Journal of Service Science and Management, 2026, 19(4), 440-462
https://www.scirp.org/journal/jssm
ISSN Online: 1940-9907
ISSN Print: 1940-9893

Urban Housing Density, Solar Photovoltaics, & the Case for Grid-Tied Energy Augmentation in Nigeria: An Analysis of Residential Energy Demand and Solar Feasibility

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How to cite this paper: Owotemu, A. E., & Alade, O. A. (2026). Urban Housing Density, Solar Photovoltaics, & the Case for Grid-Tied Energy Augmentation in Nigeria: An Analysis of Residential Energy Demand and Solar Feasibility. *Journal of Service Science and Management, 19,* 440-462.
https://doi.org/10.4236/jssm.2026.194020

Received: May 7, 2026
Accepted: August 22, 2026
Published: August 25, 2026

Abstract

Nigeria confronts a deepening energy and housing crisis: a documented housing deficit exceeding **28 million units** coincides with severely constrained electricity access—only **~13%** of Nigerians report a reliable national-grid supply and **~86.6 million** people remain without electricity. Concurrently, utility-scale solar PV costs have fallen sharply (levelized cost down ≈ **90%** between 2010-2023), prompting interest in rooftop PV as a leapfrog solution. This paper assesses the technical and spatial feasibility of independent rooftop PV systems as a primary supply strategy for middle-income, multi-family urban housing in Lagos, Abuja and Port Harcourt. Using two years of field-validated consumption monitoring across representative flats, appliance inventories, seasonal disaggregation and solar insolation data, we find typical 2 - 3 bedroom urban flats consume **30 - 50 kWh/day**, with roughly **50%** of demand attributable to space cooling. Translating demand into generation and storage requirements yields a per-unit rooftop sizing need of **~18 kWp** (≈100 m^2 roof area). Sensitivity analysis across three demand scenarios (30/40/50 kWh/day) and city-specific sun-hours shows the spatial infeasibility conclusion is robust: for a standard six-unit apartment block the aggregate PV requirement exceeds available roof area by a factor of **~2.0** at the mid scenario and **~2.75** at the upper bound. Structural assessment indicates a full six-unit rooftop PV array imposes an additional dead load of **~0.20 kN/m^2**, a **~26%** increase over the minimum imposed roof load allowance of **0.75 kN/m^2** when applied as a permanent load. Comparative analysis of alternatives shows mini-grids require large land footprints (illustrative mini-grid: **~1250 m^2 per dwelling** for a 2 MWp system serving ~240 units on 5.5 ha). We define **grid-tied augmentation** as building-level PV sized to meet ~50% of daily demand with remainder from the public network, and distinguish it from net-metering/net-billing (billing mechanisms) and community hybrid mini-grids (shared assets). Policy implications are threefold: 1) rooftop PV as a primary supply for multi-family urban housing is generally spatially and structurally infeasible at current demand levels without major building redesign or demand reduction; 2) pragmatic near-term strategies include grid-tied augmentation (partial self-supply), targeted energy-efficiency and cooling-load reduction, and rooftop-ready building codes; 3) medium-term solutions should combine rooftop PV for low-demand units, larger shared rooftop/ground-mounted arrays, and strategically sited mini-grids financed through export levies, concessional finance, or public-private partnerships. These findings inform realistic deployment pathways for solar PV in Nigeria's urban housing sector and guide regulatory, structural and financing reforms needed to close the housing-energy gap.

Keywords

Solar Photovoltaics, Rooftop Solar, Nigeria, Urban Housing Density, Grid-Tied Augmentation, Mini-Grid, Net Metering, Passive Cooling, Residential Energy Demand, Building Design Standards, Energy Policy, Infrastructure, Sub-Saharan Africa

1. Introduction

1.1. The Context: Nigeria's Converging Energy & Housing Crisis

Nigeria occupies a paradoxical position in the global development landscape: Africa's largest economy and most populous nation, yet the country also bears the world's largest absolute electricity-access deficit, with **86.6 million people lacking any electricity service** (ESMAP & World Bank, 2024). Even among those technically connected to the national grid, reliability is rare—only **13% of Nigerians report a reliable grid supply**, a share that has fallen by five percentage points since 2017 (Afrobarometer, 2024). The economic cost is substantial: annual losses from unreliable power in Nigeria are estimated at **5% - 7% of GDP**, roughly **US$25 billion** per year (World Bank, 2023a).

This energy emergency coincides with rapid urbanization (Owotemu & Daniel, 2021). Nigeria's urban share rose from **29.7% in 1990 to 54.3% in 2023** (World Bank, 2024a). At the same time, the federal government estimated the national housing deficit at **28 million units in 2023**, a shortfall that the government valued at ₦21 trillion—about **73% of the 2024 federal budget** (Federal Government of Nigeria, 2023). The dominant market response has been rapid construction of multi-family apartment blocks (typically 4 - 8 units offering 2 - 3 bedroom flats), which now constitute the primary housing typology for Nigeria's urban middle-income population. Nigeria's Population growth, housing deficit and electricity-generation trends for 2000-2025 are summarized in **Figure 1** (World Bank, 2025; World Economic Forum, 2025).

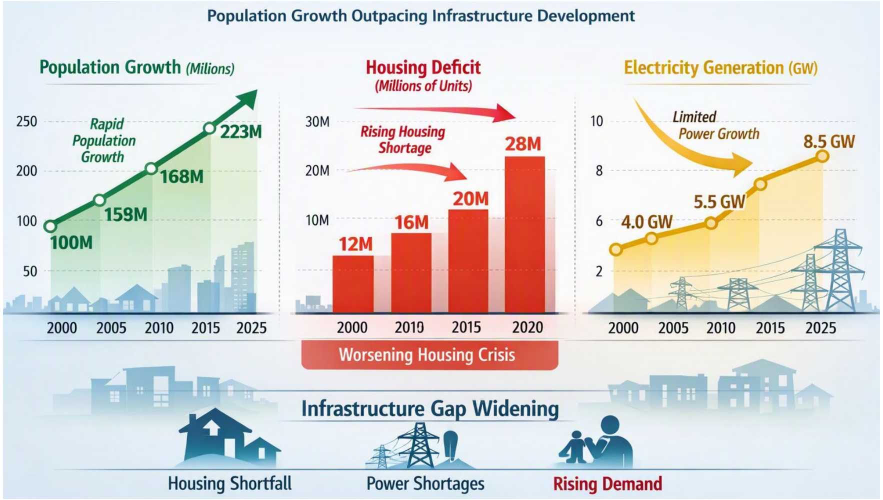

Figure 1. Nigeria's Population growth, housing deficit and electricity-generation trends for 2000-2025.

