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Assessing and mapping electricity access patterns in a developing country

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Abstract

Despite low electricity access rates and weakened electricity sector governance under the pressure of population growth, modes of access to electricity in Lubumbashi vary spatially and in their typologies. However, to date, there is no detailed information on mapping households' modes of access to the National Electricity Company (SNEL) electricity network. This study aims to assess and map both formal and informal methods of household access to electricity in Lubumbashi. A socio-technical survey was conducted among 1211 households in the 7 communes or districts of the city. The results showed that the electricity access rate in the different districts of Lubumbashi varies between 41.6 and 78.3%, with an urban average of 63.8 %. The lowest rate is observed in the Annex district, while the highest is kept in the Kamalondo commune. At both the rural and urban levels, the most dominant method of access to electricity is a connection to the grid (formal and legal methods), with the highest rate in the Kamalondo, Kenya and Lubumbashi districts. Clandestine electrical connections are most common in the communities of Kamalondo and Kenya. The Annexe and Lubumbashi districts have the lowest rates of illegal electric connections. This study showed that the spatial distribution of cases of electricity theft and non-payment of bills in Lubumbashi is influenced by complex factors, such as the interaction between urban growth, household income level and the governance mode. The fight against fraudulent connections should be based on the present study to propose localized and adequate solutions in the different districts.

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Keywords: Energy demand; Energy efficiency; Democratic Republic of Congo (RDC); Illegal access; Load shedding; Lubumbashi; Renewable energy

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1. Introduction

Access to the power grid is critical for sustainable human development and poverty reduction [1–3]. Energy is recognized as an essential ingredient for economic growth and meets basic needs, such as lighting, cooking, and drinking water and improves, among others, communication, education, and productivity [4]. Overall, continued access to quality electrical service in Africa remains a significant problem and a challenge that hinders development in several areas [5,6]. Despite the African continent's immense energy potential, energy consumption in general, and in particular, is deficient [7]. The deployment of stand-alone microgrids can effectively assist in increasing the energy security policies of several African countries [8]. Moreover, some poor urban communities cannot have secure access to the power grid because much of the produced energy is for high-income demand and the industrial sector [9,10]. This can be seen as a brake on the continent's development. To develop and improve the standard of living for the communities, it is therefore essential that access to energy services be affordable and appropriate [11]. Renewable energy is also considered one of the best options for a secure power supply in developing countries [12].

In DR. Congo, household access to electricity is about 9% in urban areas and only 1% in rural areas [13]. While solar power is the powerhouse of the present sustainable energy resources [14], people still do not have access to the power grid in several developing countries [15]. In Lubumbashi, despite low access to electricity and weak policies in the electricity sector under the pressure of population growth, modes of access to the power grid are dominated by the informal sector [16]. Thus, the power system reliability and resilience can be negatively affected, leading to low performance of distributed networks [17]. Lubumbashi has three electrical network access methods: connection to the network, connection to a neighbour's house, and clandestine connection [16]. The understanding of the rate, patterns and quality of access to electricity in Lubumbashi is based on a series of studies by Banza et al. [13]. This paper assesses the results of socio-economic and technical surveys related to access to electricity in the seven districts of the city of Lubumbashi. Besides, the solid demographic growth that Lubumbashi is experiencing requires an update of the data and our knowledge of the evolution of the rates and modes of access to electricity. Furthermore, there is currently no mapping of the methods of access to electricity throughout the city of Lubumbashi. Therefore, this study aims to assess and map both formal and informal modes of household access to electricity in Lubumbashi.

2. Methodology

2.1. Study area

The socio-technical surveys were conducted in November 2021 in the city of Lubumbashi. Lubumbashi is the capital of the province of Haut-Katanga, located in the southeastern part of the Democratic Republic of Congo (11° 20′-12° 00′S, 27° 10′-10° 27E). The city has seven districts or communes: Lubumbashi, Kenya, Kamalondo, Katuba, Kampemba, Ruashi and Annexe. Lubumbashi is experiencing a double growth spurt, namely urban expansion and population growth [13]. However, this double growth is associated with weak governance resulting in a lack of efficient urban planning and poor electrical service. Lubumbashi had a population of 413,000 in 1973 and 700,000 in 1988. Recently, the city's population has grown to over 2,000,000.

