Electrification of Suburbs of Lubumbashi in DRC with Hybrid Energy System

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Abstract: - The gradual electrification of areas not yet connected to the main electricity grid has mainly been achieved through the installation of decentralized diesel generators and, to a lesser extent, through autonomous PV systems. This study presents in its first part the spatial distribution of alternative sources of electricity by identifying the socioeconomic factors of households explaining this distribution. And in its second part the study presents, the optimal results of a hybrid PV/diesel system with storage. Socio-economic survey data from 5,270 households across the city of Lubumbashi revealed 163 mini-grids fueled by diesel generators serving 1143 households, or 21.6 percent of households surveyed. These surveys reveal that there is a positive and more significant link between access to mini-diesel grids and socio-economic variables such as secondary education level and other income source (the combination of several identified sources of income). The data taken from these mini-diesel networks made it possible to develop the consumption profile of the study area. After simulation, optimization and sensitivity analysis with the HOMER software the study revealed that the optimal solution is obtained when the load is fed by a PV / diesel system with storage on 96 batteries of 1 kWh, this configuration offers the cost of lowest energy is $ 0.385/kWh compared to diesel alone and PV/diesel configurations. From an environmental point of view, the case study presented here shows that the use of PV-diesel-batteries reduces emissions by more than 34% compared to purely diesel generation. This study recommends replacing diesel mini-grids with PV-diesel hybrid mini-grids as an effective measure to reduce diesel fuel consumption and greenhouse gas emissions, while providing 24-hour electrical service in non-electrified neighborhoods

Key-Words: - Leave one blank line after the Abstract and write your Key-Words (6 - 10 words)

1 Introduction

Energy is a very important resource for socio-economic development [1-2], it is one of the key measures to achieve sustainable human development and reduce poverty [3-4]. Disparities in access to electricity occur at all levels, they are visible between the different continents, between the countries of the same continent, between the regions of the same country, between the districts of the same city and even between households in the same neighborhood [5]. According to estimation conducted by the IEA (International Energy Agency), nearly 1.1 billion people (14% of the world's population) do not have access to electricity and more than 95% of them are found in sub-Saharan Africa and Asia [6-7]. Energy consumption in general and electricity in particular is very low in Africa, despite the huge energy potential of the continent [8-9]. Only 30% of the population has access to electricity and the economy of many African countries is severely handicapped by the quality and quantity of electricity available [10]. With 14% of the world's population, Africa consumes only 3% of the world's energy use [11]. In sub-Saharan Africa, two out of three people do not have access to electricity [12]. This would be at the root of the region's low economic growth potential, thus perpetuating the vicious circle of poverty and social malaise [13].

In DR Congo, the national electrification rate is currently 9%, and only 1% if only the rural world (76.8% of the Congolese population) is considered. In Lubumbashi, the second largest city in DR Congo, [14] reported an electricity access rate of 61.6% at the urban scale characterized by frequent and unpredictable power cuts. In Lubumbashi, as in most developing cities, the electrification of low-density peripheral neighborhoods represents a significant investment [15]. Low building density is usually accompanied by a relatively high network connection cost for a household [15]. More numerous in Lubumbashi, these low densities and expensive to serve neighborhoods where live sometimes low-income populations, raise issues of profitability and sustainability of projects for their electrification. The weak capacity of the SNEL (National Electricity Company) to extend the power grids and the uncontrolled urbanization under which most of these Lush neighborhoods are born require urgent recourse to appropriate and appropriate policies. For low-income households in particular, extending the network is not an option [16]. In addition, the criteria used to select the neighborhoods to be electrified (for example, the distance from the network, the size of the population, the ability of households to pay connection fees and the costs of services) only favor central districts and high-income households [17].

