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A geospatial perspective on electrification strategy in urbanizing Africa

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ABSTRACT

Efforts to achieve Sustainable Development Goal (SDG) 7, to ensure modern energy for all, have largely followed models of rural electrification premised on extending the provision of electricity to remote, low-income populations. Yet, urbanization in Africa has produced complex and densifying human settlement patterns with diverse economic and energetic needs. Much of the body of work supporting SDG 7 relies on a binary rural-urban categorization and has yet to engage critically with the increasing spatial, demographic, and economic heterogeneity of these spaces. This analysis uses geospatial techniques to evaluate the distribution of the unelectrified in sub-Saharan Africa along a 30-category spatial framework which describes space along a rural-urban continuum. Our results highlight large concentrations of unelectrified people in the peripheries of small to medium cities, which themselves are often poorly electrified. More sophisticated ways of understanding the spatiality of electrification can provide strategic insights on how we assess the needs and barriers to access for diverse communities, select and innovate appropriate technologies and solutions, and define effective jurisdictions for government institutions.

1. Introduction

The uneven coverage of affordable, reliable, and adequate electricity services across human societies undermines efforts to improve livelihood opportunities, health, education, gender equality, and other dimensions of global poverty (Sovacool, 2012). Globally, 670 million lack any form of access to electrical energy, with sub-Saharan Africa (SSA) comprising 85 % of the unelectrified population (IEA, IRENA, UNSSD, World Bank, and WHO, 2023). Within SSA, the majority (470 million) of those lacking access are considered rural, and a persistent urban-rural divide is commonly cited as a key challenge to achieving Sustainable Development Goal (SDG) 7 "to ensure access to affordable, reliable, sustainable, and modern energy for all" (Babayomi et al., 2023; IEA, 2023). From a spatial perspective, interventions to address access deficits have focused around two paradigms: one focused on leveraging off-grid technology to service sparsely-populated, low-earning rural populations, and another which has sought to extend central grids to dense urban pockets (Fall et al., 2008; Guillou & Girard, 2022; Rutherford & Coutard, 2014).

The existing literature dedicated to characterizing inequalities in access to electricity does not critically engage with the heterogeneity of "rural" and "urban" as spatial categories. Studies examining electrification policy, technology selection, economic impact, and governance rely conceptually and empirically on a binary rural-urban distinction without due attention to the effects of rapid and widespread urbanization on the African continent and how they are fundamentally reshaping human settlement and energy use patterns (Acheampong et al., 2021; Akbas et al., 2022; Gamette et al., 2024; Sarkodie & Adams, 2020; Trotter, 2016). Between 1950 and 2015, Africa's urban population grew by 2000 % (OECD/SWAC, 2020). Existing cities have significantly expanded beyond their formal administrative barriers, often merging with new towns and cities in densifying "rural" areas. The majority of new urban growth has happened in informal, self-built communities (Fox, 2014). An OECD study recorded the "existence of hundreds of urban agglomerations that are not recorded in official statistics, in areas generally considered to be rural," some of which have more than one million inhabitants (OECD/SWAC, 2020). Across these spaces that defy a clear rural or urban distinction, a burgeoning body of literature is calling attention to inequitable access electricity (Fall et al., 2008; Karekezi & Majoro, 2002; Kersey et al., 2023; Mahumane & Mulder, 2022; Singh et al., 2015). Electrification research must be more attentive to the spatial nuances of urbanization, else it risks perpetuating planning models that fail to address the needs of the growing population in these transitional spaces.

Despite innovations in remote sensing techniques, particularly around detecting nighttime lights which have allowed researchers to track electricity access rates at increasing resolutions and frequencies (Falchetta et al., 2019, 2020; Min et al., 2024), limited empirical work

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has sought to understand access patterns as they relate to the demographic and spatial dynamics of large-scale urbanization. Yet, there are clear strategic implications at this intersection for academic and practitioner audiences working across multiple sustainable development sectors (Cattaneo et al., 2021; Satterthwaite & Tacoli, 2002). Urbanization produces significant changes in the socioeconomic fabric of communities. Agglomeration economies arise in areas of increasing population densification and can drive economic diversification and more efficient provision of services (Nkalu et al., 2019). These benefits accrue not only to those living in densifying urban areas, but to a wider network of communities who can commute to access emerging opportunities, services, and other resources (Satterthwaite & Tacoli, 2002). Energy is essential to these processes. When electricity is supplied in sufficient amounts, at high quality, and at an affordable cost, it can support low-carbon, sustainable development in these emerging economies (Kersey & Koo, 2024).

The analytical objective of this article is to explore how energy access deficits – specifically access to electricity – are spatially manifesting amid sustained urbanization in SSA. Towards this end, we present the results of geospatial analysis which describes the distribution of SSA's unelectrified population across a 30-category spatial framework called the Urban Rural Catchment Area (URCA). Published by Cattaneo et al. (2021), the URCA framework describes space as catchment areas based on the commute time to the nearest urban point of reference (Cattaneo et al., 2021). URCA allows for patterns of infrastructure (in)access to be seen in relation to the demographic and economic shifts that are constitutive of urbanization. With these insights, we comment on how a predominantly rural-urban framing has hindered how we understand the energy access challenges of diverse communities. We suggest that frameworks like URCA can provide strategic direction in how to evaluate technical and economic solutions, allocate resources, structure institutional responsibilities, model technoeconomic interventions, and strategically target appropriate interventions.

2. Literature review

2.1. Urbanization and access to basic infrastructure

Urban expansion has proceeded rapidly in SSA. Between 1950 and 2015, Africa's urban population grew from 27 million to 567 million; African cities are expected to absorb an additional 950 million people by 2050 (OECD/SWAC, 2020). Past decades have seen growth in the number of cities across all size categories, with towns growing into small cities, cities growing into large metropolises, and so on. Much urban growth has been driven by *in situ* urbanization, where towns and cities spontaneously emerge in erstwhile "rural" zones. In terms of population distribution along the urban hierarchy, towns and small cities with between 20,000 and 250,000 inhabitants hold the largest percentage (29 %) of SSA's population. An additional 15 % live in a city of one million people or more, and 8 % live in an intermediate city with between 250,000 and one million inhabitants (Cattaneo et al., 2021). The urban periphery is also rapidly expanding in demographic significance. Roughly one-third (33 %) of SSA's population lives within 1 h travel time of a town or city, with the majority (20 % of total SSA population) clustered in the peripheries of towns and small cities (Cattaneo et al., 2021).

The concentration of energy poverty in urbanizing Africa is driven by a myriad of pull and push factors. Pull factors attracting villagers to nearby cities include more diverse jobs and higher wages, particularly in trade, services and industry. Cities also provide better healthcare, education, transportation, and social services, creating constant demand pressure for supporting infrastructures like electricity (Awumbila et al., 2016). Push factors include limited non-farm employment opportunities outside of urban agglomerations and environmental degradation, such as desertification and erratic rainfall. Political or social instability and conflict, in some geographies, also drive the spontaneous and unplanned displacement of large rural populations towards urban center (McAuliffe & Oucho, 2024).

Most of Africa's urban population growth is occurring in small and intermediate cities rather than in megacities like Lagos or Cairo, with 75 % of new urban residents settling in cities with populations between 100,000 and 1 million (OECD/SWAC, 2020). These secondary and tertiary cities, which serve as regional economic hubs, are experiencing rapid expansion but lack the infrastructure necessary to support their growing populations. Small cities (<100,000) may not be prioritized for grid extensions, resulting in high dependence on off-grid solutions like solar home systems or diesel generators. These may serve as first points of urban entry for rural migrants, many of which later move to slightly larger urban centers. While these medium-sized cities currently host the bulk of Africa's demographic transition, many medium cities experience land disputes due to unclear property rights, resulting in conflict between urban expansion and land tenure systems. Lastly, cities on the cusp of becoming major metropolitan areas contend with transport congestion and urban sprawl, complicating equitable service delivery and electrification efforts despite relatively high overall access rates (Lall et al., 2017).