2.2. Surveys and data collection

The fieldwork consisted mainly of a socio-technical survey and the taking of geographical coordinates to map the modes of access to electricity. The survey was conducted using a random stratified method, considering the different communes of the city of Lubumbashi as strata. This method provides a representative sample, as each individual in the population has an equal probability of being included in the sample. To estimate the sample size, the method proposed in [18] consists in using the table constructed by Krejcie and Morgan in 1970 [19] and applies the following formula:

$$S = \frac{X^2 N P\,(1-P)}{\left(d^2\,(N-1) + X^2 P\,(1-P)\right)} \tag{1}$$

where S is the required sample size, X^2 is the chi-square value for one degree of freedom at the desired confidence level, N is the population size, P is the proportion of the population (assumed to be 0.50 as this would provide the maximum sample size), and d is the degree of precision expressed as a proportion (0.05).

The access rate in Lubumbashi is about 62%, with 20% of the population illegally accessing the power grid [20,21]. In 2019 the number of households in Lubumbashi was estimated at 230,000, considering the rate of 62% access to the electricity network, which gives 142,600 households connected to the electricity network. This brings us to a target population (20% of the illicit connection in the residential sector) of approximately 28520.

In this work, the surveys were conducted in all seven communes. This leads to 6 degrees of freedom, with a confidence interval of 95% and a margin of error of 5%. Using (1), the ideal sample size is 1208 households. However, this sample size was reduced to 1211, for the 7 communes of Lubumbashi, to allow us to have 173 households per commune and thus include as many households as possible with varying socio-economic levels.

2.3. Data processing

A principal component analysis was conducted using the survey data to characterize the different communes. In addition, a Pearson correlation matrix was conducted to evaluate the relationships between the different variables. The geographic coordinates of the surveyed plots were superimposed on the vector map of the city of Lubumbashi to produce the thematic maps. Each coordinate was associated with both access mode and socio-economic information. Q-GIS software was used to create the thematic maps. Statistical analyses were conducted using R and Prism Graphpad software.

3. Results

3.1. Assessment of the rate and patterns of access to electricity

Fig. 1 presents the principal component analysis, which showed over 35% variance in the database. Different modes (formal and informal) of access to the SNEL network were found in all the communes. In terms of LV distribution network typology, the underground lines dominate the Ruashi commune. In contrast, the Kampemba commune and, to a lesser extent, the Annexe commune are dominated by overhead lines. Even in the communes with the highest monthly income (e.g., Lubumbashi and Ruashi), the modes and practices of access to electricity are similar to those observed in the communes with the lowest average monthly income.

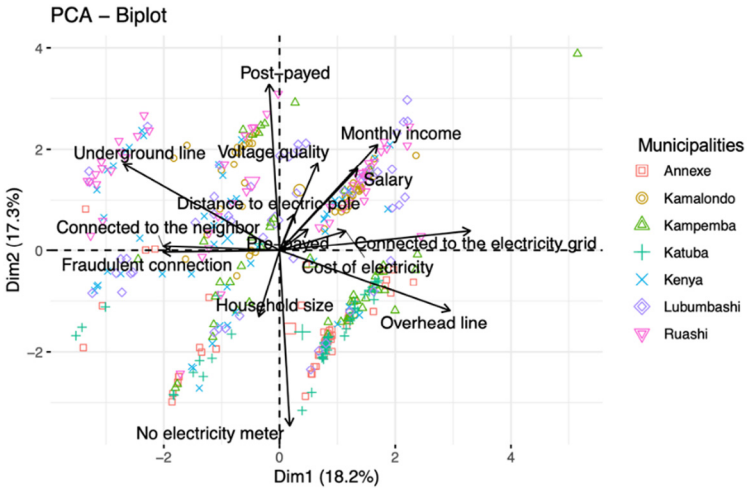

Fig. 1. Principal component analysis characterizing the different communes of the city of Lubumbashi based on their modes of access to electricity.

