Remote Sensing Applications: Society and Environment 38 (2025) 101619

Contents lists available at ScienceDirect

Remote Sensing Applications: Society and Environment

journal homepage: www.elsevier.com/locate/rsase

Dark development: Satellite analysis of building density and electricity provision in Ghana's urban areas

Jeffrey Blay [a,b,*], Karen C. Seto [a], Tzu-Hsin Karen Chen [a,c,d]

[a] Yale School of the Environment, Yale University, New Haven, USA
[b] Department of Built Environment, North Carolina A&T State University, Greensboro, USA
[c] Department of Urban Design and Planning, University of Washington, Seattle, USA
[d] Department of Environmental and Occupational Health Sciences, University of Washington, Seattle, USA

ARTICLE INFO

Keywords:
Building density
Electricity infrastructure
Satellite imagery
Deep learning
Sustainable urban development

ABSTRACT

Energy infrastructure is increasingly accessible in Sub-Saharan Africa. However, significant disparities in energy access persist within cities, and little is known about their relationship with urban spatial growth and development. This study explores the spatial distribution of building density and its co-occurrence with electricity infrastructure in metropolitan cities across Ghana. Utilising Landsat and nighttime light satellite imagery, combined with a UNet regression algorithm and a statistical difference method, we uncover energy insufficiencies within high-density built environments in Ghanaian cities. Notably, 21 % of the urban area in Kumasi, 9.6 % in Tamale, 0.9 % in Accra, and 0.5 % in Sekondi-Takoradi exhibit high building density but limited electricity provision. This disparity is more prevalent in inland cities with single concentric layout configurations compared to coastal cities characterised by a polycentric high-density. Our findings provide insights into the energy-density relationship, offering a foundation for evidence-based urban policy development aimed at sustainable urban development and equitable access to electricity in Ghana and beyond. We therefore recommend that city governments prioritise the concurrent development of building structures and electricity infrastructure, especially in fast developing regions.

1. Introduction

Sub-Saharan Africa is one of the fastest-urbanising regions worldwide. It's urban population is projected to triple over 40 years, from 395 million in 2010 to 1.34 billion in 2050 (Korah et al., 2019; UN-DESA, 2019). This rapid urbanisation is transforming the built environment within the region, with a projected 23 % increase in urban land between 2020 and 2050 (Huang et al., 2019). Moreover, urban expansion has been associated with various environmental, social, and economic challenges such as agricultural land loss, increased energy consumption, and inadequate urban infrastructure services (UN-DESA, 2019; Zhou et al., 2022). Energy provision and maintenance is one of the top crises in the region, with governments struggling to keep pace with the needs of the rapid development (Satterthwaite, 2017). This lack of investment in infrastructure is largely due to a gap between the needs of expanding cities and the financial capacity of city governments (Arimah, 2017). Across Sub-Saharan Africa, over a third of the urban population lives in overcrowding conditions, and nearly half, or 600 million people, lack access to electricity (Ogundipe et al., 2018; Satterthwaite, 2017).

* Corresponding author. North Carolina A&T State University, 3604 Hewitt St., Greensboro, USA.
E-mail address: jblay@aggies.ncat.edu (J. Blay).

https://doi.org/10.1016/j.rsase.2025.101619
Received 26 November 2024; Received in revised form 13 May 2025; Accepted 3 June 2025
Available online 7 June 2025

As the region is expected to become a global urbanisation hotspot, it is critical to understand how the urban expansion can support sustainable development and equitable access to energy.

Originating from Western societies, the compact city theory suggests that higher urban density leads to greater energy efficiency and accessibility (Güneralp et al., 2017). Dense urban areas often benefit from shorter distances between homes, workplaces, and services, reducing energy consumption for transportation and improving access to public transit, which is typically more energy-efficient and less prone to energy shortages compared to sprawling cities (Breheny, 1995; Stone, 2008). Higher density can also lead to more shared services (e.g., district heating, shared vehicle service) and economies of scale in energy distribution, which can improve energy accessibility and reduce consumption (Rode et al., 2014). However, there are also contrasting findings between building density and energy accessibility. Higher urban density can contribute to the urban heat island effect, where cities with concentrated human activity and built-up areas experience higher temperatures than surrounding environments. This can lead to increased energy demand for cooling, which may strain energy accessibility, particularly during peak demand periods (Santamouris et al., 2015). Additionally, high-density, overcrowding neighbourhoods often correlate with lower socioeconomic status, which might limit energy accessibility due to financial barriers (Jessel et al., 2019). This is more common in the Global South (Satterthwaite, 2017).

Ghana, like many countries in Sub-Saharan Africa, is undergoing rapid urban expansion and infrastructure transformation, particularly within its metropolitan regions. Since gaining independence in 1957, Ghana's major cities have attracted significant rural-to-urban and cross-border migration driven by job opportunities and investment potential. This sustained influx, combined with natural population growth, has led to accelerated urbanisation and a severe housing deficit by the mid-1990s (Abusah and Lind, 2004). In response, the government, through the State Housing Company, launched housing development programmes, supplemented by private sector and individual investments. However, the expansion of formal housing and infrastructure has faced persistent challenges, including a complex land tenure system, financial constraints, and an underdeveloped mortgage market (Agyemang et al., 2019; Owusu and Oteng-Ababio, 2015; Yeboah, 2000).

Approximately 13 % of land in Ghana is state-owned, while nearly 80 % is held under private tenure (Abusah and Lind, 2004). Under expansion in this context is largely driven by individuals and contractors, often characterised by incremental development, where buildings and service are designed and built over several years, rather than months (Diko and Tipple, 1992). Without access to mortgage financing, residents typically build housing in phases, subcontracting services when funds allow, or anticipate that public infrastructure (e.g., roads, drainage, or electricity) will be extended later through patronage or negotiation with public sectors (Yeboah, 2000). However, this model also faces complications. Land transactions in the private sector often involve poorly defined plot boundaries, resulting in disputes and delays in service provision (Abusah and Lind, 2004). Compounding these issues is the state's limited financial and logistical capacity to acquire and develop land at the scale required to meet growing urban demand. High land prices in urban centres further limit access to fully serviced housing for low-to middle-income residents. These intersecting constraints have contributed to the proliferation of unplanned, incremental development across Ghanaian cities—typically underserviced and in some areas lacking essential infrastructure such as electricity (Abusah and Lind, 2004; Agyabeng et al., 2022; Korah et al., 2019; Yeboah, 2000).

Considerable research has been conducted in Ghana to investigate the relationship between urbanisation and electricity infrastructure. Economic growth, urban sprawl, and increasingly diverse housing systems have led to increased electricity demand across sprawling areas (Silver, 2015). This has resulted in isolated development between housing and electricity infrastructure, influencing the transformation of the city's energy provision landscape. The expanding industrial sector in major Ghanaian cities provides job opportunities and further fuel urbanisation, leading to electricity demand outpacing infrastructure supply, especially in Accra, Tema, Takoradi, and Kumasi (Eshun and Amoako-Tuffour, 2016). In Accra, formally planned neighbourhoods with integrated electricity

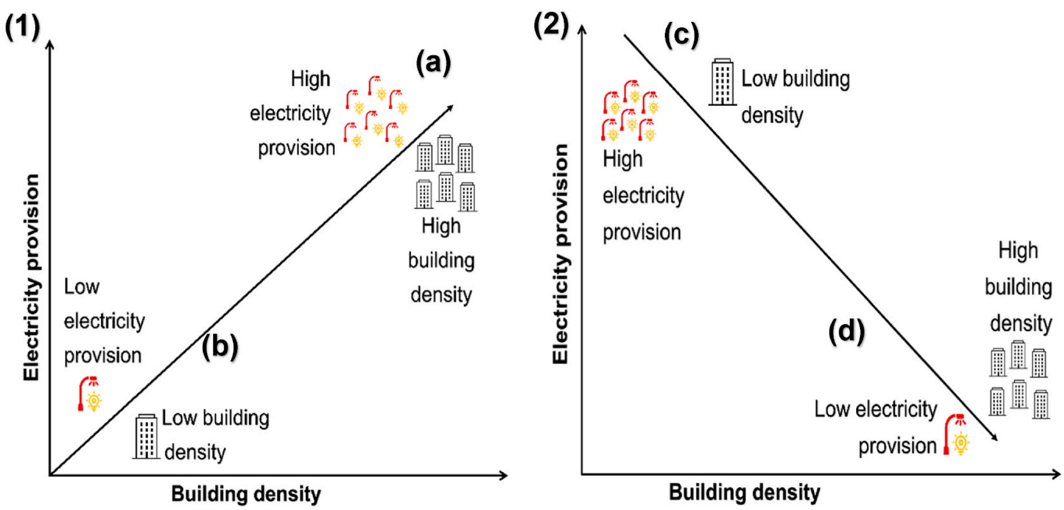

Fig. 1. Infrastructure development systems that are either (1) consistent (a. high-high; b. low-low), or (2) contradictory (c. low-high; d. high-low) between building density and electricity provision.

infrastructure tend to have stable electricity supply, while unplanned neighbourhoods with poorly integrated electricity infrastructure face inadequacies (Eledi Kuusaana et al., 2023).

These studies affirm concerns about electricity infrastructure demands during rapid urbanisation. However, to our knowledge, it remains unknown how within-city building density is associated with electricity provision in Ghana. Currently, electricity provision data is only available at the regional level, overlooking electricity service inadequacies at the sub-regional level. This poses a significant challenge for obtaining spatial information crucial for managing rapidly urbanising areas, a fundamental step toward promoting sustainable urban management.