Infrastructure services have not kept pace with urbanization in SSA. There are two key trends of note. First, informality is an overarching feature of urbanization. Much urban growth, particularly in peri-urban areas and just outside of cities, occurs informally and spontaneously. Yet, formal planning and investment have disproportionately prioritized central business districts and wealthier, planned neighborhoods, leaving informal settlements with marginal or nonexistent access to infrastructure. Because infrastructure planning tends to be reactive rather than proactive, expansion follows a fragmented, ad-hoc pattern, often implemented through piecemeal projects rather than comprehensive urban service planning. As a result, services such as electricity, water, and sanitation are extended unevenly, with gaps forming in rapidly growing areas. Recent studies have shown that larger cities tend to exhibit greater levels of inequality in infrastructure access, with well-served core areas and high-income districts coexisting alongside vast underserved informal settlements (Pandey et al., 2022). Work in informal settlements, in particular, has highlighted affordability and legal barriers as key drivers for non-connection to the electricity grid (Kersey et al., 2023; Singh et al., 2015).

Second, infrastructure services are generally less available in smaller cities and secondary urban centers. Large cities, despite their disparities, tend to have better overall infrastructure coverage relative to smaller urban areas, where local governments and utilities often lack the financial and technical capacity to expand services efficiently. Many small and intermediate cities, which are absorbing much of SSA's urban population growth, face critical gaps in electrification, piped water supply, and waste management. While some large cities benefit from donor-funded projects or national-level investment in infrastructure expansion, smaller cities frequently rely on limited municipal budgets and decentralized, informal service providers. As urbanization accelerates across the region, these gaps risk becoming more entrenched, reinforcing spatial inequalities in infrastructure access.

It is important to note that electrification is not binary, and lies along a spectrum. Even where a household may be connected to a grid or other power source, the reliability and quality of the power supplied calls into question the extent to which individuals are able to derive benefits from electricity (Ribot & Peluso, 2009). Frequent outages limit the economic potential electrification can bring to small businesses, while voltage levels below or above standard thresholds (typically ±10 % of 220–240 V in Africa) can fail to power devices plugged into outlets, accelerate their degradation, or even cause their spontaneous failure (Jacome et al., 2019). Other work has examined the prevalence of informal electricity service arrangements in low-income urban communities, and the limited nature of access they provide (Kersey et al., 2025). These factors, while not examined in this article, further complicate access to electricity for urban populations.

2.2. The rural-urban binary

The rural-urban binary – the assumption that there are clear, useful, and measurable differences between rural and urban spaces and people – remains deeply entrenched in development discourse and practice despite mounting evidence that these concepts are subjective, value-laden, and empirically inaccurate (Dymitrow, 2017; Rusta, 2018). These and other shortcomings of theorizing space in terms of a rural-urban binary have been exhaustively documented across a variety of disciplines, including geography, sociology, urban planning and economics (Baird, 2022). As early as 1918, Galpin et al. write that "rural and urban [are] vague and contradictory and [their] use should be discontinued for scientific work" (Galpin et al., 1918). Given the extensive and well-documented academic lineage of this critique, its treatment in this work is limited to a discussion of its practical implications for infrastructure planning and provision in sub-Saharan Africa. For a theoretical discussion of the topic, the authors direct readers to Hutchings et al. (2022), Baird (2022), Dymitrow and Brauer (2018), and Cloke and Johnson (2005).

The rural-urban binary construct for electrification presents logistical as well as conceptual challenges. Statistics on urbanization have long accounted for the unelectrified as a percentage of three categories: the urban population, the "rural residual," (a demographic accounting practice by which the rural population is determined as the difference between urban and national population estimates) and a national average of both. Table 1 shows the key limitations of a rural/urban spatial framing as they are relevant to infrastructure provision.

Table 1
Key limitations of a rural-urban binary for infrastructure provision.

Limitation	Description
Urban definitions lack comparability	Definitions of urban and rural vary significantly across countries and depend on a variety of factors such as population thresholds, economic structure, legal designation, and in some cases the presence or absence of public services such as telecommunications, water and sanitation (Cohen, 2004; Utzinger & Keiser, 2006). This variability makes international comparisons difficult if not meaningless for infrastructure planners rationalizing investments across a multi-country portfolio.
Reliance on outdated demographic data	The accuracy of rural/urban demographic accounting is reliant on national censuses of variable consistency, quality and recency. Given the expense and complexity of conducting censuses many countries in SSA use projections based on censuses conducted in the 1980s or 1990s, meaning that current rural/urban delineations are unlikely to capture the demographic shifts induced by sustained urbanization (Satterthwaite, 2010).
Subjectivity of urban boundaries	Given the implications of spatial delimitations on taxation, land rights, and claims to basic service provisions, administrative urban/rural boundaries are often reflective of ideological or political motives which serve to privilege certain groups more so than to accurately capture technical, geographical, or spatial characteristics relevant to infrastructure provision. Thus, the use of nationally-defined rural-urban boundaries in some cases can embed existing societal inequities within physical infrastructure (OECD/SWAC, 2020; Silver, 2015; Subbaraman et al., 2012).

2.3. Rural-urban continuum approaches

The concept of rural and urban as a continuum, rather than as bounded spaces, arose in the early 20th century in the social sciences as a response to mounting critiques of the binary paradigm (Hutchings et al., 2022). Various territorial approaches and frameworks have built on a continuum approach to highlight different aspects of spatial organization. Some have sought to understand the interactions of rural and urban areas in terms of linkages and flows, which allows for a focus on the interdependencies of these spaces, networked relational dynamics, and the movement of people, goods, services, and information (Tacoli, 1998; Yang et al., 2024). Other approaches have characterized space as sites of transition, employing concepts of the peri-urban interface, urban fringe, or urban periphery to describe zones of flux where urban expansion, shifting land use, and hybrid governance structures create overlapping rural and urban characteristics (Adam & Dadi, 2024; Adell, 1999).

Central place theory (CPT), developed by Walter Christaller in 1933, has arguably been the most influential of these theories (Christaller, 1933). CPT seeks to understand space as a catchment area around a central (urban) place of reference. CPT pushed the academic debate on the conceptualization of space in two key ways. First, it introduced a concept of an urban hierarchy as a proxy for understanding the types and breadth of goods and services available in and around a particular urban center. Second, it brought to the fore the concept of connectivity between an urban point and its surrounding countryside in terms of markets, labor, services, transportation and other tangible and intangible interactions.

It is only recently that the evolution of earth observation as a discipline and methodology has enabled continuum approaches to be operationalized at scale, introducing much-needed consistency, accuracy and nuance to spatial analysis. This has led to the development of novel frameworks such as the Index of Relative Rurality (Waldorf & Kim, 2018), the European Commission's Degree of Urbanization (European Commission. Statistical Office of the European Union, 2021), and other datasets like Open Buildings from Google which provide high-resolution insight into urbanization dynamics (Sirko et al., 2021). However, with some exceptions, their spatial extent and application has been primarily limited to the Global North.

Cattaneo et al. (2021) were among the first to take up the challenge of applying a continuum approach to issues of infrastructure services in low-income contexts. The approach uses GIS techniques to estimate travel distances from an urban point of reference over a gridded cost surface, producing a global database with 30 categories of urban-rural catchment areas (URCA) at a 1 km^2 resolution. Cattaneo et al.'s work identified that although small and intermediate cities and their catchment areas serve an outsized percentage of the global population, they face some of the most severe deficits in access to basic services. The URCA framework has already been used widely in the academic literature to make demographic dynamics visible (Hutchings et al., 2022), explore climate vulnerabilities (Malashock et al., 2022), assess the coverage of social infrastructure (Guo et al., 2024), and many other domains.

2.4. Spatializing SDG 7

While geospatial innovations in general have yielded significant interest and novel methods in electrification planning, the spatial implications of rapid and widespread urbanization on patterns of energy access has yet to receive critical engagement among the SDG 7 community (Falchetta et al., 2019; Korkovelos et al., 2022; Mentis et al., 2016, 2017). The dominant practice among authoritative sources or custodian agencies of electrification research, data, and finance, like the World Bank's Energy Sector Management Assistance Program (ESMAP), to the International Renewable Energy Agency (IRENA), and the International Energy Agency (IEA), is to track progress towards electricity access along a rural-urban binary (Hirmer et al., 2024). A key consequence of this consensus is the portrayal of energy poverty as a largely rural phenomenon; of the 603 million estimated as unelectrified in SSA, 78 % are designated as rural with an overall rural electrification rate of 28 % (IEA, 2023).