The negative and significant correlations are observed between the presence and absence of prepaid meters, grid connection and illicit connection, grid connection and neighbour's connection, and underground and overhead lines, as presented in Fig. 2. The positive correlations are observed between formal network access and the type of LV overhead network, legal network access and monthly income. Grid connection is positively but weakly correlated

with the presence of prepaid meters. Similarly, the overhead line is positively correlated with the distance to the pole. Although weak, the wage is negatively correlated with the absence of a meter, the illegal connection, and the connection to the neighbour's house. There is no correlation between the lack of a meter and the cost of electricity, the connection to the network, and the illegal connection. Similarly, the cost of electricity does not correlate.

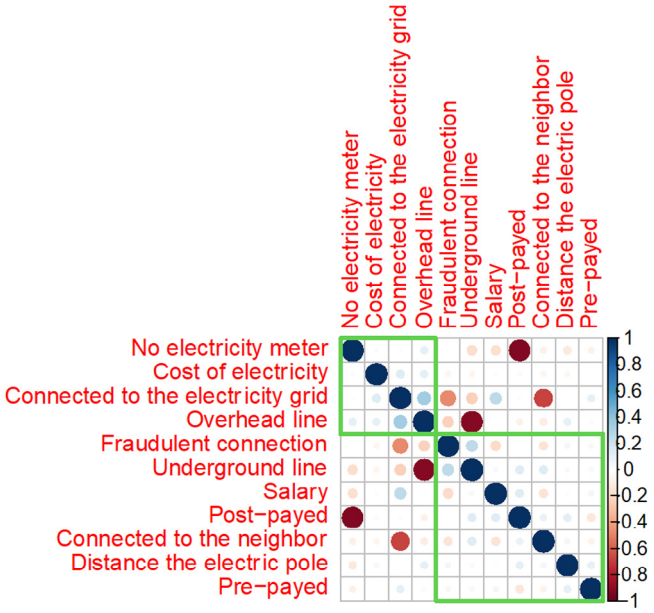

Fig. 2. Pearson's correlations between the different characteristic variables of access to electricity in Lubumbashi.

The electricity access rate in the various communes of Lubumbashi varies between 41.6 and 78.3 percent, with an urban average of 63.8 percent, as shown in Fig. 3. The lowest rate is observed in the Annexe commune. At the same time, the highest is kept in the Kamalondo commune. The commune of Kamalondo is followed by the commune of Kenya and then the commune of Lubumbashi. In both the peripheral and central neighbourhoods that make up the city, the most dominant mode of access to electricity is the legal and illegal connection to the network, with the highest rate in the communes of Kamalondo, Kenya, and Lubumbashi, with the highest rate in the communes of Kamalondo, Kenya and Lubumbashi, as described in Fig. 4. The connection to a neighbour's house is most dominant in Annexe and Kampemba. The lowest connection rate to a neighbour's house is observed in the commune of Kamalondo, followed by the commune of Katuba. Clandestine connections are most common in the communes of Kamalondo and Kenya, followed by the communes of Katuba and Kampemba. The lowest rate of illegal connections is observed in the communes of Annexe and Lubumbashi.

3.2. Mapping modes of access to electricity

Reduced meter readings, tapping upstream of the meter, illegal connections and non-payment of bills are the most frequent practices in neighbourhoods such as Njanja, Gambela, Luvua, Kinyama, Kigoma, Industriel and even more peripheral areas, such as Munua. For instance, this can be shown in Fig. 5. These practices are rare in many parts of the Annex commune, consisting of neighbourhoods such as Kasapa, Kimbeimbe, Luwowoshi, Kisanga, Kasungami, Kalebuka, etc. It is also observable that some communities in the urban core are spared from these practices, such as Kiwele, Makutano and Bel-Air 2. However, non-payment of bills is a dominant practice in some of the Naviundu, Luwowoshi and Ruashi neighbourhoods. A high incidence of illegal connections was also observed in the Mampala, Luvua, Luapula, Kimilolo, and Kisale neighbourhoods. Fig. 6 shows the spatial distribution of fraudulent access to electricity in Lubumbashi.