In this study, we leverage remotely sensed satellite data to investigate building density, electricity provision, and their spatial co-occurrence within Ghanaian metropolitan cities. Based on the compact city theory, we expect higher-density neighbourhoods to be more likely to have sufficient electricity services. To test this hypothesis in Ghana, we address the following questions.

1. What are the patterns of building density within each metropolitan city?
2. To what extent and in which locations do disparities exist between electricity provision and building density within each city?
3. What are the similarities and differences in the energy-density patterns among Ghanaian cities?

1.1. Conceptual framework of building density and energy infrastructure

We define two fundamental concepts: the consistent infrastructure development system and the contradictory infrastructure development system (Fig. 1). In the consistent system, high building density areas aligns with high electricity infrastructure services (high – high), while low building density areas aligns with low electricity (low-low), reflecting a symbiotic relationship between urban development and electricity provision. In Contrast, the contradictory system highlights potential disparities, such as high building density areas with low electricity infrastructure (high-low) or low building density areas with unexpected high electricity infrastructure (low-high). These disparities suggest uneven infrastructure distribution and the influence of underlying factors beyond building density.

2. Study area

This study focuses on all the metropolitan cities in Ghana: Accra-Tema, Kumasi, Sekondi-Takoradi, Tamale, and Cape Coast (Fig. 2). The built-up area within these metropolitan cities have expanded beyond their administrative boundaries into adjacent areas. As such,

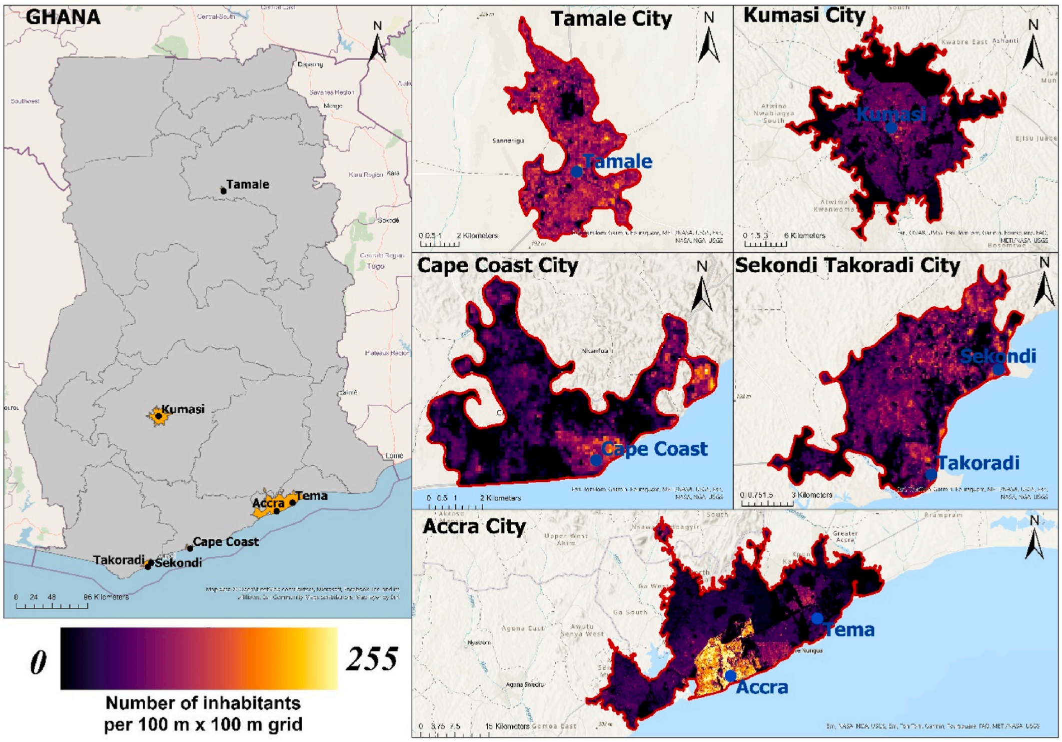

Fig. 2. Study area map showing the population distribution in Ghana's metropolitan cities in 2020. The spatial distribution of population within each city for 2020, expressed as the number of people per 100m × 100m cell (Schiavina et al., 2023).

we define the extent of the urban area within each metropolitan city as the contiguous built-up area based on the Global Urban Boundary Layer (Li et al., 2020). Since the 1970s, over 40 % of Ghana's urban population has resided in these metropolitan cities (G. Owusu and Oteng-Ababio, 2015).

2.1. Accra – Tema metropolitan city

This metropolitan city encompasses the urban areas of two administrative metropolitan areas and extends into surrounding municipal and district areas. The Accra Metropolitan Area (AMA) is one of the two urban cores, dominated by the service industry: the other being Tema Metropolitan Area, an industrial hub. The rapid expansion of these urban cores has extended into many surrounding peri-urban areas such as Madina, Adenta, Ashaiman, Kpone, Prampram, and as far as Kasoa and Nsawam in the Central and Eastern regions, respectively (G. Owusu and Oteng-Ababio, 2015). They form a city region with a population estimate of about 4.3 million (Ghana Statistical Service, 2020). Since becoming the national capital of the country in 1887, Accra has transformed from Indigenous fishing communities into the main socio-economic hub of the country. This transformation is attributed to the rapid urban expansion and population growth of Greater Accra, which houses about 30 % of Ghana's urban population and 18 % of the national population (Accra Metropolitan Assembly & C40 Cities, 2020). Accra generates about 25 % of Ghana's GDP. The city also has a dominant informal sector (self-employed persons-traders, artisan, and craft workers, etc.), accounting for approximately 80 % of its employment (Accra Metropolitan Assembly & C40 Cities, 2020).

2.2. Kumasi metropolitan city

Kumasi began as the capital city of the new Asante state, founded in the 1680s by King Osei Tutu I (Ghana Statistical Service, 2014). It is currently the second-largest city in the country, with a population of about 2.4 million (Ghana Statistical Service, 2020). This encompasses some settlement areas within the Atwima Nwabiagya, Afigya Kwabre, Kwabre East, and Asokore Mampong municipal areas, reflecting the city's growth. Kumasi is a major commercial hub, home to one of the largest markets in West Africa, known as the Kejetia Market. The city's strategic location has made it a significant hub for commercial activities, playing a pivotal role in the distribution of goods within Ghana and to other African countries. The predominant industry in the city is wholesale and retail, accounting for about 38.4 % of the employed population (Ghana Statistical Service, 2014b). The city's growth follows an outward concentric pattern, primarily along arterial road networks. The central business district and the surrounding old residential areas consist of older low-rise buildings typically with 2–3 floors in height (Field work, 2022).

2.3. Sekondi – Takoradi metropolitan city

Sekondi-Takoradi Metropolitan City has an estimated population of 727,915 (Ghana Statistical Service, 2020). This includes the administrative Effia-Kwesimintsim and the Ahanta West municipal areas. It serves as the capital of Ghana's Western region and boasts a rich industrial history, including being home to the country's oldest harbour. During the colonial era, it was a thriving industrial hub, accommodating various industries such as timber and cocoa processing, plywood manufacturing, shipbuilding, and railway repairs, among others. While manufacturing (16.8 %) continues to play a significant role in the city's economy, wholesale and retail services have now taken the lead, dominating the economic landscape at 28.5 %. Furthermore, a substantial portion of the economically active population, approximately 47.2 %, is self-employed (Ghana Statistical Service, 2014c). As an old industrial harbour city, the built areas are concentrated along the coast. For example, the central business district, known as Market Circle, is situated approximately 1.3 km from the harbour. This section of the city is well-planned, featuring well-maintained road networks, and it is characterized by older low-rise buildings typically ranging from 1 to 3 floors in height. Similar attributes are observed in other high-income residential areas such as Beach Road, Anaji, and Airport Ridge (Google Satellite Imagery (2019) and Street View (2016)).

2.4. Cape Coast metropolitan city

Cape Coast, one of Ghana's oldest cities, served as the capital of the Gold Coast colony until 1877 and continues to be a prominent tourism hub. It boasts a population of 197,893 (Ghana Statistical Service, 2020) and currently serves as the regional capital of Ghana's Central region. According to (Ghana Statistical Service, 2014a), Cape Coast stands as the sole city in Ghana with the most extensive surviving historic core of buildings predating the 1900s. Among these structures is the Cape Coast Castle, recognized as a UNESCO World Heritage site due to its pivotal role in the Atlantic gold and slave trade. These significantly boost tourism within the city. The wholesale and retail trade industry are the largest within the metropolis, employing about 25.1 % of the economically active population. This is also an informal economy, with about 68.4 % of the employed population in the private informal sector, and 21.4 % being public sector workers. Furthermore, Cape Coast serves as a prominent educational centre in the country, housing a multitude of schools ranging from basic to tertiary institutions. Many of the nation's top high schools are located within this city, drawing individuals from across the country and the West African sub-region (Ghana Statistical Service, 2014a).

2.5. Tamale metropolitan city

Tamale City is the most populous city in the northern part of the country, with a population of 275,364 (Ghana Statistical Service, 2020). It serves as the regional capital of the Northern region in Ghana, located inland in the central part of the Northern region.

Tamale is a significant commercial centre in the northern part of the country, owing to its strategic location, which provides market potential for local agricultural and commercial goods within northern Ghana.

According to (Ghana Statistical Service, 2014d), the road networks within the city are well-developed, particularly those linking the city to surrounding settlement areas. The city's economy is primarily characterized by the wholesale and retail industry, employing approximately 33.4 % of the working population. It is also largely dominated by the informal sector, employing about 83.2 % of the economically active population. The city is characterized by single-building structures that are spread across its expanding landscape (Field work, 2022).

