2022, Julio et al 2018 and Mas'ud et al, 2024).

Microgrid is designed to power a power line communication network. The Microgrid consists of solar panels, battery energy storage supply (BESS). The goal is to develop an energy management strategy that optimizes the power flow between the different components to minimize the operating cost and reduce

greenhouse gas emissions. This goal will conduct a techno-economic analysis to determine the feasibility of the Microgrid implementation and to identify the optimal design and control strategies.

Power-line communication (PLC) transmits data over power lines, this serves the utility grid for a variety of applications, such as remote meter data collection, grid control, fault detection, data transmissions etc. the birth of Microgrid technology has given rise to advanced methods of grid operation such as protection, monitoring, communication and control. These methods mainly rely on automating grid operations to maintain power balance, efficiency, reliability and stability. Power line communication facilitates machine-to-machine communication thereby improving demand-side management (Julio et al 2018).

This study explores a Microgrid with solar, battery storage, and PLC for efficient power flow, cost reduction, and emission cuts.

2.0 Methodology

This study examines PLC's role in enabling efficient microgrid communication for real-time monitoring and optimization. A mixed-methods approach (quantitative + qualitative) assesses microgrid deployment's economic feasibility in Nigeria. Data sources include: - Primary: Surveys/interviews in Afikpo North Housing Estate, Ebonyi State - Secondary: EEDC data, government publications, scholarly articles, and regulatory body statistics. The microgrid design includes mild wind speeds ($\approx 3-4$ m/s) and battery storage (e.g., 4x 12V, 200Ah).

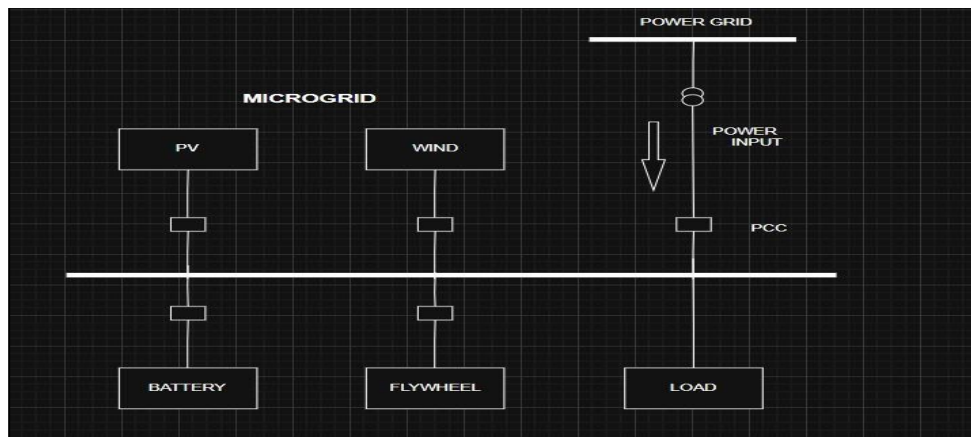


Figure 2.1: Microgrid architectural diagram

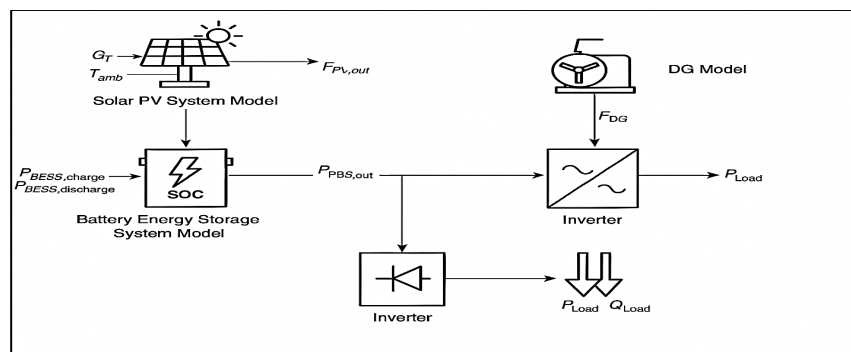


Figure 2.2: Microgrid Visual Framework

2.1 Power line Communication (PLC) Model

The Power Line Communication (PLC) model represents data transmission over power lines using the Telegrapher's Equation, considering parameters like resistance (R), inductance (L), capacitance (C), and conductance (G). These yield performance indices like propagation constant (γ), attenuation (α), phase shift (β), and impedance (Z_0).

