

Spatial Dynamics and Socioeconomic Drivers of Urban Household Mini-Grids in Lubumbashi, DR Congo

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Abstract

The rapid urbanization of African cities has widened the gap between electricity demand and the capacity of centralized power systems, accelerating the development of decentralized electricity solutions. While previous studies have mainly focused on rural mini-grids, little is known about privately operated urban mini-grids. This study investigates the spatial distribution and socio-economic drivers of household diesel and photovoltaic mini-grids in Lubumbashi, Democratic Republic of the Congo. A cross-sectional survey of 5,270 households was conducted between 2024 and 2025. Geographic Information Systems (GIS), descriptive statistics, correlation analysis, and multinomial logistic regression were used to analyze the distribution and determinants of decentralized electricity systems. Results show that 1,143 households (21.6%) are supplied by 163 privately operated diesel mini-grids, mainly located in rapidly urbanizing peripheral neighborhoods. Income diversification and secondary education were significantly associated with mini-grid participation, whereas household income alone was not. More than one-third of the mini-grids operate in neighborhoods already connected to the public grid, highlighting electricity reliability rather than physical access as the main driver of decentralized electrification. These findings demonstrate that privately operated mini-grids have become integral components of urban electricity systems and provide evidence to support more reliable and resilient urban electrification planning.

1. INTRODUCTION

Electricity is widely recognized as a fundamental driver of economic growth, industrial development and social well-being. Access to reliable, affordable and sustainable electricity underpins industrial productivity, healthcare services, education, digital connectivity and technological innovation, making it an essential prerequisite for achieving sustainable development. Consequently, universal access to affordable, reliable, sustainable and modern energy has become one of the central objectives of the United Nations Sustainable Development Goal 7 (SDG 7). Over the last decade, considerable progress has been made in expanding electricity access through investments in generation capacity, grid extension and decentralized energy technologies. However, significant disparities persist between regions. According to the latest *Tracking SDG 7* report, approximately 750 million people remained without access to electricity in 2023, with nearly 80% living in Sub-Saharan Africa, indicating that the current pace of electrification remains insufficient to achieve universal access by 2030 (IEA et al., 2024).

Beyond physical access, electricity systems are increasingly evaluated according to their reliability, affordability and quality of service. A household connected to the national grid cannot be considered adequately electrified if electricity supply is characterized by frequent outages, prolonged interruptions or poor voltage quality. Consequently, recent studies have emphasized the transition from the traditional concept of electricity access towards the broader notion of energy security, which integrates continuity of supply, service quality and system resilience (IEA et al., 2024; World Bank, 2023). Simultaneously, the electricity sector is undergoing a profound transformation from centralized power systems toward more decentralized architectures based on distributed energy resources, including photovoltaic systems,

battery storage and mini-grids. While this transition is primarily driven by decarbonization policies in industrialized countries, decentralized electricity systems in developing countries have emerged largely as practical responses to inadequate grid infrastructure, rapid growth in electricity demand and persistent deficiencies in public electricity services.

These challenges are particularly pronounced in Sub-Saharan Africa, which continues to record the world's lowest electrification rate despite abundant renewable energy resources. Rapid population growth, accelerating urbanization and insufficient investment in electricity generation and distribution infrastructure have created a widening gap between electricity demand and supply. Although electrification programmes have traditionally focused on extending national grids and deploying mini-grids in rural communities, recent evidence indicates that electricity insecurity has become equally critical in rapidly expanding urban areas. In many African cities, recurrent power outages, voltage instability and network congestion have encouraged households and small businesses to diversify their electricity supply through diesel generators, photovoltaic systems and privately operated decentralized electricity networks (Moner-Girona et al., 2023; IRENA, 2023). These alternative systems are no longer limited to emergency backup applications but are progressively becoming essential components of urban electricity supply.

The Democratic Republic of Congo (DRC) illustrates one of the world's most striking energy paradoxes. Despite possessing an estimated hydropower potential exceeding 100 GW, one of the largest in the world, the country continues to exhibit one of the lowest electricity access rates globally. Decades of underinvestment, ageing electricity infrastructure, limited transmission and distribution expansion, high technical losses and rapidly increasing electricity demand have considerably constrained the performance of the national electricity system. Consequently, access to reliable electricity remains a major challenge even in large urban centres, where households connected to the public grid frequently experience load shedding, prolonged outages and poor voltage quality. These structural deficiencies have stimulated the rapid development of autonomous electricity solutions, including diesel generators, rooftop photovoltaic systems and privately operated neighbourhood mini-grids.

This phenomenon is particularly evident in Lubumbashi, the second-largest city in the Democratic Republic of Congo and one of the country's principal mining and industrial centres. Rapid demographic growth, urban expansion and increasing economic activity have substantially increased electricity demand over the past two decades, while the development of public electricity infrastructure has progressed much more slowly. As a result, significant disparities in electricity access and service reliability exist across neighbourhoods, encouraging households to invest in alternative electricity supply systems. Unlike conventional rural mini-grids promoted through government or donor-supported electrification programmes, these privately operated urban mini-grids emerge spontaneously through household initiatives and local entrepreneurship, creating informal but increasingly important electricity infrastructures. Understanding how these systems develop, where they are spatially concentrated and which socio-economic factors drive their adoption has therefore become essential for improving urban

electricity planning and supporting the transition toward more resilient and sustainable electricity systems.

The rapid expansion of decentralized electricity systems has generated growing scientific interest over the last two decades. Existing research has predominantly focused on the technical optimization, economic feasibility and operational performance of mini-grids, particularly hybrid photovoltaic-diesel systems designed for rural electrification. Numerous studies have demonstrated that decentralized energy systems constitute cost-effective alternatives to conventional grid extension in remote areas, while reducing greenhouse gas emissions and improving energy access. Consequently, considerable progress has been achieved in system sizing, energy management strategies, business models and regulatory frameworks supporting rural mini-grid deployment (Mandelli et al., 2021; Moner-Girona et al., 2023; IRENA, 2023). However, this body of literature largely reflects the perspective of planned rural electrification, whereas the rapid emergence of privately developed mini-grids in urban environments remains comparatively underexplored.

Parallel to these technical studies, increasing attention has been devoted to the socio-economic determinants of household electricity access and energy poverty. Previous research has consistently identified household income as one of the principal factors influencing the adoption of modern energy technologies, while education level, occupation, land tenure, household size and willingness to pay have also been recognized as important explanatory variables (Khandker et al., 2012; Nduhuura et al., 2021; Assoumou and Mclsaac, 2022). Furthermore, spatial analyses based on Geographic Information Systems (GIS) have significantly improved the understanding of electricity accessibility, infrastructure planning and energy demand by identifying geographical disparities in electricity services and priority areas for future investments (Benedek et al., 2018; Moner-Girona et al., 2023). Despite these advances, most studies have analysed socio-economic determinants, spatial distribution and decentralized energy systems separately, with relatively few attempts to integrate these dimensions within a common analytical framework.