3. Data and methods

3.1. Data

3.1.1. Landsat imagery

We used cloud-free annual composites of all available Landsat 7 and 8 images for the year 2019 to predict building density. We acquired the atmospherically corrected Collection 2 Tier 1 data product from on Google Earth Engine. The product represents surface reflectance at 30-m spatial resolution along with pixel-quality information. To overcome cloud cover in the region, we used the pixel quality information to mask out and remove pixels covered by clouds and cloud shadows. We then used a five-year composite to fill cloud-masked pixels, and selected the median value to represent each pixel (Chen et al., 2020; Yeh et al., 2020).

3.1.2. VIIRS data

Nighttime light data from satellite imagery have been proved to be an effective proxy for electricity provision and power outage (Levin et al., 2020; Stokes and Seto, 2019). We acquired the Visible Infrared Imaging Radiometer Suite (VIIRS) monthly average nighttime radiance composite on Google Earth Engine. The VNL V2 data product is pre-processed by the Earth Observation Group, Colorado School of Mines. The dataset has a spatial resolution of 15 arc second (~500 m at the equator). They are cloud-free and stray light-corrected, which are void of non-anthropogenic sources of light such as ephemeral lights, and cloud cover. The resulting dataset showcases nighttime lights originating from human sources, making it a reliable indicator for the study of electricity provision in urban areas (Fehrer and Krarti, 2018).

3.2. Methodology

First, we estimated building density within all metropolitan cities using a U-Net regression algorithm. Subsequently, we used statistical methods to process and extract the nightlight data for electricity analysis. Combining the two datasets, we analysed the spatial co-occurrence between levels of building density and electricity provision, using the difference method. Finally, we evaluated the accuracies of the generated results and summarize statistics for each city (Fig. 3).

3.2.1. Estimating building density from the Landsat imagery

We defined building density as the fraction of each 30 m × 30 m pixel covered by buildings. Overall, the pattern of building density is similar to population distribution in Fig. 2, but they are not the same, as building density reflects the land occupied by human settlements. We estimated the building density going through a series of steps: (1) training data collection, (2) model training and prediction, and (3) post-classification processing.

(1) Training data collection

We gathered training data extracted from OpenStreetMap (OSM) building footprints for six training sites located in Sub-Saharan

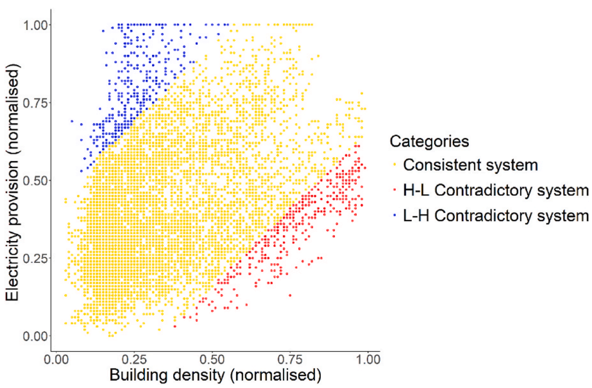

Fig. 3. Building density and electricity provision normalisation plot, with three co-occurrence categories.

(Appendix B). These areas have varying population sizes, but they are situated within a similar urban ecoregion as our study area (Appendix B). They have comparable urban characteristics such as building materials, type of building structure types (Demuzere et al., 2019). This approach allowed us to acquire training samples that exhibited similar physical traits to our study areas. Our choice of selecting these sample sites was also guided by the availability of OSM building footprints, which served as our primary data source.

We processed and transformed the training data from the OSM vector data into a raster format; we created a 30 m × 30 m fishnet, and labelled the fraction covered by the OSM building footprints for each pixel, ranging from 0 to 1. We also resampled the label to reduce class imbalance and patch heterogeneity, which have been raised by other studies (Chen et al., 2020; Demuzere et al., 2019). For instance, each data sample site included non-built-up areas to ensure the class balance between built-up and non-built-up areas. However, areas with high quantity, and quality footprints are mostly urban centres with few non-built-up areas. So, most of the labelling patches were built-up patches. Therefore, to ensure patch heterogeneity, non-built-up training samples were added to the training data. All the Landsat images were then normalised (Min-Max) to improve the performance of the deep learning model (Ghosh et al., 2020). The pair of building density labels and Landsat images were then processed into patches (32 × 32 patch size). The patches were divided into training and validation sets, with 75 % (160 patches) for training and 25 % for validation (51 patches).

(2) Model training and prediction

We trained the Convolutional Neural Network (CNN) regression algorithm – with the U-Net model architecture, and the ResNet-18 backbone to predict building density for each city (Chen et al., 2023; Ronneberger et al., 2015). The ResNet backbone is asserted to solve vanishing gradient problems in CNN models, and it has pre-trained weights for faster and better convergence (Fig. 4).

A batch size of 8 was used for training, and prediction. Batch normalisation was utilised to reduce the "internal covariance shift" between activation layers, which helped to improve the model time for convergence, and overreliance on hyper-parameter training (Ghosh et al., 2020). We then used the sigmoid activation function, since the building density prediction in the range of [0, 1]. We also used the Adam optimizer with a learning rate of 0.001, and 100 training epochs. Other learning rates (0.01, 0.0001, and 0.00001), and training epochs (40, 50, 60, 80, and 200) were experimented, but the aforementioned had better performance.

Also, the Structural Similarity Index (SSIM) was used as a loss function for building density estimates (Chen et al., 2020). To avoid overfitting, a model checkpoint was initialized to monitor the validation loss and only saved the model weights with the best validation loss during training. Afterwards, we used the trained model to predict building density at 30-m resolution across the study area.

(3) Post-classification Processing

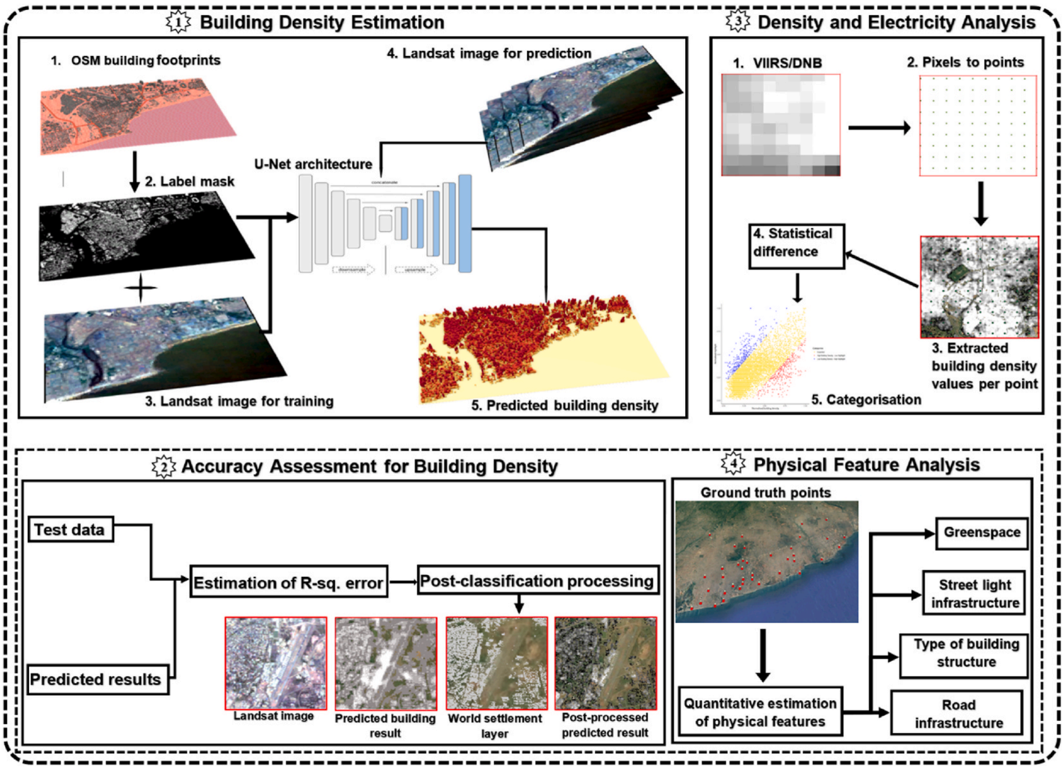

Fig. 4. Methodology workflow, including 1) building density estimation, 2) building density and electricity provision analysis, and 3) accuracy assessment for predicted building density, and 4) physical feature analysis of the density-electricity categories.

We utilised the World Settlement Footprint (Appendix A) as an ancillary dataset to perform post-classification processing (Marconcini et al., 2021). The post-classification processing involved leveraging high resolution building mask reference data to refine the estimated building density results. We performed this to further reduce false positives. This process masked out transportation infrastructures (e.g., roads and airport tarmacs), other non-building impervious surfaces (e.g., concrete grounds), as well as other land cover (e.g., barelands) that could be falsely predicted as buildings. The estimated building density values for each 30 m × 30 m grid were then categorised into four quantile levels, including low density (0 %–25 %), middle-low density (25 %–50 %), high density (>50 %), and very high density (>75 %) (Fig. 3). For consistency with electricity provision data, we calculated the mean building density at 500-m resolution (Fig. 4).

3.2.2. Estimating electricity provision from the VIIRS data

Since the spectral values and the resolution of the VIIRS data differs from the building density estimates, we normalised the nightlight data using the range of all study areas, leading to values ranging from 0 to 1. Subsequently, we converted the VIIRS raster data to vector points data based on each pixel's centroid. Each point had an attribute of the radiance values for each corresponding pixel. In this case, each centroid showed the level of luminosity, which we used as a proxy for electricity provision (Fig. 4).