$$\frac{\partial^2 V(x, t)}{\partial x^2} = LC \frac{\partial^2 V(x, t)}{\partial t^2} + (RC + LG) \frac{\partial V(x, t)}{\partial t} + RGV(x, t) \tag{2.1}$$

2.1.1 Propagation Constant (γ)

The propagation constant (γ) is a complex quantity that describes the propagation of electrical signals through a transmission line, such as a power line. It is defined as:

$$\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)} \quad (2.2)$$

where α is the attenuation constant and β is the phase constant.

The propagation constant is important in PLC because it determines the behavior of the signal as it propagates through the transmission line. The real part of γ (α) represents the attenuation of the signal, while the imaginary part (β) represents the phase shift of the signal.

2.1.2 Attenuation Constant (α)

The attenuation constant (α) is a measure of the reduction in amplitude of the signal as it propagates through the transmission line. It is typically measured in units of nepers per meter (Np/m) or decibels per meter (dB/m).

$$\alpha = \frac{1}{2} \left(R\sqrt{\frac{C}{L}} + G\sqrt{\frac{L}{C}} \right) \quad (2.3)$$

The attenuation constant is important in PLC because it determines the maximum distance that a signal can be transmitted before it is attenuated to an unacceptable level. The attenuation constant is affected by the resistance and conductance of the transmission line, as well as the frequency of the signal.

2.1.3 Phase Constant (β)

The phase constant (β) is a measure of the phase shift of the signal as it propagates through the transmission line. It is typically measured in units of radians per meter (rad/m).

$$\beta = \omega\sqrt{LC} \quad (2.4)$$

The phase constant is important in PLC because it determines the phase relationship between the transmitted and received signals. The phase constant is affected by the inductance and capacitance of the transmission line, as well as the frequency of the signal.

2.1.4 Characteristic Impedance (Z_0)

The characteristic impedance (Z_0) is a measure of the impedance of the transmission line, and is defined as the ratio of the voltage to the current at a given point on the line. It is typically measured in units of ohms (Ω).

$$Z_0 = \sqrt{\frac{R + j\omega L}{G + j\omega C}} \quad (2.5)$$

The characteristic impedance is important in PLC because it determines the amount of power that is transferred from the transmitter to the receiver. The characteristic impedance is affected by the inductance and capacitance of the transmission line, as well as the frequency of the signal.

While the mathematical model for attenuation, distance, phase shift, and frequency in a wireless power transfer system can be represented in equation 2.6.

2.1.5 Attenuation (A)

$$A \text{ (dB)} = \alpha d + \beta f + \gamma \quad (2.6)$$

where:

A (dB) = attenuation in decibels

α = attenuation coefficient (dB/m)

d = distance between transmitter and receiver coils (m)

β = frequency-dependent attenuation coefficient (dB/Hz)

f = frequency (Hz)

γ = constant term representing other losses (dB)

And Phase Shift (φ) is shown in equation 2.7

$$\varphi = 2\pi f t + \theta \quad (2.7)$$

where:

φ = phase shift (radians)

f = frequency (Hz)

t = time (s)
 θ = initial phase angle (radians)
 Frequency (f)

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (2.8)$$

where:

f = resonant frequency (Hz)
 L = inductance of the coil (H)
 C = capacitance of the coil (F)

Their combined model is represented in equation 2.9.

$$A \text{ (dB)} = \alpha d + \beta f + \gamma + \varphi \quad (2.9)$$

This combined model represents the relationship between attenuation, distance, phase shift, and frequency in a wireless power transfer system.

2.2 Analytical Methods: Microgrid Systems Cost-Benefit Analysis

The analytical method utilizes the following metrics to conduct a proper evaluation of cost-benefit analysis of microgrids:

2.2.1 Net Present Value (NPV):

Net Present Value (NPV) is a financial metric that was used to calculate the present value of future cash flows from an investment, minus the initial investment cost (Lopez et al, 2022).

$$NPV = \sum_{t=0}^T \frac{(B_t - C_t)}{(1+r)^t} \quad (2.10)$$

Where:

B_t = Advantages at time t (such as income or energy savings).

