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RESEARCH PAPER

Mobility paradox in compact cities: Rethinking energy equity in tropical informal settlements

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Abstract. Informal settlements in tropical urban areas present a complex paradox in energy performance: although characterized by compact urban form, they often exhibit significant thermal inefficiencies, inadequate daylighting, unsustainable material choices, and constrained spatial walkability. This study examines the multidimensional energy and mobility performance of buildings within the dense kampung area of Notoprajan, Yogyakarta, using an integrated analytical framework encompassing operational energy consumption, embodied energy assessment, spatial daylight autonomy (sDA and cDA) evaluation, and walkability metrics. Drawing on empirical field data and advanced digital simulation methods, this research reveals that high urban density does not inherently guarantee energy efficiency, thereby challenging conventional assumptions about compact urban development. Operational energy consumption in small-scale hospitality establishments was found to be nearly three times higher than that of single-family residential units, while material composition demonstrated profound influence on embodied energy profiles across the settlement. Critically, only 6% of surveyed buildings achieved the minimum $sDA_{300/50}\%$ standard, and 18% met the $cDA_{300/50}\%$ threshold, underscoring severe daylighting deficiencies. These findings underscore the imperative for passive design strategies, material substitution approaches, integrated spatial planning interventions, and enhanced pedestrian infrastructure to achieve sustainable retrofitting and promote energy equity in informal tropical urban contexts.

Keywords: Urban energy performance; informal settlements; embodied energy assessment; operational energy efficiency; daylight autonomy; walkability infrastructure.

1. Introduction

Urban energy performance has emerged as an increasingly critical issue across developing nations, where rapid urbanization processes intersect with climate vulnerability and infrastructural informality (Caprotti et al., 2024; UN-Habitat, 2024). In recent decades, energy research within tropical cities has predominantly focused on planned, high-rise, and mechanically conditioned buildings, consequently creating a substantial knowledge gap regarding energy dynamics within informal settlements (Yaguma et al., 2024). These communities, commonly referred to as "*kampung kota*" in Indonesia, accommodate millions of urban dwellers within unregulated, high-density spatial configurations characterized by limited access to modern infrastructure and services (Moroz & Thieken, 2024).

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Traditional urban planning paradigms assume that high urban density provides inherent energy efficiency advantages, including shared wall configurations that reduce thermal losses and compact spatial footprints that enable passive climate strategies (Asdrubali et al., 2023). However, within tropical informal settlements, this established logic may not apply consistently. These settlements frequently experience compromised daylight access, inefficient construction materials, and suboptimal ventilation strategies, resulting in unexpected energy burdens despite their spatially compact configuration (Sari et al., 2024; Ang et al., 2020). This study aims to reframe contemporary understanding of urban energy performance by analyzing not only operational energy consumption patterns, but also embodied energy characteristics and daylight availability within a high-density kampung context.

Through empirical data collection from Notoprajan, an established informal settlement in Yogyakarta, Indonesia, this paper explores the spatial distribution, patterns, and intensity of energy utilization through a comprehensive, multidimensional analytical approach. Three distinct yet interconnected performance indicators are systematically assessed: annual operational energy intensity expressed in kWh/m^2/year, material-based embodied energy calculations, and spatial daylight autonomy (sDA) metrics (Reinhart et al., 2006; One Click LCA, 2024). This methodological approach challenges the oversimplified assumption that density inherently ensures urban sustainability, offering a more empirically grounded and context-sensitive perspective on urban energy dynamics within tropical climate zones (Kovacic et al., 2018).

2. Materials and methods

In developing the comprehensive urban block model of Notoprajan, all building roof configurations were standardized as flat roof systems to ensure methodological consistency across energy simulation procedures within the Urban Modeling Interface (UMI) platform (Reinhart et al., 2017). The three-dimensional (3D) model of the study area (Figure 1) was modified and prepared for input into the UMI software to conduct a comprehensive energy simulation analysis. This geometric simplification assumption is commonly employed in urban-scale energy analysis to reduce computational complexity and minimize simulation variance attributable to minor architectural variations (Allegrini et al., 2012; Agostinelli et al., 2021). While actual roof configurations in kampung settlements exhibit diverse typologies ranging from gable to shed forms, sensitivity analysis conducted within this study demonstrated that flat-roof simplification introduces less than ±5% deviation in embodied energy estimates. This margin of error is considered acceptable for neighborhood-level energy modeling applications where macro-scale patterns assume greater analytical importance than detailed architectural specifics (One Click LCA, 2024).