3.2.3. Co-occurrence of building density and electricity provision

We combined the building density and electricity provision datasets by a same set of points at 500 m resolution, with missing values excluded. Next, we analysed the co-occurrence of building density and electricity provision levels by a simple differencing method. Here, we calculated the difference between the values of building density, and electricity provision, using the formula:

$$D_i = EP_i - BD_i$$

where EP_i refers to the normalised electricity provision value at locale *i* and BD_i is the normalised building density value at locale *i*.

To categorise the spatial inconsistencies between building density and electricity infrastructures, we defined thresholds based on the 5th and 95th percentiles of the difference values across the study region, which correspond to - 0.34 and 0.44, respectively. Based on the defined thresholds, we defined a locale as the low-high contradictory development system (low building density-high electricity provision), when the difference value is lower than the 5th percentile; and a locale as a high-low contradictory development system, when the difference value is higher than the 95th percentile. Also, a locale is defined as the consistent system (high-high or low-low) when the difference value is between the 5th and the 95th percentile (see Table 1; Fig. 3).

3.2.4. Accuracy assessment for building density estimation

To evaluate the performance of the CNN algorithm for predicting building density, a sample test data was collected from the city of Accra. An area of 14.14 km^2, with 17,837 building footprints (Appendix B), was used to evaluate the performance of the U-Net algorithm. The assessment showed that the U-Net algorithm had a prediction accuracy of 73 % for Ghanaian cities.

3.2.5. Physical features associated with the density-electricity co-occurrence

To interpret the physical characteristics of the three co-occurrence categories between building density and electricity provision, we assessed and counted the condition of specific physical features using Accra as a case. The features included streetlight, type of building, road, and greenspace, which are selected based on our fieldwork in 2022 in Accra. The stratified random sampling method was employed to select 40 points within Accra: 20 from the consistent system and 20 from the contradictory system (low building density – high electricity provision). At each sample location, we manually examined high-resolution Google Earth satellite imagery and the Google Street View to evaluate the conditions of the chosen features (see Appendix C). The frequency of these conditions was then counted for interpretation.

4. Results

4.1. Distinctive building density patterns between the coast and inland

All the metropolitan cities in Ghana have more than 50 % of buildings among the total urban area, but the within-city density patterns varied (Appendix D). Coastal cities are distinctive from those situate further inland. The coastal cities displayed multiple cores of high building density, with many of them concentrated along the coastal shoreline. In contrast, the inland cities displayed single core

Table 1
Building density and luminosity categories and interpretation.

Category	Threshold	Interpretation
Consistent system (high-high or low-low)	Difference in value between the 5th and the 95th percentiles.	Areas with higher building density tends to have higher electricity provision during the night and vice versa.
High-low contradictory system	Difference value lower than the 5th percentile	Areas with electricity provision fallen behind despite their high building density.
Low-high contradictory system	Difference value higher than the 95th percentile	Areas exhibiting high electricity provision during the night despite their low building density.

of high building density, where density decreases outward in all directions to the periphery. For each urban core, most cities present a concentric pattern, where the concentration of the building density reduces along the urban-rural gradient.

On average, coastal cities featured a sprawling, low-density built environment, with more than three-quarters of the built-up areas having building density lower than 50 % (Fig. 5). In contrast, inland metropolitan cities were denser. Each inland city had at least 40 % of the built-up area with high building density.

4.1.1. Coastal metropolitan cities

4.1.1.1. Accra-Tema metropolitan city. The Accra-Tema Metropolitan City had a built-up area of 771 km^2, representing 72 % of the city. Most of the city was characterised by low density, constituting 44 % of its total building area (Fig. 5). Additionally, a significant portion (34 %) of the city exhibited middle-low building density. Middle-low density areas were common in the northern part of the city and the core areas. They encompassed the growing peri-urban neighbourhoods within the surrounding administrative municipal areas that have expanded into the metropolitan region. Examples include Kwabenya Musuko, Agbogba, Frafraha, Senpene, Adenta, which are primarily residential areas.

Less than 25 % of Accra displayed a high building density, with only about 4 % of the city having a very high building density (Fig. 5). These areas were characterised by commercial and residential neighbourhoods located within both urban and peri-urban areas. This category also encompassed the urban centres of surrounding peri-urban neighbourhoods. Examples include the Central Business District, Osu, Kaneshie, Adabraka, Nima, Lapaz, Tema, Kasoa, Madina, Ashaiman, all of which are located within the commercial and residential urban and peri-urban areas.

4.1.1.2. Sekondi-Takoradi Metropolitan City. The Sekondi-Takoradi Metropolitan City encompassed a total built-up area of 44 km^2, representing 56 % of the city. Most of the city is characterised with low building density. Less than 10 % of the total building area had high density. Additionally, only about 2 % of the total building area exhibited very high density. High-density areas were situated in the south-central part of the city, featuring concentrated clusters that extend across the city. These density clusters were particularly located in the central parts and along the coast (Fig. 6), characterised with old residential settlements and commercial centres. They

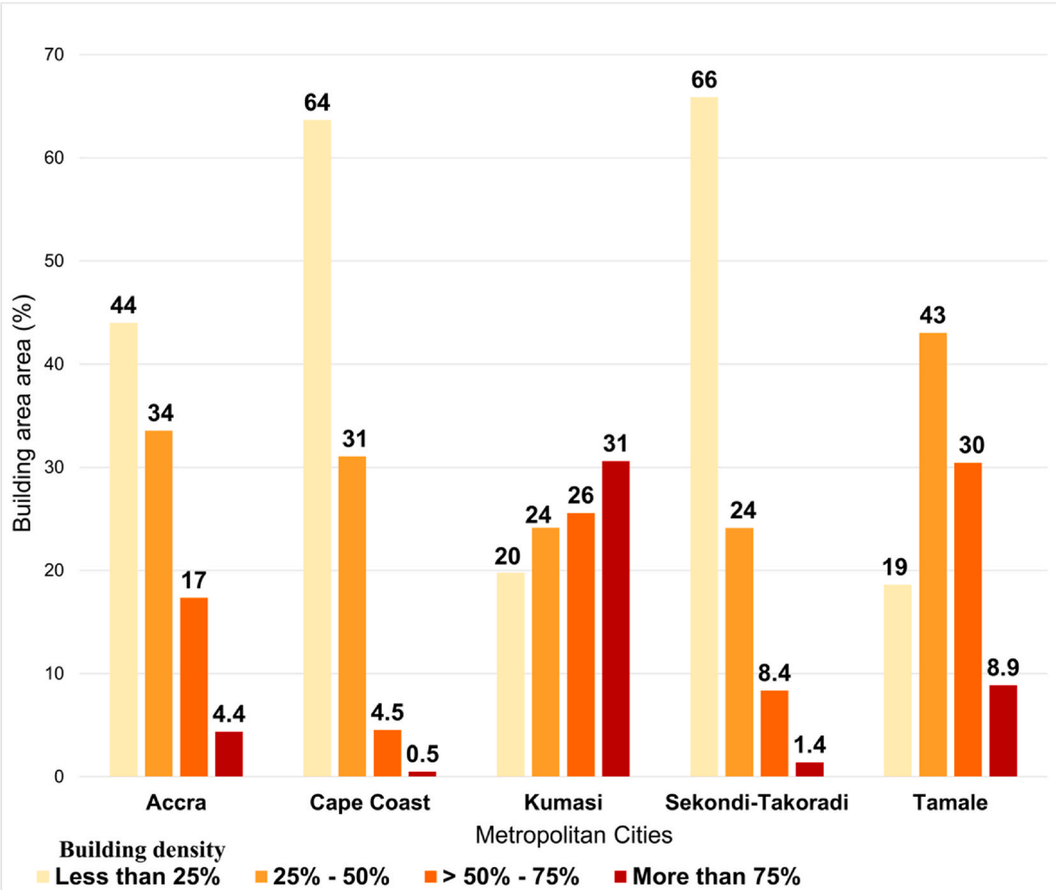

Fig. 5. Percentage of building density buckets for each metropolitan city.

include the Market Circle, Effiakuma, East Tanokrom, and Kwesimintsim.

In contrast, most of the city's total building area (66 %) was characterised by low building density. Additionally, about a quarter of the total building area featured middle-low building density. These areas were concentrated in the northern part of the city and extended to the eastern and western portions of the city, including Lagos Town, Esikado, and Airport Ridge (Fig. 6).

4.1.1.3. Cape Coast metropolitan city. The Cape Coast Metropolitan City also showed a building area of 56 %, or 20 km^2. A substantial portion (95 %) of the total building area of the city demonstrated low building density. About 64 % of the total built-up area had low density, and 31 % had middle-low building density. These areas surrounded the various high-building-density clusters within the city, often found in growing peri-urban neighbourhoods surrounding the urban cores. Only 5 % of the city's total building area was characterised by high building density, with a trivial portion (0.5 %) with very high density. These areas are concentrated in the central business district and the main urban centres of the surrounding peri-urban areas within the city.

4.1.2. Inland metropolitan cities

4.1.2.1. Kumasi metropolitan city. The Kumasi Metropolitan City had a built-up area coverage of 76 %, or 302 km^2. Our findings designated Kumasi as the densest city in Ghana, with 56 % of the total building area featuring high building density, and 31 % exhibiting very high density (Fig. 5). These areas were primarily concentrated in the central and central-northern parts of the city. This is an expansive area that encompassed the central business district, including Adum and Asafo markets. It further included old commercial areas, and residential neighbourhoods such as Kejetia, Suame, Tafo, Krofuom, Bantama, Ashtown, and Dichemso. These high density areas also extended outward from the city's core, reaching into peri-urban and outskirt regions, including Ayeduase, Kokoben, Atimatim, Meduma, and Afrancho, all of which are neighbourhoods of the surrounding administrative municipal areas.