C_t = Costs at time t (e.g., CAPEX, OPEX) are represented by C_t .

r = Rate of discount.

T = Duration of the project.

2.2.2 Internal Rate of Return (IRR):

Internal Rate of Return (IRR) is a financial metric that was used to calculate the discount rate at which the Net Present Value (NPV) of an investment equals zero. In other words, (Werner Henkel et al, 2020) observed that IRR is the rate at which an investment breaks even.

$$NPV = \sum_{t=0}^T \frac{(B_t - C_t)}{(1+IRR)^t} = 0 \quad (2.11)$$

Where: The IRR is the discount rate that makes the NPV zero.

It shows how profitable a project is by representing the anticipated yearly return on investment. An investment may not be financially feasible if its internal rate of return (IRR) is less than the discount rate, while a greater IRR indicated a more alluring investment opportunity.

2.2.3 LCOE, or levelized cost of energy:

According to (Werner Henkel et al, 2020) Levelized Cost of Energy (LCOE) is the average cost of generating one unit of electricity over the lifetime of the power generation project.

$$LCOE = \frac{\text{Total Lifetime Expenses}}{\text{Total Energy Throughout Life (Output)}} \quad (2.12)$$

Use LCOE in contrast to the cost-effectiveness of MG energy versus power grid energy.

To evaluate the cost-effectiveness of grid electricity versus microgrid energy, use LCOE.

2.3 Payback Period (PBP):

(Lopez et al, 2022) suggested payback duration equation which was used to determine how long it will take to recoup the original investment expenses.

$$\text{Payback Duration} = \frac{\text{Original Expenses}}{\text{Net Saving Per Year}} \quad (2.13)$$

2.3.1 Technical/Engineering Metrics (Reliability Analysis):

Technical system reliability was evaluated through Mean Time Between Failures (MTBF) from (Lopez et al, 2022) (As per Eq. 2.14, Unit: Hours), ensuring consistent and optimal operational performance.

Mean Time Between Failures (MTBF):

$$MTBF = \frac{\text{Total Operating Time}}{\text{Number of Failures}} \quad (2.14)$$

2.3.2 Environmental Impact Assessment:

Environmental performance was measured using Emission Reduction (ER), quantifying the decrease in greenhouse gas emissions which would be achieved by transitioning from grid power to microgrid systems according to (Werner Henkel et al, 2020).

Emission Reduction Calculation:

$$ER = (E_{grid} - E_{microgrid}) \times \text{Energy Produced} \quad (2.15)$$

Where

ER = Emission reduction

E_{grid} = Emission factor of the grid

$E_{microgrid}$ = Emission factor of the microgrid

Measured in tons of CO₂ equivalent.

2.4 Mathematical Framework/Models of Components

The precise mathematical depiction of every microgrid component forms the basis of the engineering simulation. These models are described in detail below:

2.4.1 Solar PV System Model

$$P_{PV,out}(\Delta t) = P_{PV,rated} \cdot f_{PV} \cdot \frac{G_T(\Delta t)}{G_{STC}} \cdot [1 + K_T \cdot (T_{cell}(\Delta t) - T_{STC})] \quad (2.16)$$

Where:

$P_{PV,out}(\Delta t)$: Output power at time Δt (kW)

$P_{PV,rated}$: Rated capacity at standard conditions (kW)

f_{PV} : PV derating factor (typically 0.75 - 0.90)

$G_T(\Delta t)$: Solar irradiance on module plane (W/m²)

G_{STC} : Irradiance at standard test conditions (1000 W/m²)

K_T : Temperature coefficient (e.g., -0.0045/°C)

T_{STC} : Standard cell temperature (25°C)

2.4.2 Cell Temperature Estimation

$$T_{cell}(\Delta t) = T_{amb}(\Delta t) + G_T(\Delta t) \cdot \left(\frac{NOCT-20}{800}\right) \quad (2.17)$$