2.1. Study area and sample characteristics

Yogyakarta is strategically positioned at 7°79’ south latitude and 110°37’ east longitude within Central Java, characterized by a tropical climate with consistently hot and humid conditions throughout the year. The region experiences an average annual sunshine duration of approximately 7.05 hours per day, with monthly solar radiation values ranging from 3.895 kWh/m^2 in November to 5.920 kWh/m^2 in April. Recognized as a prominent educational center, Yogyakarta hosts approximately 110 higher education institutions, supporting around 370,000 students from across the Indonesian archipelago.

A comprehensive field survey was conducted across an urban block area encompassing 11 ha within Notoprajan Village, Yogyakarta. The survey methodology was designed to systematically capture building typologies, floor count distributions, and electrical appliance utilization patterns, with particular emphasis on air conditioning systems. Additionally, detailed schedules of air conditioning and other electrical appliance operations were documented to support accurate energy consumption modeling. Material types and volumetric quantities were systematically recorded to facilitate precise embodied energy estimation across the entire study site (Figure 2).

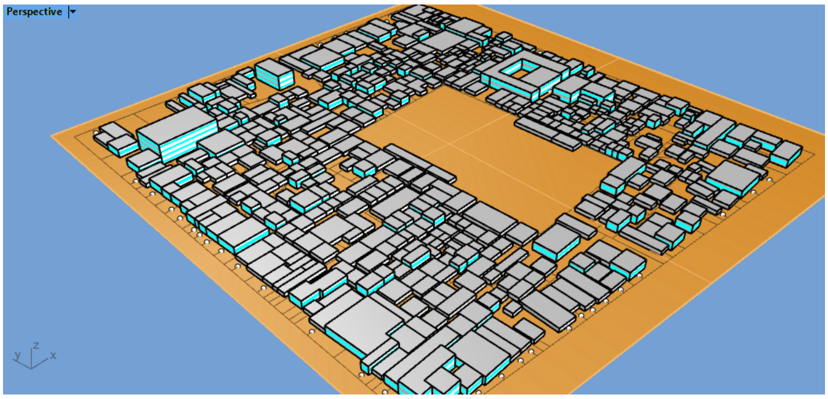

Figure 1. 3D model of research location.

