

Probabilistic Multi-Criteria Optimization of Hybrid Renewable Systems for Rural Electrification in Nigeria: A Case Study of Oleh

OLOMO JUDE OGHENEKENO¹, EYENUBO O. JONATHAN², GBIGBIDJE FAVOUR PETER³,
EBISINE E. EBIMENE⁴

^{1,2,3,4}*Department of Electrical/Electronic Engineering, Delta State University, Abraka - Oleh Campus, Delta State, Nigeria.*

Abstract- Rural electrification in Nigeria faces chronic reliability and affordability challenges due to overreliance on volatile diesel generation. This study develops a probabilistic, multi-criteria framework to optimize hybrid renewable energy systems (HRES) for off-grid communities, using Oleh, Delta State, as a case study. The methodology integrates GIS-based resource assessment, Markov chain reliability pre-screening, HOMER Pro techno-economic optimization, weighted multi-criteria decision analysis, and Monte Carlo post-validation under uncertainty. Six configurations ranging from diesel-only to fully renewable PV-BESS-H₂ systems were evaluated. Results demonstrate that the PV-BESS-H₂-DG hybrid achieves a 43.75% diesel capacity reduction, 98.87% fuel displacement, and the lowest Net Present Cost (₦34.78B) and Levelized Cost of Energy (93.34/kWh), while maintaining 99.99% system availability. Monte Carlo validation confirms its resilience against stochastic load, solar, and component failure uncertainties. The study concludes that integrating hydrogen storage with moderate diesel backup yields the optimal balance of reliability, economic viability, and sustainability, providing a replicable decision-support framework for rural microgrid deployment in Nigeria.

Index Terms: Hybrid renewable energy systems, Markov chain modeling, Monte Carlo simulation, Rural electrification, Probabilistic optimization.

I. INTRODUCTION

In Nigeria, over 40% of the rural population lacks access to affordable and reliable electricity, relying predominantly on inefficient petrol and diesel generators [1]. This dependence results in high operational costs, severe environmental pollution, and frequent system failures due to fuel scarcity and price volatility. Fuel expenses can constitute over 70% of the Levelized Cost of Energy (LCOE) in off-

grid communities, severely undermining energy access initiatives [2]. Communities like Oleh suffer from chronic power outages and lack stable electricity supply, making hybrid renewable energy systems (HRES) a promising alternative.

Existing HRES studies in Nigeria predominantly employ deterministic, single-objective optimization focused solely on cost or emissions [3]. These approaches overlook critical real-world uncertainties such as fuel price fluctuations, component degradation, and solar irradiance variability. Consequently, many proposed designs underperform operationally, incur unexpected expenses, and fail to capture the complex trade-offs between reliability and sustainability [4]. Furthermore, most studies bypass rigorous pre-screening for technical feasibility and post-validation under stochastic conditions, leading to over-optimistic performance projections. This study addresses these gaps by developing a probabilistic, multi-criteria planning framework that explicitly integrates reliability under uncertainty with techno-economic and environmental objectives. The primary aim is to conduct a probabilistic multi-criteria optimization of hybrid renewable systems for rural electrification in Nigeria: A Case Study of Oleh, using Oleh, Delta State, as a representative case study [5]. The specific objectives are to:

- 1) Utilize GIS for geospatial resource assessment
- 2) Perform Markov chain reliability pre-screening
- 3) Conduct comparative techno-economic optimization of six system configurations
- 4) Apply a weighted multi-criteria decision model

5) Validate system resilience through Monte Carlo simulation.

II. RESEARCH ELABORATIONS

A. Study Area and Resource Assessment

Oleh, Delta State, represents a typical off-grid Nigerian community with a total annual energy demand of 40.35 GWh (110.78 MWh/day), an average power demand of 4.6 MW, and a peak demand of 7.2 MW (load factor: 0.64). Utilizing GIS acquired meteorological data from NASA POWER indicates an average daily Global Horizontal Irradiance (GHI) of 4.53 kWh/m²/day, with seasonal peaks during the dry season (November - February) and reductions during the rainy season (July - August), confirming high solar potential [6].

