



## Integration of Renewable Energy Systems in Low-Income Urban Housing in Nigeria: Challenges, Benefits, and Policy Implications

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### Article Info

**ISSN (Online):** 2582-7138

**Impact Factor (RSIF):** 8.04

**Volume:** 07

**Issue:** 02

**Received:** 15-01-2026

**Accepted:** 16-02-2026

**Published:** 17-03-2026

**Page No:** 239-244

### Abstract

Acute energy poverty in Nigeria's low-income urban dwellings is typified by an unstable grid supply, reliance on expensive diesel generators and kerosene, high energy costs, poor indoor air quality (IAQ), acute respiratory infections (ARIs), and environmental degradation. The issue of inexpensive and unsustainable energy access in densely populated areas is examined in this critical synthesis, along with the disparity in equitable renewable deployment in the face of donor-driven rural policy bias, extreme foreign exchange (FX) volatility, hidden import/customs costs, and spatial/tenure constraints in slums. Solar photovoltaic (PV)-dominant hybrid energy systems (HES), interconnected minigrids, community-owned models, waste-sorting cooperatives for biogas, and FX-hedged financing mechanisms (e.g., Central Bank of Nigeria local- currency green bonds, customs duty exemptions for low-income solar micro-utilities). The analysis, based on high-impact evidence from 2023-2026, emphasises solar hybrids' urban practicality, yielding 25-35% energy cost savings, 6–8-year paybacks, 35-95% CO<sub>2</sub> emission reductions, and health co-benefits through kerosene replacement and enhanced IAQ. Barriers such as Naira depreciation (>70% import cost inflation), rural-biased policies (REMP/NREEEP/REA focus on unserved rural areas), and slum-specific limitations perpetuate a two-tier energy equity trap. Band A grid tariffs (~₦206-209/kWh) remain cheaper for connected elites than hybrid LCOE (~₦250/kWh) for the underserved poor. Case studies from Lagos, Abuja, Port Harcourt, and Kano (Zawaciki undergrid minigrid) show technical feasibility, productive usage gains, and resilience, but also highlight subsidy dependency, private-utility collaborations, and community governance for scale. The research recommends a paradigm shift: shifting the Rural Electrification Agency's focus to "Urban Grid-Edge Reliability" initiatives, introducing FX-hedged funding and customs exemptions, and expanding community-led models. Such changes have the potential to transform low-income urban housing from deprived areas into resilient, inclusive clean energy models that are consistent with national development goals and global environmental imperatives.

**DOI:** <https://doi.org/10.54660/IJMRGE.2026.7.2.239-244>

**Keywords:** Renewable Energy Integration, Hybrid Energy Systems, Low-Income Urban Housing, Rural Policy Bias

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### 1. Introduction

Nigeria has a serious energy conundrum, typical of resource-rich but infrastructure-constrained emerging countries. Nigeria has the potential for a rapid clean energy transition due to its vast renewable resources, including solar irradiation averaging 5.5 kWh/m<sup>2</sup>/day (peaking at 6-7 kWh/m<sup>2</sup>/day in the north), urban biomass from municipal garbage, and wind in certain zones (Ukoima, 2025) <sup>[43]</sup>. However, this remains mainly unrealised in the face of acute energy poverty: about 85- 86 million