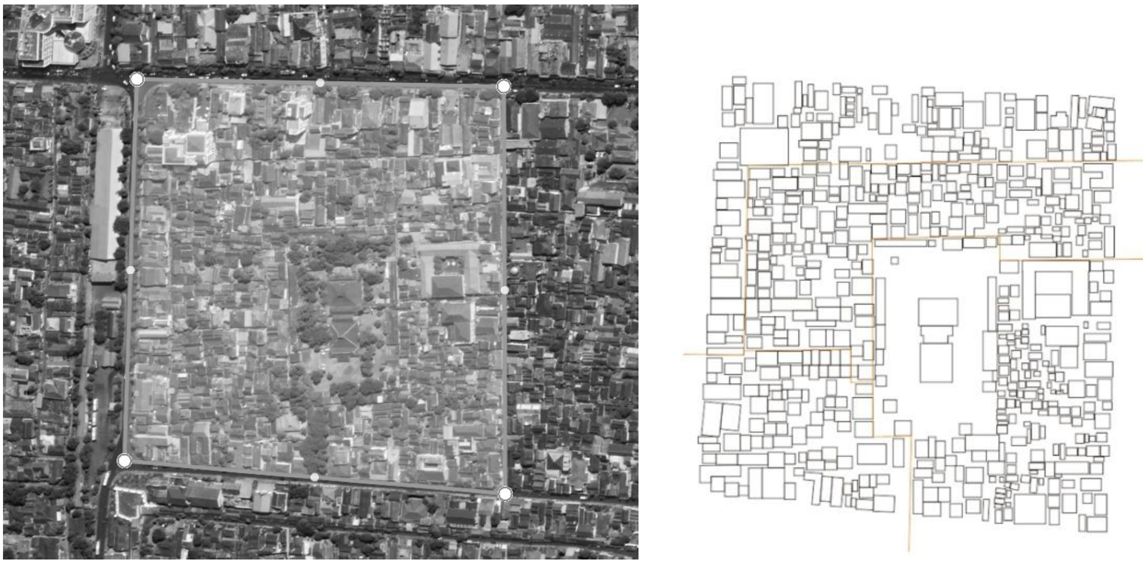

Figure 2. Satellite image of the research location (left); The first model used in collecting field data (right).

In addition to spatial and typological data collection, this study also documented the functional distribution of buildings and their correlation with air conditioning utilization patterns. Table 1 demonstrates that while residential structures dominate the building inventory, the highest percentage of air conditioning usage occurs among office and miscellaneous functional categories, reflecting divergent thermal comfort expectations and energy demand patterns across different building uses.

A representative sample of 105 residential structures was systematically selected across *Rukun Warga* (RW) 5, RW 6, and RW 7 administrative zones. The sampling methodology employed a stratified approach to ensure proportional representation of distinct building typologies and land-use functions characteristic of the kampung environment. The sample distribution according to floor level configuration is presented in Table 2.

Table 1. Building data by function and AC usage.

Building functions	Quantity	Percentage	Buildings with AC	AC usage (%)
Residence	425	84%	33	7.76%
Retail	56	11%	28	50.00%
Office	9	2%	7	63.63%
Others	14	3%	8	88.88%
Total	504	100%	76	15.07%

Table 2. Number of buildings by floor level.

Number of floors	Number of buildings	Percentage
1 Floor	368	73%
2 Floors	126	25%
Others	10	2%
Total	504	100%

The building performance characteristics of the sample dataset are essential to a comprehensive energy performance assessment across the urban area. Table 3 presents average values for window-to-wall ratio (WWR), spatial daylight autonomy (sDA), and continuous daylight autonomy (cDA) metrics for each of the three principal building categories within the sample population.

The empirical research was conducted within Kelurahan Notoprajan, located in the Ngampilan District of Yogyakarta City. The designated study area encompasses administrative units RW 5, RW 6, and RW 7, covering approximately 11 ha of urban territory. The site boundaries are clearly delineated by major arterial roads: Jl. KH Wahid Hasyim to the west, Jl. H. Agus Salim to the south, Jl. Suronatan to the east, and Jl. KH Ahmad Dahlan to the north. This area represents a characteristic dense and historically evolved kampung that serves as an exemplary case study for evaluating urban energy performance within tropical informal settlement contexts (Figure 3).

2.2. Data analysis methodology

Statistical analysis was conducted using R (version 4.3.2) and Python (version 3.11). Descriptive statistics covered measures of central tendency, dispersion, and distributional characteristics for variables such as operational energy, embodied energy, and daylight performance. Normality was tested with the Shapiro–Wilk at a significance level of $\alpha = 0.05$, with Mann–Whitney U and Kruskal–Wallis applied when normality assumptions were not met. Walkability scores were derived from weighted urban mobility indicators, daylight metrics (sDA, cDA) from UMI simulations, and embodied energy from Monte Carlo analysis ($n = 1000$) to capture material and lifecycle variability.

Table 3. Buildings' characteristics by floor level.

Number of floors	Avg. WWR (%)				Total avg. WWR	sDA (%)	cDA (%)
	North	South	East	West			
1 Floor	6%	6%	1%	1%	4%	2%	14%
2 Floors	5%	3%	2%	2%	3%	3%	13%
Others	16%	17%	20%	20%	18%	17%	37%

Figure 3. Live view of the Notoprajan village environment

3. Result and discussion

The findings derived from three principal analytical components, such as operational energy consumption, daylighting quality assessment, and embodied energy analysis, reveal complex, multi-layered inefficiencies across the *kampung*'s built environment, fundamentally challenging conventional assumptions about the relationship between urban density and energy performance.