B. Markov Chain Reliability Pre-Screening

A Continuous Time Markov Chain (CTMC) model was developed to simulate stochastic system behavior over synthetic years, addressing the risk of optimizing configurations that seem cost effective but fail under real world conditions. The state-space integrates discrete weather and irradiance states, component availability (up/down governed by failure λ and repair μ rates), and discretized storage dynamics (BESS SOC and H₂ tank levels) [7]. Pre-screening thresholds were set at LOLE \leq 5 hours/year and EENS \leq 0.05% of annual load. Iterative sizing across 20 configurations identified a feasible design space before HOMER optimization, filtering out configurations that fail to meet the reliability threshold [8].

C. Techno-Economic Optimization and Dispatch Strategies

HOMER Pro was used to optimize six configurations: (C1) PV+BESS+H₂+DG, (C2) PV+BESS+H₂, (C3) PV+BESS+DG, (C4) BESS+H₂+DG, (C5) BESS+DG, and (C6) DG-only [3]. Two dispatch algorithms were evaluated: Load Following (LF) and Cycle Charging (CC). CC was adopted for hybrid systems due to its superior efficiency in reducing generator runtime and partial loading. Capital costs, operational expenditures, and component degradation parameters were integrated into the simulation to reflect realistic market conditions in Nigeria [9].

D. Multi-Criteria Decision Framework

A weighted decision matrix normalized performance across three categories: Economic (NPC, LCOE, fuel cost; 40%), Reliability (LOLP, LOLE, availability; 30%), and Environmental (CO₂, Renewable Fraction; 30%). Scores were aggregated to rank configurations using a standardized normalization approach [10]. Consistent with multi-criteria frameworks applied to residential renewable systems [11].

E. Post-Optimization Monte Carlo Validation

The top two configurations passed through 1,000 Monte Carlo trials simulating \pm 20% load variability, \pm 15% solar fluctuation, and probabilistic component outages (DG: 5%, PV: 1%, BESS: 3%, FC/EL: 2%). Outputs included probability distributions for reliability, economic risk, and emissions. This stochastic validation approach aligns with best practices for quantifying uncertainty in hybrid energy system design [3]; [12].

III. Results and Discussion

A. Configuration Sizing and Trade-Off Analysis

Optimized sizing as seen in Table 1 reveals a clear inverse relationship between diesel displacement and storage requirements. Figure 1 shows that eliminating diesel entirely (C2) demands substantial oversizing (86.3 MW PV, 124.2 MWh BESS, 7,000 kg H₂), increasing capital expenditure. Conversely, the balanced hybrid (C1) achieves a 43.75% DG capacity reduction with moderate storage (81 MWh BESS, 6,000 kg H₂), demonstrating that hydrogen enables long-duration storage without excessive battery scaling [13]; [14].

Table 1: Comparative System Configuration Component Sizing from HOMER PRO Result

Scenario	PV MW	BESS MWh	Fuel Cell MW	Electrolyzer MW	H ₂ Tank kg	DG MW
C1: PV – BESS – H ₂ – DG	74.91	81	3	3	6,000	4.5

C2: PV – BESS – H ₂	86.3	124. 2	3	3	7,00 0	0
C3: PV – BESS – DG	179	90.9	0	0	0	4.5
C4: BESS – H ₂ – DG	0	92.7	3	3	4,50 0	6
C5: BESS – DG	0	174. 6	0	0	0	8
C6: DG only system	0	0	0	0	0	8