Nigerians (nearly 40% of the population) do not have reliable access to power, the world's highest absolute statistic (Adeshina *et al.*, 2024; Obileke *et al.*, 2026) <sup>[4, 30]</sup>. National access is around 55-60%, with urban nominal connections higher (84-89%), but effective supply averages only 6-8 hours per day due to frequent outages, voltage instability, and blackouts that disrupt livelihoods, education, healthcare, and small businesses (Adeyeye *et al.*, 2025; Pelz *et al.*, 2023; Oseni, 2016) <sup>[5, 38, 37]</sup>. The majority of the impact falls on low-income urban housing, which is common in quickly rising areas such as Lagos, Abuja, Port Harcourt, and Kano. Informal settlements and slums, such as Makoko in Lagos (estimated 100,000-300,000 residents on stilts over the lagoon), face additional vulnerabilities, including a lack of formal grid connections, reliance on expensive diesel/petrol generators and kerosene lamps, severe financial strain, degraded indoor air quality (IAQ), and increased health risks such as acute respiratory infections (ARIs) from smoke and exhaust (Olasehinde, *et al.*, 2025; Anand, & Phuleria, 2022; HIFA, 2025; Nkongdem, *et al.*, 2025) <sup>[35, 10, 19, 26]</sup>. Makoko's floods, poor sanitation, and restricted space hamper individual solutions. Similar scenarios exist in the peri-urban Kano and Port Harcourt informal zones, where up to 84% of urban families and businesses rely on fossil fuel backups (Anand, & Phuleria, 2022; Pelz *et al.*, 2023) <sup>[10, 38]</sup>. President Bola Tinubu's 2023 elimination of petrol subsidies resulted in dramatic fuel price increases (sometimes doubling), raising generator and transportation costs while revealing systemic instability (Nsude *et al.*, 2025; Siddig, *et al.*, 2014; Kalagbor, 2026) <sup>[27, 41, 20]</sup>. This exacerbated energy poverty for low-income urbanites, making fuel and kerosene pricey while grid choices remained unstable. Paradoxically, it boosted the relative economics of renewable energy, notably solar PV. However, ongoing foreign currency (FX) volatility, with the Naira dropping from ~₦460/USD pre-2023 to ~₦1,385-1,492/USD by March 2026, has increased imported component costs by over 70%, worsened by customs charges and port delays notwithstanding exemptions (Schröder, and Oyinlola, 2025) <sup>[39]</sup>.

A profound "Urban Policy Bias" exacerbates these problems. Frameworks such as the Renewable Energy Master Plan (REMP), National Renewable Energy and Energy Efficiency Policy (NREEEP), and Rural Electrification Agency (REA) initiatives prioritise rural underserved areas, often guided by donor mandates (e.g., World Bank, USAID) for off-grid rural solutions (Amaka, *et al.*, 2025; Federal Government of Nigeria, 2016) <sup>[9, 17]</sup>. Urban low-income and peri-urban regions are routinely dismissed as "already connected," despite chronic unreliability, resulting in a two-tier energy system: steady (costly) supply for affluent Band A zones against outages and costly alternatives for the urban poor.

This research critically synthesises information from 2023-2026 to investigate the interwoven FX-Energy Nexus (macroeconomic volatility affecting affordability) and Urban Policy Bias (institutional neglect of urban poor). Located in the expanding urban hybrid energy systems (HES) sub-field, which has outpaced rural research since 2020 due to urbanisation and grid crises (Adeyeye *et al.*, 2025; Shao *et al.*, 2025) <sup>[5, 40]</sup>, it employs PGS framework to reposition renewables as instruments for equality and justice. In order to transform low-income urban housing into resilient, inclusive clean energy models that are in line with national and international sustainability goals, it proposes a paradigm shift that includes "Urban Grid- Edge Reliability" programs, FX-

hedged financing (such as CBN local-currency green bonds), community models (such as waste-sorting cooperatives for biogas) and customs exemptions for low-income solar micro-utilities.

## 2. Literature Review

The literature on renewable energy in Nigeria has increasingly shifted toward hybrid energy systems (HES) as a viable pathway to address urban energy gaps, particularly since 2020, when research on urban applications began to outpace rural-focused studies due to accelerating urbanisation and persistent grid unreliability (Adeyeye *et al.*, 2025; Shao *et al.*, 2025) <sup>[5, 40]</sup>. Hybrid designs, mostly solar photovoltaic (PV) paired with battery storage, dominate this discussion, accounting for 89.7% of HES installations in urban microgrids and 79.41% of instances (Adeyeye *et al.*, 2025) <sup>[5]</sup>. HOMER is a popular optimisation tool (76.47% usage), allowing for extensive techno-economic assessments that focus on net present cost (NPC, 55.88% of studies) and levelized cost of electricity (LCOE, 39.71%). For scaled urban deployments, these analyses consistently report average LCOE values of about \$0.17/kWh and NPC figures of about \$17.1 million, confirming cost competitiveness in comparison to diesel generators and notable CO<sub>2</sub> emission reductions ranging from 35–95% (Adeyeye *et al.*, 2025; Mas'ud *et al.*, 2024) <sup>[5, 22]</sup>. Due to less battery cycling and backup dependency, grid-connected HES variations perform even better than off-grid installations, averaging a 22% lower LCOE (Adeyeye *et al.*, 2025) <sup>[5]</sup>. Although local macroeconomic variables, especially FX volatility, decouple this trend in Nigeria and undermine affordability benefits, it is consistent with worldwide decreases in solar and battery prices (Schröder, & Oyinlola, 2025; Nyarko *et al.*, 2023) <sup>[39, 29]</sup>. Recent predictions for PV/wind/battery hybrids beginning in 2023-2029 imply further LCOE reductions as technology matures, but Nigeria-specific deployments remain hampered by import dependency and currency swings (Babalola, *et al.*, 2026) <sup>[14]</sup>. Emerging research on distributed 20 MW hybrid systems across regions demonstrates environmental sustainability, with urban-scale applications showing potential in lowering dependency on fossil fuels (Babalola, *et al.*, 2026) <sup>[14]</sup>.