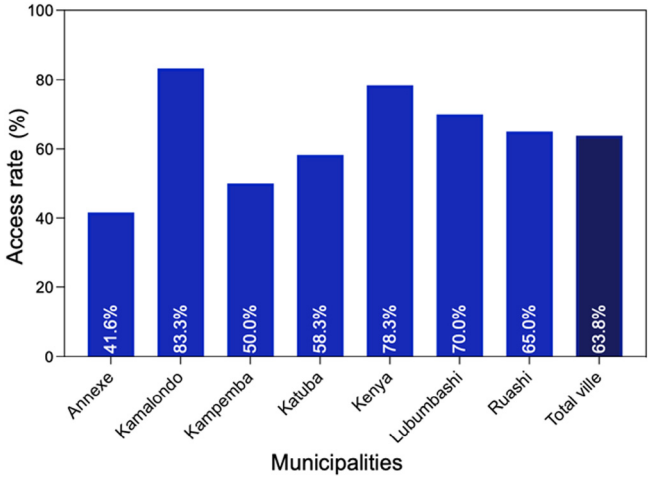

Fig. 3. Rate of access to electricity at the communal and urban levels in Lubumbashi.

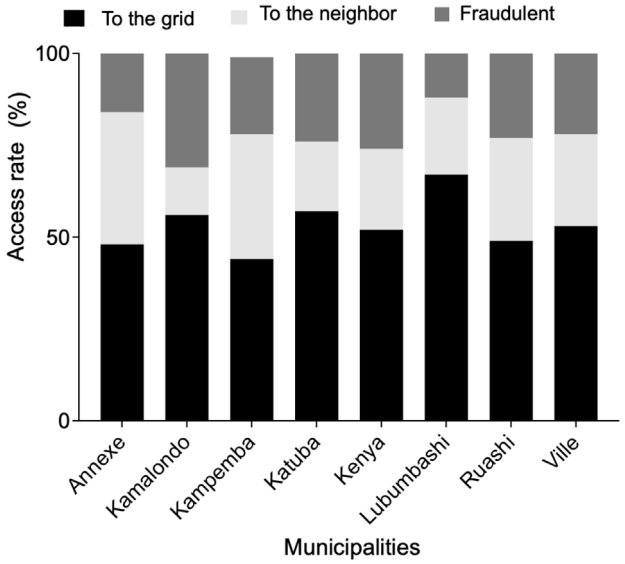

Fig. 4. Mode of access to electricity at the communal and urban levels in Lubumbashi.

4. Discussion

4.1. Modes and rates of access to electricity

The rate and patterns of access to electricity at the communal and urban levels in Lubumbashi show significant disparities. Nevertheless, even in the communes with the highest monthly income (e.g., Lubumbashi and Ruashi), the modes and practices of access to electricity are similar to those observed in the communes with the lowest average monthly income. Furthermore, all proportions of different techniques differ from one commune to another. This observation is essential in the fight against fraudulent access to the electricity grid because it suggests that the methods for fighting electricity theft should be the same regardless of the commune. Indeed, our results show that, contrary to the magnitude, the occurrence of different illicit modes of access to electricity is not related to the average socio-economic status of households. This can be explained by the fact that no commune in the city of Lubumbashi is exclusively reserved for high-income households. On the contrary, all communes are full of poor

Fig. 5. (a) Bypassing analog and prepaid meters. (b) Illegal supply from a neighbouring SNEL subscriber.