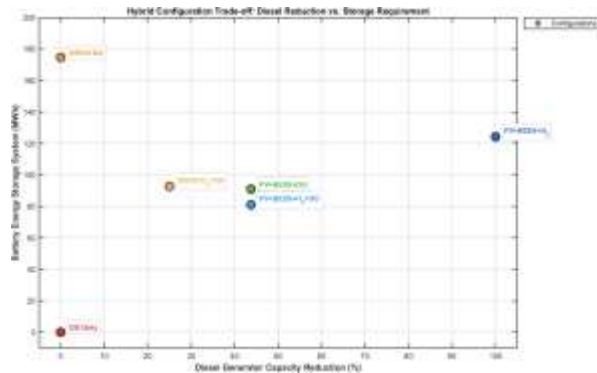


Figure 1: Comparative Analysis of Diesel Capacity Reduction vs. Battery Storage Requirements

B. Techno-Economic, Environmental, and Reliability Performance

Presented in Table 2, shows that C1 (PV+BESS+H₂+DG) emerged as the least-cost option with a NPC: ₦34.78B, LCOE: ₦93.34/kWh, outperforming conventional systems with a NPC above ₦105B and LCOE: ₦282–296.1/kWh. It achieved 98.87% diesel displacement, 98.1% renewable fraction, and 0.32 kt CO₂/yr. While C2 achieved zero emissions, its higher NPC (₦35.91B) and lower availability (99.94%) highlight the reliability penalty of removing dispatchable backup. Conventional and storage-only hybrids showed negligible fuel savings (<2%) and remained economically unviable. These findings corroborate that hybrid systems with high renewable penetration

can achieve lower LCOE in high-insolation regions when capital costs and storage are optimized [15].

Table 2: Comparative Analysis and Summary of System Economic, Environmental and Reliability Performance from HOMER PRO Result

Scenario	NPC (x10 ⁹) ₦	LCOE (₦/ kWh)	Diesel L/yr (x10 ⁶)	Diesel Displacement %	RF %	CO ₂ /yr (x10 ³)	ENE (MWh)	Availability %
C1: PV – BESS – H ₂ – DG	34.78	93.34	0.122	98.87	98.10	0.32	3.04	99.99
C2: PV – BESS – H ₂	35.91	96.43	0	100.00	99.70	0.00	24.42	99.94
C3: PV – BESS – DG	10.58	28.39	10.59	2.41	0.71	27.44	5.23	99.99
C4: BESS – H ₂ – DG	11.96	32.10	10.77	0.74	0.00	27.91	0	100.00
C5: BESS – DG	10.57	28.39	10.66	1.73	0.00	27.63	8.40	99.98

C6:	11	29	10	0.00	0.	28.	0	100.0
DG	0.3	6.1	.8		00	12		0
only	4	0	5					
system								

Figure 2 illustrates a clear inverse correlation between renewable integration and diesel generator capacity across six hybrid configurations. As renewable penetration increases, diesel requirements decline proportionally. C5 which is a conventional BESS–DG systems require maximum diesel capacity (8 MW) with zero renewables, while C2 fully renewable PV–BESS–H2 setups eliminate diesel entirely. C1 the optimal PV–BESS– H2–DG configuration strategically balances moderate diesel capacity (4.5 MW) with a high renewable fraction of 98.1% achieving a 43.75% diesel reduction. This confirms hydrogen storage as a critical enabler for long-duration energy management without costly oversizing. Other configurations align with this trend, validating the predictable trade-off between renewable investment and diesel fuel dependence.

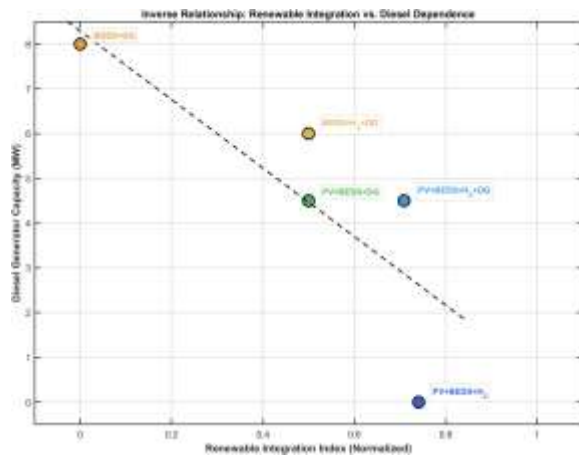


Figure 2: Renewable Integration vs. Diesel Dependence

C. Multi-Criteria Ranking

Table 3 presents the application of the weighted scoring model, C1 ranked first (9.15/10), followed by C2 (8.65). C1’s dominance stems from optimal economic performance, near-perfect reliability (99.99% availability), and high environmental sustainability. Conventional and partial-hybrid configurations scored poorly due to high fuel dependence and emissions, this evaluation