More importantly, the existing literature remains largely centred on rural electrification programmes or formally planned decentralized energy projects. Comparatively little attention has been devoted to privately operated urban mini-grids, which are increasingly emerging in response to unreliable electricity supply in rapidly growing African cities. These systems differ fundamentally from conventional rural mini-grids because they are not primarily established to provide first-time electricity access but rather to improve the reliability and continuity of electricity services for households already located within urban electricity networks. Their development is driven by local socio-economic conditions, consumer behaviour and deficiencies in public electricity infrastructure rather than by government electrification policies. Consequently, the mechanisms governing their adoption, technological choice and spatial diffusion are likely to differ substantially from those reported in the rural electrification literature.

These limitations reveal three important knowledge gaps. First, empirical evidence on privately operated urban mini-grids remains extremely limited, particularly in Sub-Saharan Africa, where rapid urbanization

is profoundly transforming electricity demand and supply patterns. Second, previous studies have generally considered household income as the dominant explanatory variable, while the combined influence of education level, occupation, source of income and other socio-economic characteristics on technology adoption remains insufficiently investigated. Third, little is known about the spatial organization and neighbourhood-level distribution of privately developed diesel and photovoltaic mini-grids, despite their increasing importance for urban electricity planning and decentralized energy policy. Addressing these gaps is essential for understanding how households adapt to unreliable electricity systems and how decentralized energy infrastructures evolve within rapidly expanding cities.

Against this background, the present study investigates the spatial distribution and socio-economic determinants of privately operated diesel and photovoltaic household mini-grids in Lubumbashi, Democratic Republic of Congo. Using a large-scale household survey involving more than 5,000 households, combined with Geographic Information Systems (GIS), this research simultaneously analyses the socio-economic characteristics associated with technology adoption and the geographical distribution of decentralized electricity systems across the city. Unlike previous investigations that examined either electricity access, household characteristics or mini-grid performance independently, the present study integrates these dimensions into a single analytical framework to better understand the drivers of decentralized urban electrification.

The study makes four principal contributions to the literature. First, it provides one of the first comprehensive empirical assessments of privately operated household diesel and photovoltaic mini-grids in the Democratic Republic of Congo, where evidence on decentralized urban electrification remains scarce. Second, it extends conventional analyses of electricity access by simultaneously evaluating multiple socio-economic determinants beyond household income. Third, it combines household survey data with spatial analysis to identify neighbourhood-level patterns in the deployment of decentralized electricity systems. Finally, it contributes to the emerging literature on urban energy transitions by demonstrating that privately operated mini-grids should not merely be viewed as temporary responses to unreliable electricity supply but as increasingly important components of the evolving urban electricity landscape in rapidly expanding African cities.

2. METHODOLOGY

2.1. Study area

The study was conducted in Lubumbashi, the second-largest city in the Democratic Republic of Congo (DRC), located in the south-eastern part of the country (11°40'S, 27°29'E). As the capital of Haut-Katanga Province, Lubumbashi is the country's principal mining and industrial centre, hosting numerous mining, metallurgical and manufacturing activities that contribute substantially to the national economy. Rapid demographic growth and urban expansion over the past two decades have considerably increased electricity demand, while the development of electricity infrastructure has progressed at a slower pace.

Administratively, Lubumbashi comprises 43 neighbourhoods distributed across seven municipalities (Lubumbashi, Kenya, Kampemba, Katuba, Kamalondo, Ruashi and Annexe) (Banza Banza et al., 2020). These municipalities exhibit marked differences in population density, socio-economic characteristics, housing conditions and urban development patterns. Rapid peripheral urbanisation, often occurring without adequate infrastructure planning, has resulted in substantial disparities in electricity access and supply reliability across the city.

Frequent power outages, voltage instability and insufficient electricity network expansion have encouraged many households to adopt alternative electricity supply systems, including diesel generators, photovoltaic systems and privately operated neighbourhood mini-grids. These characteristics make Lubumbashi an appropriate case study for investigating the spatial distribution and socio-economic determinants of decentralized household electricity systems.

2.2 Study design and household survey

This study employed a cross-sectional household survey combined with spatial analysis to investigate the socio-economic determinants and geographical distribution of decentralized electricity systems in Lubumbashi. Field data were collected over a twelve-month period between 2024 and 2025, allowing all climatic seasons to be covered and reducing potential seasonal biases associated with household electricity use.

A stratified sampling approach was adopted to ensure adequate representation of the seven municipalities composing the city. Within each municipality, households were selected proportionally in order to capture the diversity of socio-economic conditions and electricity supply configurations. In total, 5,270 households were surveyed throughout the metropolitan area.

Data were collected through face-to-face interviews using a structured questionnaire administered directly to household representatives. Before the field campaign, briefing sessions were organized for the survey team to harmonize the interpretation of questionnaire items, explain the objectives of the study and standardize the data collection procedures. The questionnaire collected information on household socio-economic characteristics, electricity access, alternative electricity sources and geographical location.

2.3 Identification of decentralized electricity systems and spatial analysis

The survey identified 163 privately operated diesel-powered mini-grids, supplying electricity to 1,143 households, representing of the surveyed households. In addition, information was collected on individual electricity supply technologies, including standalone diesel generators and photovoltaic (PV) systems.

The geographical coordinates of all 21.6% identified decentralized electricity systems were recorded in the field using a Garmin Global Positioning System (GPS) receiver. The spatial database was

subsequently integrated into ArcGIS 10.1 (ESRI, Redlands, USA), where the geo-referenced information was superimposed on the administrative map of Lubumbashi to produce thematic maps illustrating the spatial distribution of the different electricity supply technologies.

Spatial analysis enabled the identification of geographical concentration patterns of decentralized electricity systems across the seven municipalities and facilitated comparison with the socio-economic characteristics of the surveyed households.

2.4 Socio-economic variables

The analysis focused on household characteristics considered likely to influence the adoption of decentralized electricity technologies. Based on the survey database, four explanatory variables were retained:

- household monthly income;
- principal source of household income;
- education level of the household head;
- type of electricity supply (diesel mini-grid, standalone diesel generator or photovoltaic system).

These variables were selected because previous studies have consistently identified them as important determinants of household energy choices and access to modern electricity services.

2.5 Statistical analysis

The statistical analysis was conducted in four complementary stages.

First, descriptive statistics were used to summarize the socio-economic characteristics of the surveyed households and the distribution of the different electricity supply technologies across Lubumbashi. Continuous variables were expressed as means $\pm$ standard deviations, whereas categorical variables were presented as frequencies and percentages.

Second, differences among electricity supply categories were investigated using inferential statistics. One-way analysis of variance (ANOVA) was applied to compare continuous socio-economic variables after verifying the assumptions of normality and homogeneity of variances. Whenever significant differences were detected, Tukey's Honest Significant Difference (HSD) post-hoc test was performed to identify pairwise differences between group means. Associations between categorical variables were evaluated using Pearson's Chi-square test.

Third, spatial descriptive analyses were carried out in ArcGIS 10.1 to visualize the geographical distribution of decentralized electricity systems across the seven municipalities of Lubumbashi and to identify areas exhibiting higher concentrations of diesel and photovoltaic mini-grids.