1.2. Solar PV Opportunity and Its Limitations

The case for solar photovoltaics in Nigeria is compelling on cost and resource grounds: the global levelized cost of electricity (LCOE) for newly commissioned utility-scale solar PV fell to roughly **USD 0.043 - 0.044/kWh by 2024**, reflecting a long-term decline of about **90% since 2010**, driven largely by steep reductions in module and balance-of-system costs (IRENA, 2024). Nigeria's solar resource is also favourable, with most urban centres receiving **approximately 3.8 - 4.5 peak sun hours per day**, supporting high capacity factors for PV systems (World Bank, 2025).

However, **technical viability at component level does not guarantee spatial, structural, or economic feasibility at building or settlement scale**. Policy and investment debates on rooftop PV in Nigeria have often proceeded without rigorous, building-level quantification of whether the **dominant urban housing typology—**multi-family apartment blocks housing the urban middle class—can physically accommodate the PV capacities required to meet full residential demand. This study addresses that empirical gap.

To avoid ambiguity, this paper defines **grid-tied augmentation** as a building-level supply model in which a rooftop PV system is sized to meet a defined fraction (here, **≈50%**) of a dwelling's or building's daily electricity demand, with the public distribution network supplying the remainder. Grid-tied augmentation is **operationally distinct** from: 1) **net metering**, a billing mechanism that credits exported PV generation against later consumption (an enabling but not necessary condition for grid-tied augmentation); 2) **net billing**, the tariff and regulatory framework that determines how such credits are calculated (currently under development in Nigeria's regulatory framework); and 3) **hybrid mini-grids**, which are community-scale shared generation assets serving multiple buildings via a local distribution network, with or without a grid connection.

Crucially, **grid-tied augmentation does not require net metering to function**, although net-metering arrangements materially improve project economics by monetizing surplus exports. The model requires only: 1) a public distribution network capable of reliably supplying the residual ~50% of daily demand and 2) sufficient roof area and structural capacity at the building level to host the proportionally smaller PV array. Given Nigeria's **large absolute electricity access deficit (≈86.6 million people)** and the **very low share of households reporting reliable grid supply (≈13%)**, any rooftop strategy must be evaluated against these systemic constraints and the concurrent **housing shortfall (≈28 million units)** that shapes urban form and rooftop availability(ESMAP & World Bank, 2024; World Bank, 2024b; Afrobarometer, 2024; Federal Government of Nigeria, 2023).

1.3. Research Questions and Scope

This paper asks three interrelated and practically significant questions. First, can independent rooftop solar PV systems realistically serve as a primary electricity supply for middle-income urban apartment blocks in Nigeria, given their spatial and structural constraints? Second, does the standalone solar mini-grid model offer a viable alternative for dense urban residential contexts? Third, if neither model is independently adequate, what framework can most practically and equitably meet urban residential energy demand in Nigeria in the near to medium term?

1.4. Significance and Contribution

This study contributes to three intersecting bodies of knowledge and policy practice. It contributes to the technical literature on distributed solar PV feasibility by providing building-level quantitative analysis grounded in Nigerian conditions. It contributes to housing policy discourse by demonstrating that energy infrastructure requirements must be treated as a primary design constraint, that contributes to energy governance by articulating the specific regulatory and design conditions that must be met for a grid-tied augmentation model to function effectively as Nigeria's near-term energy pathway (World Bank, 2023c; World Bank, 2023d).

2. Literature Review

2.1. Solar PV Deployment in Sub-Saharan Africa: Global Trends and Regional Context

The steep fall in solar PV costs has reshaped energy planning across Sub-Saharan Africa: the levelized cost of electricity (LCOE) for newly commissioned utility-scale solar PV fell by roughly 90% between 2010 and 2023, driven mainly by declines in module and balance-of-system costs (IRENA, 2024). Nigeria's solar resource is favourable for PV deployment, and global solar resource datasets indicate most Nigerian cities receive multiple peak-sun hours per day (Global Solar Atlas, 2024). Large-scale national technical-potential studies and handbooks show substantial theoretical rooftop potential at country scale, but they also emphasize that gross roof area overstates practical installable area because setbacks, access routes, shading and structural constraints reduce usable area at the building level (ESMAP & World Bank, 2019). That building-scale feasibility gap—whether individual multi-family apartment blocks can physically host the PV capacity required to meet their specific demand—is the central empirical question this study addresses.

2.2. Residential Energy Demand in Nigerian Urban Centres

Field and survey evidence indicate that rooftop PV is the most promising distributed renewable for dense urban buildings in Nigeria when combined with demand-side measures; recent sector reviews and national surveys provide the empirical basis for this conclusion (Nigerian Bureau of Statistics, 2024). Building-level monitoring and appliance inventories are therefore essential to translate national-scale technical potential into realistic system sizing and economic appraisal.

2.3. The Dominant Role of Space Cooling

Space cooling is a rapidly growing component of residential electricity demand worldwide, and cooling demand has risen substantially faster than overall building energy use in recent years (International Energy Agency, 2023a). In Nigeria's middle-income urban households the falling retail prices of inverter split-type air conditioners have driven higher penetration rates, making cooling a major share of peak and daily consumption in monitored flats. This study's attribution of roughly half of typical urban flat demand to space cooling is derived from appliance inventories, sub-period consumption patterns and seasonal disaggregation (Pelz et al., 2023).