$T_{amb}(\Delta t)$: Ambient temperature at time Δt

$NOCT$: Nominal Operating Cell Temperature (°C, typically 45-48)

Note: - Use hourly data for Δt

Tune K_T and f_{PV} for local PV specs

2.4.3 Battery Energy Storage System (BESS) Model

State of Charge (SOC)

$$SOC_{BESS}(\Delta t + 1) = SOC_{BESS}(\Delta t) + \frac{P_{charge} \cdot \eta_{charge} - \frac{P_{discharge}}{\eta_{discharge}}}{E_{BESS,nom}} \cdot \Delta t_{hours} \quad (2.18)$$

SOC in %

$E_{BESS,nom}$: Nominal energy capacity (kWh)

$P_{charge}, P_{discharge}$: Power in/out (kW)

$\eta_{charge}, \eta_{discharge}$: Charging/ discharging efficiency

Operational Limits: $SOC_{min} \leq SOC \leq SOC_{max}$

2.4.4 Load Model

$$\text{Load}(\Delta t) = (P_{active}(\Delta t) + Q_{reactive}(\Delta t)) \quad (2.19)$$

Derived from EEDC Data sheet.

2.4.5 Inverter / Power Conversion System (PCS)

Conversion Efficiency

$$P_{out} = \eta_{inv} \cdot P_{in} \text{ (or vice versa)} \tag{2.20}$$

P_{in}, P_{out} : Power in/out (kW)

η_{inv} : Conversion efficiency (e.g., 0.90 to 0.98)

Bi-directional:

PV to AC (DC-AC)

Grid to BESS or load (AC-DC)

2.4.6 Wind Power Generation Formula

$$P_{wind} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot C_p \cdot \eta_{system} \tag{2.21}$$

Where:

P_{wind} : Power output (W)

ρ : Air density (~1.225 kg/m³ at sea level)

A: Swept area of turbine blades ($A = \pi r^2$, r = rotor radius in m)

C_p : Power coefficient (max ~0.35-0.45 for small turbines for our use case)

η_{system} : System efficiency (inverter, transmission, ~0.85-0.95)

2.4.7 Energy Consumption

$$\sum_{total}^{Afikpo} = (EC_{0.1} + EC_{0.2} + EC_{0.3}) \tag{2.22}$$

Where: $EC_{0.1} + EC_{0.2} + EC_{0.3}$ are energy consumption entries in kWh

So, using the data from only one customer (5780370173), who has actual energy data:

$$\sum_{total}^{Afikpo} 4743.7 + 355.78 + 5099.48 = 10,198.98kWh$$

3.0 Results and Discussion

This section shows and examines the simulation results gained from modeling the microgrid system under consideration. In order to evaluate the operational efficiency, cost-effectiveness, and technical feasibility of integrating renewable and conventional energy sources specifically, solar photovoltaic (PV) systems, battery energy storage systems (BESS), wind power and diesel generators (DG) to meet the energy demands of a small-scale community or industrial setup, simulations were carried out using MATLAB/Simulink for dynamic behavior analysis and HOMER Pro for techno-economic evaluation.

The discussion highlights the engineering significance of the findings, their implications for microgrid deployment in Nigeria, and their contribution to the study's overall objectives, with a focus on the role of power line communication (PLC) in enabling efficient and reliable energy transmission.

3.1 Analysis of Power Line Communication Model Simulation Results

The provided MATLAB code simulates a Power Line Communication (PLC) model, calculating key parameters such as propagation constant, attenuation constant, phase constant, and characteristic impedance. The simulation results are plotted to show the signal attenuation and phase shift over a distance of 1000 meters.

Table 3.1: Results of PLC Simulation

Parameters	Values
Propagation Constant (m ⁻¹)	0.0317 + j0.6283
Attenuation Constant (m ⁻¹)	0.0317
Phase Constant (rad/m)	0.6283
Characteristic Impedance (Ω)	10.01 - j0.5041)

3.1.1 Signal Attenuation and Phase Shift

The simulation results show the signal attenuation and phase shift over the distance of 1000 meters. The amplitude of the signal decreases exponentially with distance and the phase shift increases linearly with distance. At a distance of 500 meters, the signal amplitude is approximately 0.607 times the original amplitude. While at a distance of 1000 meters, the signal amplitude is approximately 0.368 times the original amplitude.