The remaining portion (44 %) of the total building area exhibited either low or middle-low density. These areas dominated the outskirts of the city, with concentrated clusters within and around some high-density areas. They were situated in the western part of the city, and extended southwards along the city's boundary, particularly in neighbourhoods like Boko, Kromoase, and Denkyemuoso, all of which are within the Atwima Kwanwoma and Kwadaso municipal areas (Fig. 6).

4.1.2.2. Tamale metropolitan city. The Tamale Metropolitan City demonstrated a building area coverage of 86 % (31 km^2). Our findings further revealed that the city was primarily characterised by building density values ranging between 25 % and 50 %. These areas were notably concentrated in the northern part of the city, particularly within the peri-urban areas. They were also sparsely distributed across various locations within the city, especially along the eastern and southwestern boundaries. Close to 40 % of the

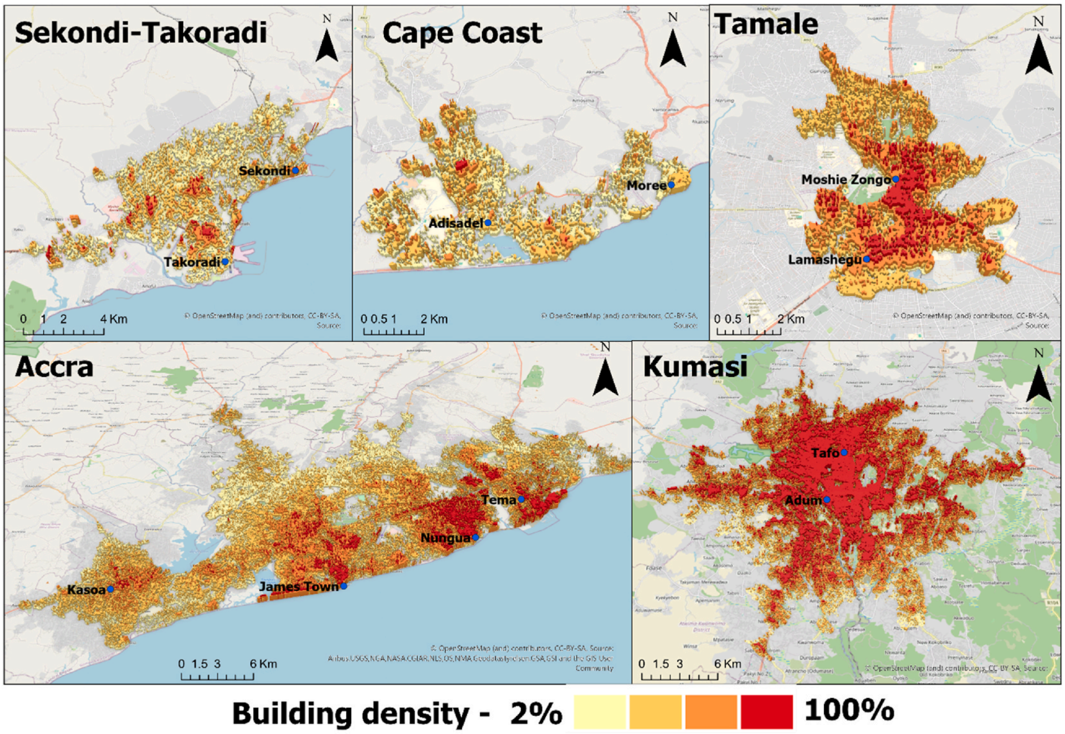

Fig. 6. Building density distribution for each metropolitan city at 30-m resolution. Building density values range from 2 to 100 %, and they are grouped and visualised in four quantile buckets.

city's total building area had high density, with 9 % showcasing very high density. These areas encompassed the central business district of the city, and the surrounding neighbourhoods, including Aboabo, Gukpegu, Kalandan, Sabon-Gida, Chengli, and Lamashegu (Fig. 6).

4.2. *Alignment and discrepancies between building density and electricity provision*

Our analysis revealed distinct patterns of building density and electricity provision distribution across each metropolitan city, despite some cities sharing similarities in their building density distribution.

4.2.1. *The consistent infrastructure development system*

The consistent system represented about 92 % of the building areas within the Ghanaian metropolitan cities, indicating that most areas followed the hypothesis of higher density being associated with higher electricity provision (Fig. 7). The highest percentage per city was found in Cape Coast (100 %), Sekondi-Takoradi (98 %), Accra (91 %), followed by Tamale (90 %), and Kumasi (79 %). The geolocation of the consistent system varied across the cities, but in general, there are two typical spots: (1) the city centres (e.g., Accra Central and Kumasi-Adum), (2) the outskirts (e.g., Abokobi and Kromoase).

4.2.2. *The high-low contradictory infrastructure development system*

Approximately 6 % of the total built-up area across all the metropolitan cities showed the contradictory system, with this pattern appearing in all cities except Cape Coast. Kumasi had the highest percentage (21 %), followed by Tamale (9.6 %), Accra (0.9 %), and Sekondi-Takoradi (0.5 %). In Kumasi, areas with the contradictory system were concentrated in the central-northern part and spread outward into the outskirts, covering neighbourhoods like Old Tafo, Breman, and Kronom. In Tamale, these areas were concentrated on the outskirts, particularly towards the south and west. In Accra, the contradictory system was distributed along the coastline covering neighbourhoods such as Nungua, Teshie, James Town, and Tema New Town (Fig. 7). Sekondi-Takoradi had the lowest percentage, with these areas concentrated on the city's western outskirts (Fig. 8). Notably, 85 % of these areas were characterised by single detached buildings (Ghana Statistical Service, 2021), with 55 % accompanied by road infrastructures and 14 % surrounded by greenspace in Accra (Fig. 9, Table 2).

4.2.3. *The low-high contradictory infrastructure development system*

Across all the metropolitan cities, 2 % of the total building area exhibited low building density with high electricity infrastructure services, marking them as outliers. These outliers covered only Accra and Sekondi-Takoradi, covering approximately 8 % and 2 %, respectively. In Accra, these areas were primarily concentrated in the central part of the city, extending from the north to the south.

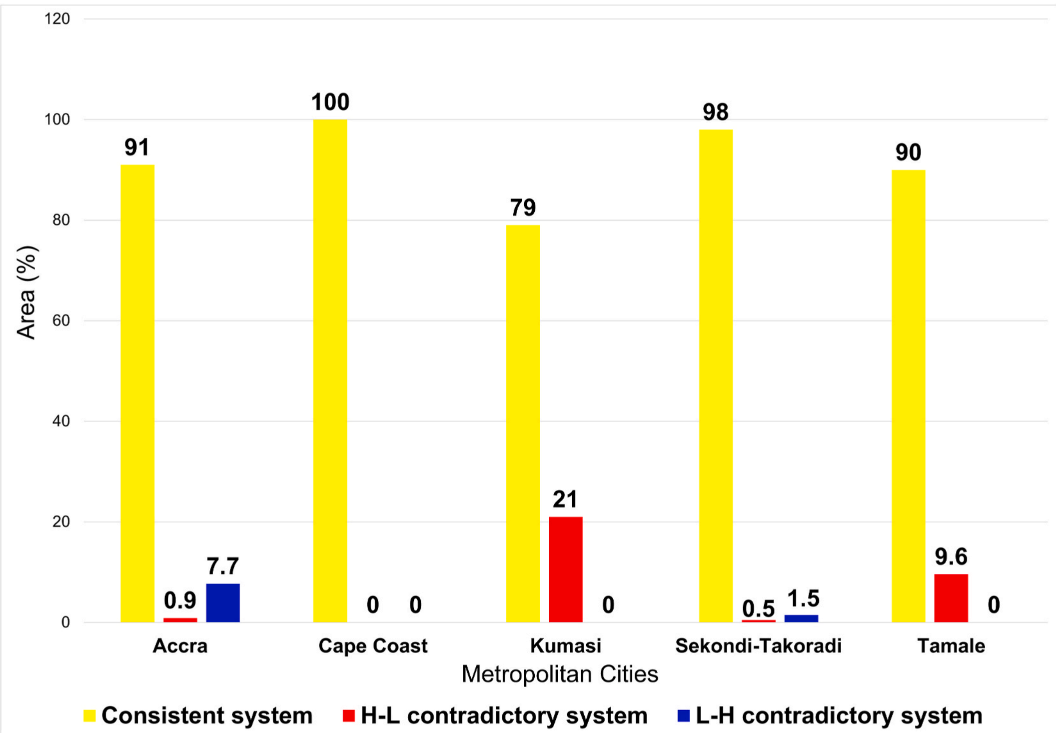

Fig. 7. Percentage of building and lighting infrastructure categories for each metropolitan city.