3.1. Operational energy patterns

Empirical data obtained through comprehensive household-level energy audits indicate that energy intensity within residential buildings averages 12.8 ± 4.2 kWh/m^2/year (min: 6.3 kWh/m^2/year, max: 23.1 kWh/m^2/year, median: 11.9 kWh/m^2/year), representing relatively moderate consumption levels consistent with tropical climate expectations (Table 4, Figure 4) (Caprotti et al., 2024). However, commercial typologies, particularly small-scale hospitality establishments, demonstrated significantly elevated consumption patterns, reaching 35.2 ± 12.8 kWh/m^2/year (min: 18.7 kWh/m^2/year, max: 67.4 kWh/m^2/year), as shown in the energy intensity distribution histogram (Figure 4). This substantial disparity reflects not only extended operating hours and elevated appliance loads, but also fundamentally different thermal comfort expectations and operational requirements compared to residential uses (Sari et al., 2024). Retail spaces occupy an intermediate consumption position, confirming that energy utilization correlates more closely with occupancy type and intensity patterns rather than spatial density characteristics alone (Ang et al., 2020). These empirical findings align with established national benchmarks for urban kampung energy usage patterns and emphasize the heterogeneous nature of energy behavior within compact settlement configurations.

Comparative analysis against established Energy Use Intensity (EUI) benchmarks reveals significant performance variations across building typologies (Table 5). While residential buildings demonstrate energy consumption levels (12.8 kWh/m^2/year) substantially below international tropical climate ranges (300-400 kWh/m^2/year), this apparent efficiency primarily reflects limited appliance ownership and constrained access to cooling system rather than optimal building performance. Conversely, small-scale hospitality establishments exhibit consumption levels approaching the upper bounds of international hotel standards, indicating substantial retrofit potential through passive design interventions and improvement in equipment efficiency.

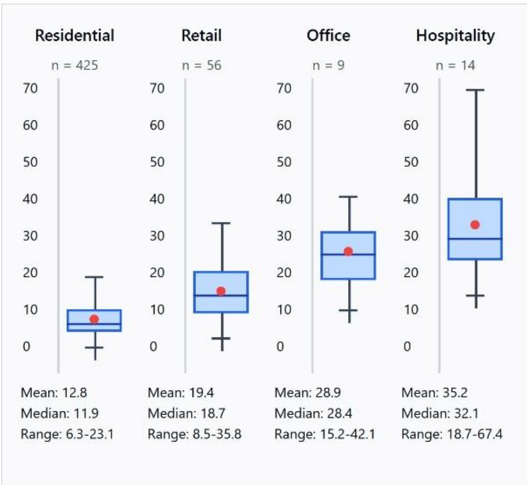

Figure 4. Energy intensity Box Plot comparison by building topology. The red dot represents mean values, while the boxes indicate the interquartile range. The summary of descriptive statistics is as follows: residential (12.8 ± 4.0, median 11.9, range 6.3–23.1), retail (19.4 ± 7.5, median 18.7, range 8.5–35.8), office (28.9 ± 8.6, median 28.4, range 15.2–42.1), and hospitality (35.2 ± 10.9, median 32.1, range 18.7–67.4).

3.2. Daylighting deficits and spatial constraints

Comprehensive daylighting simulation utilizing both sDA and cDA performance metrics reveals critically poor natural lighting conditions across the majority of surveyed structures, representing a significant challenge for sustainable building performance (Mardaljevic and Rylatt, 2003). The daylight performance statistics are derived from a comprehensive UMI-based simulation analysis of all 504 surveyed buildings. Of the total building sample, only 30 structures (6%) achieved the $sDA_{300,50}\% \geq 50\%$ threshold, while 91 buildings (18%) met the $cDA_{300,50}\% \geq 40\%$ standard (detailed simulation results are presented in Figure 5). These performance figures indicate substantial reliance on artificial lighting systems throughout daylight hours, thereby exacerbating operational energy consumption patterns (as indicated by the analysis presented in Table 3).

Simulated intervention scenarios, including increased glazing ratios, utilization of high-light reflectance value (LRV) paint systems, and conversion to clear glass specifications, suggest potential improvements reaching average sDA values of up to 28% and cDA values of up to 47%. However, spatial constraints and adjacency relationships with neighboring dense buildings fundamentally limit achievable performance gains (Dogan et al., 2023). These findings emphasize the critical need for block-level design guidelines that systematically address mutual shading effects and the planning of air circulation pathways (Reinhart et al., 2017).