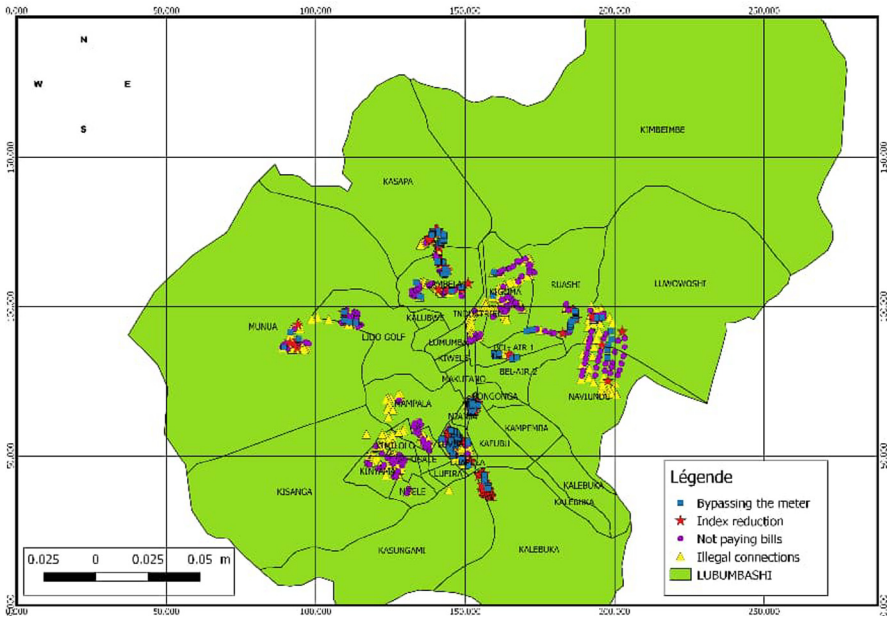

Fig. 6. Mapping of electricity theft patterns in Lubumbashi.

and wealthy families but in varying proportions. These results are consistent with previous studies conducted in low-income households [22] and high-income households [23].

Negative and significant correlations are observed between the presence and absence of prepaid meters, connection to the network (formal subscribers) and illicit connection, connection to the network and connection to a neighbour's house, and underground and overhead lines, as detailed in Fig. 2. These negative correlations indicate that an increase in one variable leads to a decrease in the other. On the other hand, positive correlations are observed between legal network access (connection) and the overhead network, legal access and monthly income, and illegal network access and the underground network. These observations suggest that the type of network (overhead or underground) is a crucial determinant of the mode of fraudulent access to the electrical network. This is because the overhead grid increases with legal access to the grid, while the underground grid promotes electricity theft.

Moreover, legal access to the grid increases with growing income. This implies that high-income households generally have formal access to electricity. Thus, fraudulent connection in Lubumbashi is partly a consequence of poverty and the failure to manage the electricity service. This corroborates with the work of [18], which showed that the cost of electricity is among the factors that encourage electricity theft, especially among low-income households. The observation that fraudulent connections are positively correlated with underground lines indicates that these lines should be avoided in communities where electricity theft is recurrent. Although electricity theft occurs from overhead lines [16], illicit connections are easy to detect, unlike the underground network. This study showed that at both the communal and urban levels, the most dominant mode of access to electricity is the connection to the grid (formal and legal mode), with the highest rate in the commune of Lubumbashi, which is the original core of the city, as presented in Fig. 4. This observation is probably related to the strong presence of SNEL agents who control and promote formal electricity service in these communes [13].

The neighbour-to-neighbour connection is most dominant in Annexe and Kampemba. Contrary to the observations of [13] indicating low household density in the Annexe commune, which would limit neighbour-to-neighbour electricity connection. The population of Lubumbashi is growing rapidly and thus continues to densify most neighbourhoods that were once sparse. This explains the high proportion of neighbour-to-neighbour connections in the Annex commune as a mode of electricity theft. Clandestine connections are most common in the communes of Kamalondo and Kenya, followed by Katuba and Kampemba. The lowest rate of illegal connections is observed in the communes of Annexe and Lubumbashi. This observation can be explained by the low proportion of electrical infrastructure in the Annex commune and in the commune of Lubumbashi, the strong presence of activities, offices and other services of SNEL, in this case, the sales and services centers (CVS) [13,16,21]. The high density of households in Kamalondo and Kenya is thought to be a factor in fraudulent connections.

The electricity access rate in the various communes of Lubumbashi varies between 41.6 and 78.3 percent, with an urban average of 63.8 percent, as presented in Fig. 3. The lowest rate is observed in the Annexe commune, while the highest is in the Kamalondo commune. The commune of Kamalondo is followed by the commune of Kenya and then the commune of Lubumbashi. This is in line with the results of [13,16]. Their observations reveal a high concentration of electricity infrastructure in the commune of Kamalondo, which increases the possibility of households being connected to the grid. The urban access rate observed in this study (63.8%) showed only a slight increase over the rate observed (62%) by [16] in its surveys. This finding verifies the argument that the rate of access to electricity varies over time through improvements in infrastructure quality.