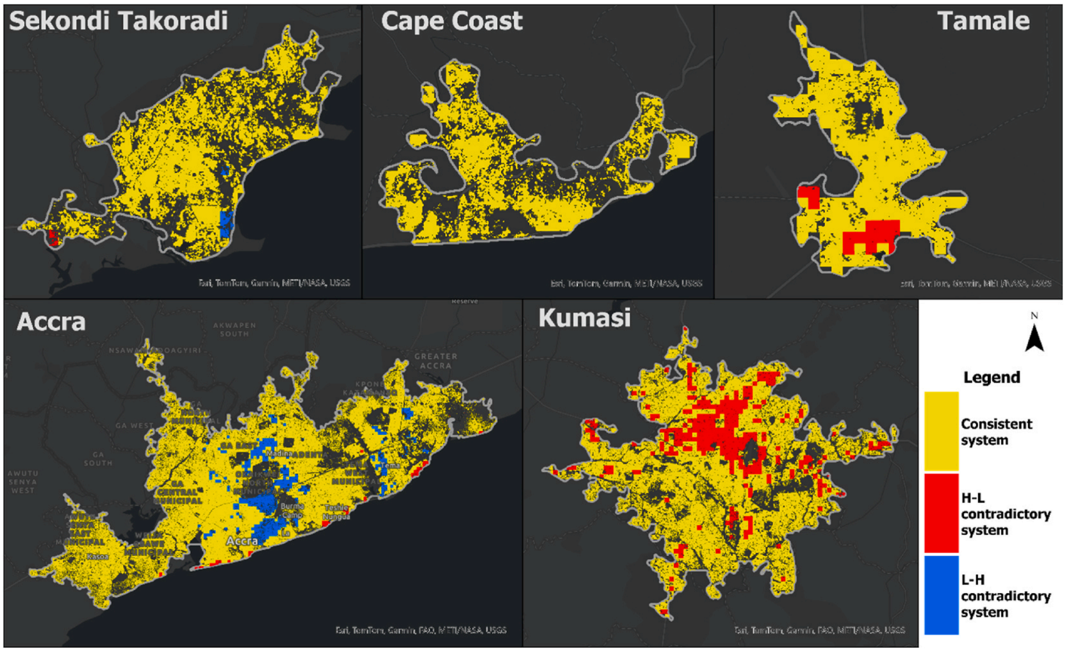

Fig. 8. Maps for each metropolitan city showing the co-occurrence of building density and electricity provision in three categories: the consistent system, high-low contradictory system, and low-high contradictory system.

They encompassed neighbourhoods such as Cantonments, North Ridge, Roman Ridge, Dzorwulu, and East legon. Other notable concentrations were found in the eastern part of the city, covering neighbourhoods such as Tema Community 3, Community 10, and Community 22. In Sekondi-Takoradi, the outliers were concentrated along southern coastline, covering the harbour and its immediate surroundings (Fig. 8).

5. Discussion

5.1. Building density patterns

Our results demonstrate how building structures are configured, and distributed across space, revealing differences and similarities in distribution among the various metropolitan cities in Ghana. The coastal cities of Accra, Sekondi Takoradi, and Cape Coast showed similar polycentric pattern of high building density distribution. In contrast, the inland cities, Kumasi, and Tamale displayed a concentric-outward pattern of high building density distribution. These distribution patterns can be attributed to historical urban development precedents influenced by colonial legacies, access to land resources, as well as the rapid urbanisation of these cities. Colonial influences established these cities as centres of commerce and administration, fostering urban concentrations to attract population and development (Adarkwa, 2012). Despite the significant growth of population and building area during the post-colonial period (Yakubu, 2021), our findings reveal that the spatial distribution of new development continues to reflect these historical settlement patterns. For example, Accra city originated from indigenous Ga coastal neighbourhoods, established in the 16th Century (Otiso and Owusu, 2008). These neighbourhoods, such as Accra Central, Osu, James Town, and Tema, have evolved into urban centres within the city. Our findings identified these neighbourhoods as some of the high building density nuclei of the polycentric distribution patterns within the city (Fig. 6). Similarly, Cape Coast city served as the administrative capital of the Gold Coast colony until 1877 and remained a vital trading port and educational centre, with multiple urban cores such as Adisadel Village and Moree spread across the city. Sekondi-Takoradi also emerged as the principal port city during the colonial era, with the commercial harbour in Takoradi, and the fishing harbour situated in Sekondi (Fig. 6). These cities' regional roles drew population and spurred development, particularly along the coast within these cities (Adarkwa, 2012). However, the escalating cost of land and housing within these established centres continues to displace low- and middle-income populations toward the urban peripheries. As noted by Abusah and Lind (2004), individuals in these income categories typically acquire land from traditional authorities due to the high cost of plots in formally developed areas. These lands, often located at the urban fringe, are incrementally developed using personal savings or remittances from relatives abroad. Such expansion is frequently shaped by socio-economic ties and affordability constraints, reinforcing a peripheral pattern of urban growth patterns around multiple urban centres and contributing to the cities polycentric structure. Consequently, this tendency helps explain the notable concentration of building structures along the coastal shoreline, as revealed in our findings, despite building development expanding inland currently (Fig. 6).

In contrast, the inland city of Kumasi has long served as a major urban centre and the capital of the Ashanti Kingdom. Kumasi was

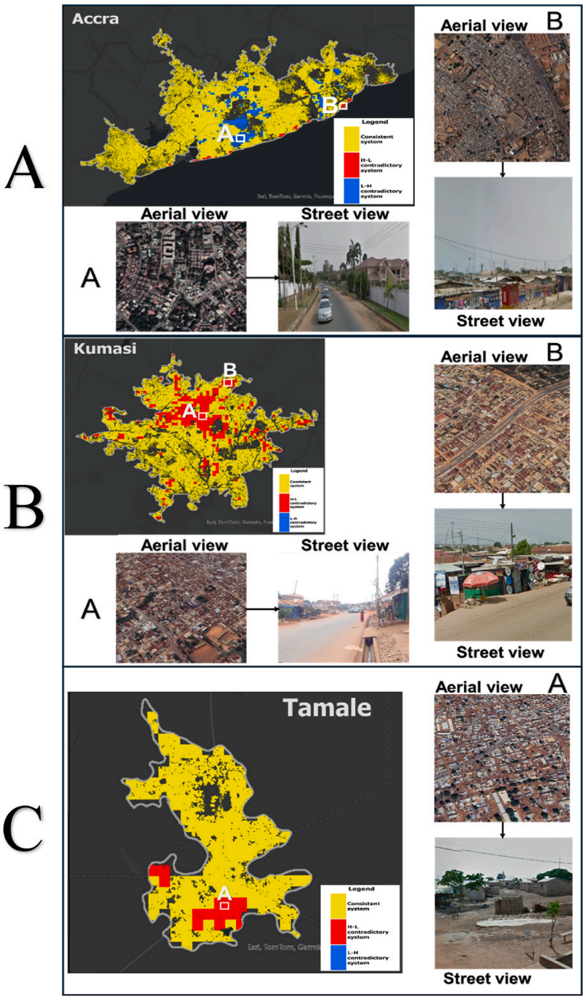

Fig. 9. Ground-truth images of the contradictory systems in (A) Accra, (B) Kumasi and (C) Tamale.

acknowledged as a vital commercial hub connecting the northern and southern parts of the country. Renowned for its interconnected transportation networks, Kumasi was also characterised with planned neighbourhoods, built with unique 1-3 storey building architectures following a grid-like pattern (Adarkwa, 2012; Otiso and Owusu, 2008). This distinctive building distribution is evident by our building density findings, demonstrating a concentric pattern spread from the highest in the central business district, decreasing along the transportation networks toward the outskirts. The other inland city, Tamale, exhibited a similar well-planned building density pattern. It served as a colonial administrative centre for Northern Ghana during the colonial period (Otiso and Owusu, 2008). In 1907, Tamale constituted a cluster of Dagomba villages. However, less than a decade after the British established their administrative headquarters for the northern part of Ghana (formerly Gold Coast) in 1908, it transitioned into a vibrant urban centre. This transition included the development of transportation networks connecting various parts of northern Ghana (Adarkwa, 2012).

In many developing countries, the expansion of urban areas is often characterised by the proliferation of squatter settlements, characterised by minimal basic services and infrastructure provisions such as electricity, water supplies, sanitation, roads, etc. (Abusah and Lind, 2004; Agyabeng et al., 2022). Factors such as rapid population growth, unequal income distribution, and inadequate government policies have collectively contributed to housing shortages, driving the growth of squatter settlements and shaping building distribution patterns in these cities (Abusah and Lind, 2004). This trend continues to influence the spatial distribution of buildings in urban areas today.

5.2. *The building density-electricity provision dynamics*

Our findings reveal multifaceted relationships between building density and electricity provision in Ghanaian metropolitan cities. While we anticipated that a significant proportion of these cities would align with the compact city theory, where higher density is associated with higher electricity provision, our results reveal a surprising outcome. Approximately 8 % of the studied metropolitan areas exhibited disparities, with 6 % classified as having a high-low contradictory development system, and 2 % as low-high

Table 2
Physical features for density-electricity categories with high resolution google street view images.

Low building density – high electricity provision (L-H contradictory system)			High building density – low electricity Provision (H-L contradictory system)		
Variables	Estimated Percent	High resolution image	Variables	Estimated Percent	High resolution image
Street light infrastructure	79 %		Street light infrastructure	28 %	
Type of building structure	69 % (Two-storey building)		Type of building structure	85 % (Single detached building)	
Road infrastructure	83 %		Road infrastructure	55 %	
Greenspace	73 %		Greenspace	14 %	

contradictory development system. This disparity prompted further analysis to comprehend the dynamic nature of these areas within the metropolitan cities.

Areas with the high-low contradictory infrastructure development system, constituted informal and less developed areas within the metropolitan cities. These areas typically exhibited inadequate street lighting and road infrastructures, characterised by single-detached buildings with limited greenspace cover (Table 2). Additionally, our analysis unveiled that certain rapidly expanding residential and commercial neighbourhoods within the metropolitan cities also exhibited the high-low contradictory system, such as Kasoa in Accra and Fawoade in Kumasi. This pattern is likely influenced by prolonged delays in the building permit acquisition, which can about 3–15 years depending on the type of development. Such administrative bottlenecks often create opportunities for informal construction, allowing physical development to outpace formal urban development processes (Abusah and Lind, 2004). Notably, Kasoa's built-up area expanded by 88 % between 1991 and 2018 (A. B. Owusu et al., 2023). Informal settlements typically lack essential social amenities and have limited access to infrastructure provisions such as electricity, roads, and water supply. Their non-compliance with urban planning regulations and non-legal status further hinders the provision of electricity infrastructure (Eledi Kuusaana et al., 2023). Consequently, integrating and enhancing electricity infrastructure in these densely built but informally developed areas become significantly more costly in the later stages of development (Romero Lankao et al., 2019).