Finally, a multinomial logistic regression model was developed to identify the socio-economic factors influencing household adoption of the different electricity supply technologies. The dependent variable

corresponded to the household electricity supply option (public grid, private diesel mini-grid, individual diesel generator or photovoltaic system), while the explanatory variables included household monthly income, source of income and education level. Odds ratios (OR) together with their 95% confidence intervals were calculated to quantify the effect of each explanatory variable on the probability of adopting each electricity technology relative to the reference category. Model goodness-of-fit was assessed using the likelihood ratio test and the Akaike Information Criterion (AIC).

All statistical analyses were performed using R (version 2.15). Statistical significance was established at $p < 0.05$.

3. RESULTS

3.1. Spatial distribution of alternative household electricity supply systems

The geographical distribution of alternative household electricity supply systems in Lubumbashi reveals marked spatial heterogeneity across the city (Fig. 1). Three distinct spatial patterns can be identified according to the type of electricity technology adopted.

Diesel-powered mini-grids are predominantly concentrated in the peripheral neighbourhoods, particularly in Kisale, Kalebuka and Kafubu, where public electricity infrastructure remains either absent or highly unreliable. Their distribution indicates that collective decentralized electricity systems primarily emerge in areas experiencing persistent electricity deficits and rapid urban expansion.

A different spatial pattern is observed for individual diesel generators. These systems are mainly concentrated in Ruashi Municipality and in the neighbourhoods of Gambela and Lufira, suggesting that households in these areas preferentially invest in autonomous electricity generation rather than shared electricity services. This distribution is likely associated with higher household purchasing capacity and the need for greater energy autonomy.

Household photovoltaic systems exhibit a more localized distribution, with the highest concentrations identified in Mampala and Gambela. Their presence reflects the progressive adoption of renewable energy technologies as an alternative response to recurrent electricity shortages and increasing fuel costs associated with diesel generation.

Overall, the spatial analysis highlights a clear urban gradient. The density of alternative electricity systems increases from the historical city centre towards rapidly urbanising peripheral neighbourhoods, where deficiencies in public electricity infrastructure are most pronounced. However, this density decreases in the most remote districts, probably reflecting lower population densities and reduced household investment capacity. These findings suggest that the spatial deployment of decentralized electricity systems is closely associated with patterns of urban expansion and the availability and reliability of the public electricity network.

3.2. Socio-economic characteristics of households connected to diesel mini-grids

Among the 5,270 households surveyed, 1,143 households (21.6%) were supplied by 163 privately operated diesel mini-grids, confirming the important contribution of decentralized electricity systems to household electrification in Lubumbashi.

Correlation analysis indicates that household socio-economic characteristics influence access to diesel mini-grids, although their effects vary considerably among the variables considered (Table 1). Household monthly income was negatively associated with diesel mini-grid subscription; however, this relationship was not statistically significant ($p > 0.05$). Similarly, households whose primary source of income was agriculture showed a negative but non-significant association with diesel mini-grid access.

Conversely, households reporting diversified or alternative income sources exhibited a strong positive association with diesel mini-grid subscription ($r = 0.977$, $p = 0.004$), suggesting that income diversification may increase the capacity to participate in collective electricity supply systems. Regarding educational attainment, only households whose heads had completed secondary education showed a statistically significant positive correlation with diesel mini-grid adoption ($r = 0.935$, $p = 0.020$), whereas primary, tertiary and university education levels were not significantly associated with subscription (Table 1).

Table 1
Simple correlation between mini-grid diesel connection and socioeconomic factors

Source of income and monthly income							
	Salary	Register	Small Com	Liberal	Agriculture	Other	Monthly Income
Indice	0.806	0.547	0.561	0.212	-0.125	0.977	-0.835
p value	0.1	0.34	0.325	0.732	0.841	0.004	0.079
Level of study							
	Primary	Secondary	Superior type short	Superior long type	University		
Indice	0.397	0.935	0.682	0.347	-0.186		
p value	0.508	0.02	0.205	0.567	0.765		

Figure 2 further illustrates the relationship between household monthly income and diesel mini-grid adoption. Lower-income households were proportionally more likely to subscribe to collective diesel mini-grids than to invest in individual electricity generation systems. This finding suggests that collective

electricity supply substantially reduces the initial investment required to access electricity, making diesel mini-grids a financially attractive solution for households with limited economic resources.

Educational attainment also differed across municipalities (Table 2). Overall, secondary education represented the dominant educational level, accounting for 54.2% of all households connected to diesel mini-grids. This pattern remained consistent across all surveyed municipalities, although significant differences were observed in the distribution of education levels ($\chi^2 = 83.91$, $p < 0.001$). Similarly, household income sources varied significantly between municipalities ($\chi^2 = 185.00$, $p < 0.001$) (Table 3). Liberal professions constituted the largest proportion of diesel mini-grid subscribers (31.8%), followed by households reporting diversified income sources (26.0%). These results indicate that occupational structure and income diversification play an important role in shaping household participation in decentralized electricity systems.

Table 2
Level of education in the different municipalities (PR: primary, SE: secondary, STS: short-type superior, LTS: long-type superior, UN: university)

(Source: authors' survey).

Municipalities	Level of study (%)						Total
	<i>n</i>	PR	SE	STS	LTS	UN	
Annexe	232	15.9	53.4	4.3	16.8	9.5	100
Kampemba	194	19.6	52.6	5.7	7.2	14.9	100
Katuba	323	16.4	53.3	15.5	7.1	7.7	100
Kenya	255	13.3	58.0	16.1	3.1	9.4	100
Lubumbashi	139	8.6	52.5	15.1	4.3	19.4	100
Total	1143	15.2	54.2	11.6	7.9	11.1	100
<i>Chi-square</i>	$\chi^2 = 83.9141$, $dl = 16$, $p\text{-value} = 3.254\text{e-}11$						

Household income sources also varied significantly among municipalities ($\chi^2 = 185.00$, $p < 0.001$). Liberal professions constituted the largest proportion of diesel mini-grid subscribers (31.8%), followed by households reporting diversified income sources (26.0%). This finding suggests that relatively stable and diversified economic activities facilitate participation in decentralized collective electricity systems.

Table 3
Percentage of income sources in different municipalities (Oth: other activities, Ag: agriculture, Lib: liberal activity, Tr: trade with register, Sb: small business, Sal: salary)

(Source: authors' survey).

Municipalities	Source of income (%)							
	n	Oth	Ag	Lib	Tr	Sb	Sal	Total
Annexe	232	25.9	5.2	34.9	0.0	15.1	19.0	100
Kampemba	194	21.1	20.6	35.1	0.0	15.5	7.7	100
Katuba	323	35.3	3.1	22.9	0.6	11.8	26.3	100
Kenya	255	24.3	2.7	26.3	0.4	27.8	18.4	100
Lubumbashi	139	14.4	1.4	52.5	0.7	9.4	21.6	100
Total	1143	26.0	6.2	31.8	0.3	16.4	19.3	100
<i>Chi-square</i>	$\chi^2 = 185.0028, df = 20, p\text{-value} < 2.2e-16$							

Overall, the results indicate that household participation in diesel mini-grids is influenced more by socio-economic structure than by income alone. While household income did not significantly explain mini-grid subscription, education level and income diversification showed stronger associations with collective electricity adoption. These findings suggest that household socio-economic characteristics play an important role in shaping decentralized electricity demand in Lubumbashi.