4.2. Mapping modes of access to electricity

This study showed that the reduction of the meter reading, tapping upstream of the meter, illegal connections and non-payment of bills are the most frequent practices in the neighbourhoods of Kenya, Katuba, Ruashi and Kampemba, and even in some outlying communities such as Munua in the Annex commune, as shown in Fig. 6. This revelation is crucial in implementing methods to fight against fraudulent connections. It will enable us to act more effectively in the areas most affected and thus reduce the loss of income created by the theft of electricity and the non-payment of bills. However, these practices are rare in large parts of the Annex municipality consisting of neighbourhoods such as Kasapa, Kimbeimbe, Luwowoshi, Kisanga, Kasungami, Kalebuka etc. It is also observable that some communities in the urban core are spared these practices, for example, Kiwele, Makutano and Bel-Air 2. This observation is both in the old neighbourhoods that form the centre of the city and in those of the periphery; it suggests a complexity of factors at the root of electricity theft and non-payment of bills. These factors would likely be the interaction between urban growth, household income levels, and governance, as demonstrated in [24]. The integration of renewable energy can also be considered to solve several challenges of the power network [8,25] without forgetting to include gridable electric vehicle opportunities that also assist in improving the energy trilemma [26].

5. Conclusion

This study revealed that the different modes of illicit electricity access are unrelated to the types of communes. Thus, the methods for combating electricity theft should be the same regardless of the commune. In Lubumbashi, the kind of lines is a determining factor in the mode of access to electricity. Overhead lines explain the formal connection to the network, while underground piping favours clandestine connections. Fraudulent connection in Lubumbashi

is partly a consequence of household poverty coupled with the weakness of the management of the electricity service. Although electricity theft is also practised from overhead pipes, illicit connections are easy to detect, unlike underground pipes. This study also showed that the strong presence of SNEL agents who control and promote the formal supply of electricity would be decisive in limiting fraudulent connections. It emerged that the population of Lubumbashi is overgrowing and continues to densify most of the neighbourhoods, which were previously sparsely populated, thus promoting the proliferation of neighbour-to-neighbour access in the Annex commune. However, urbanization conditions and the low density of electrical infrastructure in this commune limit the proliferation of illegal connections. The urban access rate in this study (63.8%) showed only a slight increase compared to that observed (62%) five years earlier. Finally, the study showed that the spatial distribution of electricity theft patterns in Lubumbashi is influenced by factors such as household location away from the city's core towards its periphery and household income level. In the future, it would be interesting to design mechanisms to combat electricity theft in developing cities by proposing solutions that meet the electricity needs of households.

Declaration of competing interest

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

Data availability

Data will be made available on request.