High resolution spatial datasets generated using remotely sensed data to describe access to electricity and consumption of energy across the continent remain largely delineated using rural and urban boundaries. This occurs in model development, communication of findings, or statistical inference, neglecting the rapidly shifting human geography across and around these boundaries. Energy system planning models produced by researchers and practitioners have largely reflected and reproduced this rough categorization, principally by incorporating some level of estimation or adjustment based on a priori designation of areas as rural or urban (Kemausuor et al., 2014; Korkovelos et al., 2019; Mentis et al., 2017; Ohiare, 2015). Demand estimation, in particular, is a key input to such models which suffers from a well-noted lack of empirical data and is thus sensitive to input assumptions (Lukuyu & Taneja, 2023). Despite this, many least-cost planning models build demand estimates based on a binary rural or urban spatial categorization.

Mentis et al. (2016), for example, apply an annual consumption estimate of 150 kWh per capita and 300 kWh per capita for rural and urban areas, assumptions which have carried into the OpeN Source Spatial Electrification Toolkit (ONSeTT) model and some applications of its World Bank offshoot like the Global Electrification Platform (Mentis et al., 2016). Other ways in which the rural-urban binary are parameterized within these models include as population growth rates, household population sizes, and assumptions around appropriate targets for access tiers (Egli et al., 2023). These assumptions have enormous influence on technology selection in electrification planning, specifically

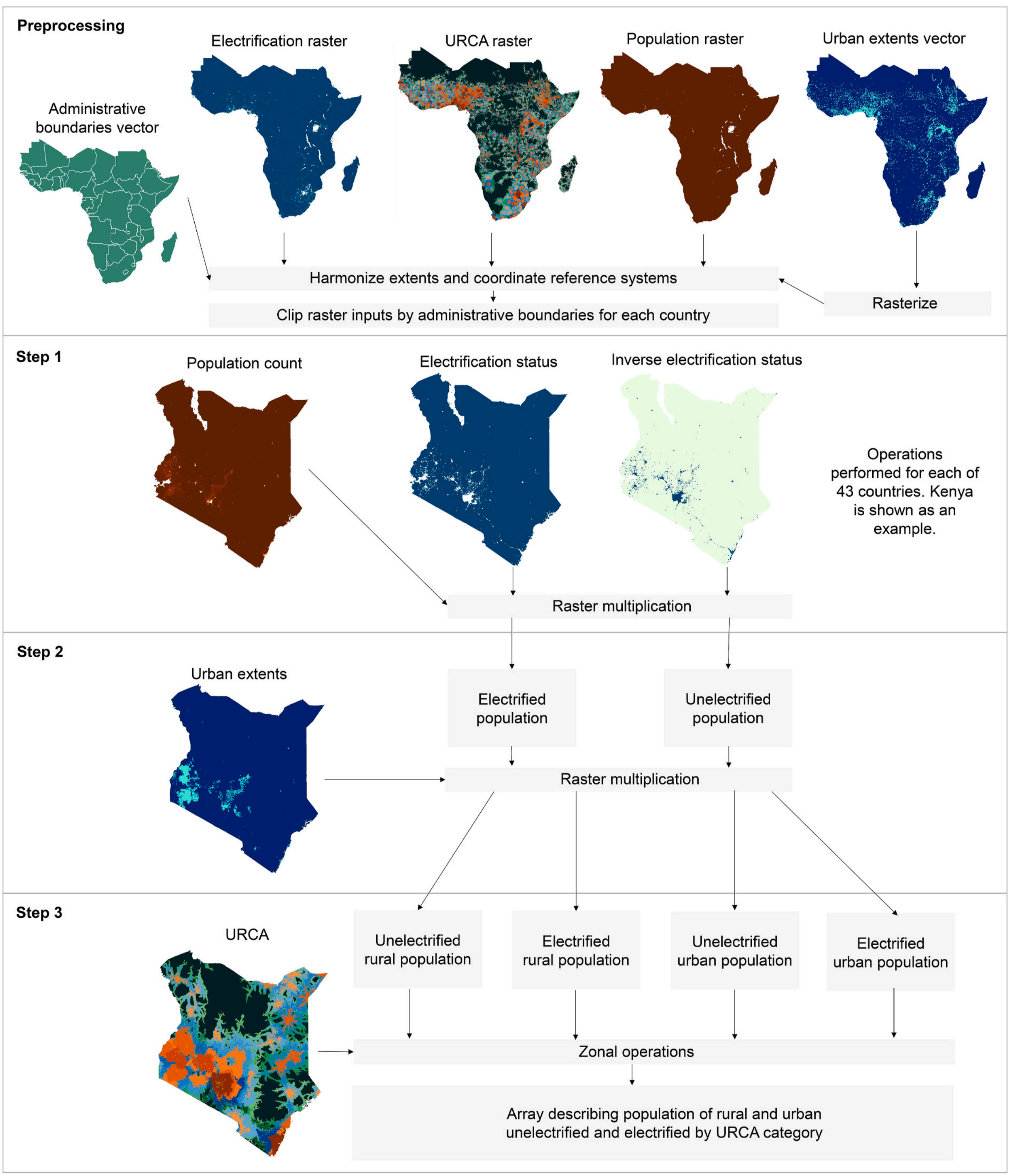

Fig. 1. Flow diagram of analytical process.

in driving the cost calculus for where to focus on extending traditional grids versus distributed energy technologies.

The predominant spatial framing of energy access as either rural or urban issues also has institutional and policy implications. Municipal governments are responsible for managing access to infrastructure services to populations within their "urban" administrative boundaries, while national rural electrification authorities tend to focus on more remote populations. The plight of the peri-urban and other inhabitants of ambiguous, mixed or transitioning spaces embody these challenges most starkly: as they cannot be neatly classified as rural or urban, these growing communities often fall through gaps created by fragmented institutional jurisdictions (Singh et al., 2015). There have also been examples of this framing being employed in racialized ways, such as in South Africa where predominantly black "rural" citizens are designated by policy for lower-capacity energy systems relative to adjacent "urban" areas (Monyei et al., 2018).

3. Methods

3.1. Analysis process flow

The main analytical task is to calculate and compare the distribution of the unelectrified and electrified populations in 43 sub-Saharan African countries along the 30-category URCA framework. The three-step analytical process is visualized in Fig. 1.

The first step involves harmonizing geospatial datasets, including population, electrification, and URCA data, and clipping them to national administrative boundaries. This step produces country-level layers counting up the unelectrified by multiplying, per pixel, estimated population and electrification rate. In the second step, we rasterize an urban extents vector dataset which identifies agglomerations with more than 10,000 people. We use this dataset to provide consistent "urban" and "rural" delineations in lieu of inconsistent and often unavailable country-level administrative boundaries. The third step involves using zonal operations to reclassify electrified and unelectrified populations allocated across the rural/urban split to one of 30 urban catchment categorizations. The result is an array describing the population of rural unelectrified, rural electrified, urban unelectrified and urban electrified within each of the 30 URCA categories. As these categories are mutually exclusive, each row sums to the total population of each country.

We complement our analysis by translating these findings to physical distance, which is a unit more readily understood by energy system planners and policymakers. At the level of each URCA category, we calculate the average distance between an unelectrified cell and the nearest electrified cell (by centroid) in kilometers (km). Similarly, we perform a hotspot analysis by calculating the number of unelectrified people within a 20 km radius of each of the nearly 6000 urban agglomerations in our urban extents database.

3.2. Datasets

Five geospatial datasets underlie this analysis: a population raster, an electrification status raster, the URCA raster, and a vector dataset identifying urban extents. Administrative boundaries to mask rasters based on national borders were sourced from the Database of Global Administrative Areas (Database of Global Administrative Areas, nd). Table 2 summarizes the source, type, spatial coverage, resolution, and temporal extent of each data input, and the following subsections provide further details on each. The population and electrification datasets were accessed through a collaboration with Atlas AI, and are based principally on predictive estimations trained on high resolution satellite imagery (Atlas, n.d.-a). A sample of the population and electrification rasters for the country of Kenya in 2015 are made available, along with the code supporting data analysis and visualization, in a public Github repository to enable replication of this study's results (Kersey, 2025).