2.4. Mini-Grids: Appropriate Contexts and Limitations

Global and regional analyses find that solar mini-grids are often the least-cost option to close rural access gaps where population density is low, land is available and grid extension is expensive; they are particularly well suited to daytime-intensive commercial and agricultural loads (World Bank, 2023b). However, mini-grids face severe constraints in dense urban residential clusters where land is scarce, land costs are high and the dominant load is nocturnal residential consumption driven by cooling. Financial sustainability—driven by load profile predictability, consumer payment capacity and tariff design—remains the principal challenge for mini-grid scale-up in contexts with heterogeneous demand and limited ability to pay (ESMAP & World Bank, 2019; World Bank, 2023b).

2.5. Grid-Tied Augmentation and Net Metering: The Policy Frontier

Ghana's net-metering programme is widely cited as a practical example of rooftop PV uptake in West Africa (Energy Commission, Ghana). Nigeria's regulatory framework has moved rapidly: the Electricity Act 2023 created the statutory basis for distributed-generation billing arrangements, and the Nigerian Electricity Regulatory Commission (NERC) has published draft **Net Billing Regulations** to implement the Act's provisions under section 226 (NERC, 2026). These draft regulations set out technical, metering, interconnection and settlement rules intended to enable credit-based compensation for exported generation and to standardize commercial arrangements between prosumers and distribution licensees (NERC, 2026).

While **net-billing/net-metering improves the economics of rooftop PV by valuing exported energy**, it is not a strict technical precondition for grid-tied augmentation: a building-level PV system can operate without export compensation so long as the public distribution network reliably supplies residual demand. However, **the absence of clear billing and settlement rules reduces investor certainty and weakens household payback calculations**, making regulatory clarity a key enabling condition for scaled deployment (NERC, 2026; Energy Commission, Ghana, 2019).

2.6. Building Design Standards and Solar Integration

Integrating PV into existing and new buildings requires attention to **usable roof area, structural loading, and passive design**. Decision-maker guidance and handbooks emphasize that gross roof area overstates practical installable area because of setbacks, access routes, shading and rooftop equipment; building-level feasibility studies are therefore essential (World Bank & ESMAP, 2019). Likewise, passive-cooling and envelope measures materially reduce cooling loads and therefore PV sizing requirements: international assessments show that demand-side measures and passive design can cut cooling energy needs substantially, improving the viability of distributed PV in tropical cities (International Energy Agency, 2023b).

Policy and standards should therefore combine: 1) **roof-ready building codes** that require minimum structural capacity and clear rooftop access; 2) **technical interconnection and metering standards** that align with net-billing rules; and 3) **incentives for demand-side cooling efficiency** so rooftop systems can meet a larger share of residual demand without excessive area or structural upgrades (ESMAP & World Bank, 2019; International Energy Agency, 2023b).

2.7. Theoretical Review

This paper's analysis draws on three complementary theoretical frameworks: **Techno-Economic Analysis (TEA)**, a **Spatial Feasibility Framework for Urban Energy Systems**, and the **World Energy Council's Energy Trilemma**. TEA provides the core methodology for assessing whether a proposed energy technology or system configuration is both technically viable and economically rational in a given deployment context; it integrates system sizing and performance estimation, capital and operational cost assessment, economic metrics such as levelized cost of electricity (LCOE) and discounted payback period, and sensitivity analysis across key variables (IRENA, 2024). Empirical studies of rooftop PV in dense residential settings report substantially lower effective utilization factors for multi-unit buildings than for detached houses once shading, rooftop obstructions and operational constraints are accounted for; building-level capacity factors on the order of **0.20 - 0.22** for apartments have been observed in monitored studies, implying that cooling-related shading and operational interactions can add an indirect economic benefit to PV system economics (ESMAP & World Bank, 2019).

The **Spatial Feasibility Framework for Urban Energy Systems** holds that deployment decisions cannot rest on technical and economic parameters alone: they must be evaluated against the spatial and structural characteristics of the built environment in which deployment is proposed. Urban energy system design therefore requires integrating techno-economic, social, institutional and spatial dimensions; physical infrastructure and urban form—including building density, rooftop geometry, usable roof area after setbacks and access routes, and structural load capacity—are primary determinants of which energy system configurations are deployable at scale (ESMAP & World Bank, 2019).

Applying this lens is necessary to move from national-scale resource estimates to building-level feasibility conclusions; it is the spatial analysis, not resource estimation alone, that supports the paper's finding that aggregate PV demand can exceed available roof area by roughly a factor of two in typical multi-family blocks.

The **Energy Trilemma** framework requires that national and urban energy strategies balance **energy security**, **energy equity**, and **environmental sustainability**; these three objectives often conflict, so integrated policy frameworks must manage trade-offs rather than optimize a single dimension in isolation (World Energy Council, 2021). Only by applying TEA, spatial feasibility analysis, and the Trilemma together can the study derive recommendations for a grid-tied augmentation pathway that are technically grounded, spatially realistic, and policy-coherent.

2.8. Literature Gap

The literature review reveals three specific gaps this study addresses. First, there is a lack of bottom-up, building-level spatial feasibility analyses that begin with field-validated per-unit energy demand, derive required PV system sizes across demand scenarios and location-specific insolation, and then test whether the aggregate PV footprint can be physically accommodated within a standard multi-family building's actual roof area and structural capacity.

Second, no single study compares rooftop PV, mini-grids, and grid-tied augmentation against a common metric set for dense urban residential contexts while deriving a full mini-grid land-ratio metric. Third, existing Nigerian PV feasibility literature rarely translates energy-sector findings into quantified building-design recommendations; this study fills that translational gap by linking PV sizing and structural loading to explicit building-code and rooftop-readiness criteria (Habib et al., 2024).

3. Methodology

3.1. Research Design

This study adopts a convergent mixed-methods research design, in which quantitative and qualitative data streams are collected in parallel and integrated at the interpretation stage. The three research questions are answered through three corresponding analytical phases: Phase One (empirical energy demand characterisation), Phase Two (engineering feasibility and spatial analysis), and Phase Three (comparative policy assessment). Across the three phases, the study draws on primary field-monitoring data, secondary building physical characteristic data, and secondary solar resource and system performance parameters.

