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Hybrid Solar PV-Battery System Modelling for Rural Electrification in Mada Community, Nigeria

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Abstract—*Mada Community, an unelectrified farming locality in Isara-Remo, Ogun State, Nigeria, has no grid connection and no published, disaggregated electricity demand baseline. This study addresses that gap by developing a validated model of a standalone hybrid solar photovoltaic and battery storage system for the community, using field-surveyed demand data and site-specific solar resource data. A bottom-up field survey of 200 buildings, sampled using the Taro Yamane formula, produced an hourly community demand profile, cross-validated against 8,760-hour NASA POWER solar resource data. Two system configurations, one sized from the survey data and one benchmarked against the published, operating Gbamu-Gbamu mini-grid, were simulated hour by hour under lithium iron phosphate (LFP) and valve-regulated lead-acid (VRLA) battery chemistries. Only the Gbamu-Gbamu-benchmarked configuration under LFP met the study's 5% Loss of Power Supply Probability (LPSP) target, achieving 4.48% against a Renewable Energy Fraction of 95.52%, at a Levelised Cost of Energy of approximately ₦289/kWh, the lowest of the four scenarios evaluated. The performance and cost gap between chemistries was found to be driven principally by depth of discharge and battery replacement frequency. Three of the four modelled configurations returned a lower lifecycle cost than the community's current energy expenditure. An 85 kWp photovoltaic array paired with a 768.6 kWh LFP battery bank is recommended for Mada Community.*

Keywords—*hybrid solar PV-battery system; rural electrification; loss of power supply probability; lithium iron phosphate; valve-regulated lead-acid; techno-economic analysis; Ogun State, Nigeria*

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I. INTRODUCTION

Access to electricity remains a consistent determinant of economic and social development, yet grid-connected Nigerian households receive an average of only 6.6 hours of supply per day, and rural access stands at approximately 24.6% of the national population [1]. Ogun State exhibits this deficit at close range, with households and enterprises routinely resorting to petrol generators, kerosene lanterns, and dry-cell batteries at disproportionate cost [2], [3]. Decentralised solar photovoltaic mini-grids and standalone systems have been identified as the least-cost electrification pathway for the majority of Nigeria's unelectrified communities [4].

Mada Community, a farming locality within Isara-Remo town, Remo North Local Government Area, Ogun State, has no grid electricity connection and no published, disaggregated demand baseline. The Gbamu-Gbamu mini-grid, Ogun State, provides the most geographically proximate operating precedent [5], [6], but evaluates a system already installed rather than providing a predictive model for an unelectrified community. A comparable design study for Itele community, Ogun State, confirms that site-specific photovoltaic modelling is an established, publishable methodology within the state, but does not extend to survey-based demand profiling, battery storage integration, or a formal reliability metric [7]. No published study models a standalone hybrid solar photovoltaic and battery storage system against a field-surveyed demand profile for Mada Community or a comparable unelectrified Remo North locality. This study addresses that gap.

II. RELATED WORK

Elegeonye et al. [5] and Ogunjuyigbe et al. [6] independently assessed the 85 kWp Gbamu-Gbamu mini-grid using RETScreen and HOMER Pro respectively, confirming its technical and financial viability and validating NASA POWER solar data for Ogun State. Babalola et al. [8] found that mini-grid connection at Gbamu-Gbamu reduced monthly enterprise energy expenditure by approximately 60% while raising enterprise income by 39.5%. Scott and Coley [9] found that productive-use loads in Tanzanian mini-grids predominantly operate during daylight hours, a pattern this study's demand model adopts. Wieczorek et al. [10] demonstrated that VRLA cells are acutely vulnerable to the incomplete recharge cycling produced by consecutive low-irradiance days, while

LFP cells are not equally susceptible, a finding of direct relevance given the three-day low-irradiance stretch identified in Mada Community's solar resource data. Koholé et al. [11] demonstrated that systems evaluated only on annual energy balance can mask reliability failures that hourly LPSP-based dispatch simulation reveals, the approach adopted in this study.

III. MATERIAL AND METHODS

A. Study Area and Data Collection

Mada Community is situated within Isara-Remo town at approximately 6.9815°N, 3.6863°E. A physical enumeration identified 350–400 buildings; applying the Taro Yamane formula at a 95% confidence level (1) yielded a minimum sample of 200 buildings, from 250 questionnaires administered.

$$n = N / (1 + Ne^2) \quad (1)$$

Solar resource data were retrieved from NASA POWER for the site coordinates: a 20-year monthly climatology (2001–2020) and an 8,760-hour dataset for 2023, cross-validated against each other at the July design month (3.82 vs. 3.81 kWh/m²/day, a 0.3% difference), confirming 2023 as representative of the site's long-run seasonal pattern.

B. System Model

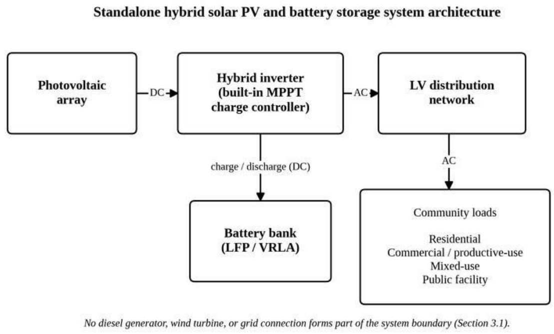

Fig. 1. Standalone hybrid PV-battery system architecture. No diesel generator, wind turbine, or grid connection forms part of the system boundary.