Atlas AI's Population raster is a continent-wide dataset estimating the population (count and density) in human settlement locations at a grid resolution of 1 km^2. The gridded raster is a derived product, combining one or more of four similar population estimation products, to account for their respective strengths and limitations: Global Human Settlement Layer (GHSL) (Freire et al., 2016), the Gridded Population of World Version 4 (GPW4.11) (Center For International Earth Science Information Network-CIESIN-Columbia University, 2018), WorldPop (Tatem, 2017), and the High-Resolution Settlement Layer (Facebook Connectivity Lab, & Center for International Earth Science Information Network, 2016). Each of these is a statistical inference product, generated at different grid resolutions, time horizons, and instances, using machine learning and related methods. Atlas AI's harmonization process re-aligns the products to a common, globally consistent reference grid. The reconciliation process accounts for the presence of human settlements, control volumes calibrated to national, sub-national, and local census estimates, as well as consensus publications such as United Nations population projections. Interpolation and gap filling is used to fill in missing values in source estimates. The derived Atlas AI product is generated in time series format spanning 2000–2020, although we use 2015 estimates in this study for consistency with the other inputs.

Atlas AI's electrification access raster is a continent-wide dataset estimating the availability of electricity at a particular settlement location (i.e., the presence or absence of electrification) at a grid resolution of 1 km^2. At any moment in time, the electrification status is binary — either a settlement location is electrified, 'yes' (=1), or not, 'no' (=0). The main sensor-based input into the electrification product is Night Time Light (NTL) luminosity obtained from the Visible Infrared Imager Radiometer Suite (VIIRS) sensors aboard Suomi National Polar-orbiting Partnership (SNPP) satellite (CEOS, nd). The specific measurements

Table 2
Overview of the geospatial datasets used in this analysis.

Dataset	Description	Type	Spatial Coverage	Spatial Resolution	Temporal Extent	Source
Population	Provides the count of people (number)	Raster	African continent and India	1 km^2	2000–2020, 2015 used	(Atlas, n.d.-c)
Electrification status	Describes the presence (1) or absence (0) of electricity access	Raster	African continent and India	1 km^2	2012–2020, 2015 used	(Atlas, n.d.-b)
Administrative boundaries	National administrative boundaries	Vector	Global	–	2022	(Database of Global Administrative Areas, n.d.)
Urban rural catchment area (URCA)	Assigns one of 30 categories to each non-urban grid cell based on travel time to the nearest urban center of reference	Raster	Global	1 km^2	2015	Cattaneo et al. (2021)
Urban extents	Provides the extent of urban agglomerations exceeding 10,000 people and containing no unbuilt spaces greater than 200 m	Vector	African continent	–	2015	OECD/SWAC (2020)

used are the visible band radiance provided by the Day/Night Band (DNB), which are available from stable sensor operations beginning in April 2012 with a base resolution of 15 arcseconds, translating to 463 m^2 at the equator. Of the many possible post-processed versions available, the Atlas AI product integrates the monthly cloud-free composites to maximize the likelihood of unobscured identification and non-zero luminosity measurement, while avoiding stray light interference (Elvidge et al., 2009). The electrification data production pipeline further post-processes the monthly composites to account for stray light, atmospheric distortions, or measurement error such as negative luminosity values and extreme positive values through luminosity thresholding (see Falchetta & Noussan, 2019 for the importance of thresholding) and masking (Falchetta & Noussan, 2019).

URCA is a global raster dataset developed by Cattaneo et al., 2021 to operationalize CPT. In the URCA dataset, each 1 km^2 grid cell is assigned to one of 30 URCA categories as shown in Table 3 (see Supplementary Information (SI) Table S1 for an extended description of the URCA categorization). URCA categories represent the estimated time needed to travel to the closest urban center of a particular population size. As an example of interpreting the URCA categories, category 10 corresponds to a place located less than 1 h's travel time from a city with 500,000 to 1 million inhabitants.

The calculation of travel time within URCA is based on a methodology developed by Weiss et al. (2015), which identifies the least-cost-path algorithm over a cost surface accounting for transport networks and modes, land cover data, and international borders (Weiss et al., 2018). Linking to CPT, travel time is a conceptual proxy for access to and cost of reaching services and economic opportunities. Cities are disaggregated by population size as a proxy for the breadth of available services and opportunities. When determining the urban center of reference for a particular grid cell, larger urban centers take precedence over smaller ones in the same travel time category. The URCA dataset was used in its original form with no modifications. We refer readers seeking further methodological detail or access to the original dataset to Cattaneo et al. (2021). Fig. 2 visualizes URCA at the scale of SSA.

As no comprehensive dataset of nationally-defined urban-rural administrative boundaries is publicly available, the Africapolis dataset from OECD/SWAC (2020) is used as a proxy (OECD/SWAC, 2020). This dataset cross-references national population statistics, satellite imagery, and geo-referenced maps to identify, merge, and polygonize clusters of densely populated 1 km^2 grid cells. Each polygon is then verified manually. Under this methodology, an agglomeration is defined as urban "if its population exceeds 10,000 people and its built environment contains no unbuilt spaces greater than 200 m". The dataset identifies 5822 unique urban settlements in SSA with 430 million inhabitants.

4. Results

Fig. 3 shows the results of reclassifying the spatial distribution of SSA's population by electrification status along the URCA framework.

Table 3
URCA categorization.

Population threshold	Travel time to urban core				
	Within urban core	<1 h	1–2 h	2–3 h	>3 h
>5 million	1	8	15	22	29[a], 30[b]
1–5 million	2	9	16	23	
500,000–1 million	3	10	17	24	
250,000–500,000	4	11	18	25	
100,000–250,000	5	12	19	26	
50,000–100,000	6	13	20	27	
20,000–50,000	7	14	21	28	

[a] Dispersed towns are agglomerations of at least 5000 inhabitants which are more than 3 h travel time from any other urban point of reference.
[b] Hinterlands are individual grid cells which are more than 3 h travel time from any urban point of reference.

We draw attention to three key trends: i) the most remote areas (URCA 29 and 30) contain only 5 % of the total population and 8 % of the unelectrified, ii) a majority of the unelectrified in SSA live in areas within a 1-h travel time of an urban agglomeration (URCA 8–14), these areas represent 47 % of the total population, but an outsized 57 % of the unelectrified, and iii) cities of 100–250,000 inhabitants and their peripheries are important nodes of electricity access deficits. These areas (URCA 12 and 19) hold 28 % of the unelectrified, amounting to 184 million people. We direct readers to SI Fig. S1 and Table S2 for a national-level breakdown of unelectrified populations by rural or urban designation. Fig. S2 in the SI presents the distribution of populations by electrification status at the national level for five example countries.

To comment on urban hierarchy, electrification rates are high in cities with populations above one million inhabitants but fall off sharply as the population threshold decreases. In cities with populations greater than one million (URCA 1–3) the electrification rate is 96 %, compared to 64 % for cities of 50,000 to 100,000 inhabitants (URCA 6), and 54 % for the smallest agglomerations of 20,000 to 50,000 inhabitants (URCA 7). These trends are mirrored moving into the urban periphery. Electricity access rates drop moving in the immediate outskirts of larger cities, but are much lower in areas surrounding less populous towns and cities.

Cities of an intermediate size range and their immediate catchment areas hold the majority of SSA's unelectrified. Fig. S3 in the SI re-orders the URCA framework to group categories by the population range of the city of reference. It shows the unelectrified population in each URCA category, and their distribution among six reference countries (the Democratic Republic of the Congo (DRC), Ethiopia, Kenya, Nigeria, Tanzania, and Uganda). These six reference countries account for 61 % of SSA's access deficits. This allows an interpretation of the results that provides insight into where access deficits are clustered in terms of urban hierarchy. Electricity access deficits are largest in absolute terms in the catchment areas of cities with between 50,000 and 500,000 inhabitants. Cities with between 100,000 and 250,000 inhabitants and their catchment areas specifically hold 132 million electrified people — 31 % of SSA's unelectrified.