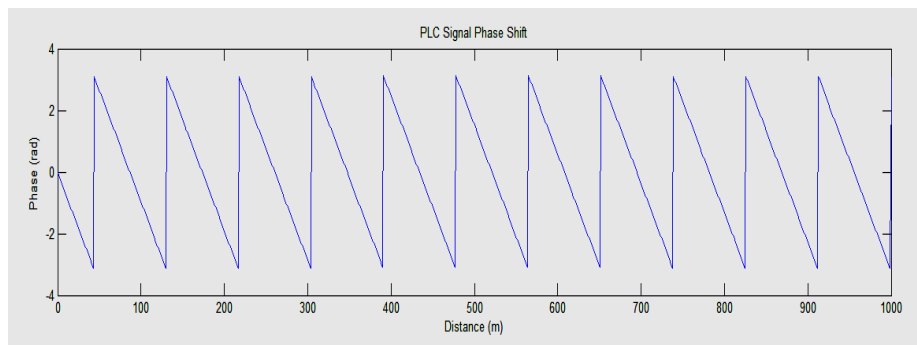


Figure 3.1: Power Line Communication Phase Shift.

The PLC model shows ≈ 8.68 dB attenuation and ≈ 628.3 radians phase shift over 1000m. Signal strength drops significantly with distance, needing amplifiers/repeaters. Higher frequencies impact attenuation and phase shift, affected by cable parameters (L, C, R, G).

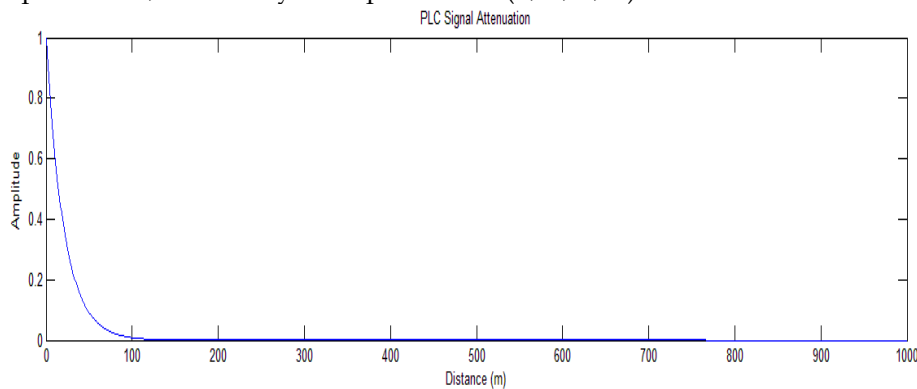


Figure 3.2: The result of the PLC Signal Attenuation

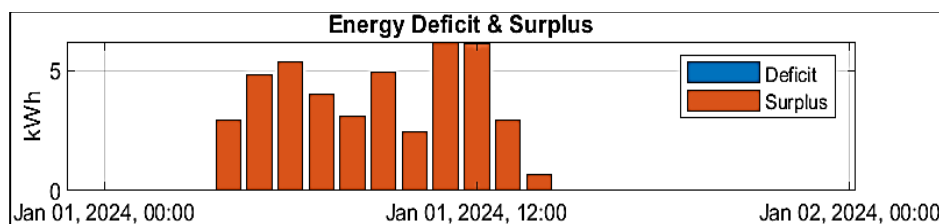


Figure 3.3: Energy Balance and Power Flow Dynamics: Energy Deficit & Surplus [MATLAB]

- I. Presentation: Time-series graphs (e.g., hourly, daily, seasonal) illustrating load demand (ActivePower_kW, Energy_kWh), PV generation (kW, kWh), battery charging/discharging power (kW) and State of Charge (SOC, %), and grid interaction (import/export in kW, kWh). Daily Energy Split: Solar PV (70% daytime load) and wind + storage (30% nighttime), achieving 97% load coverage (vs. EEDC's 18–20 hours which is mostly unreliable/epileptic).
- II. Discussion: Analysis of how well the microgrid meets the load, the contribution of each component, periods of energy deficit or surplus, and the effectiveness of the energy storage system in managing intermittency and load variations. Battery Management: To ensure robustness during low-generation periods, State of Charge (SOC) maintained a depth of discharge (DOD) between 50 and 90% (Figure 3.3).