Very recently, [14] showed that in the face of a lack of access to electricity and /or poor-quality services, Lush households use oversized alternative energy sources. Indeed, the majority of households in informal neighborhoods make more use of collective solutions such as the generator and individual such as solar panels as an alternative source of electricity. However, according to AIE-PVPS (2013), however, each of these two technologies has limitations. The current challenge is to put in place solutions that are accessible on the one hand and efficient on the other. Several examples of cases show that most studies have focused on the PV-diesel couple in rural areas in different African countries (IEA-PVPS, 2013). However, no study (to our knowledge) has attempted to develop a peri-urban electrification scheme based on the PV-diesel system with storage. Recently, in-depth analyzes on access to energy have been proposed. The studies of Alkon [19] and Alam & Bhattacharyya in [12] highlight the willingness to pay for modern energy, while Khandker et al. [20] show a strong relationship between income and energy poverty. Other studies, on the other hand, only explain rural electrification and access to energy [21-22]. The role of socio-economic factors in access to mini-grids fueled by diesel groups has so far been less elucidated.

Based on the literature, no study has so far been conducted in Lubumbashi to evaluate the feasibility of a hybrid PV-generator mini-grid. Another novelty of this study is that, to our knowledge, most of the feasibility studies for mini PV-diesel networks in most developing countries have focused on rural areas [23-24], and that only the techno-economic feasibility has been made in these different studies and without optimal dispatch of sources according to electricity demand, an analysis of the sensitivity of the system to the change in the price of electricity, fuel and the load, environmental analysis is as yet unclear. So far, little is known about the feasibility of a mini PV-generator network aimed at solving the problems of unequal access to the electricity of the spontaneous neighborhoods by integrating the solar panels, the batteries, converters and diesel engines coupled to an alternator. This research answers the following questions:

- Do households' socio-economic conditions explain the current spatial distribution of different energy sources in the city of Lubumbashi?
- Is the use of hybrid PV-diesel solution a technically and economically feasible way of considering the efficient environmental aspect for non-electrified households' in Lubumbashi?

To answer these questions the following actions will be taken: 1. Mapping the current spatial distribution of PV modules and mini-grids powered by diesel generators and identifying the social and economic factors that may explain this distribution across un-serviced neighborhoods; 2. To evaluate the technical-economic and environmental feasibility of a mini PV-diesel hybrid network in a non-electrified pilot district in Lubumbashi. The rest of this work is structured in the following way: in section 2, the methodology used and its implementation are presented. Section 3 presents the results as well as their discussions. A brief conclusion is given in section 4.

2 Methodology

2.1 Field of Study

This study was conducted in Lubumbashi (south-east of the country, at 11 ° 40 'S and 27 ° 29' East), the second largest city in the Democratic Republic of Congo after the capital Kinshasa. Administratively, the city is composed of 43 neighborhoods grouped in 7 communes [25] including: Lubumbashi, Kenya, Kampemba, Katuba, Kamalondo, Ruashi and Annex. These communes, like the neighborhoods, are very dissimilar in size, population, land use, and so on. The current city of Lubumbashi is confronted with several difficulties: the existence of under-equipped and unstructured peripheral districts, a confusion in the roles and responsibilities of the actors concerning town planning and urban management, an excessive spreading of the city by the creation of subdivisions without a master plan, coherence, access roads and equipment reserves [26]. The Luwowoshi district located in the north-east of Lubumbashi city has been selected as a pilot district to evaluate the technical-economic and environmental feasibility of a mini PV-diesel hybrid network. This district has a population of about 70,000 inhabitants, or 3.5% of the population of Lubumbashi and it covers an area of 38.9 km2. The choice of this site was dictated by the high degree of concentration of the households (this to avoid the losses due to the distribution of electricity) and the absence of the electricity network of the National Society of Electricity (SNEL) [27].

2.2 Data Collection

2.2.1 Solar radiation in Lubumbashi

These data represent the mean monthly illuminance in kWh/m2/day on a horizontal surface at ground level. This average is taken over 22 years (July 1983 -June 2005). Each monthly average is calculated from measurements taken every three hours. Figure 1 represents the average illumination on the city of Lubumbashi. These data are taken from the National Aeronautics and Space Administration (NASA) website. These data were used during the simulation under HOMER (Hybrid Optimization Model for Energy Renewable), because the power of the solar panels that this computation software depends on the incident average illumination [28]. HOMER is a software developed for small power generation systems. It allows simulations of systems with renewable energies and with fossil energies. One of its great strengths is the possibility of being able to simulate hybrid systems combining different sources of energy, be it renewable or fossil [29]. This tool is efficient and makes it possible to use a maximum combination of renewable energy sources and to make a technical-economic and environmental analysis to compare with other tools that exist as shown by Sinha and Chandel [30].