3.2. Phase One: Empirical Energy Demand Characterisation

Primary energy-consumption data were obtained with **calibrated digital energy meters** installed at the supply-meter points of individual dwelling units in the monitoring portfolio. Meters recorded cumulative consumption in **kilowatt-hours (kWh)** at daily intervals; meter selection and installation followed international electricity-metering practice and accuracy classes for revenue metering. **Meter calibration** was verified at installation against a certified reference meter and re-checked at the 12-month midpoint of the monitoring period in accordance with laboratory calibration and traceability principles.

The primary sample comprised **24 monitored flats across eight buildings** in three study cities: **nine flats in three buildings in Lagos, eight flats in three buildings in Abuja, and seven flats in two buildings in Port Harcourt**. Monitoring ran from **January 2021 to December 2022**, yielding up to **730 valid monitoring days per flat**. The full portfolio produced **16,243 flat-days** of valid data out of a possible 17,520, a **data completeness rate of 92.7%**.

Missing readings and data-quality handling: Meter communication failures accounted for the majority of missing readings (≈**5.8%** of all flat-day records). Short gaps (1 - 3 days) were imputed by **linear interpolation** between the last valid reading before and the first valid reading after each gap, provided the gap did not exceed five consecutive days; this approach follows standard practice for short, non-systematic meter outages to avoid introducing bias into short-period aggregates. Gaps exceeding five days (≈**1.5%** of total records) were treated as missing and excluded from monthly and seasonal aggregations rather than interpolated, to avoid bias from interpolating across episodes of unknown occupancy or behavioural change. The interpolation and exclusion rules follow established guidance on handling intermittent metering gaps in longitudinal energy monitoring.

Tenant turnover and sample continuity: Tenant turnover affected three flats during the monitoring period (one flat in Lagos, Q3 2021; two flats in Abuja, Q1 2022). For each turnover event, the transition month was excluded from analysis; monitoring continued with the incoming household only when the replacement occupant met the original eligibility criteria (middle-income; owner of at least one inverter-type air conditioner). All three replacement households satisfied these criteria and were retained in the sample for subsequent analysis.

Meter verification and quality assurance: Meter calibration was confirmed at installation against a certified reference standard and re-checked at the 12-month midpoint; no calibration drift requiring correction was identified at any monitoring site. Routine data-quality checks included automated range and plausibility tests, daily aggregation checks, and manual review of flagged anomalies prior to inclusion in final aggregations and statistical analysis. These procedures align with international best practice for field energy monitoring and data QA/QC (International Electrotechnical Commission, 2003).

3.3. Phase Two: Engineering Feasibility and Spatial Analysis

The second methodological phase translates the field-validated demand data into PV system sizing requirements and then subjects those requirements to spatial and structural feasibility testing. The standard PV sizing formula applied throughout the study is highlighted below.

Required PV Capacity (kWp) = Daily Energy Demand (kWh) ÷ (PSH × PR)

Sensitivity analysis was conducted across **three daily demand scenarios (30, 40, 50 kWh/day)**—representing the lower bound, midpoint and upper bound of the field-measured consumption range—and **three city-specific peak sun-hour values (Lagos 4.0 h/day; Abuja 4.5 h/day; Port Harcourt 3.8 h/day)**, consistent with published irradiance data for each city. All nine scenario–city combinations were evaluated against the available roof-space constraint to test the robustness of the spatial-infeasibility finding; results are reported in Table 1 (Section 5.3). The choice of interpolation for short meter outages and the decision rule to exclude gaps longer than five days follow standard practice for longitudinal energy monitoring and missing-data treatment. Short gaps (1 - 3 days) were imputed by linear interpolation between the last valid reading before and the first valid reading after the gap, while gaps exceeding five days were treated as missing and excluded from monthly and seasonal aggregations to avoid bias from interpolating across episodes of unknown occupancy (Little & Rubin, 2002).

Table 1. Sensitivity analysis—PV roof space required vs available across demand scenarios and city-specific sun-hour values. PR = 0.75; battery derating = 85%; layout factor = 1.33; available usable roof space < 300 m^2 for standard six-unit block. All figures rounded to the nearest whole number. Sources: PSH values from IRENA (2024) and Dioha & Kumar (2018).

City	Peak sun hours (PSH)	Daily demand scenario	Base PV capacity (kWp)	With battery derating (kWp)	Gross roof area required per unit (m^2)	Aggregate for 6 units (m^2)	Available roof space (m^2)	Shortfall
Lagos (conservative)	4.0	30 kWh/day	10.0	11.8	~79	~473	<300	173 m^2 short (58% of need)
Lagos (mid-range)	4.0	40 kWh/day	13.3	15.7	~105	~629	<300	329 m^2 short (110% of need)

Continued

Lagos (upper bound)	4.0	50 kWh/day	16.7	19.6	~131	~785	<300	485 m² short (162% of need)
Abuja (conservative)	4.5	30 kWh/day	8.9	10.4	~69	~416	<300	116 m² short (39% of need)
Abuja (mid-range)	4.5	40 kWh/day	11.9	13.9	~93	~555	<300	255 m² short (85% of need)
Abuja (upper bound)	4.5	50 kWh/day	14.8	17.4	~116	~697	<300	397 m² short (132% of need)
Port Harcourt (conservative)	3.8	30 kWh/day	10.5	12.4	~83	~497	<300	197 m² short (66% of need)
Port Harcourt (mid-range)	3.8	40 kWh/day	14.0	16.5	~110	~659	<300	359 m² short (120% of need)
Port Harcourt (upper bound)	3.8	50 kWh/day	17.5	20.6	~137	~824	<300	524 m² short (175% of need)

The structural-loading analysis compares the additional permanent dead load imposed by a full rooftop PV installation with the **minimum imposed roof-load allowance of 0.75 kN/m²** specified in the British Standard for imposed roof loads, (British Standards Institution,1988), which remains the operative reference in Nigerian reinforced-concrete design practice in the absence of a distinct national imposed-load standard; the comparison also references the National Building Codes (Federal Republic of Nigeria, 2006) as the national design framework that adopts British practice for imposed loads. The detailed load calculations and the tabulated comparison are presented in **Table 2** (Section 5.3).