Further disaggregating results by the six reference countries, Fig. 4 highlights how electricity access deficits are distributed across the URCA framework at the country level. Fig. S4 in the SI visualizes the results spatially in terms of unelectrified population density averaged across each URCA category. These ways of visualizing the results also call attention to a large concentration of unelectrified people that live within 1 h of a city or town (URCA 8–14). Nigeria is heavily represented in these categories. We estimate that 75 % of Nigeria's 116 million unelectrified live within an hour of a city or town with more than 100,000 inhabitants (URCA 8–12). Only 10 % of the country's unelectrified live in more remote areas.

Fig. 5 shows the cumulative percentage of the total unelectrified population for all 43 countries moving from the most "urban" category (URCA 1) to the most remote (URCA 30). The sharp upticks in the 1-h catchment area of a city or town (URCA 8–14) provide further evidence for the argument that a large concentration of the unelectrified live in the immediate vicinities of the continent's many growing cities and towns. For example, in Nigeria, 90 % of the unelectrified population live in a city or in its 1-h catchment area.

However, country-level results also show significant diversity in how the unelectrified population is distributed across the URCA framework. While Nigeria represents the general trend of the unelectrified being disproportionately clustered around the peripheries of cities, countries like Mauritania, Gabon, Republic of Congo, and the DRC represent the other end of the spectrum. In these countries, 50–60 % of the unelectrified populations reside in URCA 30, which represents areas further than 3 h from any urban point of reference. This distributional heterogeneity helps highlight outliers; in the DRC, for example, the spread of unelectrified across all levels of remoteness suggest strategies are needed that diverge from the rest of the continent. In the context of

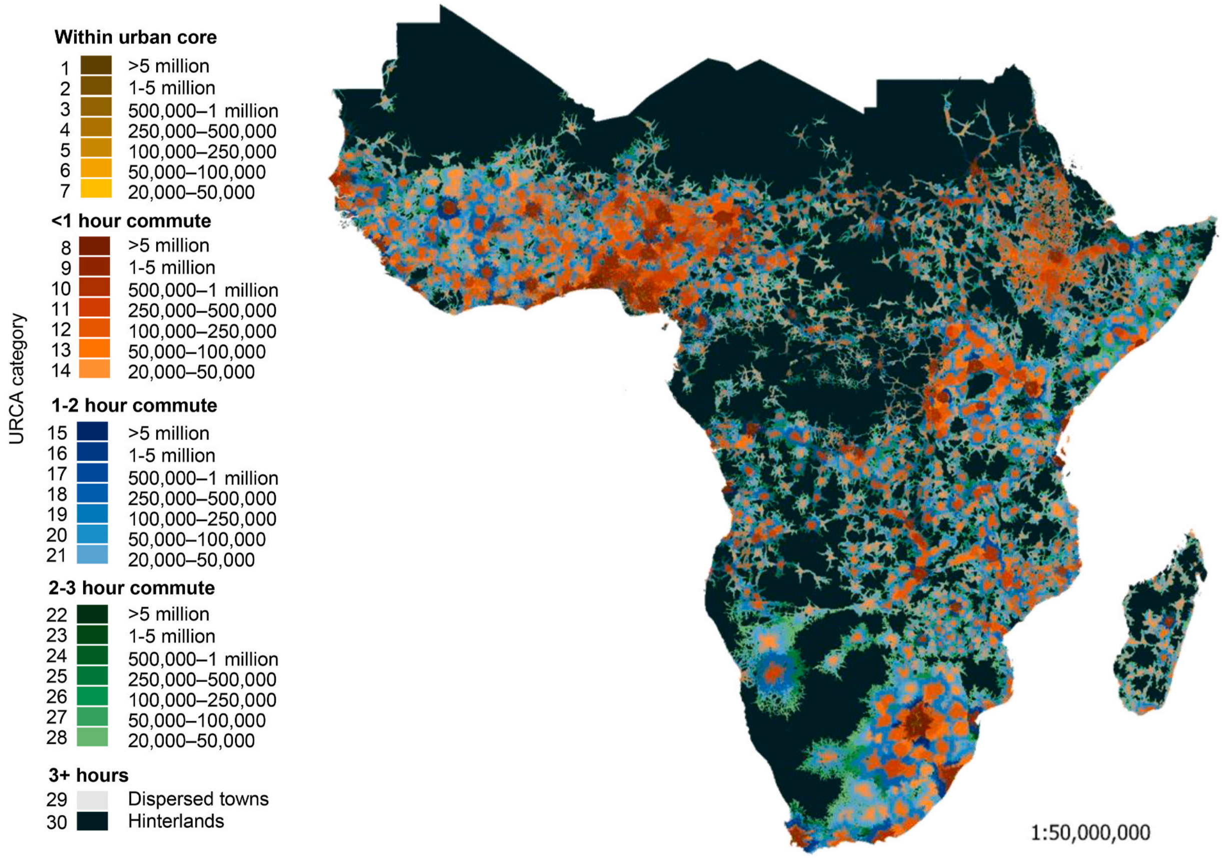

Fig. 2. Visualization of URCA dataset in SSA.

multi-country investment funds for infrastructure, such trends help highlight the need for comparable methodologies for developing country-specific strategies tailored for the socio-demographic specificities of distinct geographies at sub-regional scales (Mulugetta et al., 2022).

It is helpful to understand how the URCA categories translate to physical distance. The distance of unelectrified populations from existing urban centers is more intuitive, and is also relevant because of its usefulness to energy system planning (e.g. cost estimations based on estimates per linear kilometer of grid extension). Fig. 6 shows distance in km between unelectrified grid cells of each URCA category to the nearest electrified cell, providing insight into distribution of remoteness and access to electricity in SSA overall and the six representative countries. As a supporting analysis, Fig. S5 in the SI shows the electrification rate within 5, 10, 20, 30, and 50 km radium from urban reference points.

This view of the distribution of the continent's unelectrified population shows, at a continental average and at the country-level, that much of the unelectrified population is physically close to an existing electrified settlement. Across SSA, we estimate that 29 % of the unelectrified population lives less than 5 km from an electrified area. In Uganda, Kenya, Nigeria, Tanzania, 60 %, 75 %, 60 %, and 48 %, respectively, of the unelectrified populations live within 10 km of an electrified area. Again, however, we observe important variations at the country level. In the DRC, a vast country with 67 million unelectrified distributed across remote communities, the average distance of unelectrified populations from electrified areas is nearly 50 km.

Zooming out to the scale of SSA, Fig. 7 shows the unelectrified population in 1,000s and the electrification rate within a 20 km radius of each urban agglomeration captured in the Africapolis database. This hotspot analysis reveals areas of concentrated electricity access deficits among coastal populations in West Africa along the Gulf of Guinea stretching from Benin and Togo to the Niger Delta, and arid inland agglomerations along the Niger-Nigeria border and Ethiopian highlands. In addition to these two large geographical blocks, deficits in the Great Lakes region of East and Central Africa are distributed across Kenya, Tanzania, Uganda, Rwanda, Burundi, and the DRC. Mbuji-Mayi, a city in central DRC, is also readily visible and noteworthy for its singularly high unelectrified population (around 3.3 million people) and low electrification rate.

5. Discussion

In contrast to entrenched narratives that have framed energy access as a challenge for predominantly "rural" and remote communities, our analysis suggests that – like other forms of poverty (Ravallion et al., 2007) – energy poverty may be urbanizing in SSA (Fall et al., 2008; Kersey et al., 2023; Mahumane & Mulder, 2022; Singh et al., 2015). Finding that 62 % of unelectrified people continent-wide live in or within an hour of a major urban center (URCA 1–14), we argue that energy access deficits are clustered in locations that might be better described as urban, urbanizing, or urban-proximate. The description of "remote" may at least be a more accurate descriptor for what is today commonly (and, as we argue, too often inaccurately) imagined as "rural". The central question for this discussion is: what are the strategic advantages of visualizing access patterns through the lens of urbanization?