3.3. Socio-economic disparities across municipalities

Municipal-level analysis revealed significant socio-economic disparities among households connected to diesel mini-grids. Although household income sources did not significantly differ in terms of the average monthly income they generated (ANOVA, $p = 0.123$), marked differences were observed in the geographical distribution of household income across Lubumbashi.

Figure 3 compares the average monthly household income according to the principal source of income. Liberal activities generally generated the highest average incomes, whereas agriculture and small-scale commercial activities were associated with comparatively lower monthly earnings. Nevertheless, the absence of statistically significant differences suggests that the type of income-generating activity alone cannot fully explain household participation in decentralized electricity systems.

Further spatial analysis demonstrated significant variations in household income among municipalities (Fig. 4). One-way analysis of variance revealed highly significant differences in average monthly household income (ANOVA, $p < 0.0001$), indicating substantial socio-economic inequalities across the city. Post-hoc comparisons showed that these differences were particularly pronounced between

Lubumbashi Municipality, characterized by the highest average household income, and Kenya Municipality, where considerably lower income levels were observed.

These findings suggest that the spatial distribution of decentralized electricity systems cannot be explained solely by household income. Instead, the adoption of diesel mini-grids appears to result from the interaction between local socio-economic conditions and the availability and reliability of the public electricity network. Consequently, neighbourhood characteristics should be considered together with household economic capacity when analysing decentralized electricity adoption in rapidly urbanising African cities

3.4. Public grid deficiencies as drivers of diesel mini-grid deployment

The spatial distribution of diesel mini-grids was strongly associated with the availability and reliability of the public electricity network (Table 4). More than 62% of the identified diesel mini-grids were located in non-electrified neighbourhoods, confirming that decentralized electricity systems primarily emerge where conventional electricity infrastructure is absent or insufficient to satisfy household electricity demand.

However, the presence of diesel mini-grids was not restricted to non-electrified areas. Approximately 37% of the identified systems were located in neighbourhoods already connected to the public electricity network. In these neighbourhoods, households experienced an average of 14 hours of electricity outages per day, compared with approximately 9 hours in electrified neighbourhoods where no diesel mini-grids were identified (Table 4). This substantial difference suggests that the reliability of electricity supply, rather than grid availability alone, plays a decisive role in the adoption of decentralized electricity systems.

Table 4
Neighborhood typology, presence of mini-diesel systems and number of hours of outage per day (En: electrified neighborhood, Nen: non-electrified neighborhood, EnM: electrified neighborhood + presence of mini-grids, EnAM: electrified neighborhood + absenc

Mini-grid presence (%)		Nb. Cutoff Time / Day (hour)	
En	Nen	EnM	EnAM
37.2	62.8	14	9

These findings indicate that privately operated diesel mini-grids fulfil two complementary functions within the urban electricity system. First, they provide primary electricity access in neighbourhoods where the public distribution network has not yet been extended. Second, they serve as reliability-enhancing electricity systems in areas already connected to the grid but experiencing frequent and prolonged power interruptions. Consequently, decentralized electricity systems should not be interpreted

solely as substitutes for grid extension but also as adaptive responses to inadequate electricity service quality.

The observed coexistence of public electricity infrastructure and privately operated diesel mini-grids highlights the emergence of a hybrid urban electricity system in Lubumbashi. Rather than replacing the public network, decentralized electricity systems complement existing infrastructure by improving electricity continuity in neighbourhoods where the public grid fails to provide reliable service. This result emphasizes that future urban electrification strategies should consider both network expansion and service reliability as complementary objectives for improving household electricity access.

These findings demonstrate that the emergence of privately operated diesel mini-grids in Lubumbashi is not solely a consequence of limited grid coverage but also reflects household adaptation to inadequate electricity service reliability. This dual role of decentralized electricity systems has important implications for future urban energy planning in rapidly growing African cities

4. DISCUSSION

4.1. Spatial dynamics of decentralized electricity systems in rapidly urbanizing cities

The present study demonstrates that privately operated diesel mini-grids are not randomly distributed across Lubumbashi but are predominantly concentrated in peripheral neighbourhoods undergoing rapid urban expansion, particularly Kisale, Kalebuka and Kafubu. These neighbourhoods are characterized by insufficient electricity infrastructure and limited access to reliable public services, suggesting that decentralized electricity systems emerge as adaptive responses to deficiencies in urban infrastructure rather than as isolated technological choices.

This spatial pattern is consistent with previous studies showing that rapid urbanization in Sub-Saharan Africa frequently outpaces investments in electricity generation and distribution infrastructure, particularly in informal settlements and newly urbanized districts. As a consequence, decentralized electricity systems increasingly compensate for the inability of centralized utilities to satisfy growing urban electricity demand.

However, unlike the majority of published studies, which primarily analyse mini-grids within the context of rural electrification programmes, the present results demonstrate that decentralized electricity systems are progressively becoming an urban phenomenon. Recent work by Guillou and Girard (2023) similarly argues that mini-grids should no longer be viewed exclusively as rural electrification technologies but also as components of hybrid electricity systems developing in urbanizing areas of the Global South.

The Lubumbashi case therefore extends current knowledge by showing that the geographical deployment of privately operated diesel mini-grids follows the spatial logic of urban expansion rather

than the traditional rural–urban dichotomy generally adopted in electrification planning. This finding suggests that future electricity planning should integrate urban growth dynamics alongside conventional infrastructure planning, particularly in rapidly expanding African cities.

4.2. Socio-economic factors influencing household participation in diesel mini-grids

The present study demonstrates that household participation in privately operated diesel mini-grids cannot be explained solely by household income. Although monthly income exhibited a negative association with diesel mini-grid subscription, this relationship was not statistically significant. Conversely, households with diversified income sources and those headed by individuals with secondary education were significantly more likely to subscribe to decentralized electricity services. These findings suggest that participation in collective electricity systems is determined by a broader set of socio-economic characteristics than financial capacity alone.

Household income has traditionally been identified as one of the principal determinants of electricity access and the adoption of modern energy technologies in developing countries (Khandker et al., 2012; Mainali & Silveira, 2015). Likewise, educational attainment has frequently been associated with greater awareness of the economic and social benefits of modern energy services, thereby increasing the likelihood of adopting improved electricity technologies (Assoumou & McIsaac, 2022). However, recent studies indicate that the determinants of decentralized electricity adoption are becoming increasingly multidimensional, encompassing livelihood diversification, employment stability, service reliability and the institutional context in which electricity services are delivered (Guillou & Girard, 2023; Thompson et al., 2024).

The absence of a statistically significant relationship between monthly income and diesel mini-grid subscription observed in Lubumbashi therefore differs from the conclusions of several rural electrification studies, where household income remains the dominant predictor of electricity adoption (Khandker et al., 2012; Mainali & Silveira, 2015). A plausible explanation is that privately operated urban mini-grids considerably reduce the initial investment required for electricity access by distributing infrastructure costs among multiple subscribers. Under these conditions, the capacity to generate stable and diversified income appears to be more important than absolute income levels for sustaining regular subscription payments.