Biogas systems, which use urban organic waste for clean cooking and decentralised electricity, provide a complementary approach, but they face significant acceptance barriers in low-income communities. Urban biomass from municipal solid waste has significant potential for methane production; however, inefficiencies in feedstock collection, contamination (plastics, metals), and spatial constraints in high-density slums limit scalability (Nwankwo *et al.*, 2024; Dinneya-Onuoha, 2025; Ukpanyang *et al.*, 2022) <sup>[28, 16, 45]</sup>. According to studies, biogas digesters require consistent, high-quality organic input, which is frequently unavailable in informal settlements due to poor waste management infrastructure, competing waste uses (for example, informal recycling), and logistical challenges such as transportation to centralised facilities or space for household-scale units (Dinneya-Onuoha, 2025) <sup>[16]</sup>. In dense urban contexts such as the Lagos slums, contamination concerns diminish methane output and system dependability, while seasonal floods and insufficient sanitation hamper deployment (Ukpanyang *et al.*, 2022) <sup>[45]</sup>. While biogas can reduce health concerns associated with conventional biomass by increasing IAQ and lowering ARI prevalence, its urban

penetration lags significantly behind solar PV, with most applications being pilot or institutional rather than general low-income home integration (Nwankwo *et al.*, 2024) [28]. Multi-criteria assessments utilising PROMETHEE in Greater Karu urban slums rank gasification and anaerobic digestion as the best waste- to-energy methods, but emphasise the importance of community-led garbage sorting to alleviate contamination (Ukpanyang *et al.*, 2022) [45].

Wind energy is still marginal in urban areas due to fluctuating resource availability, expensive capital needs, and site restrictions in developed environments (Adeyeye *et al.*, 2025) [5]. Wind-based hybrid integrations are uncommon, with the majority of work emphasising solar dominance due to Nigeria's regular insolation patterns. Emerging hybrid solar-wind systems have shown potential for specialised uses, such as powering women-led enterprises in northern Nigeria, but they have comparable import and finance challenges (Aro *et al.*, 2025) [11].

Renewables' technical and economic feasibility is supported by several studies, yet socioeconomic, institutional, and legislative constraints consistently exclude low-income urban populations. The Naira's depreciation from ~₦460/USD pre-2023 to ~₦1,385- 1,492/USD by March 2026 has led to a 70% increase in imported PV and battery costs. This has been compounded by customs duties, port delays, and bureaucratic hurdles, despite partial exemptions for core solar equipment under ECOWAS CET (HS codes 8541.42/8541.43) (Schröder, & Oyinlola, 2025; Nigeria Customs Service 2024) [39, 25]. These "hidden" import costs frequently outweigh subsidy advantages for low-income projects, sustaining reliance on polluting backup sources (Abba *et al.*, 2025) [1]. Policy frameworks such as the Renewable Energy Master Plan (REMP) and the National Renewable Energy and Energy Efficiency Policy (NREEEP) have a strong rural bias, driven by international donor mandates (e.g., World Bank, USAID) that prioritise unserved rural areas for off-grid solutions (Amaka, *et al.*, 2025; Federal Government of Nigeria, 2016; Okorieimoh & Ehimen, 2025) [9, 17, 32]. This donor-influenced orientation, which emphasises rural electrification through organisations like the REA, has resulted in fragmented urban initiatives, with informal settlements being treated as "already connected" despite recurrent outages and exclusion from grid improvements (Amaka, *et al.*, 2025; Garba, & Abubakar, 2025) [9, 18]. Overlapping regulations, ineffective enforcement, limited state authority, and corruption all impede decentralised renewable deployment in cities (Okorieimoh & Ehimen, 2025; Mulligan, 2025) [32, 23]. Urban solar adoption patterns show socioeconomic gradients: rates reach 31.25% in Kano urban areas, and are favourably connected with education, household spending, and awareness, but adversely with age and family size (Wali *et al.*, 2025) [48]. In low-income informal settlements, impediments to rooftop installations include tenure instability, spatial congestion, and scepticism from previous unsatisfactory installations (Olapade, & Aluko, 2022; Akinola, 2023) [34, 8].