Plane-of-array irradiance was computed using the Perez anisotropic transposition model [12], and photovoltaic output using a temperature-corrected model referenced to Standard Test Conditions:

$$P_{PV}(t) = \eta_{STC} \times A \times G_{POA}(t) \times [1 - \beta_T \times (T_c(t) - 25)] \quad (2)$$

The battery bank was dispatched hour by hour: photovoltaic generation served load first, surplus charged the battery, and any deficit was drawn from storage subject to the chemistry-specific minimum state of charge, with residual deficit recorded as unserved load. System reliability was evaluated using Loss of Power Supply Probability (3) and Renewable Energy Fraction:

$$LPSP = \Sigma\, LPS(t) / \Sigma\, [P_{load}(t) \times \Delta t] \quad (3)$$

Economic performance was evaluated using Levelised Cost of Energy and Net Present Cost over a 20-year project life at a 10% discount rate:

$$LCOE = C_{ann} / E_{ann} \; ; \; NPC = C_{cap} + \Sigma\, [(C_{rep} + C_{O\&M}) / (1 + i)^n] (4)$$

C. System Configurations and Battery Chemistries

Two configurations were evaluated against Mada Community's demand and solar resource data: a configuration sized deterministically from the survey data (battery capacity from the longest low-irradiance stretch multiplied by average daily demand; array capacity from average daily demand divided by peak sun hours), and a configuration adopting the published Gbamu-Gbamu specifications (85 kWp, 768.6 kWh nominal battery capacity) as a literature-derived benchmark. Both configurations were simulated under LFP (95% depth of discharge, Table I) and VRLA (55% depth of discharge) chemistries, giving four scenarios in total.

TABLE I. BASELINE BATTERY PARAMETERS

Parameter	LFP	VRLA
Depth of discharge	95%	55%
Cycle life	≥6,000	400–800

Field life (tropical)	8–12 yr	2–4 yr
Unit price (2026, NGN)	₦2,100,000	₦275,000

IV. RESULTS AND DISCUSSION

The achieved 200-building sample produced a community demand of approximately 128,000 kWh/year, with an evening peak of 36.2 kW and a load factor of 0.41.

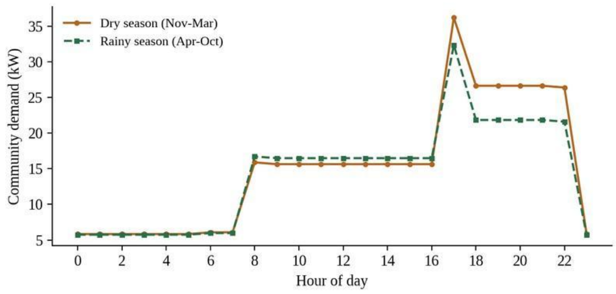

Fig. 2. Representative 24-hour community load profile, dry versus rainy season.

TABLE II. SYSTEM PERFORMANCE, ALL FOUR SCENARIOS

Config.	Chem.	LPSP	REF	LCOE
Gbamu-Gbamu	LFP	4.48%	95.52%	288.7
Gbamu-Gbamu	VRLA	10.08%	89.92%	387.0
Mada Comm.	LFP	9.99%	90.01%	419.9
Mada Comm.	VRLA	18.06%	81.94%	992.9

LCOE in Naira/kWh.

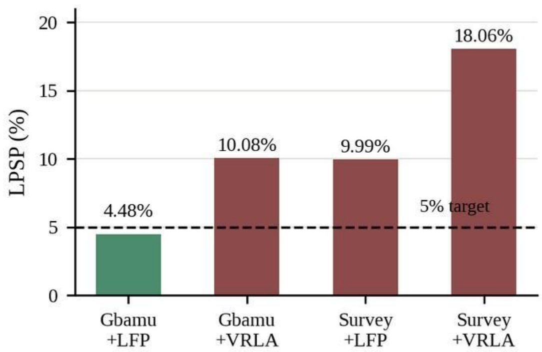

Fig. 3. Loss of Power Supply Probability against the 5% reliability target, all four scenarios.

Only the Gbamu-Gbamu-benchmarked configuration under LFP met the study's 5% LPSP target. The reliability and cost gap between chemistries is attributable principally to depth of discharge: an identical 768.6 kWh battery bank delivered markedly different outcomes depending on chemistry, since LFP makes approximately 95% of nominal capacity usable against approximately 55% for VRLA. This is consistent with Wieczorek et al.'s finding that VRLA is disproportionately vulnerable to the consecutive low-irradiance conditions present in Mada Community's own solar resource data [10].

On lifecycle cost, VRLA's lower unit price was outweighed by replacement frequency, two replacements over the 20-year project life for LFP against six for VRLA, consistent with Aderemi et al. and White et al.'s finding that battery replacement, not purchase price, dominates lifecycle cost in comparable African hybrid systems [13], [14]. Three of the four modelled configurations returned a lower 20-year cost than Mada Community's current energy expenditure on generators, kerosene, and dry-cell batteries. Sensitivity analysis identified battery capital cost and discount rate as the dominant drivers of economic outcome, consistent with Tran and Smith [15].

V. CONCLUSION

This study developed and validated a hybrid solar photovoltaic and battery storage model for Mada Community using field-surveyed demand data and site-specific solar resource data, evaluated against a formal reliability standard and benchmarked against an operating same-state reference system. An 85 kWp photovoltaic array paired with a 768.6 kWh LFP battery bank is recommended, the only evaluated configuration meeting the 5% LPSP reliability target while returning the lowest lifecycle cost.

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