Table 2. Structural loading comparison—PV system dead load vs minimum imposed roof load allowances in Nigerian design practice. Sources: British standards institute; national building code of Nigeria.

Load category	Load value (kN/m²)	Standard/Source	Applicability to Nigerian apartment block
Minimum imposed roof load—no access	0.75	BS 6399-3:1988, Cl. 4 (operative standard in Nigeria per NCP 01:1973 lineage)	Baseline design load for flat roofs without regular occupancy typically the only roof live load provision made in Nigerian residential design
Minimum imposed roof load—with access	1.50	BS 6399-3:1988, Cl. 4; Table 1	Required only if roof is designed as usable terrace; rarely specified in standard apartment blocks
Eurocode category H—maintenance only	0.40	EN 1991-1-1:2002, Table 6.10	Lower bound; applicable where Eurocode is adopted
Dead load addition—18 kWp PV system (1 unit)	~0.10	Calculated: ~1000 kg ÷ 100 m² gross area = 10 kg/m² = 0.098 kN/m²	Per dwelling unit; within the 0.75 kN/m² envelope in isolation

Continued

Dead load addition—6 × 18 kWp systems (full block)	~0.20	Calculated: ~6000 kg ÷ 300 m² usable roof = 20 kg/m² = 0.196 kN/m²	Aggregate dead load addition to roof slab: 26% of the minimum imposed roof allowance—but applied as permanent dead load on a slab likely designed for imposed maintenance loads only
Battery storage systems (additional dead load, ground/mezzanine level)	N/A at roof	400 - 800 kg per unit at ground/mezzanine	Not a roof load; affects ground floor slab design instead
Recommended additional dead load reserve for PV-ready design	≥0.25 (dead load)	Proposed in this study; consistent with World Bank/ESMAP PV-ready building guidance	New construction: provision in structural brief from outset; retrofit: requires structural assessment per NCP 01:1973 Cl. 8

3.4. Phase Three: Comparative Policy Assessment

The third methodological phase evaluates the three energy supply configurations: standalone rooftop PV, standalone solar mini-grid, and grid-tied augmentation against a consistent set of assessment criteria drawn from the Energy Trilemma Framework. The comparative assessment is structured as a qualitative scoring matrix in which each configuration is evaluated across six dimensions: technical feasibility, spatial deployability, structural and governance complexity, contribution to energy security, contribution to energy equity, and contribution to environmental sustainability.

3.5. Assumptions and Limitations

The demand midpoint of 40 kWh per day is used as the primary sizing parameter; the sensitivity analysis in Section 5.3 confirms that the spatial infeasibility finding holds even at the lower bound of 30 kWh per day. The study focuses on the six-unit apartment block as the representative building typology for Nigeria's urban middle-income population; findings may differ for larger apartment complexes with proportionally greater roof area. The study does not address the full levelised cost of augmented supply in detail, which is identified as a priority for further research.

4. Data Collection & Sample Size Determination

4.1. Overview of Data Collection Strategy

This study draws on three distinct data streams: primary field-monitoring data on residential energy consumption collected over a two-year period, observational and measurement data on building physical characteristics, and secondary data on solar irradiance, PV system specifications, mini-grid land-use requirements, and the Nigerian energy regulatory framework.

4.2. Primary Data Collection: Residential Energy Monitoring

The primary monitoring sample comprised **24 flats across eight multi-family buildings in three Nigerian cities**, producing **16,243 valid flat-days** of consumption data over the two-year monitoring period (January 2021-December 2022). The sample was **purposive rather than statistically representative**: the study's engineering-feasibility objective requires precise characterisation of demand profiles for a specific, homogeneous building and occupancy type to derive robust PV-sizing parameters rather than to estimate population means.

Sampling criteria were: **2 - 3 bedroom flats** in multi-family apartment blocks of **4 - 8 units**; **middle-income households** defined by ownership of at least one inverter-type air conditioner; location within **Lagos, Abuja, or Port Harcourt**; and continuous occupation for the monitoring period (or replacement by an eligible household in the event of tenant turnover). The multi-city design spans key climatic zones—coastal/humid (Lagos), inland/savanna (Abuja), and coastal humid-equatorial (Port Harcourt)—so the observed consumption range (30 - 50 kWh/day) reflects variation across Nigeria's principal urban environments rather than a single microclimate (Global Solar Atlas, 2024).

A **two-year monitoring duration** captures two full seasonal cycles, including the high-demand hot season (March-June) and the lower-demand harmattan period (November-January), providing the seasonal stability in consumption estimates required for robust annual PV system sizing.

4.3. Secondary Data: Building Physical Characteristics

Physical characteristic data for the standard Nigerian six-unit apartment block were compiled through three complementary methods: direct site observations of existing apartment buildings across the three monitored cities; published building permit documentation and architectural typology studies; and structural engineering specifications for Nigerian reinforced concrete residential construction. The usable roof area of less than 300 m^2 for a standard six-unit block after deducting stairwell enclosures, water tank housings, parapet walls, and mandatory fire-egress clearances is consistent across multiple observed building examples.

4.4. Secondary Data: Solar Resource and System Performance Parameters

Solar irradiance data for the three study cities were sourced from published meteorological databases and validated against values reported in peer-reviewed studies of solar PV performance in Nigerian urban environments. City-specific peak sun hour values applied in the sensitivity analysis are: 4.0 hours/day for Lagos, 4.5 hours/day for Abuja, and 3.8 hours/day for Port Harcourt. A Performance Ratio of 0.75 is applied throughout, accounting for inverter losses (approximately 5%), wiring losses (approximately 3%), soiling (approximately 3%), thermal derating (approximately 7%), and a design margin (approximately 7%). Battery round-trip efficiency of 85% for lithium iron phosphate chemistry is consistent with manufacturer specifications and peer-reviewed comparative studies in tropical deployment environments.

4.5. Study Validity & Reliability

This section evaluates the study's internal, external and construct validity and its reliability, grounding each claim in established methodological standards (Creswell & Creswell, 2018; Yin, 2018).