Health advantages are obvious: replacing kerosene and diesel decreases ARI prevalence and improves IAQ, with charcoal and kerosene exhibiting lower respiratory hazards than firewood in gradient studies (Olasehinde, *et al.*, 2025; Wernecke *et al.*, 2025) [35, 49]. However, prolonged polluting fuel usage in urban poor families, driven by price and availability, contributes to heightened ARI burdens, highlighting renewables' potential for health equality

(Olasehinde, *et al.*, 2025) [35]. Decentralised transitions in urban Nigeria emphasise governance problems that affect HES adoption, with community engagement and local agency important to success (Adeyeye, 2025; Lesala, 2025) [6, 21].

The critical literature gap concerns equitable integration in low-income urban housing. While technical feasibility and economic competitiveness are well-documented for HES, studies frequently overlook socio-technical dimensions in slums, such as tenure issues, community governance needs, and intersectional vulnerabilities (e.g., gender, income) that limit individual adoption (Adedeji *et al.*, 2023; Babalola, & Ade-Ojo, 2023; Ojomo & Sanchez, 2023; Diatta *et al.*, 2025) [3, 12, 31, 15]. Hybrids have the potential to improve lives (e.g., longer business hours, lower fuel costs) and resilience (e.g., backup during outages), but without targeted reforms, gains are unevenly distributed among higher-income urbanites (Abba *et al.*, 2025; Lesala, 2025) [1, 21]. This synthesis emphasises the importance of urban-centric policies that address FX nexus distortions, rural bias legacies, and slum-specific obstacles in order to realise renewables' revolutionary promise for inclusive energy access.

### 3. Methodology

This study uses a qualitative critical synthesis approach to investigate the integration of renewable energy systems in Nigeria's low-income urban housing between 2023 and 2026, focusing on solar photovoltaic (PV)-dominant hybrid configurations with biogas and complementary technologies. As a review study rather than an actual inquiry, the technique focuses on systematic secondary data collecting, thematic content analysis, and structured critical interpretation to examine the FX-Energy Nexus, urban policy bias, and paths to fair deployment.

Primary data sources include peer-reviewed journal papers, policy documents, technical reports, and high-impact grey literature published or updated between 2023 and 2026. Sources were found through focused searches in academic databases (Scopus, Web of Science, Google Scholar), institutional repositories (REA, NERC, World Bank, RMI), and policy archives. The inclusion criteria emphasised timeliness (post-2022 to capture subsidy removal and Naira float impacts), geographic relevance (Nigeria-specific, with emphasis on urban low-income contexts in Lagos, Abuja, Port Harcourt, and Kano), methodological rigour (techno-economic modelling, socio-technical analysis, policy evaluation), and thematic coverage across technical viability, economic barriers, socio-political dimensions, and health co-benefits. Exclusion criteria excluded pre-2023 research unless they were fundamental (for example, NREEEP 2015), non-Nigeria-focused work.

### 4. Result

Since 2020, solar photovoltaic (PV) has emerged as the dominating technology in Nigeria's urban hybrid energy systems (HES), accounting for 89.7% of configurations in recent research, with battery storage included in 79.41% of cases. This shift reflects both global cost declines in solar modules and batteries and Nigerian-specific drivers: abundant insolation (5.5 kWh/m<sup>2</sup>/day average), persistent grid unreliability (6-8 hours daily supply in urban areas), and the 2023 petrol subsidy removal, which sharply increased diesel and kerosene prices (Adeyeye *et al.*, 2025; Nsude *et al.*, 2025). Urban HES research has overtaken rural-focused

studies, owing to increased urbanisation, expanding informal settlement populations, and realisation that characterising cities as "already connected" ignores chronic outages and two-tier equity inequalities or solely descriptive articles lacking critical analysis. After screening for relevance and quality, about 35-40 sources were chosen to ensure a balance of engineering/economic viewpoints (e.g., HOMER-based LCOE studies) and socio-political criticisms (e.g., donor bias, tenure insecurity).