We argue that understanding patterns of electricity access deficits in terms of urban proximity provides important insight into the nature of the access barriers faced by diverse populations across the rural-urban spectrum. Our findings are in line with existing work which has suggested that some of the most intractable access challenges lie with "rural" but urban-proximate populations that live at or near the grid edge (Lee et al., 2020). For the third (29 %) of SSA's unelectrified that live within 5 km of an existing grid, the availability of physical

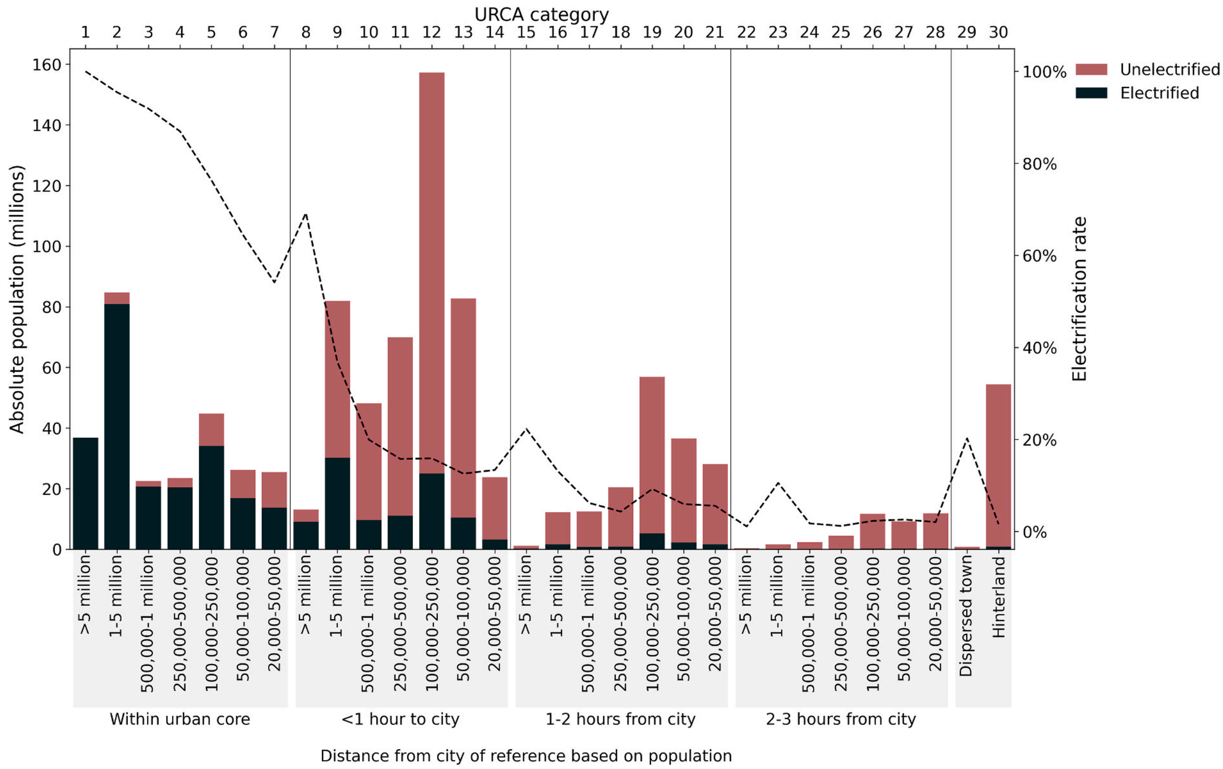

Fig. 3. Distribution of population and electrification rate across the URCA framework. The primary y-axis shows the total population of SSA by URCA category. The red bars correspond to the unelectrified population, and the black correspond to electrified. The dashed line of the secondary y-axis shows the electrification rate by URCA category. The x-axes represent the URCA categorization. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

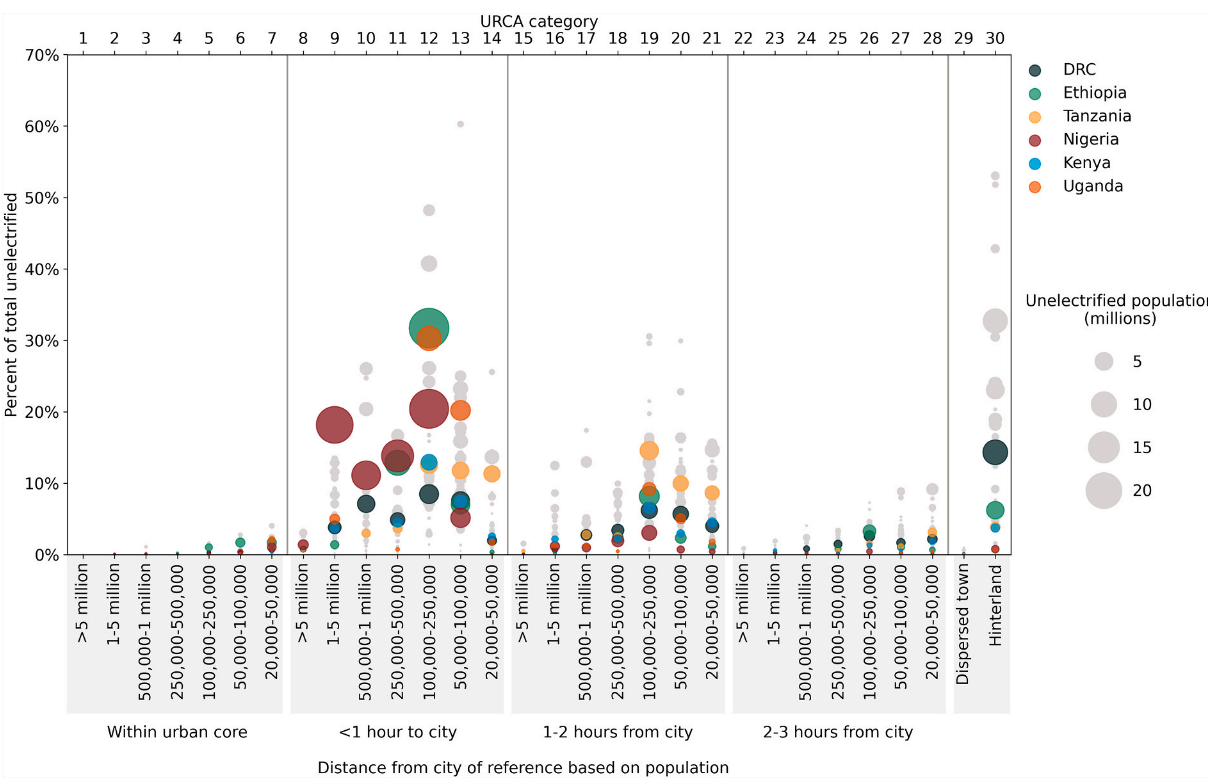

Fig. 4. Country-level visualization which highlights the electricity access deficits in the 1-h catchment zones. The y-axis represents the unelectrified population within each URCA category as a percent of the total unelectrified population in each country. The bubble size represents the unelectrified population it represents in real terms of (millions of people).