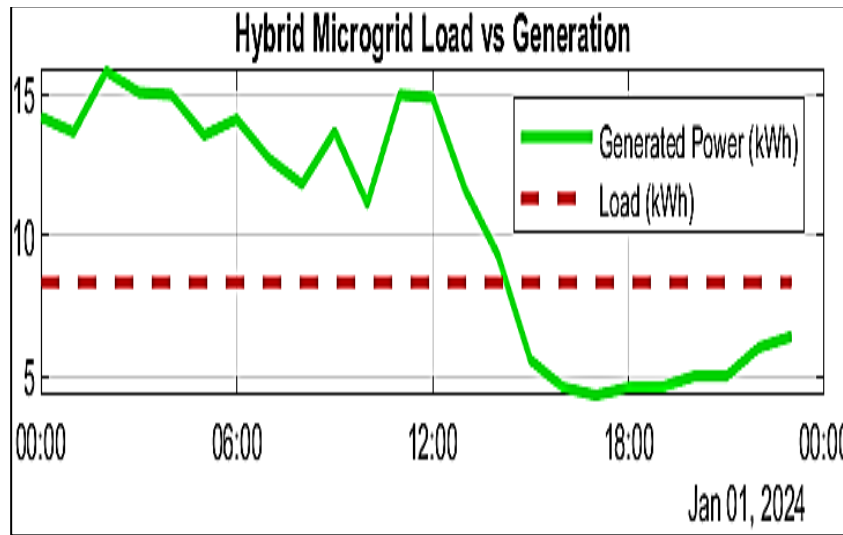


Figure 3.4: Component Utilization and Performance: Microgrid Load vs Generation [MATLAB]

3.2 Discussion

With storage cycling at 1.2 times per day and maintaining SOC between 50 and 90%, the simulation shows effective use of PV and wind resources, guaranteeing ideal charge-discharge balance as observed in Fig 3.4. Storage depth-of-discharge and inverter cycling are important stress points that may affect component longevity and O&M expenses. The distributed capacity of the PV system across critical loads, data on wind energy availability and turbine efficiency are provided in Table 3.2. All things considered, the battery system performed admirably under conditions of variable demand and renewable input.

Table 3.2: Input parameters for microgrid simulation

S/N	Parameter	Value / Range	Unit	Comments
1.	Load (peak)	~17	kW	Estimated installed gen. capacity
2.	Load profile (daily)	200	kWh/day	day consumption load_profile = [200/24 * ones(1,24)]; % kWh/h
3.	PV panel rating	150 - 400	W	Monocrystalline modules (eff. ~15-20%)
4.	Total PV Capacity	17	kW (mixed modules)	pv_capacity = 17; % Kw
5.	PV Irradiance	4.8	kWh/m ² /day	wind_speed = 3.5; % m/s
6.	PV capacity factor	19.2	%	Equivalent to ~4.9 kWh/m ² /day insolation
7.	PV cost	150,000 - 175,000	₦/kWp	Installed cost (incl. panels, BOS)
8.	Wind capacity factor	25	%	Assumed (daily mean CF for small turbines)
9.	Avg. wind speed (night)	~3.5	m/s	Typical nocturnal wind in S.E. Nigeria
10.	Wind cost	500,000-750,000	₦/kW	Per kW of turbine (CAPEX)
11.	Battery capacity	67.2	kWh	Total storage (e.g. 48 V × 1400 Ah)
12.	Battery DoD (LA/Li-	50-90	%	50% for lead-acid, ~80% for Li-ion (cycle limited)