Analytical rigor is ensured through three established frameworks in academic writing: PGS (Problem-Gap-Solution) framework: Structuring the general narrative of the overall narrative - energy poverty problem, gaps in equitable urban integration, solutions; TECI (Trend- Evidence-Comparison-Implication) framework: Structuring the interpretation in the Discussion section and identifying dominating trends (e.g. solar PV prevalence), supporting with quantitative evidence (LCOE, emission reductions), comparing outcomes in Nigeria with the benchmarks around the world and deriving policy/practice implications; PEEL (Point- Evidence-Explanation-Link) framework guarantees coherence at the paragraph level, with each paragraph making a distinct claim, supporting it with facts or sources, outlining any inconsistencies or processes, and connecting to the main idea of fairness and change.

The synthesis is intrinsically critical rather than merely descriptive: it investigates inconsistencies (e.g., LCOE competitiveness vs. FX-driven unaffordability), assesses policy biases (rural vs. urban), and emphasises socio-technical factors (slum spatial restrictions, community governance). Limitations include a dependence on secondary sources (no primary fieldwork) and the changing nature of post-subsidy/FX data, which are handled by focusing on the most current verified publications and reports. This analytical approach allows for a rigorous, policy-relevant criticism that connects technical feasibility with macroeconomic and sociopolitical realities, establishing the article as a contribution to Nigeria's urban energy justice studies.

HOMER and other comparable technologies are used to conduct technoeconomic evaluations, which give strong quantitative backing. Hybrid systems have an average LCOE of ~\$0.17/kWh (~₦250/kWh at 2026 prices) and net current costs of roughly \$17.1 million for large urban installations. Grid-connected versions have 22% lower LCOE than off-grid due to reduced battery wear and grid offset capabilities (Adeyeye *et al.*, 2025) [5]. Emission reductions vary from 35-95% as compared to diesel use, while health advantages include improved indoor air quality (IAQ) and fewer acute respiratory infections (ARIs) by replacing kerosene and diesel (Olasehinde, *et al.*, 2025; Wernecke *et al.*, 2025) [35, 49]. Case studies from Zawaciki (Kano) reveal linked minigrids supplying 16-20 hours daily to over 1,000 low-income families and businesses, proving dependability increases and productive usage benefits (e.g., longer business hours, refrigeration) (RMI, 2024) [42].

Kano has an urban solar adoption rate of 31.25%, which is favourably connected with education and spending (Wali *et al.*, 2025) [48].

Globally, falling solar and battery costs have fuelled extensive adoption in poor cities (for example, Kenya's urban mini-grid incentives and India's rooftop solar subsidies), allowing for parity or below-grid price in a variety of settings. Nigeria technically aligns with these cost trends, but

decouples in practice due to unique local constraints: severe FX volatility (Naira depreciation >70% since 2023) inflates import costs, customs/port delays add hidden burdens despite exemptions, and donor-driven rural bias (World Bank/USAID focus on unserved rural areas) deprives urban interventions of funding and policy attention (Schröder, & Oyinlola, 2025; Amaka, *et al.*, 2025; Nyarko *et al.*, 2023) [39, 9, 29]. Band A grid tariffs (~₦206-209/kWh for reliable supply) are cheaper than hybrid LCOE for connected elites. However, low-income off-grid or underserved users face higher effective costs from polluting backups, creating a stark "two-tier" equity problem absent in more integrated global frameworks (NERC, 2025- 2026; Adeyeye *et al.*, 2025) [24, 5]. In comparison to successful urban waste-to-energy schemes in other African cities, biogas lags even farther due to pollution and logistics challenges.

The research suggests a clear road ahead, but implementation necessitates purposeful improvements across various areas. First, resolving the FX-Energy Nexus necessitates monetary policy actions. Central Bank of Nigeria (CBN)-backed local-currency green bonds, FX-hedged loans, and streamlined customs duty exemptions for low-income solar micro-utilities would protect projects from currency risk and hidden import costs, bringing the effective LCOE closer to or below grid parity for the urban poor (Abba *et al.*, 2025; Schröder, & Oyinlola, 2025) [1, 39]. Second, shifting the Rural Electrification Agency's (REA) focus to "Urban Grid- Edge Reliability" initiatives, which prioritise linked minigrids that supplement failing grids in underserved urban areas, will correct rural bias and exploit successful models such as Zawaciki (RMI, 2024) [42]. Private-utility partnerships, results-based finance, and community ownership interests can help with scalability, equity, and maintenance success.