References

[1] Banza B, Banza W. Causes of deterioration of the electrical service quality at the household scale in lubumbashi, DR congo. Trends Appl Sci Res 2019;14(1):12–8.
[2] Mbungu NT, Naidoo R, Bansal RC, Bipath M. Optimal single phase smart meter design. J Eng 2017;2017(13):1220–4.
[3] Mondejar ME, et al. Digitalization to achieve sustainable development goals: Steps towards a smart green planet. Sci Total Environ 2021;794:148539.
[4] Gielen D, Boshell F, Saygin D, Bazilian MD, Wagner N, Gorini R. The role of renewable energy in the global energy transformation. Energy Strateg Rev 2019;24(June 2018):38–50.
[5] Falk J, Angelmahr M, Schade W, Schenk-Mathes H. Socio-economic impacts and challenges associated with the electrification of a remote area in rural tanzania through a mini-grid system. Energy, Ecol Environ 2021;6(6):513–30.
[6] Madiba T, Bansal RC, Mbungu NT, Bettayeb M. Under-frequency load shedding of microgrid systems : a review. Int J Model Simul 2021;00(00):1–27.
[7] Dalla Longa F, van der Zwaan B. Heart of light: an assessment of enhanced electricity access in Africa. Renew Sustain Energy Rev 2021;136(October 2020):110399.
[8] Siti MW, Mbungu NT, Tungadio DH, Banza BB, Ngoma L. Application of load frequency control method to a multi-microgrid with energy storage system. J Energy Storage 2022;52:104629.
[9] Cabello Eras JJ, Mendoza Fandiño JM, Sagastume Gutiérrez A, Rueda Bayona JG, Sofan German SJ. The inequality of electricity consumption in Colombia. Projections and implications. Energy 2022;249.
[10] Mbungu NT, Bansal RC, Naidoo RM, Siti MW, Tungadio DH. Modelling of a smart hybrid water-power system for freshwater and energy supply network. In: 2020 1st Int. conf. power, control comput. technol. ICPC2T 2020. 2020, p. 6–9.
[11] Mukoro V, Sharmina M, Gallego-Schmid A. A review of business models for access to affordable and clean energy in Africa: Do they deliver social, economic, and environmental value? Energy Res Soc Sci 2022;88(September 2021):102530.
[12] Mbungu NT, et al. Economic optimal load management control of microgrid system using energy storage system. J Energy Storage 2022;46:103843.
[13] Bonaventur BWB, Flory KT, Bouillard P. Spatial distribution of electrical infrastructures: Impact of urban sprawl in lubumbashi, DR congo. Asian J Ind Eng 2015;8(1):10–7.
[14] Hamid AK, Mbungu NT, Elnady A, Bansal RC, Ismail AA, AlShabi MA. A systematic review of grid-connected photovoltaic and photovoltaic/thermal systems: Benefits, challenges and mitigation. Energy Environ 2022.
[15] Come Zebra EI, van der Windt HJ, Nhumaio G, Faaij APC. A review of hybrid renewable energy systems in mini-grids for off-grid electrification in developing countries. Renew Sustain Energy Rev 2021;144:111036.
[16] Bonaventur BWB. Causes of deterioration of the electrical service quality at the household scale in lubumbashi, DR congo. Trends Appl Sci Res 2019;14(1):12–8.
[17] Thomas R, van Zyl S, Naidoo RM, Bansal RC, Mbungu NT, Bipath M. Recloser based energy exposure assessment of a distribution network. J Energy South Africa 2019;30(4):41–50.
[18] Milambo Kasumba D, Banza Wa Banza B. Identification of factors encouraging household consumers to engage in theft of electricity in lubumbashi, DR congo. Rev Ind Eng Lett 2019;5(1):22–30.
[19] Bukhari SAR. Sample size determination using krejcie and morgan table. Kenya Proj Organ 2021;(February):607–10.

[20] Wa B, Bonaventure B, Mbungu NT, Siti MW. ScienceDirect critical analysis of the electricity market in developing country municipality. Energy Rep 2022;1–10.
[21] Bonaventur BWB, Nene MT. Identification and analysis of off-grid energy sources used at the household scale in lubumbashi, DR congo. Asian J Ind Eng 2018;11(1):1–7.
[22] Mutumbi U, Thondhlana G, Ruwanza S. Reported behavioural patterns of electricity use among low-income households in makhanda, South Africa. Sustain 2021;13(13).
[23] Williams SP, Thondhlana G, Kua HW. Electricity use behaviour in a high-income neighbourhood in johannesburg, South Africa. Sustain 2020;12(11):1–19.
[24] Banza Banza BW, Flory Tshikala K, Bouillard P, Hyacinthe Tungadio D. Electrification of suburbs of lubumbashi in DRC with hybrid energy system. Int J Renew Energy Sources 2020;05:1–19.
[25] Siti MW, Mbungu NT, Tungadio DH, Banza BB, Ngoma L, Tiako R. Economic dispatch in a stand-alone system using a combinatorial energy management system. J Energy Storage 2022;55:105695.
[26] Ismail AA, Mbungu NT, Elnady A, Bansal RC, Hamid A-K, AlShabi M. Impact of electric vehicles on smart grid and future predictions: a survey. 2022, p. 1–17. http://dx.doi.org/10.1080/02286203.2022.2148180.