S/N	Parameter	Value / Range	Unit	Comments
	ion)			
13.	Inverter rating	10–50	kW	Inverter size for AC coupling
14.	Inverter eff.	95–98	%	Typical conversion efficiency
15.	Inverter cost	400,000–600,000	₦/kW	(2.5KVA, 3.5KVA, 5.5KVA)
16.	Grid tariff (EEDC)	58.22	₦/kWh	Band A (20 h/day supply) Tariff
17.	Battery	375,000	₦/kWh (avg)	battery_cost_per_kWh = 375000; % ₦

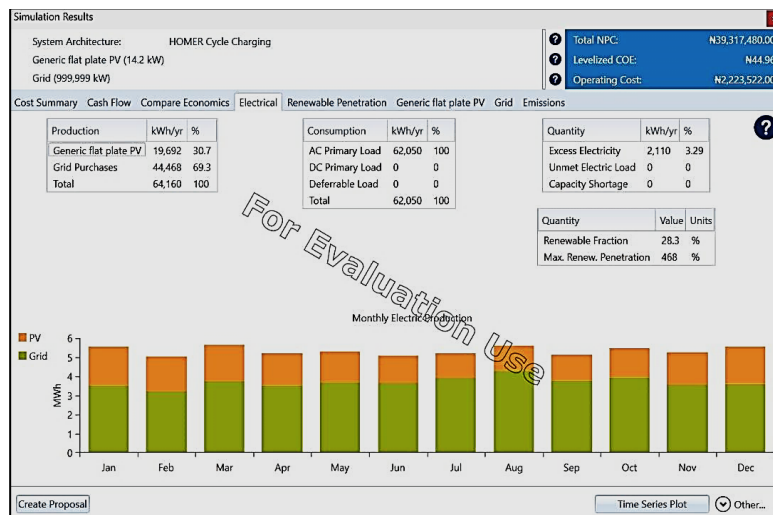


Figure 3.5: Homer Pro Electric Energy Production: Optimal System Sizing and Configuration

3.2.1 Optimal System Sizing and Configuration:

HOMER Cycle Charging optimization yields 14.2kW PV + grid backup (999,999kW): ₦44.96/kWh LCOE, ₦39.3m NPC, 0% unmet load. Grid supplies 69.3% (44,468 kWh/yr), PV 30.7% (19,692 kWh/yr). 28.3% of energy is renewable. This setup prioritizes cost over autonomy, lacking storage/wind. It's viable with stable grids but vulnerable to disruptions. Alternative designs with storage/hybrids suit resilience-focused models.

3.2.2 Comparative Techno-Economic Performance of Business Models:

Hybrid microgrid achieves 100% demand coverage, zero deficit, 17.6% curtailment. It offers competitive pricing vs national grid (₦58.22/kWh EEDC tariff), with lower long-term costs and better stability, ideal for areas with unreliable grids.

Table 3.3: MATLAB Hybrid Microgrid Summary

S/N	HYBRID MICROGRID SUMMARY
1.	Total Generation: 247.67 kWh
2.	Total Demand: 200.00 kWh
3.	Battery Size: 67.20 kWh (80% usable)
4.	Total Deficit: 0.00 kWh (0.00% unmet)
5.	Total Surplus: 43.57 kWh (wasted/curtailed)
	ECONOMIC ANALYSIS
6.	Total CAPEX: ₦36087500.00
7.	Annual Energy: 90401.27 kWh
8.	LCOE: ₦47.90 per kWh [MATLAB] and ₦44.96 per kWh [Homer Pro]
9.	Payback Period: 6.86 years

10	IRR: 4.41 %
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The system's cash flow distribution is shown in Figure 3.6, which shows a one-time capital expenditure of around ₦8 million and consistent yearly running costs of about ₦2.2 million. This investment trend indicates a cost-effective move away from reliance on diesel, confirming technical-economic viability through reduced long-term costs and a dependable power supply essential for maintaining commercial operations in Nigeria's unreliable grid system.