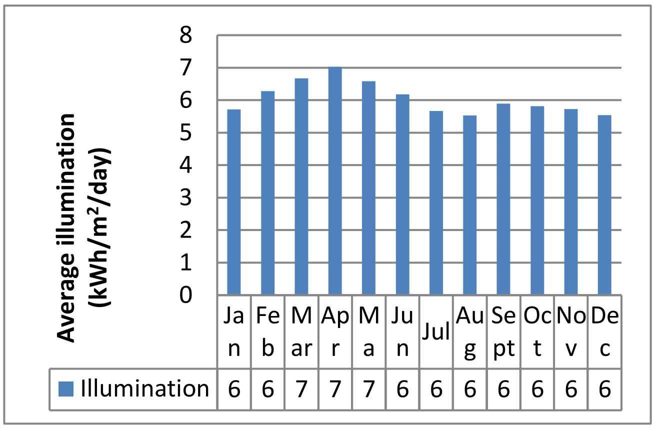


Figure 1. Average illumination (kWh / m2 / day) of the city of Lubumbashi, study environment [31]

2.2.2 Data

The socio-economic data come from our large database of surveys covering 5,270 households throughout the city of Lubumbashi [14]. A total of 163 mini-grids fueled by diesel generators serving 1143 households, or 21.6% of households surveyed, were identified. These mini-grids and data relating to individual alternatives (generator, PV system) were subsequently geo-located (geographical coordinates taken using a Garmin GPS) and superimposed on the administrative map of the city to produce a thematic map from the ArcGIS 10.1 software. For each household connected to the mini-diesel network, the following socio-economic variables were selected: source of income, average monthly income and level of education. A trip was organized in the Luwowoshi district to collect loads from consumers at the one-hour interval during a day for four weeks. Figure 2 shows that the peak consumption is around 19 hours, we also notice that during the day, for instance between 7 am and 6 pm, demand varies little, with an average around 11kW. This profile has the typical shape of a residential area as defined by Lambert [28], characterized by a peak in the evening [32]. These data were taken from a mini-grid powered by a 25kW generator, supplying 17 households whose main uses of energy are: radio, television, lighting, telecommunication/phone charging, laptop, etc. The energy consumption surveys were conducted for four weeks between July and October 2018, during the dry season and the rainy season respectively, using the method proposed by [33-35]. This method consists in simultaneously measuring the electric current and the voltage. Powers in kW were found assuming the power factor at 0.85 [35-36].

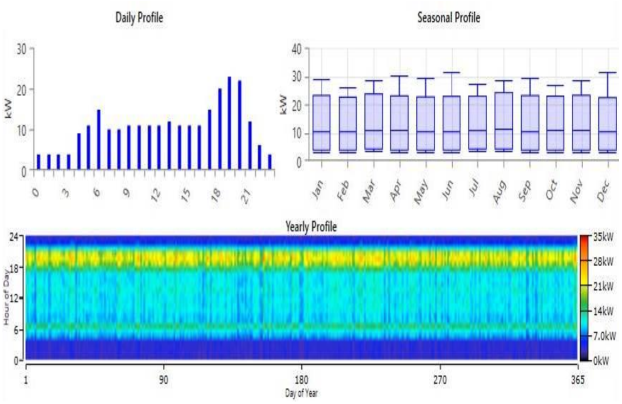


Figure 2. Luwowoshi district mini-grid load profiles (Source: Authors from HOMER)