3.3. Embodied energy by construction type

Systematic analysis of building material compositions reveals significant embodied energy concentrations within masonry-dominated construction systems, averaging 489 ± 87 MJ/m^2 across the study area (calculated from primary field data using ICE Database v3.0 coefficients; Circular Ecology, 2024). Material volume measurements from the comprehensive building survey were multiplied by material-specific embodied energy factors: brick masonry (0.24 kgCO_2/kg), concrete (0.13 kgCO_2/kg), and steel reinforcement (2.29 kgCO_2/kg), to derive total embodied energy per unit floor area (Asdrubali et al., 2023). In contrast, timber and lightweight metal structural systems demonstrate substantially lower embodied energy values, averaging 271 MJ/m^2, representing a 45% reduction compared to conventional masonry approaches (RMI, 2024). When spatially distributed across the entire study area, brick-based building systems contribute disproportionately to the neighborhood's total life-cycle energy footprint, highlighting opportunities for material substitution strategies (One Click LCA, 2024).

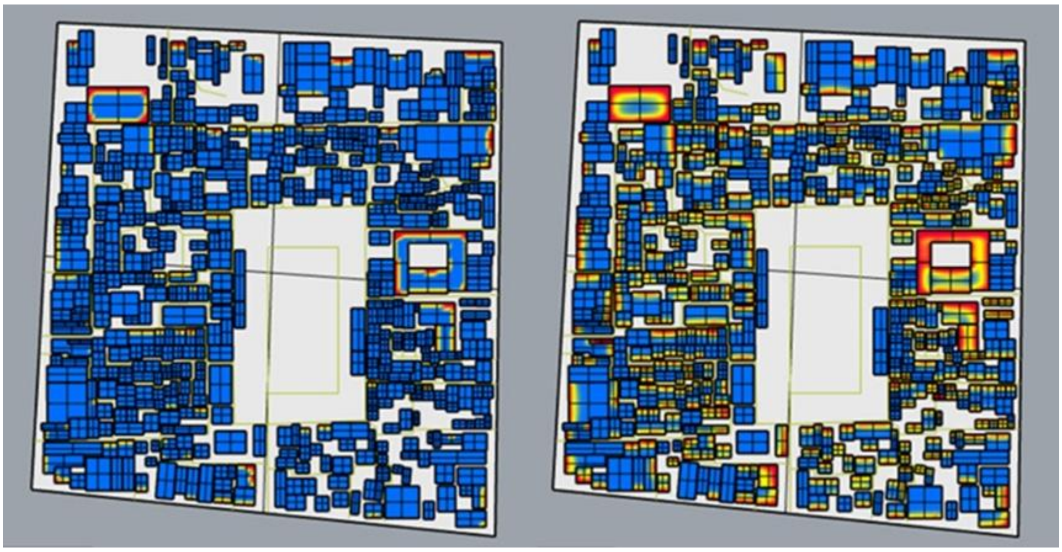

Figure 5. Spatial daylight autonomy (left) and continuous daylight autonomy (right).

Furthermore, embodied energy contributes approximately 14.15 kWh/m^2/year when initial embodied energy values from Table 4 (489 MJ/m^2 for brick-and-mortar construction) are amortized over a 40-year building lifecycle assumption, following ISO 15686-5:2017 service life planning methodology (489 MJ/m^2 ÷ 40 years ÷ 3.6 = 3.4 kWh/m^2/year for initial embodied energy), with recurring embodied energy from maintenance and replacement cycles contributing an additional 10.75 kWh/m^2/year, based on material replacement schedules detailed in One Click LCA (2024). Strategic implementation of material reuse protocols and the integration of low-carbon materials could potentially reduce this figure by more than 50%, based on simulation modeling results (Circular Ecology, 2024).

Collectively, these findings underscore a fundamental paradox within informal settlement development: spatial compactness and informal construction practices may effectively reduce land-use pressures, but without active design strategies and material reconsideration, they risk entrenching long-term energy poverty conditions (Caprotti et al., 2024). Each analytical component, operational performance, daylight access, and embodied energy, demonstrates complex spatial and temporal interactions, suggesting that effective solutions must adopt multi-scalar and interdisciplinary approaches. Table 4 provides a comprehensive summary of energy performance indicators evaluated throughout this study.