The low-high contradictory system, typically upper-class neighbourhoods within the metropolitan cities, were characterised by formal planning, early development, and of high housing prices. These areas featured well-established street lighting and road infrastructures, abundant greenspace cover, and predominantly consisted of one-storey detached buildings, particularly in planned neighbourhoods (Table 2). It is expected that these areas feature well-established street lighting infrastructure, given that the VIIRS nighttime imagery, used as a proxy for the electricity provision, primarily captures outdoor street lighting (Román et al., 2019). For example, Accra's Central Business District hosts extensive electricity infrastructure, including underground cable systems that are more reliable than overhead networks, along with consistent service provision. Similarly, high-income neighbourhoods such as Airport Residential Area, largely inhabited by affluent Ghanaians and foreigners, are formally planned and equipped with universal, networked electricity systems offering stable electricity service delivery (Eledi Kuusaana et al., 2023).

Although a relatively small portion of these cities exhibited darkness in densely-built neighbourhoods, the gap may increase if no action is taken, especially within rapidly growing cities like Accra and Kumasi. Prioritising these areas and guiding their planning towards sustainability is essential. This involves focusing on energy-efficient urban form and integrated electricity infrastructures in fast-developing regions in Ghana and beyond.

5.3. Data limitations

While this study provides critical insights into the spatial mismatch between electricity infrastructure and urban development in Ghanaian metropolitan areas, vital limitations of the study need to be considered. The integration of Landsat imagery (30 m spatial resolution) and VIIRS nighttime lights (approximately 500 m resolution) introduces a scale disparity that may obscure finer-grained intra-urban variations in electricity access. As a result, some complexities at the neighbourhood or block level may be spatially diluted, especially in in highly fragmented urban environments. Also, the VIIRS nighttime light data, while extensively validated as a proxy for electricity access and urban activity, does not provide direct measurements of electricity infrastructure. This reliance on the radiance as a proxy for electricity access may overlook areas with intermittent electricity access, as well as alternative off-grid sources such as solar microgrids, that emit minimal or no detectable night lights. Consequently, this approach may not fully capture the complexity and quality of electricity distribution networks.

6. Conclusions

This study estimated and analysed the spatial configuration of building density and electricity provision in all the metropolitan cities in Ghana. The research also highlighted the significance of applying publicly-available remote sensing data, combined with deep learning and statistical methods for investigating the dynamics of the built environment in the Global South. This approach is particularly crucial for rapidly expanding urban areas, as each infrastructure component within the built environment significantly impacts the sustainable functioning of the urban system (Lwasa et al., 2022). This study contributes to urban infrastructure research by uncovering how historical urban development patterns continue to shape building density across Ghanaian metropolitan cities, and by introducing the concept of consistent and contradictory infrastructure development systems to explain mismatches between building density and electricity provision. It highlights how rapid urban growth and informal development contribute to infrastructure disparities, offering a nuanced understanding of spatial equity in access to electricity.

The study's findings revealed that metropolitan cities along the coastal shoreline, including Cape Coast and Accra, faced greater challenges in electricity infrastructure provision in densely built neighbourhoods. These coastal cities were characterised by a polycentric building density pattern, with some neighbourhoods in old colonial towns and new settlements on the outskirts struggling with electricity provision. In contrast, inland metropolitan cities like Kumasi and Tamale exhibited a concentric building density pattern, with more electricity gaps in Tamale's new settlements on the outskirts. With city governments and stakeholders facing constraints in human and financial resources, prioritising the development of these evolving neighbourhood with well-integrated energy systems would be a crucial step towards realising United Nations' Sustainable Development Goal 11: sustainable cities.

Our analysis focused on the density-energy relationship in response to the compact city theory. Moving forward, future studies could benefit from incorporating additional urban metrics, such as building height, land-use activities, and electricity consumption patterns, to gain deeper insights into electricity accessibility and sustainable spatial development.

CRediT authorship contribution statement

Jeffrey Blay: Writing – original draft, Visualization, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Karen C. Seto:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Tzu-Hsin Karen Chen:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

Declaration of ethical statement

The authors declare that all ethical practices have been followed in relation to the development, writing, and publication of the article.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used ChatGPT to check grammar and typos. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This research was funded by the Tropical Resource Institute (TRI)-Yale School of the Environment summer research fellowship. The Authors also acknowledge all the field assistants (Frederick Aboagye and Henry Nii Odartey) who helped with the fieldwork activities.

Appendix A. Summary of the datasets used and their attributes

Dataset	Year	Purpose	Source
Landsat imagery	2019	Estimating building density	https://developers.google.com/earth-engine/datasets/catalog/landsat
VIIRS nighttime imagery	2019	Proxy for electricity infrastructure distribution.	https://developers.google.com/earth-engine/datasets/catalog/NOAA_VIIRS_DNB_MONTHLY_V1_VCMSLCFG
World Settlement Footprint	2019	Reference settlement layer for masking predicted urban density results	https://download.geoservice.dlr.de/WSF2019/
Global Urban Boundary	2018	Defining urban extent for each metropolitan city	X. Li et al. (2020)
Ghana Neighbourhood Boundary	2020	Neighbourhood boundary layer	https://www.statsghana.gov.gh/gssdatadownloadspage.php

Appendix B. Attributes of training and test sample sites

City	Total number of footprints	Total area (km^2)	Eco-region	Population
Training Data				
Johannesburg	3996	24.18	Tropical, Sub-tropical grassland	957,441
Nairobi	8214	11.8	Tropical, Sub-tropical grassland	473,500
Benin City	4606	17.45	Tropical, Sub-Tropical Savannah in Africa	1,781,999
Gaborone	17029	22.9	Tropical, Sub-Tropical Savannah in Africa	208,411
Dakar	11179	17.83	Tropical, Sub-Tropical Savannah in Africa	3,229,800
Damongo	3684	14.18	Tropical, Sub-Tropical Savannah in Africa	32,344
Test Data				
Accra	17837	14.14 km^2	Tropical, Sub-Tropical Savannah in Africa	2,556,972

Appendix C. Ground truth points for analysing and interpreting building density and lighting infrastructure patterns

Variable	Description	Sample size
Street light infrastructures	Weighted based on availability and quality. (From 0 to 3; - worst to best)	20
Type of building structure	Dominant building structure (single building, one-storey, two-storey, multi-storey) based on the Ghana Statistical Service building typologies for the 2021 Housing Census	20
Road infrastructures	Weighted based on road layout and condition/quality (From 0 to 3; - worst to best)	20
Greenspace	Weighted based on the availability of grass, street trees, and forest. (From 0 to 3; - worst to best)	20

Appendix D. Statistics of the total urban area and the estimated building density composition for each metropolitan city

City	Total urban area (km^2)	Building area (km^2)	% building area
Accra	1077	771	72 %
Cape Coast	36	20	56 %
Kumasi	398	302	76 %
Sekondi-Takoradi	78	44	56 %
Tamale	36	31	86 %

Appendix E. Total number of image tiles considered for compositing per city

Metropolitan city	Total number of images
Cape Coast Metropolitan City	123
Sekondi-Takoradi	123
Kumasi Metropolitan City	172
Greater Accra Metro	112
Tamale Metropolitan City	216

Data availability

Data will be made available on request.

References

Abusah, S.K., Lind, H., 2004. Access to Land for Housing Development: A Review of Land Title Registration. Accra, Ghana.

Accra Metropolitan Assembly & C40 Cities, 2020. Accra Climate Action Plan. First five-year plan. *2020-2025)*. https://cdn.locomotive.works/sites/5ab410c8a2f42204838f797e/content_entry5ab410faa2f42204838f7990/5ab5605ea2f4220acf45cfa6/files/Accra_Climate_Action_Plan.pdf?1603293785.

Adarkwa, K.K., 2012. The changing face of Ghanaian towns, 4 (1).

Agyabeng, A.N., Peprah, A.A., Mensah, J.K., Mensah, E.A., 2022. Informal settlement and urban development discourse in the Global South: evidence from Ghana. Norsk Geografisk Tidsskrift - Norwegian J. Geograp. 76 (4), 242–253. https://doi.org/10.1080/00291951.2022.2113428.

Arimah, B., 2017. Infrastructure as a catalyst for the prosperity of african cities. Procedia Eng. 198, 245–266. https://doi.org/10.1016/j.proeng.2017.07.159.

Breheny, M., 1995. The compact city and transport energy consumption. Trans. Inst. Br. Geogr. 20 (1), 81. https://doi.org/10.2307/622726.

Chen, T.-H.K., Pandey, B., Seto, K.C., 2023. Detecting subpixel human settlements in mountains using deep learning: a case of the Hindu Kush Himalaya 1990–2020. Rem. Sens. Environ. 294, 113625. https://doi.org/10.1016/j.rse.2023.113625.

Chen, T.-H.K., Qiu, C., Schmitt, M., Zhu, X.X., Sabel, C.E., Prishchepov, A.V., 2020. Mapping horizontal and vertical urban densification in Denmark with Landsat time-series from 1985 to 2018: a semantic segmentation solution. Rem. Sens. Environ. 251, 112096. https://doi.org/10.1016/j.rse.2020.112096.

Demuzere, M., Bechtel, B., Mills, G., 2019. Global transferability of local climate zone models. Urban Clim. 27, 46–63. https://doi.org/10.1016/j.uclim.2018.11.001.