framework supports transparent trade-off analysis for rural microgrid planning in developing regions [10]; [16].

Table 3: Integrated Multi-Criteria Comparison of Configurations

Scenario	Economic Score	Reliability Score (Availability %)	Environmental Score	Total Weighted Score	Rank
C1: PV – BESS – H2 – DG	9.0	9.0 (99.99%),	9.5	9.15	1
C2: PV – BESS – H2	8.5	7.0 (99.94%),	10.0	8.65	2
C3: PV – BESS – DG	4.0	8.5 (99.99%),	3.0	5.05	5
C4: BESS – H2 – DG	3.0	10.0 (100%),	2.5	4.75	6
C5: BESS – DG	4.5	8.0 (99.98%),	3.5	5.15	4
C6: DG only system	3.5	10.0 (100%)	1.0	4.45	3

Figure 3 illustrates a bar chart comparing the composite performance of six energy scenarios using total weighted scores. The results confirm that integrating hydrogen storage with renewables yields superior techno-economic outcomes, making C1 hybrid PV-BESS-H2-DG system the optimal choice.

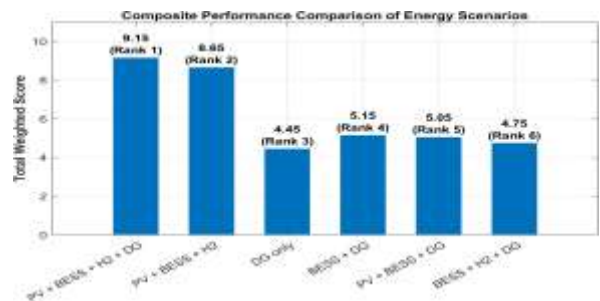


Figure 3 Energy Scenarios Ordered by Performance Rank

D. Stochastic Validation and Robustness

Monte Carlo simulation confirmed C1’s resilience under uncertainty. Table 4 shows that despite stochastic perturbations, C1 maintained a composite reliability and economic score of 0.5427, outperforming C2 (0.4573). The fully renewable configuration exhibited higher LOLP (0.5564) and EENS (15,890 MWh/yr) under real-world variability, reinforcing the necessity of minimal DG backup for grid stability. This affirms that reliability assessment under stochastic conditions is necessary for a robust odd-grid system design [7].

Table 4: Monte Carlo Reliability Validation Results

Metric [mean, lo, hi]	C1: PV – BESS – H ₂ – DG	C2: PV – BESS – H ₂
LOLP	0.1523 [0.1522, 0.1525]	0.5564 [0.5563, 0.5565]
LOLE (h/year)	1,334.4 [1,333.2, 1,335.6]	4,874.2 [4,873.1, 4,875.2]
EENS (MWh/year)	2,063.1 [2,059.5, 2,066.6]	15,890 [15,886, 15,894]
Renewable Fraction (%)	52.998 [52.99, 53.01]	60.70 [60.69, 60.71]
Curtailement (%)	0.0405 [0.0395, 0.0415]	0.1033 [0.1012, 0.1053]
Fuel Use (Million L/year)	4.676 [4.675, 4.677]	0 [0, 0]
CO ₂ Emissions (kt/year)	12.111 [12.108, 12.114]	0 [0, 0]
Composite Score (0–1)	0.5427	0.4573