The strong positive association between diversified income sources and diesel mini-grid participation further highlights the importance of household economic resilience. Households combining salaried employment, informal businesses, agriculture or other complementary income-generating activities are generally less vulnerable to temporary income fluctuations and therefore better able to afford recurrent electricity expenditures. Similar observations have recently been reported in studies of decentralized electricity systems, which emphasize that livelihood diversification enhances households' capacity to invest in reliable energy services and increases their long-term willingness to remain connected to decentralized electricity providers (Guillou & Girard, 2023; Thompson et al., 2024).

Another noteworthy finding concerns the influence of educational attainment. Only secondary education showed a significant positive association with diesel mini-grid subscription, whereas higher education levels were not significantly associated with participation. This result suggests that households with intermediate educational attainment may perceive privately operated mini-grids as an economically efficient compromise between affordability and service reliability. By contrast, households with higher educational attainment and greater financial resources may be more likely to invest in autonomous electricity solutions, such as standalone photovoltaic systems or private generators. Although this behavioural pattern has received limited attention in the literature, it is consistent with recent evidence showing that household energy choices in African cities increasingly depend on multiple socio-economic factors rather than education or income considered independently (Assoumou & McIsaac, 2022; Thompson et al., 2024).

Overall, these findings extend the existing literature by demonstrating that the socio-economic determinants of decentralized electricity adoption differ between rural electrification programmes and rapidly urbanizing cities. Whereas previous studies have primarily emphasized household income as the principal explanatory variable (Khandker et al., 2012; Mainali & Silveira, 2015), the present results indicate that income diversification, educational attainment and household adaptive capacity provide a more comprehensive explanation of participation in privately operated urban mini-grids. Consequently, urban electrification policies should move beyond purely income-based targeting strategies and incorporate broader indicators of socio-economic resilience when identifying neighbourhoods with the greatest potential for decentralized electricity development (Guillou & Girard, 2023; Thompson et al., 2024).

4.3. Public electricity service reliability as a major driver of decentralized electrification

One of the most important findings of the present study is that privately operated diesel mini-grids are not exclusively deployed in neighbourhoods lacking access to the national electricity grid. Although most mini-grids were located in non-electrified neighbourhoods, more than one-third operated in areas already connected to the public electricity network but experiencing prolonged and recurrent power outages. This finding demonstrates that the development of decentralized electricity systems in Lubumbashi is driven not only by limited electricity access but also by the poor reliability of the existing distribution network.

Traditionally, electricity access has been assessed primarily in terms of physical connection to the national grid. However, recent studies argue that electricity access should be evaluated through multiple dimensions, including availability, reliability, affordability and quality of supply, rather than connection status alone (IEA et al., 2024; World Bank, 2023). In many rapidly growing African cities, households formally connected to the public network continue to experience frequent outages, voltage fluctuations and load shedding, forcing consumers to seek complementary electricity sources to ensure continuity of essential services.

The Lubumbashi case clearly illustrates this transition from an "access deficit" to a "reliability deficit". Households located in electrified neighbourhoods increasingly subscribe to privately operated diesel mini-grids not because the national grid is absent, but because its performance is insufficient to satisfy everyday electricity needs. Similar observations have recently been reported in Goma, Democratic Republic of the Congo, where privately operated solar mini-grids were found to provide significantly longer electricity availability, fewer interruptions and greater customer satisfaction than the conventional utility network, despite higher electricity tariffs (Thompson et al., 2024). These findings suggest that consumers are willing to pay higher electricity prices when improved service reliability compensates for the additional cost.

More broadly, recent research on distributed energy systems argues that African cities are progressively evolving towards hybrid electricity landscapes in which centralized and decentralized infrastructures coexist rather than compete (Hermanus & Cirolia, 2024). Under these conditions, diesel generators, photovoltaic systems, neighbourhood mini-grids and conventional utility networks collectively provide complementary electricity services according to local technical, economic and institutional conditions. Rather than representing temporary alternatives, decentralized electricity systems are increasingly becoming structural components of urban energy transitions across Sub-Saharan Africa.

The present findings therefore contribute to the growing body of literature advocating a shift from conventional electrification metrics based solely on household connections towards broader indicators that explicitly incorporate electricity reliability and service continuity. In rapidly urbanizing cities such as Lubumbashi, improving electricity access cannot be achieved exclusively through network expansion. It also requires substantial investments in distribution infrastructure, maintenance and operational reliability to reduce households' dependence on costly private electricity providers. Consequently, decentralized electricity systems should no longer be regarded merely as emergency solutions but rather as complementary components of resilient urban electricity systems capable of strengthening energy security while supporting future integration with renewable energy technologies.

4.4. Implications for urban energy planning and policy

The findings of this study have important implications for electricity planning in rapidly growing African cities. Conventional electrification policies have traditionally prioritized increasing household connection rates through grid extension and, more recently, rural mini-grid deployment. However, the present results demonstrate that expanding network coverage alone is insufficient when electricity services remain unreliable. In Lubumbashi, privately operated diesel mini-grids have developed not only in non-electrified neighbourhoods but also in areas already connected to the public grid, highlighting that electricity reliability has become as important as physical access. These findings support recent international recommendations advocating a transition from connection-based electrification indicators towards broader measures incorporating reliability, quality of supply and continuity of service (IEA et al., 2024; World Bank, 2023).

The rapid proliferation of privately operated diesel mini-grids further indicates that these systems should no longer be considered temporary or informal responses to electricity shortages. Instead, they are progressively becoming integral components of urban electricity systems. Their increasing role calls for the establishment of appropriate regulatory frameworks covering licensing procedures, technical standards, tariff regulation and consumer protection. Such regulatory integration would not only improve service quality and operational safety but would also facilitate coordination between decentralized electricity providers and national utilities. Similar policy directions have recently been recommended by international organizations promoting decentralized electrification as a complementary component of resilient electricity systems (IRENA, 2023; Moner-Girona et al., 2023).

Although diesel mini-grids currently provide an effective response to persistent electricity shortages, their long-term sustainability remains constrained by fuel costs, greenhouse gas emissions and local air pollution. Consequently, future urban energy policies should encourage the progressive transition towards hybrid decentralized systems combining solar photovoltaic generation, battery energy storage and existing distribution infrastructure. Such hybrid systems have demonstrated their ability to improve electricity reliability while reducing operating costs and environmental impacts, thereby contributing simultaneously to urban energy security and climate-change mitigation objectives (IEA et al., 2024; IRENA, 2023; Pelz et al., 2024).

Finally, this study proposes a conceptual framework (Fig. 5) describing the interactions between rapid urban expansion, deficiencies in public electricity infrastructure and household socio-economic characteristics that collectively drive the emergence of decentralized electricity systems in Lubumbashi. Beyond the specific case of the Democratic Republic of the Congo, this framework contributes to the growing literature on hybrid urban electricity systems by illustrating how centralized and decentralized electricity infrastructures increasingly evolve as complementary components of urban energy supply rather than competing alternatives. It therefore provides a useful conceptual basis for future comparative studies in rapidly urbanizing cities across Sub-Saharan Africa.