2.3 Data processing

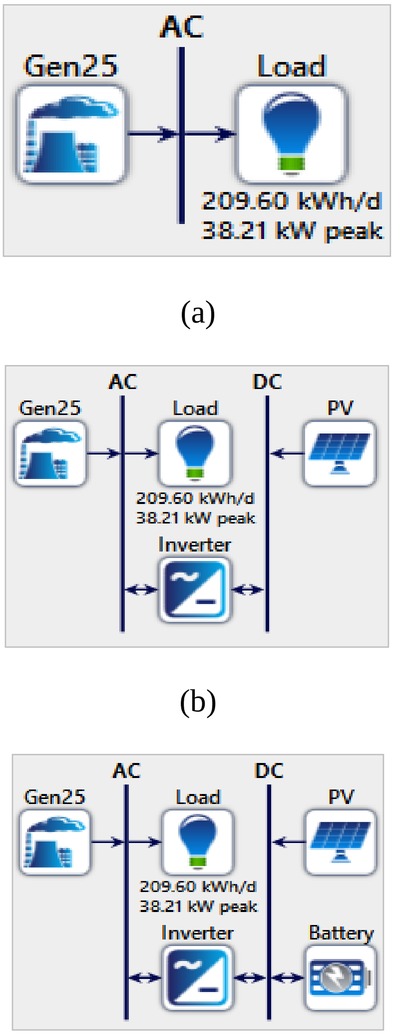
2.3.1. Statistical analyzes

To identify the socio-economic variables that explain the spatial distribution of mini-grids in the different municipalities, simple correlations have been made [37-38]. Quantitative data were subjected to one-way analysis of variance (ANOVA) [39-41]. In addition, a Tukey post-hoc test was applied to find the difference between the means for the results with a significant difference ($p < 0.05$). Qualitative data were submitted to the Chi-square test. These analyzes were performed using software R 2.15 and Past 2.01.

2.3.2. Simulation, optimization and sensitivity analysis with HOMER software

Depending on the system configuration, HOMER simulates the operation of the system by calculating the energy balance for 8760 hours / year [28, 41]. To meet the constraints defined by users, an optimization analysis is done [42-43]. In this analysis HOMER calculates the optimal configurations of the system, compares the solutions of the different possible scenarios and finds the most economical solution [28, 44-45, 42]. In the sensitivity analysis, various system scenarios and factors having the greatest impact on the design and operation of the system are evaluated. Three operating scenarios (Figure 3) of the hybrid mini-grid were tested. Three crucial steps were followed: simulation, optimization and sensitivity analysis.

During the simulation, it was discussed to verify the technical feasibility of the mini-network then the optimization made it possible to determine which configuration presents the lowest costs. And lastly, the sensitivity analysis made it possible to determine the impact of certain inputs on the cost of energy.



(a)

(b)

(c)

Figure 3. System configuration (a) diesel only group; (b) diesel - PV; (c) diesel-PV group with batteries (Source: Authors from HOMER)

2.3.2.1. PV systems

PV systems are modeled under HOMER as DC generators when exposed to solar radiation and their output power can be deduced from the following relationship [28, 46-51]:

$$P_{PV} = Y_{PV}\, f_{PV}\left(\frac{G_T}{G_{T.STC}}\right)\left[1 + a_p\left(T_C - T_{C.STC}\right)\right] \tag{1}$$

With, Y_{PV} is the rated power under standard test conditions, f_{PV} is the depreciation factor of solar panels, G_T is incident illuminance, G_T, S_{TC} is illumination under standard test conditions, αp is the coefficient panel temperature (% / °C), TC is the temperature of the PV cell in ° C, TC, STC is the temperature of the PV cell at standard conditions (25°C). In a PV-diesel hybrid mini-grid, the energy cost is greater than the cost of the conventional grid because of the high cost of storage systems and the cost of diesel [52]. To reduce this cost, we propose as part of this study that the peak loads are ensured by the diesel group there is thus limited time of use of the diesel group and reduction in fuel consumption. The PV system powers the daytime load and charges the batteries, which in turn enable frequency regulation [53-54]. The night charges are powered by the battery system. In the event of a power failure at any time during these periods for any reason, the generator must start automatically. The design criteria for the PV system were based on a demand for 11 kW off-peak power between morning and evening. Thus, the PV system must meet the loads of the day. It consists of 40 polycrystalline PV modules of 275 Wc each, a nominal voltage of 31.2 V DC and a nominal current of 8.82 A connected in parallel.