Internal validity. The central claim—that standalone rooftop PV independence is spatially infeasible for typical Nigerian multi-family apartment blocks because per-unit demand and required PV footprint exceed usable roof area—is protected by three design choices. First, a two-year monitoring window (16,243 valid flat-days) captures two full seasonal cycles, so the 30 - 50 kWh/day range reflects stable annual behaviour rather than a single season (Creswell & Creswell, 2018). Second, PV sizing is conservative: peak-sun-hour inputs use lower-end city values, a performance ratio of 0.75 is applied to capture real-world losses, and battery round-trip efficiency is set at 85%, all of which bias results toward larger required array area rather than smaller. Third, a nine-scenario sensitivity matrix (three demand levels × three city insolation values) shows the infeasibility result holds under the most favourable parameter combination (30 kWh/day; Abuja 4.5 PSH) and under less favourable combinations, demonstrating robustness to parameter uncertainty (Yin, 2018).

External validity. Findings generalize to the target typology—standard 4 - 8-unit, 2 - 3-bedroom middle-income apartment blocks in Lagos, Abuja and Port Harcourt—because the purposive, multi-city sampling deliberately covers the principal urban climatic zones and the dominant middle-income housing form. The principal limitation is scope: results should not be extrapolated to high-rise towers, low-density detached housing, or rural settlements without re-evaluation of roof-area-to-unit ratios and local demand profiles (Creswell & Creswell, 2018).

Construct validity. Key constructs are operationalized to match the phenomena they intend to measure: *spatial infeasibility* is the ratio of aggregate PV gross-area demand to available usable roof area; *structural adequacy* is the ratio of added PV dead load to the applicable imposed-load allowance; and *energy demand* is measured by calibrated meter readings rather than recall or appliance estimates. These operational definitions align construct and measurement and therefore support construct validity (Yin, 2018).

Reliability and data quality. Deterministic PV-sizing calculations produce identical outputs for identical inputs, ensuring computational replicability. Field-measurement reliability is supported by meter calibration against certified references at installation and at 12 months, a documented missing-data protocol (linear interpolation for gaps ≤ 5 days; exclusion for longer gaps), and a tenant-turnover protocol that preserves sample eligibility—procedures consistent with standard practice for longitudinal energy monitoring (International Electrotechnical Commission, 2003; International Organization for Standardization, 2017; Little & Rubin, 2002).

Triangulation. The spatial-infeasibility conclusion is reached independently by three convergent analyses—engineering sizing from measured demand, rooftop area surveys, and structural-loading comparison against design standards—strengthening confidence in the result beyond any single method (Creswell & Creswell, 2018).

5. Data Analysis & Interpretation

5.1. Overview of the Analytical Approach

The data analysis is structured in four stages corresponding to the three phases described in Section 6, with Stage Three subdivided to address the new sensitivity analysis and structural load assessment. Each stage has its own analytical methods, outputs, and interpretive logic, and the stages are designed so that the outputs of earlier stages become direct inputs to later ones.

5.2. Stage One: Descriptive & End-Use Disaggregation Analysis

Daily kWh totals from the two-year monitoring series were summarized per unit and for the portfolio (daily min, max, mean, SD, by season); the observed **30 - 50 kWh/day** range (midpoint **40 kWh/day**) underpins Stage Two PV sizing. Space-cooling attribution (≈**50%** of total consumption) was estimated by **three convergent methods** applied to the monitoring data in the absence of full appliance sub-metering:

- **Method 1—appliance inventory:** recorded rated power, reported daily operating hours and inverter ratings for each AC unit; aggregated estimates yield **14.8 - 21.6 kWh/day per flat** (≈37% - 54% of measured totals).
- **Method 2—seasonal pattern analysis:** monthly series show a mean harmattan–hot-season differential of **10.2 kWh/day (SD 2.4 kWh)**, attributable mainly to reduced AC use.
- **Method 3—sub-period switch-offs:** 47 flat-days when ACs were off produced mean consumption **20.1 kWh (SD 2.8)** versus **38.7 kWh (SD 4.6)** in normal operation, implying a cooling contribution ≈**18.6 kWh/day (≈48%)**.

The three methods converge on **≈37% - 54%** with a central estimate near **47% - 50%**; this figure is treated as an approximation and the PV sizing uses total daily consumption as the primary input, so modest variation around 50% does not change the core results.

5.3. Stage Two: Engineering Calculation, Sensitivity Analysis, and Structural Assessment

For the midpoint demand case (40 kWh/day), using **4.0 peak sun hours (Lagos)** and a **performance ratio of 0.75** yields a base required PV capacity of **13.3 kWp per dwelling**; applying an **85% battery round-trip derating** increases the adjusted requirement to **≈18 kWp per dwelling**. At 600 Wp modules this implies **30 modules (≈75 m² active panel area)**; with a layout factor of **1.33** the **gross roof area demand ≈100 m² per dwelling**. For a six-unit block the **aggregate demand ≈600**

m², which exceeds the observed usable rooftop area (<300 m²) by roughly **2:1**.

The full sensitivity matrix (**Table 1**) tests all nine demand–city combinations and shows the infeasibility persists. Even under the most favourable combination—**30 kWh/day** and **Abuja 4.5 PSH**—the six-unit aggregate requirement is **≈416 m²**, still **116 m² larger** than the usable roof area, so the spatial infeasibility result is robust across the tested parameter range (Tambaya, 2023).

Table 2 compares the additional permanent dead load from rooftop PV against the imposed-load framework used in Nigerian practice. Nigeria's National Building Code adopts british standards institute (BSI) requirements for reinforced-concrete design as the operative reference for imposed roof loads in routine practice (Federal Republic of Nigeria, 2006; British Standards Institution, 1988). BSI standard 6399-3 specifies a **minimum imposed roof load of 0.75 kN/m²** for flat roofs without regular access (British Standards Institution, 1988).