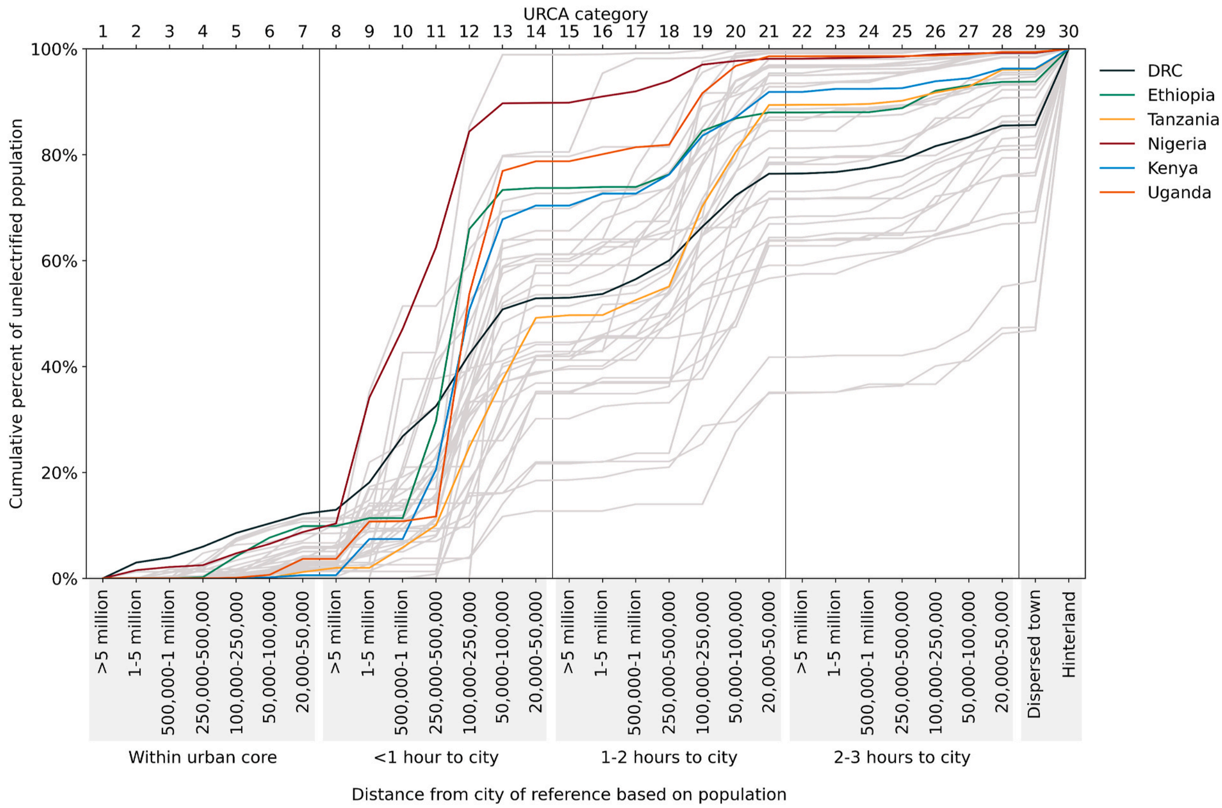

Fig. 5. Cumulative percent of the unelectrified population across the URCA framework.

infrastructure is not the primary driver of inaccess. Instead, issues like a high connection cost, the cost of domestic wiring, and cumbersome and exclusive legal requirements to register for a connection are more prominent barriers which require a fundamentally different type and structure of intervention (de Bercegol & Monstadt, 2018; Yaguma et al., 2024).

A spatial reorientation can also help identify areas where infrastructure investments should be targeted to have the largest impact on local economic development. Agglomeration dynamics reconfigure economic and energy landscapes, creating opportunities for electrification to support growth of emerging sectors like manufacturing, service, and trade in emerging cities and towns (Nkalu et al., 2019). Our results thus suggest that a larger share of electricity investments should target medium and small cities, where most of SSA's population and new economic activity is clustered and where our analysis reveals the largest electricity access deficits lie. This adds to a growing call to focus on cities on the lower end of the urban hierarchy for targeted support with infrastructure service provision (Cattaneo et al., 2021; Pandey et al., 2022; Satterthwaite & Tacoli, 2002, 2003). There is also a strong argument for electricity, among other basic services, to be strategically planned as a way to shape emerging urban forms to avoid inefficient patterns of human settlement like urban sprawl in favor of healthier, low-carbon urban development pathways (Foster & Briceno-Garmendia, 2010; Madlener & Sunak, 2011).

The use of a rural/urban binary in electrification discourse and planning may bias our conclusions about what types of technologies are appropriate for what types of spaces. Geospatial planning models like OnSSET are sensitive to input assumptions, particularly those around demand estimation which are highly spatially correlated (Agutu et al., 2022; Lukuyu & Taneja, 2023). Models that estimate demand based on an understanding of likely future growth and economic transition more accurately match the on-the-ground realities of ongoing urbanization. Integrating the URCA or similar frameworks could allow models to identify currently "rural" but emerging urban areas where growing economic activities could be supported by electrification. They could also incorporate relational insights. For example, they could prioritize higher-capacity systems in agglomerations that lie outside of the catchment area of larger cities.

The Ethiopian example in figure S4, for example, highlights relative proximity between lit and unlit cells. This might suggest the need for grid-interactive electrification scenarios that account equally for the large shares of unelectrified populations within and just beyond the reach of the existing (unreliable) grid's footprint, perhaps simultaneously expanding access while contributing to existing grid capacity and reliability. The spatial distribution of energy poverty in the DRC, on the other hand, is illustrative of large pockets of isolated, unelectrified population centers across the urban hierarchy, highlighting the "metro-grid" city electrification model emerging in the absence of national transmission and distribution networks (GEAPP, 2023). Existing least-cost electrification models — used to select electrification investments scenarios — provide limited insight into where and why these emerging operational models are appropriate, and typically only incorporate standalone photovoltaics, "rural village" mini-grid systems, or grid extension/densification.

Spatially-driven approaches like those highlighted in our results can also inform the evolution of institutional jurisdictions of the entities normally involved in electrification planning. In many countries in SSA, electrification planning is overseen by a government entity (most often a "Rural Electrification Agency") in coordination with an electricity sector regulator. These institutions are in most cases mainly concerned with the work of extending grid infrastructure into as-of-yet unelectrified "rural" places. Urban areas often are not emphasized, either because they are explicitly outside of the geographic focus or because they are considered to already be electrified because of the existence of the grid (Singh et al., 2015). Electricity is rarely within the purview or remit of municipal governments, though in many cases local institutions are the best positioned to understand and address infrastructure barriers within their administrative jurisdiction.

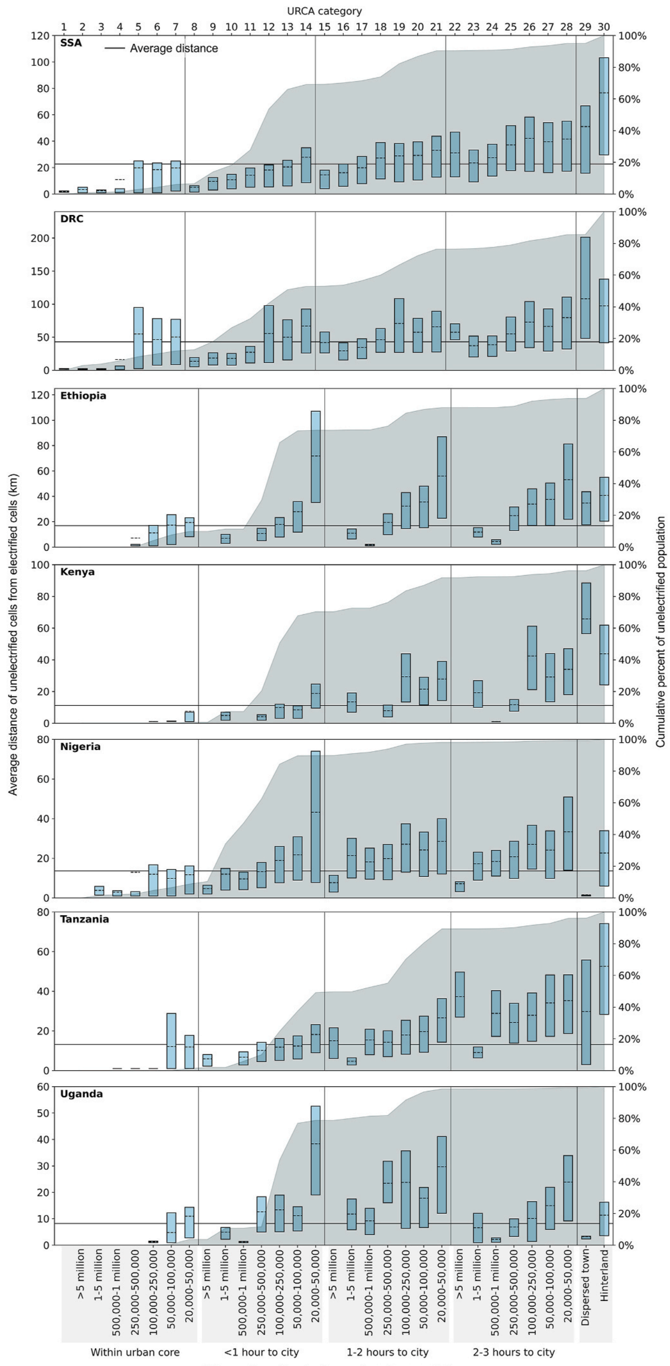

Fig. 6. Distribution of the distance of unelectrified grid cells from the nearest electrified grid cell, by country and URCA category. The gray area shows the cumulative electrification rate. The horizontal black line provides the average distance for each geography.