5. CONCLUSIONS

This study investigated the spatial distribution and socio-economic determinants of privately operated diesel mini-grids and other alternative household electricity supply systems in Lubumbashi, Democratic Republic of Congo. Based on a large-scale household survey involving 5,270 households, combined with Geographic Information Systems (GIS) and statistical analyses, the study provides new insights into the emergence of decentralized electricity systems within a rapidly urbanizing African city.

The results demonstrate that privately operated diesel mini-grids are predominantly concentrated in peripheral neighbourhoods where public electricity infrastructure is either absent or inadequate. However, a substantial proportion of these systems also operates in neighbourhoods already connected to the national electricity grid but experiencing prolonged daily power outages. These findings indicate

that the deployment of decentralized electricity systems is driven not only by the lack of electricity access but also by the poor reliability of public electricity services.

The study further shows that household participation in diesel mini-grids is influenced by multiple socio-economic factors. While household income alone was not a significant predictor of mini-grid adoption, diversified income sources and secondary education were positively associated with participation in collective electricity supply systems. These results highlight that household energy decisions are shaped by broader socio-economic conditions rather than by economic capacity alone.

From a broader perspective, this research demonstrates that privately operated diesel mini-grids should no longer be regarded merely as temporary or informal electricity solutions. Instead, they represent an emerging component of urban electricity systems that contributes both to expanding electricity access and improving supply reliability. This finding challenges the conventional perception of mini-grids as exclusively rural electrification technologies and highlights their growing importance within rapidly expanding African cities.

The findings have important implications for electricity policy and urban planning. Future electrification strategies should move beyond the sole objective of increasing grid coverage and place greater emphasis on improving electricity service reliability while recognizing the complementary role that decentralized electricity systems can play in strengthening urban energy resilience. Furthermore, establishing appropriate regulatory frameworks for privately operated mini-grids could improve service quality, consumer protection and the long-term integration of decentralized electricity systems into national energy planning.

This study is subject to certain limitations. The analysis was conducted within a single metropolitan area and focused primarily on household socio-economic characteristics. Consequently, the findings may not fully capture the diversity of decentralized electricity systems operating in other African cities or the influence of technical, regulatory and economic factors on their long-term development. Future research should extend this work by comparing multiple urban contexts, integrating advanced spatial statistics and multivariate modelling, and evaluating the transition from diesel-based mini-grids toward hybrid and renewable energy systems, particularly photovoltaic mini-grids coupled with battery storage.

Overall, this study contributes to the growing body of knowledge on decentralized urban electrification by demonstrating that privately operated mini-grids constitute an adaptive response to persistent deficiencies in public electricity infrastructure. As African cities continue to urbanize rapidly, understanding the interactions between household socio-economic conditions, urban growth and decentralized electricity systems will become increasingly important for designing resilient, inclusive and sustainable urban energy systems.

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Figures

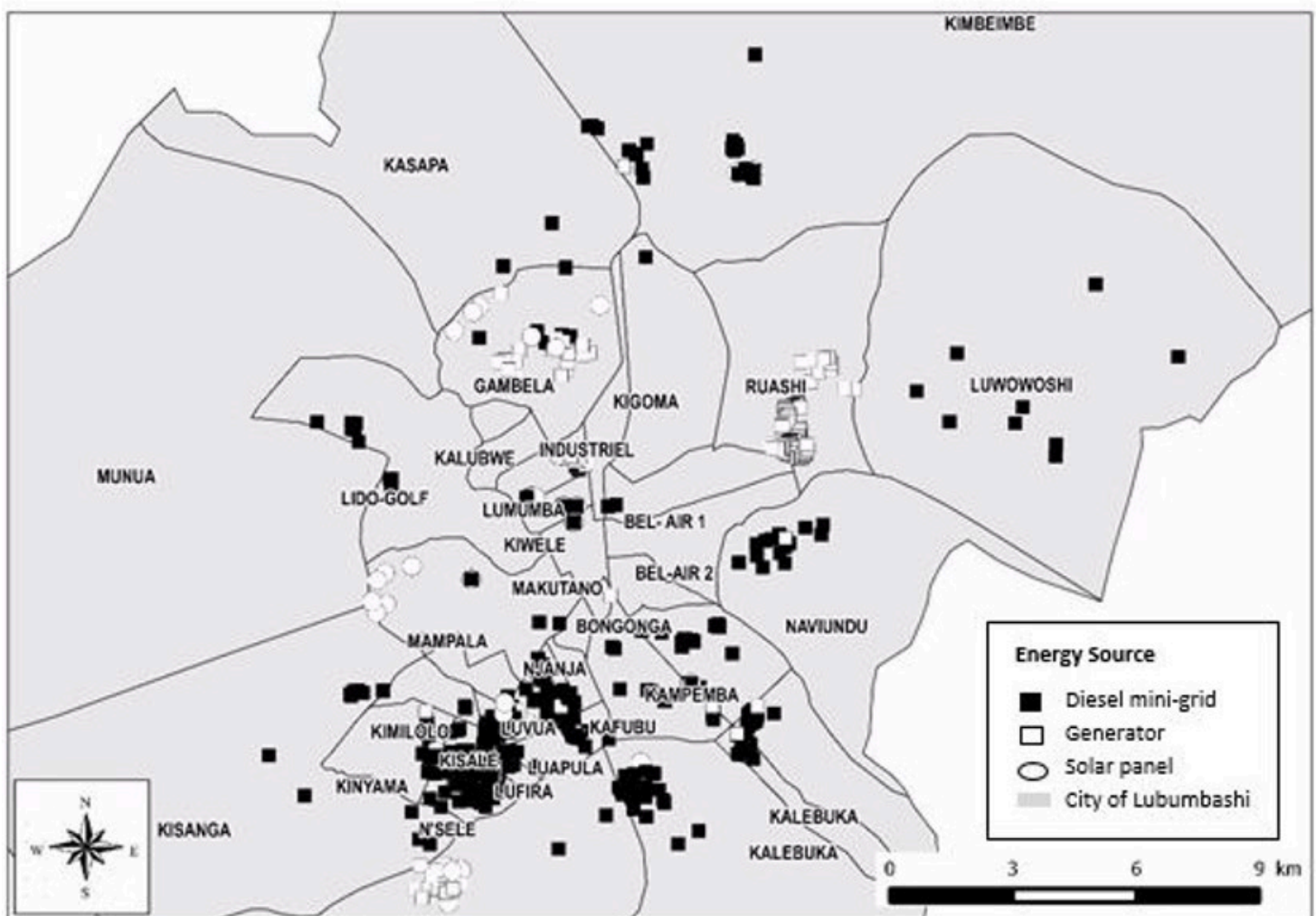


Figure 1

Spatial distribution of diesel mini-grids, individual diesel generators and household photovoltaic systems in Lubumbashi.