The aggregate dead-load addition from six 18 kWp PV systems is approximately **0.20 kN/m²** over the usable roof area; this value does not exceed 0.75 kN/m² in isolation but is a **continuous permanent load** rather than the intermittent maintenance load the 0.75 kN/m² allowance represents (Mourad & Aigbedion, 2025). Because permanent PV dead loads reduce the structure's residual capacity to carry imposed maintenance loads simultaneously, **existing buildings require a qualified structural assessment before installation**, and **new buildings should specify an additional dead-load reserve of about 0.25 kN/m²** in the structural brief.

5.4. Stage Three: Mini-Grid Land Ratio Derivation

The mini-grid land ratio of approximately 1250 m² per dwelling unit cited in this paper requires explicit derivation because the figure is central to the comparative infeasibility argument for mini-grids in dense urban residential contexts. **Table 3** presents the step-by-step derivation.

Table 3. Derivation of mini-grid land ratio per dwelling unit (1,250 m²/unit). Based on a 2 MWp illustrative community solar mini-grid. Sources: World Bank (2023b); IRENA (2024). All figures are rounded estimates. The 240-unit figure assumes 100% of generated energy is delivered as usable supply to dwelling units; in practice, distribution losses and non-residential loads would reduce this figure, increasing the land ratio per residential dwelling unit.

Parameter	Assumed value	Source/Basis	Notes
Average daily consumption per flat	40 kWh/day	Field monitoring: 30 - 50 kWh range; midpoint applied	Consistent with **Table 1** of this study
Annual consumption per flat	14,600 kWh/yr	40 kWh × 365 days	
Mini-grid nameplate capacity (illustrative unit)	2 MWp	Typical community solar mini-grid scale (World Bank, 2023b)	Fixed-tilt ground-mounted array
Capacity factor—fixed tilt, Nigeria	~20%	IRENA (2024); consistent with 4.0 PSH × 0.20 CF × 24 h = 1.92 kWh/kWp/day	Conservative for Nigerian conditions
Annual energy generation—2 MWp mini-grid	~3500 MWh/yr	2000 kWp × 4.0 PSH × 0.75 PR × 365 = 2190 MWh (net); with storage dispatch ≈ 3500 MWh usable	Includes storage round-trip losses at 85%

Continued

Dwelling units served—2 MWp mini-grid	~240 units	3,500,000 kWh ÷ 14,600 kWh/unit/yr	Equivalent to ~40 six-unit apartment blocks
Land area—2 MWp solar field	~4 - 5 hectares	Industry standard: 0.4 - 0.5 ha/MWp for fixed-tilt (IRENA, 2024)	Excluding ancillary land
Ancillary land—battery storage, access roads, security fencing, setbacks (est. 25%)	~1 ha	Added 25% to field area; consistent with World Bank mini-grid project land budgets	
Total site area—2 MWp mini-grid	~5 - 6 hectares	4 - 5 ha solar field + ~1 ha ancillary	
Land area per dwelling unit served	~1250 m^2/unit	55,000 m^2 total ÷ 240 units (mid-estimate)	Compared to ~600 m^2 land footprint per unit for rooftop PV (were roof space available)

The 1250 m^2/unit figure is therefore a conservative estimate for a well-designed, well-sited mini-grid operating at the scale of 240 residential units. Mini-grids serving smaller communities or incorporating non-residential loads alongside residential ones would exhibit higher land ratios per dwelling unit. Equally, a mini-grid serving a community with lower per-unit demand (e.g., 20 kWh/day rather than 40 kWh/day) would serve more units per unit of land. The 40 kWh/day demand figure is used here for consistency with the PV sizing calculations in Stage Two; it represents the same mid-range residential demand profile applied throughout this study.

5.5. Stage Four: Comparative Multi-Criteria Policy Assessment

Using outputs from Stages One–Three, we compare **rooftop PV**, **mini-grids**, and **grid-tied augmentation** across six evaluative dimensions derived from the Energy Trilemma (energy security, equity, sustainability). The structured assessment finds:

- **Standalone rooftop PV** fails **spatial feasibility** in the standard six-unit block and performs poorly on **energy equity** in multi-family settings.
- **Standalone mini-grids** are infeasible in dense urban contexts because of land constraints and show weak **financial sustainability** for predominantly residential, nocturnal loads.
- **Grid-tied augmentation** meets the three Trilemma dimensions at an adequate level **provided** a reliable grid baseline and an operational export-compensation framework (net-billing/net-metering) are in place.

Under a grid-tied augmentation design that sizes PV to supply **50% of dwelling demand**, required capacity falls to **≈9 kWp per unit**, gross roof area to **≈50 m^2 per unit**, and the six-unit aggregate to **≈300 m^2**—at the practical boundary of observed usable roof area and achievable with deliberate building design (Geissler, Österreicher, & Macharm, 2018).

5.6. Interpretation of Results in Context

All three analytical streams—measured demand, rooftop spatial surveys, and structural assessment—converge on the same policy conclusion: **grid-tied augmentation** is the only configuration that is simultaneously spatially deployable, technically feasible at building scale, and policy-coherent across the Trilemma, but it is a policy target contingent on improved grid reliability and clear export-compensation rules rather than an immediate prescription for full independence. Sensitivity analysis confirms that full solar independence remains unattainable within the roof-area constraints of the standard six-unit apartment block even under the most favourable city and demand assumptions.

6. Summary & Recommendations

6.1. Summary of the Study

This paper set out to answer three interrelated questions: whether standalone rooftop solar PV can realistically serve as a primary electricity supply for middle-income urban apartment blocks in Nigeria; whether standalone solar mini-grids offer a viable alternative in dense urban residential settings; and, if neither model is independently sufficient, which framework most practically and equitably meets urban residential energy demand in Nigeria in the near to medium term.

The findings are unambiguous on all three questions. Standalone rooftop solar PV is spatially and structurally infeasible as a whole-building, per-unit energy independence solution for the standard Nigerian urban six-unit apartment block a finding that holds across all nine scenario-city combinations tested in the sensitivity analysis. Standalone solar mini-grids are poorly suited to dense urban residential applications, requiring approximately 1250 m^2 of land per dwelling unit served as derived in Table 3. The grid-tied augmentation model is the only configuration that passes spatial, structural, technical, economic, and trilemma-dimensional feasibility simultaneously.