There is also evidence that certain populations like informal settlements, newly emerged towns and cities, and those in the growing urban periphery – which cannot easily be designated as rural or urban – fall between the cracks of jurisdictions and may not receive support from any planning entity (Singh et al., 2015). Certain institutions have begun to reflect this nuance, for example the DRC's "rural and peri-urban" electrification agency ANSER. In line with the SDG principle of leaving no one behind, it is crucial to spread learnings from such novel jurisdictional approaches to ensure recognition and distributional justice for urbanizing populations that too often fall through institutional cracks (Jenkins et al., 2021).

We close with a brief discussion of the limitations of our approach. First, we note that our input dataset may not fully represent the extent of electrification that has taken place through solar home systems and solar lighting products indetectable through satellite imagery. Electrification in denser, urban areas is likely overrepresented given that all urban residents may actually have access to or consistently consume electricity against the backdrop of street and urban lighting which creates a "halo" effect in luminosity measurements (Elvidge et al., 2009). Further, our study captures only one dimension of electricity access – the presence or absence of a connection providing light of sufficient intensity to be captured in nighttime lights imagery. The reliability, quality, and safety of power supply are pressing challenges for otherwise "electrified" populations but cannot be accounted for in our analysis. Emerging research has begun the task of developing remote monitoring and sensing techniques that provide large-scale visibility on these important dimensions of electricity access, but would benefit from the integration of frameworks like URCA to provide more nuanced, place-based insights (Falchetta et al., 2020; Miles et al., 2022).

6. Conclusion

A majority of the unelectrified are situated in the peripheries of the many urban centers which are emerging across the rich, multimodal landscape of urbanizing SSA. In light of this reality, we argue that the energy access discourse for SSA should move beyond the notion of 'rural electrification' as the provision of infrastructure to remote, unelectrified areas. In fact, most unelectrified communities are urban, urbanizing, or urban-proximate, with growing economies and the potential to expand access to resources, credit, and employment opportunities for large low-income populations (Satterthwaite & Tacoli, 2002). Understanding the potential for electrification in these regions to realize social and economic co-benefits, rather than collapsing them into the conceptually vague and heterogenous category of 'rural', allows for more efficient allocation of scarce resources to better target economic development and poverty alleviation.

A fruitful area of future research would be to employ frameworks like URCA to study changes in energy access patterns over time. Such a longitudinal approach would help further target key priority investment nodes, enable deeper understanding of the impacts of existing electrification efforts, and help scholars unpack how the provision of electricity and urban growth phenomena shape one another. Furthermore, the application of more precise boundaries can dramatically change modeling results and have significant consequences for targeted programs.

Our work reveals significant heterogeneity in the spatial distribution of unelectrified populations across SSA; meeting the diverse needs of an overall urban-trending population thus demands more than a generic approach to "rural electrification". We take care to note we do not argue for defunding rural programs, but rather a re-targeting of these to truly remote populations and a broader recognition that densifying agglomerations and fast-growing communities require increased consideration as an important entry point to sustainable urban development.

This has serious implications for how we think about universal electrification and calls for a reorganization of implementation strategies to serve diverse communities across the rural-urban spectrum more effectively. Commenting on the SDG 7 community of practice's focus on "rural" electrification, we echo a "need to pay greater attention to the relationship between the concepts we use and the 'reality' inadvertently drawn by those concepts" (Krzysztofik & Dymitrow, 2015). We call for energy access scholars, geographers, and infrastructure investor communities to imagine new institutions, initiatives, and collaborations that better spatially represent the energy needs and aspirations of Africa's increasingly urban population.

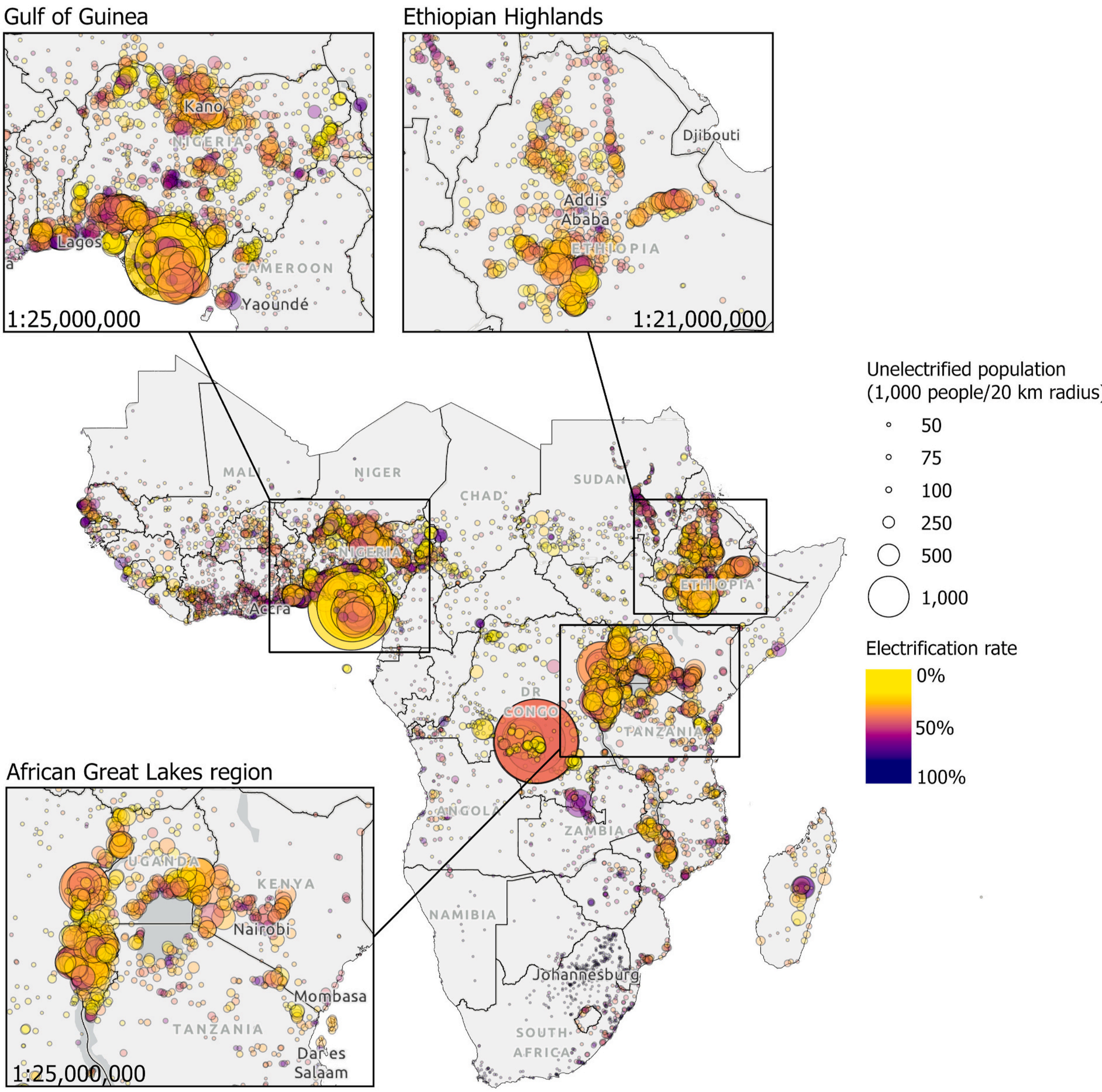

Fig. 7. Unelectrified population and electrification rate within 20 km of all 5832 urban agglomerations included in the Africapolis database.

CRediT authorship contribution statement

Jessica Kersey: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Samuel Miles:** Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Vivek Sakhrani:** Validation, Resources, Methodology, Formal analysis, Data curation. **Bryan Bonsuk Koo:** Writing – review & editing, Supervision, Resources, Investigation, Conceptualization. **Setu Pelz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Investigation, Data curation, Conceptualization.

Declaration of interest statement

The authors declare that they have no conflicts of interests that could potentially influence this research.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apgeog.2025.103647.

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