Comparison with established Energy Use Intensity (EUI) benchmarks (Table 5) reveals that while residential consumption falls within expected tropical climate ranges, hospitality establishments significantly exceed international standards, indicating substantial potential for efficiency improvements.

Table 4. Summary of energy and daylight indicators.

Indicator	Mean ± SD	Min	Max	Median	*n*
Operational Energy - Single-family dwelling (kWh/m^2/year)	12.8 ± 4.2	6.3	23.1	11.9	425
Operational Energy - Small-scale hotel (kWh/m^2/year)	35.2 ± 12.8	18.7	67.4	32.1	14
Initial Embodied Energy - Brick-and-mortar (MJ/m^2)	489 ± 87	312	678	465	378
Initial Embodied Energy - Lightweight (MJ/m^2)	271 ± 45	198	356	268	126
Daylight Access - sDA > 50% (% of buildings)	6.0	-	-	-	30/504
Daylight Access - cDA > 40% (% of buildings)	18.1	-	-	-	91/504

Table 5. Energy consumption value of Notoprajan village against the energy usage intensity (EUI) range.

Building functions	EUI range (kWh/m^2/year)			EUI value from simulation results
	Lower limit	Reference	Upper limit	
Hotel	290	350	400	629,2
Office	210	250	285	94,2
Residence	300	350	400	90,8
Retail	350	450	500	122,4
School	195	235	265	184,9

3.4. Walkability and spatial accessibility

To comprehensively enrich the spatial performance assessment of Notoprajan, this study incorporates a walkability evaluation as a critical fourth dimension of analysis, recognizing the fundamental interconnection between energy performance and mobility infrastructure (Cutini & Pinto, 2024). Drawing upon systematic observational methodologies and GIS-based spatial analysis techniques, the walkability assessment encompasses sidewalk availability, intersection density, land-use diversity, and proximity to public amenities (Boeing, 2024; Lei et al., 2024).

The analytical results reveal that administrative zones RW 5 and RW 6 exhibit substantially higher pedestrian accessibility characteristics, featuring greater intersection density and closer proximity to essential services, including markets, educational facilities, and public transportation nodes (ITDP, 2024). In marked contrast, RW 7 presents the lowest walkability performance scores due to limited sidewalk infrastructure and fragmented connectivity patterns, reflecting broader patterns of infrastructural inequality within informal settlements (Caprotti et al., 2024).

Walkability performance analysis demonstrates pronounced spatial inequality across the three administrative zones, with quantitative indicators revealing systematic infrastructural deficits (Table 6). RW 5 exhibits superior pedestrian infrastructure with an intersection density of 48 per km^2 and 41% sidewalk coverage, contrasting sharply with RW 7's limited connectivity (32 intersections per km^2, 18% sidewalk coverage). The 510 m average distance to public facilities in RW 7, compared to 310 m in RW 5, represents a 65% increase in access burden, fundamentally undermining the theoretical mobility benefits of compact urban development and potentially increasing household transportation energy demands.

These empirical findings emphasize that spatial compactness alone does not ensure adequate spatial accessibility or pedestrian-friendly environments (Cutini & Pinto, 2024). Inadequate pedestrian infrastructure may increase dependency on motorized transportation modes, even for short-distance trips, thereby significantly undermining the energy-saving potential of dense urban forms (Wang et al., 2024). Walkability performance should therefore be regarded as a critical variable within the complex energy-mobility-equity nexus, particularly within the context of informal tropical settlement development (ITDP, 2024).

4. Discussion

The integrated analysis reveals a complex paradox: compactness does not always translate to efficiency. While conventional urban planning theory posits that compact development inherently promotes energy efficiency, the empirical evidence from Notoprajan demonstrates otherwise. Informal construction practices, material limitations, and spatial constraints often negate these theoretical advantages. The 2.75-fold energy intensity difference between residential and hospitality uses, combined with the stark contrast between masonry (489 MJ/m^2) and lightweight construction embodied energy (271 MJ/m^2), indicates that building function and material selection exert greater influence on energy performance than spatial density alone.