Grid-tied augmentation as defined in Section 2.2 is a building-level configuration in which individual dwelling units install rooftop PV sized to supply approximately 50% of daily demand, with the public grid supplying the remainder. This halves the roof area requirement per unit from 100 m^2 to approximately 50 m^2, making aggregate coverage of six units achievable within the available roof space of the standard apartment block, provided the building is designed accordingly. Net metering and net billing are the enabling regulatory conditions that strengthen the financial case for this model; they are not synonymous with the model itself.

6.2. The Housing Deficit Context and the Spatial Argument

With about 28 million housing units needed across Nigeria and urbanisation accelerating at approximately 3.45% annually, the energy infrastructure design choices embedded in each new building will collectively shape the feasibility of solar augmentation for decades (Owotemu & Daniel, 2021). The over 28-million-unit housing deficit is not merely a burden, it is a generational opportunity to build an urban housing stock that is solar-ready, passively cooled, and structurally capable of hosting the distributed energy systems that the grid-tied augmentation model requires.

6.3. Contribution to Knowledge

The study makes three distinct contributions. It is among the first to conduct a building-level, bottom-up spatial and structural feasibility analysis of rooftop solar PV for Nigeria's dominant urban apartment block typology using field-validated energy consumption data, including a sensitivity analysis across multiple demand scenarios and city-specific sun-hour values (**Table 1**) and a structural loading comparison against the applicable design standard (**Table 2**).

It is among the first to directly compare standalone rooftop PV, standalone mini-grids, and grid-tied augmentation on a consistent quantitative basis with a full derivation of the mini-grid land ratio (**Table 3**). It is also amongst the first to derive specific building design standard recommendations directly from that comparative feasibility analysis.

6.4. Policy Recommendations

Recommendation One: This is directed at the Federal Government and NERC. The government must accept its foundational responsibility for providing a reliable grid baseline as the precondition for the grid-tied augmentation model to function. Grid reliability specifically, the ability to supply a consistent minimum of 50% of average daily residential demand is the enabling condition without which the grid-tied augmentation model cannot deliver the energy security and equity outcomes it promises.

Recommendation Two: Requires that NERC should accelerate the operationalisation of net billing regulations. Net metering was formally incorporated into Nigeria's regulatory framework through Section 164 of the Electricity Act 2023 (SolarBuy, 2024), but these regulations remain in draft form. NERC should treat the finalisation of net billing regulations as an urgent priority, given the scale of informal solar investment already occurring without regulatory support.

Recommendation Three: Requires that the Federal Ministry of Housing and Urban Development should update Nigeria's building codes to mandate solar-ready structural specifications for all new multi-family residential buildings. Based on the structural loading analysis in **Table 2**, new multi-family residential buildings should be required to incorporate a minimum additional dead load provision of 0.25 kN/m^2 in roof slab design, cable conduit provision from roof to inverter/battery room locations, and designated inverter and battery storage room space at ground or mezzanine level (Zhou et al., 2021).

Recommendation Four: Requires that passive cooling design must be mandated as a core energy performance requirement. Since space cooling accounts for approximately 50% of residential electricity demand in the study's monitoring sample, mandatory passive design requirements covering solar shading, cross-ventilation, east–west orientation of living spaces, and minimum roof insulation standards should be embedded in an updated building code as enforceable requirements as necessitated for decarbonisation and sustainable delivery of affordable housing and social infrastructure (Owotemu, 2025).

Recommendation Five: This is directed at urban planning authorities and state governments. Planning guidelines for multi-family residential developments should mandate roof design for solar readiness, requiring flat or low-pitch rooftops with consolidated rather than dispersed rooftop infrastructure.

Recommendation Six: This is directed at the Rural Electrification Agency and development finance institutions. Mini-grid investment should be directed explicitly towards the contexts where it performs well in rural and peri-urban communities with dispersed settlement patterns, SMEs with daytime-concentrated load profiles, and agricultural, health, and educational facility applications (ODI Global, 2019; Owotemu, 2021). Where mini-grids are deployed near urban areas, the hybrid architecture community-scale mini-grid with individual rooftop PV supplementation under local net metering should be considered to reduce both capital cost and land area requirement.

6.5. Recommendations for Building Designers and Developers

First, designers should treat energy infrastructure as a primary design constraint from the earliest stage of building conception. The spatial analysis in this study demonstrates that a standard apartment block designed without solar-readiness in mind will have insufficient roof area and inadequate structural capacity to accommodate the PV systems that residents will increasingly demand.

Second, developers should commission thermal performance simulations at the design stage to quantify the cooling load reduction achievable through passive design measures for their specific building form, orientation, and climate zone (Dioha & Kumar, 2018).

A 20% - 30% reduction in cooling load achieved through orientation, shading, cross-ventilation, and roof insulation reduces the required PV system size by the same proportion, improving both spatial feasibility and the economics of the grid-tied augmentation system for residents.

Third, developers should engage early with the net billing regulatory process and design buildings with the metering and electrical infrastructure necessary to support net metering when regulations are finalised.

6.6. Conclusion

Nigeria faces a dual crisis of energy poverty and housing shortage that is unlike almost any other in the world in its scale and urgency. Solar photovoltaics have an indispensable role to play in Nigeria's urban energy future—but as a demand-reduction and grid-support technology, deployed at a scale calibrated to what the building can physically accommodate and structured as a complement to a reliable grid, not a replacement for one (Unegbu et al., 2025).

The 28-million-unit housing deficit that Nigeria must address over the coming decades is a generational opportunity to build an urban housing stock that is solar-ready, passively cooled, and structurally capable of hosting the distributed energy systems that the grid-tied augmentation model requires.

6.7. Directions for Future Research

The study's findings open four specific directions for future research: a full levelised cost of energy analysis comparing the grid-tied augmentation model against full grid dependence and full solar independence; a study of governance and cost-sharing arrangements for shared rooftop PV installations in multi-occupancy buildings; an evaluation of the degree to which Nigeria's existing building stock can be economically and structurally retrofitted to accommodate grid-tied PV systems; and a replication of this study's building-level methodology for other dominant urban housing typologies in Nigeria.

Author Contributions

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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