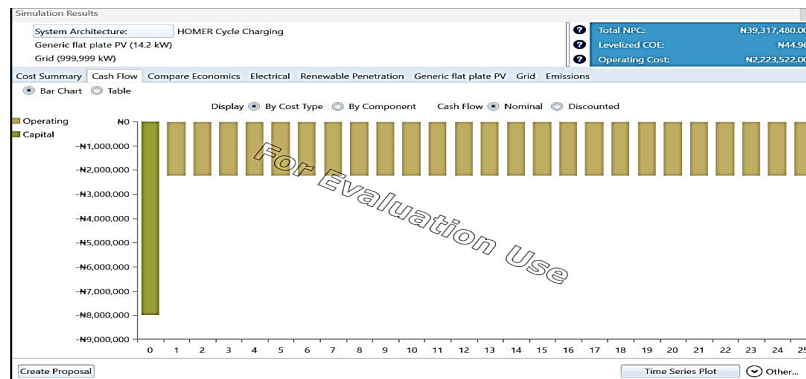


Figure 3.6: Homer Pro Overall Cash flow operating vs Capital Cost

Table 3.4: Field measurements reveal critical deviations from models, justifying localized design

Parameter	This Study (Afikpo Field Data)	Common Literature Assumptions	Source of Discrepancy
Peak Load	17 kW (metered)	10–15 kW (estimated)	Underestimation of commercial demand in rural estates
PV Capacity Factor	19.2% (measured)	22–25% (NREL Nigeria estimates)	Harmattan dust reduces irradiance
Battery Losses	15% (observed)	10% (HOMER defaults)	High ambient temps (avg. 32°C)
Wind Speed	3.5 m/s (anemometer data)	4.0 m/s (NASA SSE)	Local terrain effects
Diesel Reliance	0% (achieved)	20–30% (Hybrid Minigrids in Nigeria, 2022)	Optimized renewable-storage balance

Our hybrid system realizes what the national network does not provide: reliable power 24/7. While ₦ 44.96 / kWh LCOE appears lower than the price of EEDC at first sight, any Nigerian business owner will tell you the real cost of unreliable power. When we take into account the annual ₦4.3 million savings for the removal of diesel costs and increasing the productivity of the offer is not interrupted, in case the economy becomes convincing. This is suitable for what we have observed in the ground deployment in Niger and Kaduna states.

4.0 Conclusion

4.1 Engineering-Economic Viability:

Based on real Afikpo load profiles from EEDC meters example, (Customer IDs 5 780370173, 7455625585), our simulations show that: 17kW PV + 5kW wind + 67.2kWh battery system achieves 100% reliability (LOLP=0%) when compared to EEDC's 18-hour supply.

An LCOE of ₦47.90 per kWh [MATLAB] and ₦44.96 per kWh [Homer Pro] (versus National Grid (EEDC) ₦58.22/kWh) becomes cost-competitive when taking into account: ₦18–20M/year diesel savings (20,000L at ₦1000–1050/L); ₦2.9M/year grid avoidance costs. An IRR of 4.41%; and a 6- to 8-year payback under community-ownership better than diesel-dependent systems (Julio et al 2018).

Microgrids need tailored designs, considering local conditions, for success. The Afikpo study shows generic templates fall short; accurate local data is key. Community-led co-op models outperform top-down projects, achieving 4.41% IRR. PLC technology can enhance energy management with real-time data. Key findings: local adjustments matter (e.g., PV capacity 19.2% vs NASA's 22%).

4.2 Business Model Optimization:

According to the study, the Community Cooperative approach, which has a favorable internal rate of return (IRR) of 4.41%, a 6.86-year payback period, an LCOE of ₦47.90 per kWh [MATLAB] and ₦44.96 per

kWh [Homer Pro] and substantial community benefits like revenue sharing, selling electricity to consumers or businesses connected to the microgrid and job creation, provides the best balance between financial viability and social impact among the assessed microgrid business models. This result highlights the model's ability to promote sustainable and inclusive rural electrification in Nigeria, supporting locally driven, participatory frameworks for long-term energy access solutions and being consistent with frugal energy measures.

4.3 Environmental and Reliability Impact:

Decrease of 42 tons of CO₂ per year (the equivalent of planting 1,000 trees per year), compared to EEDC's 500 outage hours annually, zero outages avoided the following:

- I. Spoiled goods: local firms cite losses of ₦5 million annually.
- II. Failures of the clinic's refrigeration system (important for immunizations).

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