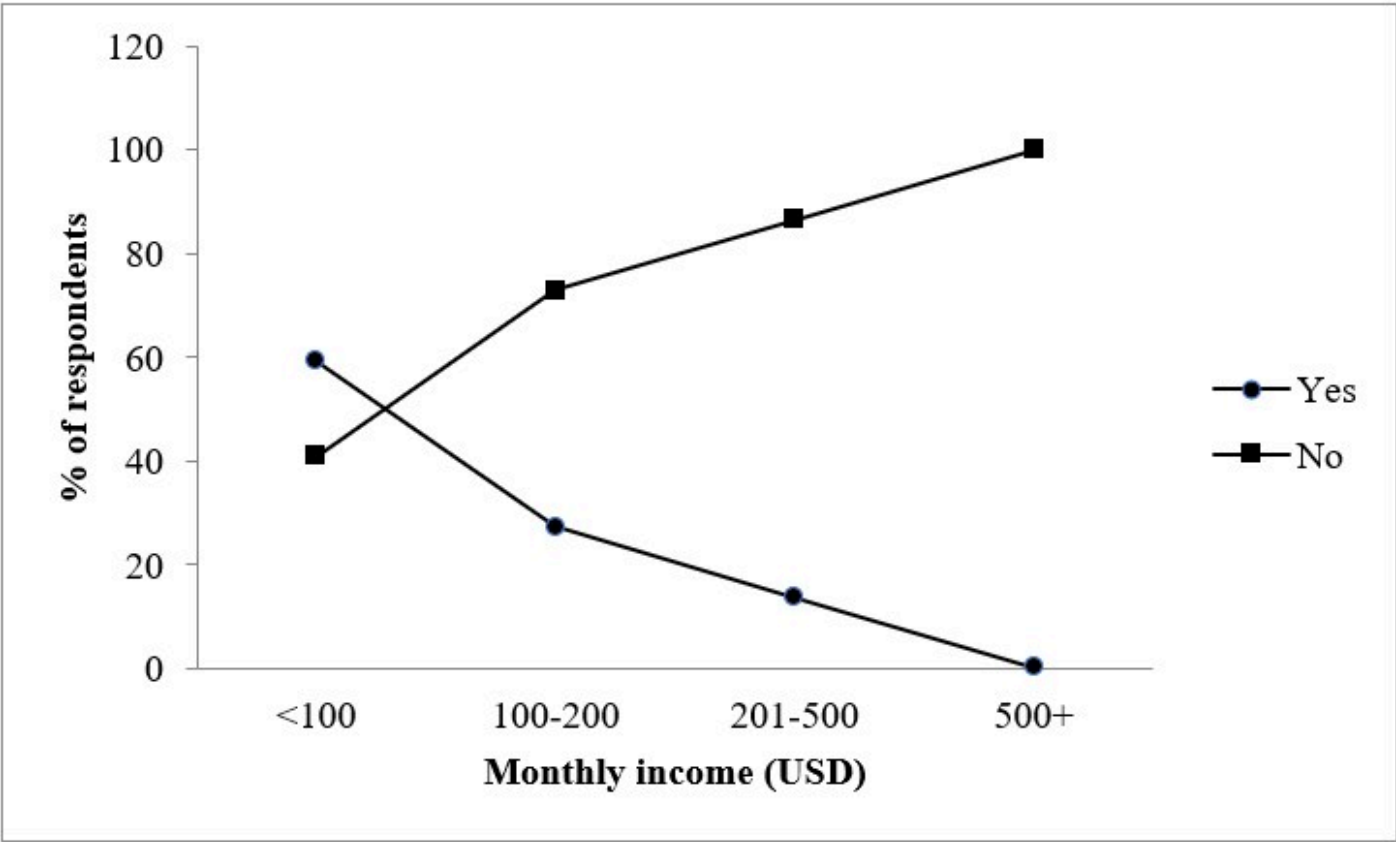


Figure 2

Household income and access to mini-grid diesel (Source: Authors).

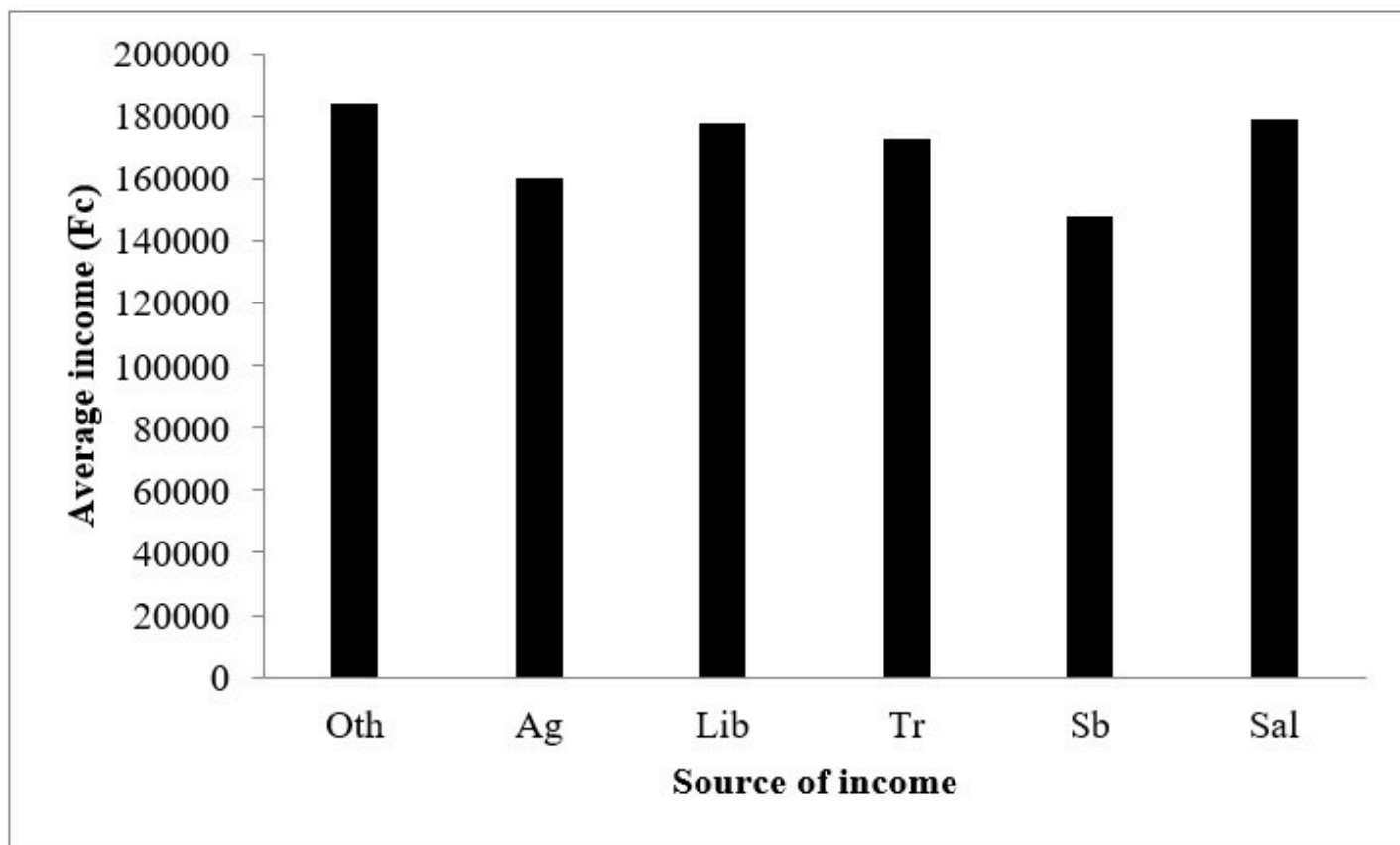


Figure 3

Relationship between monthly income according to their sources (Source: authors' survey, 1 \$ = 2000 Fc)