IV. CONCLUSION

This study demonstrates that probabilistic, multi-criteria optimization significantly improves HRES design for rural electrification. The PV-BESS-H₂-DG configuration (C1) delivers the optimal balance of economic viability (₦93.34/kWh LCOE), environmental sustainability (98.87% diesel displacement), and operational reliability (99.99% availability). Hydrogen storage proves to be a cost enabler rather than a burden, facilitating surplus solar utilization and slashing LCOE by 65% compared to diesel-only baselines. Monte Carlo validation confirms that reliability and economics are not mutually exclusive when systems are sized under stochastic constraints. The framework provides a replicable decision assessment guide for energy planners, rural development agencies, and microgrid developers. Future work should explore real-time adaptive dispatch algorithms, dynamic tariff integration, and cost-reduction pathways for electrolyzer and fuel cell technologies in emerging markets.

V. ACKNOWLEDGEMENTS

The authors acknowledge BEDC, for technical support and computational resources. Special thanks to the community stakeholders in Oleh, Delta State, for facilitating load data collection and field assessments.

REFERENCES

- [1] Pelz, S. et al. (2023). Rural energy access challenges in Sub-Saharan Africa. *Energy Policy*, 178, 113642.
- [2] World Bank. (2024). *Nigeria Off-Grid Market Assessment and LCOE Dynamics*. Washington, DC: World Bank Group.
- [3] Olatomiwa, O. et al. (2015). Techno-economic analysis of hybrid renewable energy systems for rural electrification in Nigeria. *Renewable Energy*, 80, 678-690.
- [4] Odetoye, T. et al. (2023). Multi-year techno-economic and environmental assessment of zero-emission microgrids in Nigeria.

- Sustainable Energy Technologies and Assessments, 56, 103122.
- [5] E. Obuseh, J. Eyenubo, J. Alele, A. Okpare, and I. Oghogho, "A systematic review of barriers to renewable energy integration," *J. Asian Energy Stud.*, vol. 9, pp. 26–45, 2025, doi: 10.24112/jaes.090002.
- [6] NASA Prediction of Worldwide Energy Resources (POWER), "Surface meteorology and solar energy: Global Horizontal Irradiance (GHI) data for Oleh, Delta State, Nigeria (5.2°N, 6.12°E)," NASA Langley Research Center, Hampton, VA, USA, 2023. [Online]. Available: <https://power.larc.nasa.gov/>.
- [7] Abdulkarim, A. et al. (2016). Availability modeling of standalone hybrid microgrids using Boolean-driven Markov processes. *IEEE Transactions on Sustainable Energy*, 7(2), 567-576
- [8] Chen, Y. et al. (2019). Stochastic filtering for hybrid energy system design space reduction. *Applied Energy*, 235, 1120-1133.
- [9] HOMER Energy. (2023). HOMER Pro User Manual: Dispatch Strategies & Optimization Algorithms.
- [10] Das, P. et al. (2017). Weighted multi-criteria decision making for microgrid planning. *Energy*, 138, 456-469.
- [11] Babatunde, O. et al. (2022). Multi-criteria evaluation of residential renewable energy systems with hydrogen storage. *International Journal of Hydrogen Energy*, 47(12), 7890-7905.
- [12] Billinton, R., & Allan, R. N. (1996). *Reliability Evaluation of Power Systems*. Springer.
- [13] Jumare, A. et al. (2019). Feasibility of hydrogen storage integration in Nigerian off-grid systems. *Energy Reports*, 5, 1123-1135.
- [14] Okundamiya, M. et al. (2021). Deterministic optimization of PV-hydrogen microgrids in Northern Nigeria. *Renewable Energy*, 165, 432-445.
- [15] Azimoh, C. L. et al. (2016). Hybrid mini-grid systems for rural electrification in Nigeria. *Energy for Sustainable Development*, 33, 45-56.
- [16] Jahangiri, M. et al. (2020). Techno-economic feasibility of hybrid renewable systems in developing regions. *Renewable and Sustainable Energy Reviews*, 120, 109654.