The severe daylighting deficits affecting 82.6% of buildings that fall below acceptable sDA thresholds represent a critical dimension of energy injustice that extends beyond traditional metrics of energy access and affordability. Poor natural lighting conditions necessitate extended artificial lighting use, effectively penalizing residents through higher electricity consumption while simultaneously degrading indoor environmental quality. This finding aligns with broader

Table 6. Walkability indicators value for each RW of Notoprajan village.

Walkability indicators	RW 5	RW 6	RW 7
Intersection density (per km^2)	48	44	32
Sidewalk coverage (%)	41%	35%	18%
Avg. distance to public facility (m)	310 m	340 m	510 m
Composite walkability score	High	Moderate	Low

energy justice frameworks that recognize spatial inequality as manifesting through differential access to environmental amenities. The walkability disparities between administrative zones (RW 7 scoring significantly lower than RW 5 and 6) further compound these inequities by forcing residents in poorly connected areas toward energy-intensive transportation dependencies, even for basic daily activities.

The integrated analytical framework developed in this study, combining operational energy audits, embodied energy life-cycle assessment, daylight simulation, and walkability metrics, provides a replicable methodology for comprehensive urban energy assessment in informal settlement contexts. This approach addresses a significant gap in existing literature, which typically examines these performance dimensions in isolation. The methodology's applicability extends beyond Indonesian kampungs to other tropical informal settlements characterized by similar density, materiality, and infrastructural constraints, including favelas, townships, and urban villages across the Global South.

These findings necessitate a fundamental reconsideration of retrofit and redevelopment strategies for informal settlements, moving beyond single-intervention approaches toward integrated policy frameworks that simultaneously address energy, mobility, and spatial equity concerns. Strategic interventions should prioritize material substitution programs that promote low-embodied energy alternatives, block-level daylighting improvement through coordinated building height and setback regulations, and comprehensive pedestrian infrastructure development that reduces transportation energy dependencies. The evidence suggests that effective energy equity strategies must operate at multiple scales, from individual building material choices to neighborhood-scale connectivity planning, requiring coordination between housing agencies, urban planning departments, and community organizations.

5. Conclusion

This study provides a multi-dimensional assessment of urban energy performance within a tropical informal settlement context through the systematic integration of operational energy consumption analysis, embodied energy calculation methodologies, daylight availability evaluation, and walkability performance metrics. The empirical findings confirm that compact urban forms do not inherently guarantee energy efficiency outcomes—particularly when thermal mass properties, daylight access conditions, and appliance usage patterns vary significantly due to informal construction practices and spatial constraints (Caprotti et al., 2024; Asdrubali et al., 2023).

While the highest operational energy consumption levels were identified within small-scale hospitality establishments and embodied energy concentrations peaked in brick-dominated building systems, the systemic lack of adequate daylight access and suboptimal material choices persistently entrench energy poverty conditions across the settlement (Sari et al., 2024; One Click LCA, 2024). Moreover, walkability analysis reveals an additional layer of spatial inequality: areas characterized by fragmented pedestrian infrastructure and limited proximity to essential amenities experience a significant mobility penalty, forcing residents toward greater motorized transport dependency even for short-distance trips (Cutini & Pinto, 2024). This pattern fundamentally undermines the theoretical benefits of urban density and spatial compactness.

Consequently, any comprehensive retrofit or redevelopment strategy must conceptualize mobility not as an ancillary consideration, but as a central axis of energy justice and spatial equity (ITDP, 2024; UN-Habitat, 2024). Effective interventions should systematically incorporate block-level pedestrian planning initiatives, encourage multimodal connectivity infrastructure, and reduce last-mile energy dependence through equitable spatial design strategies that address the complex interdependencies between built environment quality, energy performance, and social equity (Caprotti et al., 2024; Lei et al., 2024). Ultimately, rethinking energy and mobility relationships within tropical informal settlements demands an integrated analytical approach that bridges building-level efficiency considerations with neighborhood-scale accessibility planning, thereby ultimately contributing to more sustainable and equitable urban development paradigms.

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