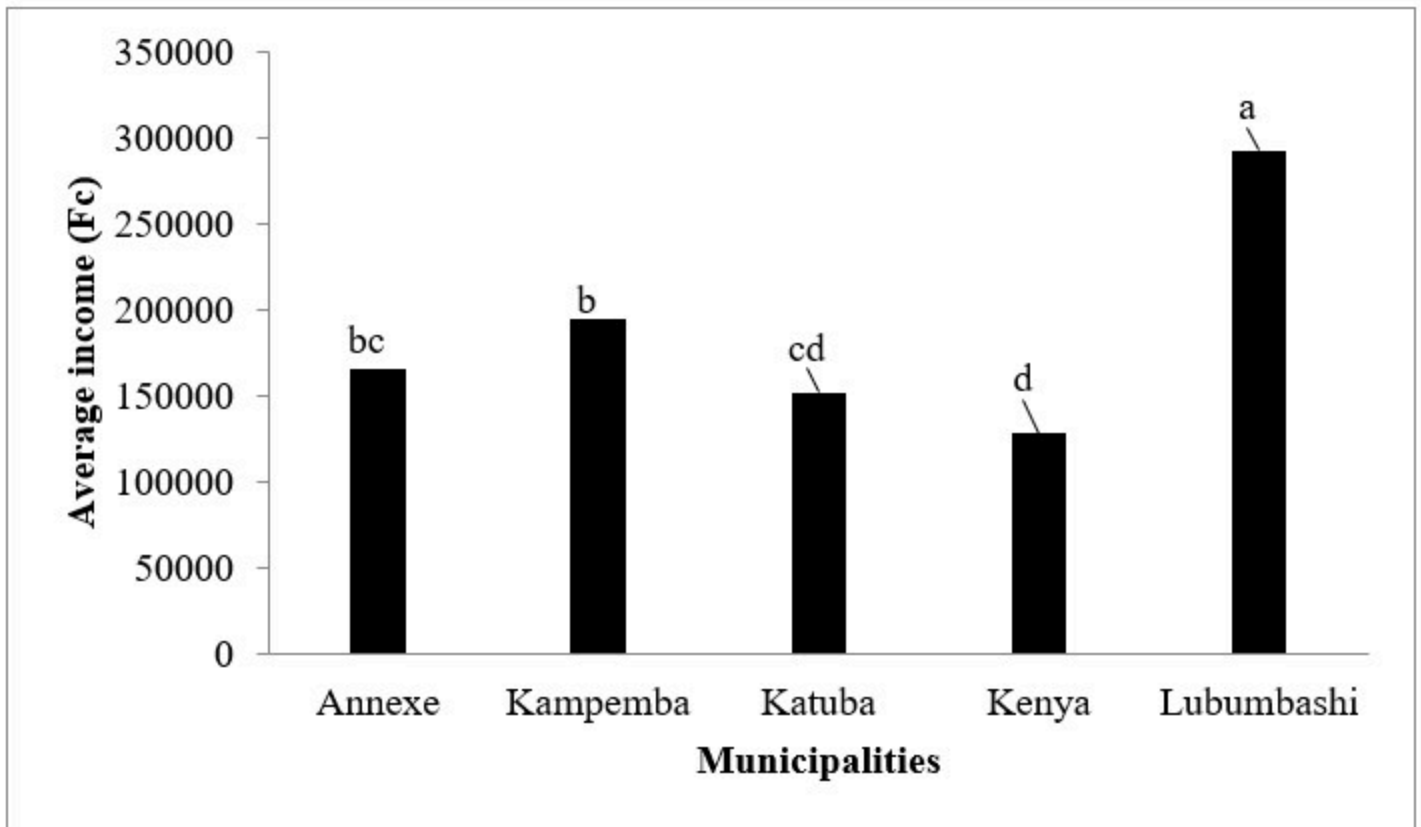


Figure 4

Municipalities of the city of Lubumbashi and the average monthly income of households (Source: authors' survey).

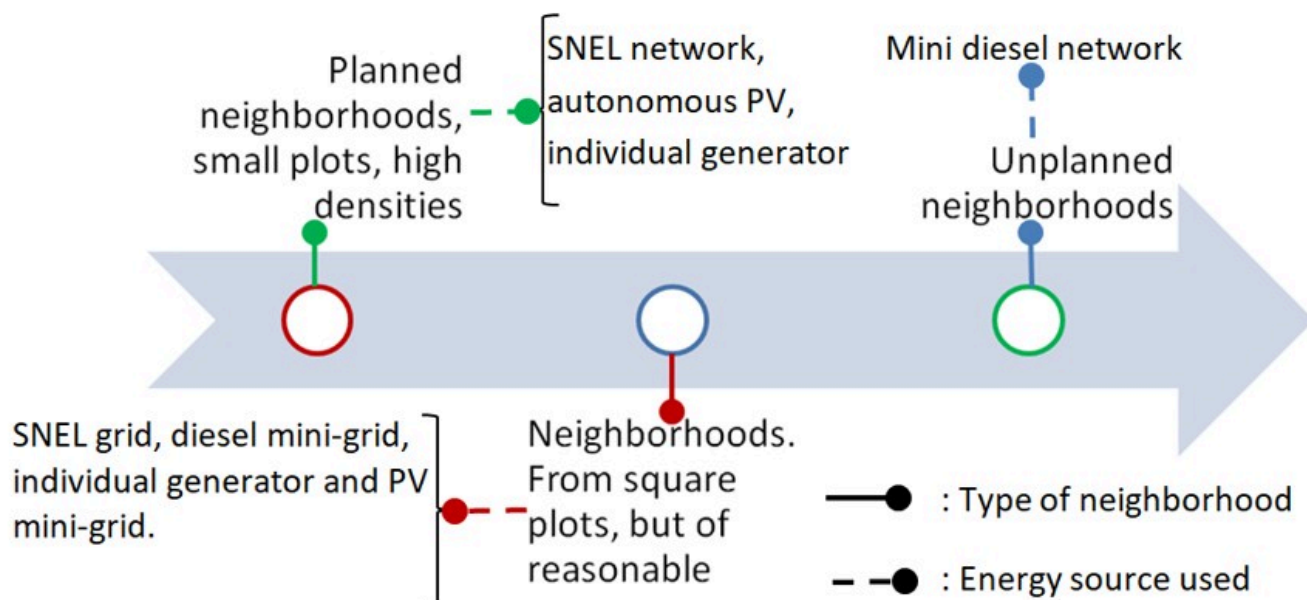


Figure 5

Model of access to electrical energy sources from the city center to the periphery