Diko, J., Tipple, A.G., 1992. Migrants build at home. Cities 9 (4), 288–294. https://doi.org/10.1016/0264-2751(92)90029-5.

Eledi Kuusaana, J.A., Monstadt, J., Smith, S., 2023. Practicing urban resilience to electricity service disruption in Accra, Ghana. Energy Res. Social Sci. 95, 102885. https://doi.org/10.1016/j.erss.2022.102885.

Eshun, M.E., Amoako-Tuffour, J., 2016. A review of the trends in Ghana's power sector. Energy Sustain. Soc. 6 (1), 9. https://doi.org/10.1186/s13705-016-0075-y.

Fehrer, D., Krarti, M., 2018. Spatial distribution of building energy use in the United States through satellite imagery of the earth at night. Build. Environ. 142, 252–264. https://doi.org/10.1016/j.buildenv.2018.06.033.

Ghana Statistical Service, 2014a. District analytical report—cape coast. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Central/Cape%20Coast.pdf.

Ghana Statistical Service, 2014b. District analytical report—kumasi. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Ashanti/KMA.pdf.

Ghana Statistical Service, 2014c. District analytical report—sekondi Takoradi. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Western/STMA.pdf.

Ghana Statistical Service, 2014d. District analytical report—tamale. https://www2.statsghana.gov.gh/docfiles/2010_District_Report/Northern/Tamale%20Metropolitan.pdf.

Ghana Statistical Service, 2020. Projected population for districts. https://statsghana.gov.gh/gssmain/fileUpload/Demography/Projected%20population%20by%20age%20and%20sex%20-%20260%20districts_2020_31st%20May%202020(1).xlsx.

Ghana Statistical Service, 2021. 2021 population and housing census—field officer's manual. https://census2021.statsghana.gov.gh/gssmain/fileUpload/pressrelease/2021%20PHC_Field%20Officers%20Manual_05.05.2021.pdf.

Ghosh, A., Sufian, A., Sultana, F., Chakrabarti, A., De, D., 2020. Fundamental concepts of convolutional neural network. In: Balas, V.E., Kumar, R., Srivastava, R. (Eds.), Recent Trends and Advances in Artificial Intelligence and Internet of Things, 172. Springer International Publishing, pp. 519–567. https://doi.org/10.1007/978-3-030-32644-9_36.

Güneralp, B., Zhou, Y., Ürge-Vorsatz, D., Gupta, M., Yu, S., Patel, P.L., Fragkias, M., Li, X., Seto, K.C., 2017. Global scenarios of urban density and its impacts on building energy use through 2050. Proc. Natl. Acad. Sci. 114 (34), 8945–8950. https://doi.org/10.1073/pnas.1606035114.

Huang, K., Li, X., Liu, X., Seto, K.C., 2019. Projecting global urban land expansion and heat island intensification through 2050. Environ. Res. Lett. 14 (11), 114037. https://doi.org/10.1088/1748-9326/ab4b71.

Jessel, S., Sawyer, S., Hernández, D., 2019. Energy, poverty, and health in climate change: a comprehensive review of an emerging literature. Front. Public Health 7, 357. https://doi.org/10.3389/fpubh.2019.00357.

Korah, P.I., Matthews, T., Tomerini, D., 2019. Characterising spatial and temporal patterns of urban evolution in Sub-Saharan Africa: the case of Accra, Ghana. Land Use Policy 87, 104049. https://doi.org/10.1016/j.landusepol.2019.104049.

Levin, N., Kyba, C.C.M., Zhang, Q., Sánchez De Miguel, A., Román, M.O., Li, X., Portnov, B.A., Molthan, A.L., Jechow, A., Miller, S.D., Wang, Z., Shrestha, R.M., Elvidge, C.D., 2020. Remote sensing of night lights: a review and an outlook for the future. Rem. Sens. Environ. 237, 111443. https://doi.org/10.1016/j.rse.2019.111443.

Li, X., Gong, P., Zhou, Y., Wang, J., Bai, Y., Chen, B., Hu, T., Xiao, Y., Xu, B., Yang, J., Liu, X., Cai, W., Huang, H., Wu, T., Wang, X., Lin, P., Li, X., Chen, J., He, C., et al., 2020. Mapping global urban boundaries from the global artificial impervious area (GAIA) data. Environ. Res. Lett. 15 (9), 094044. https://doi.org/10.1088/1748-9326/ab9be3.

Lwasa, S., Seto, K.C., Bai, X., Blanco, H., Broto, V.C., Dubeux, C.B.S., Ürge-Vorsatz, D., Keller, M., 2022. Urban Systems and Other Settlements.

Marconcini, M., Metz- Marconcini, A., Esch, T., Gorelick, N., 2021. Understanding current trends in global urbanisation—the World settlement footprint suite. GI_Forum 1, 33–38. https://doi.org/10.1553/giscience2021_01_s33.

Ogundipe, A.A., Akinyemi, O., Ogundipe, O.M., 2018. Energy access: pathway to attaining sustainable development in Africa. Int. J. Energy Econ. Pol. 8 (6).

Otiso, K.M., Owusu, G., 2008. Comparative urbanization in Ghana and Kenya in time and space. Geojournal 71 (2–3), 143–157. https://doi.org/10.1007/s10708-008-9152-x.

Owusu, A.B., Mensah, C.A., Blay, J., Fynn, I.E.M., 2023. Urban growth and land surface temperature dynamics: lessons from Ghana. Theor. Empir. Res. Urban Manag. 18 (3).

Owusu, G., Oteng-Ababio, M., 2015. Moving unruly contemporary urbanism toward sustainable urban development in Ghana by 2030. Am. Behav. Sci. 59 (3), 311–327. https://doi.org/10.1177/0002764214550302.

Rode, P., Keim, C., Robazza, G., Viejo, P., Schofield, J., 2014. Cities and energy: urban morphology and residential heat-energy demand. Environ. Plann. Plann. Des. 41 (1), 138–162. https://doi.org/10.1068/b39065.

Román, M.O., Stokes, E.C., Shrestha, R., Wang, Z., Schultz, L., Carlo, E.A.S., Sun, Q., Bell, J., Molthan, A., Kalb, V., Ji, C., Seto, K.C., McClain, S.N., Enenkel, M., 2019. Satellite-based assessment of electricity restoration efforts in Puerto Rico after Hurricane Maria. PLoS One 14 (6), e0218883. https://doi.org/10.1371/journal.pone.0218883.

Romero Lankao, P., Wilson, A., Sperling, J., Miller, C., Zimny-Schmitt, D., Bettencourt, L., Wood, E., Young, S., Muratori, M., Arent, D., O'Malley, M., Sovacool, B.K., Brown, M.A., Southworth, F., Bazilian, M., Gearhart, C., Beukes, A., Zünd, D., 2019. Urban electrification: knowledge pathway toward an integrated research and development agenda. SSRN Electron. J. https://doi.org/10.2139/ssrn.3440283.

Ronneberger, O., Fischer, P., Brox, T., 2015. U-net: convolutional networks for biomedical image segmentation. In: Navab, N., Hornegger, J., Wells, W.M., Frangi, A.F. (Eds.), Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015, vol. 9351. Springer International Publishing, pp. 234–241. https://doi.org/10.1007/978-3-319-24574-4_28.

Santamouris, M., Cartalis, C., Synnefa, A., Kolokotsa, D., 2015. On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—a review. Energy Build. 98, 119–124. https://doi.org/10.1016/j.enbuild.2014.09.052.

Satterthwaite, D., 2017. The impact of urban development on risk in sub-Saharan Africa's cities with a focus on small and intermediate urban centres. Int. J. Disaster Risk Reduct. 26, 16–23. https://doi.org/10.1016/j.ijdrr.2017.09.025.

Schiavina, M., Freire, S., Carioli, A., MacManus, K., 2023. GHS-POP R2023A - GHS Population Grid Multitemporal (1975-2030). Joint Research Centre (JRC), European Commission. https://doi.org/10.2905/2FF68A52-5B5B-4A22-8F40-C41DA8332CFE.

Silver, J., 2015. Disrupted infrastructures: an urban political ecology of interrupted electricity in Accra. Int. J. Urban Reg. Res. 39 (5), 984–1003. https://doi.org/10.1111/1468-2427.12317.

Stokes, E.C., Seto, K.C., 2019. Characterizing urban infrastructural transitions for the Sustainable Development Goals using multi-temporal land, population, and nighttime light data. Rem. Sens. Environ. 234, 111430. https://doi.org/10.1016/j.rse.2019.111430.

Stone, B., 2008. Urban sprawl and air quality in large US cities. J. Environ. Manag. 86 (4), 688–698. https://doi.org/10.1016/j.jenvman.2006.12.034.

UN-DESA, 2019. World Urbanization Prospects: the 2018 Revision.

Yakubu, I., 2021. From a cluster of villages to a city: housing politics and the dilemmas of spatial planning in Tamale, Ghana. Land Use Policy 109, 105668. https://doi.org/10.1016/j.landusepol.2021.105668.

Yeh, C., Perez, A., Driscoll, A., Azzari, G., Tang, Z., Lobell, D., Ermon, S., Burke, M., 2020. Using publicly available satellite imagery and deep learning to understand economic well-being in Africa. Nat. Commun. 11 (1), 2583. https://doi.org/10.1038/s41467-020-16185-w.

Zhou, Y., Li, X., Chen, W., Meng, L., Wu, Q., Gong, P., Seto, K.C., 2022. Satellite mapping of urban built-up heights reveals extreme infrastructure gaps and inequalities in the Global South. Proc. Natl. Acad. Sci. 119 (46), e2214813119. https://doi.org/10.1073/pnas.2214813119.