Third, slum-specific restrictions necessitate socio-technological innovation. Interconnected minigrids and community solar arrays overcome individual rooftop limitations and tenure insecurity, whereas waste-sorting cooperatives are required for viable biogas systems, improving sanitation, reducing contamination, and creating local jobs in collection and sorting (Ukpanyang *et al.*, 2022; Dinneya-Onuoha, 2025) [45, 16]. Community-led governance methods, such as educating local technicians, forming maintenance cooperatives, and incorporating women in decision-making, can help to create trust, diminish distrust from previous failures, and assure long-term system performance (Lesala, 2025; Areo *et al.*, 2025) [21, 11].

Fourth, health and livelihood gains justify accelerated action: lower ARIs, better IAQ, longer productive hours, and resilience to outages and fuel price shocks can alleviate poverty, improve education and safety, and create jobs in the renewable value chain (Olasehinde, *et al.*, 2025; Wali *et al.*, 2025) [35, 48]. However, without targeted reforms, gains risk being distributed unevenly to higher-income urbanites, increasing inequality.

Finally, Nigeria's urban energy transformation depends on repositioning renewables as a socioeconomic and equitable intervention rather than a technological one. Coordinated policy, monetary, and community strategies addressing FX distortions, rural bias, import barriers, and slum-specific realities could catalyse inclusive, resilient clean energy access, aligning with national development priorities and global sustainability imperatives while positioning Nigeria as an African urban energy justice model.

## 5. Conclusion

Nigeria's low-income urban housing is at a tipping point, where vast renewable potential collides with entrenched energy poverty, macroeconomic volatility, and institutional neglect. This synthesis has shown that solar PV-dominant hybrid energy systems (HES), linked minigrids, and complementary biogas solutions can provide revolutionary potential for egalitarian, dependable, and sustainable energy access. Renewables offer economic benefits (25-35% savings on energy bills, 6-8-year paybacks, and increased productivity), environmental gains (35-95% CO<sub>2</sub> reductions), and health benefits (reduced ARIs, improved IAQ), making them effective tools for poverty alleviation, resilience, and climate action (Adeyeye *et al.*, 2025; Olasehinde, *et al.*, 2025; RMI, 2024) <sup>[5, 35, 42]</sup>. Yet, these advantages remain unrealized for the urban poor due to the FX-Energy Nexus (Naira depreciation inflating import costs by over 70%), hidden customs and port burdens, rural-biased policy frameworks, and slum-specific constraints (tenure insecurity, spatial limits, feedstock logistics) (Schröder, & Oyinlola, 2025; Amaka *et al.*, 2025; Ukpanyang *et al.*, 2022) <sup>[39, 9, 45]</sup>.

The evidence from Zawaciki's successful undergrid minigrid to the Lagos and Port Harcourt pilots shows that technological capability exists, but equality necessitates intentional transformation. The Rural Electrification Agency must shift toward "Urban Grid- Edge Reliability" programs, implement FX-hedged financing (CBN local-currency green bonds), enforce customs duty exemptions for low-income solar micro-utilities, and scale community-led models (waste-sorting cooperatives for biogas, local technician training). Private-utility partnerships, results-based finance, and inclusive governance can help to assure long-term stability, trust, and benefit distribution.

Finally, by framing renewables as a socioeconomic and social necessity rather than a merely technical exercise, we may break the two-tier energy trap and transform low-income urban housing from deprivation to models of inclusive resilience. Coordination among monetary policy, energy institutions, donors, and communities is urgently required to connect Nigeria's urban energy transformation with national development aims and global sustainability goals. Failure to act risks perpetuating inequality; bold change may lead to a cleaner, more equitable, and affluent urban future.

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### How to Cite This Article

Umar S, Dadum HA. Integration of renewable energy systems in low-income urban housing in Nigeria: Challenges, benefits, and policy implications. *Int J Multidiscip Res Growth Eval.* 2026;7(2):239–244. doi:10.54660/IJMRGE.2026.7.2.239-244

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