2.3.2.2 Batteries

The battery system must only respond to night-time charges, which are 4 kW between 23h and 4h, mean an energy of 20 kWh, considering an average of 3, the number of days of autonomy, for a maximum discharge of 80% and η_{out} the total efficiency is given by the battery yield (0.85) multiplied by the efficiency of the inverter (0.9) which is 0.765. Using Equation (2) [55-56].

$$B_{Sc} = \frac{N_C . E_j}{Dd . \eta_{out}} \tag{2}$$

where *Nc*: number of days of autonomy; *Ej*: daily energy; *Dd*: maximum discharge; *Bsc*: storage capacity.

The storage capacity becomes approximately 98039 Wh. Since the selected DC bus voltage is 24 V, then the required amp hours of batteries will be 4085 Ah. Considering a battery of 6 V and 167 Ah. In this case there will be 24 strings connected in parallel and each string consisting of four batteries connected in series to have the 24 V DC bus, a total of 96 batteries.

2.3.2.3 Inverter

To ensure the reliability and availability of the power system, two inverters have been selected for an input voltage of 24 V and a 220 VAC output. The choice of the inverter is based on its ability to manage the expected maximum power of the loads used in alternating current. Therefore, it can be selected as 20% higher than the nominal power of the total charges presented. Thus, the rated power per inverter becomes 15 kW. The specifications of the inverter will be 15 kW, 24V DC, 220V AC and 50Hz. The inverters are connected to 2 separate 220 V AC bus bars so that during the day, each feed separate loads. At night, an inverter can be isolated for routine maintenance, for example.

2.3.2.4 Economic Evaluation

Economically, HOMER evaluates a project according to two criteria, the first is the current net cost, Net Present Cost in English (NPC) which is the present value of all costs that will occur during the lifetime of the project. This cost includes equipment purchase costs, replacement costs, maintenance costs, fuel costs and environmental penalties [28]**.** The NPC is calculated according to the formula:

$$C_{NPC} = \frac{C_{ann.tot}}{CRF(i, N)} \tag{3}$$

with, $C_{ann.tot}$ the annual financial charges, i the annual interest rate, *N* the life of the project and with *CRF (i, N)* which is given by:

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^{N-1}} \tag{4}$$

The second criterion is the cost of energy, which is the average cost per kWh of energy produced by the mini-grid. This cost is calculated according to the formula:

$$CO = \frac{C_{ann.tot}}{E_{loadserved}} \tag{5}$$

with, $E_{loadserved}$ is the energy supplied to the load.

Table 1 shows the technical and economic parameters introduced in HOMER for the different components during the simulation, the different costs were obtained on the spot in Lubumbashi. Below sensitivity analysis will be performed.

Table 1. Technical and economic parameters of the HOMER model

Component Parameters	Values
PV (Suntec crystalline Silicon module, 2018)	
Cost of capital	14000 $
Replacement cost	0 $
Dimension	11 kW
Duration	25 years
Devaluation factor	80 %
Batteries (Vision battery cell, 2018)	
Estimation	6 V, 167Ah
Initial cost per unit	300 $
Replacement cost	300 $
Maintenance cost	10 $
Number of strings	24
Duration	15 years
Converter (Anonymous, 2018)	
Capital cost	3800 $
Maintenance cost	0 $
Dimension	30 kW
Duration	15 years
Efficiency	90 %
Diesel Generator (Generator, 2018)	
Estimation	25 kW
Maximum load ratio	25 %
Initial cost per unit	15000 $
Replacement cost	0 $
Operational cost	0,75 $/hours
Duration	25 years
Efficiency	86, 2%
Economic System	
Interest rate	8 %
Interest rate	2 %
Diesel price	1,1 $/Liter

2.3.2.5 Environmental Assessment

Using HOMER, an environmental scan was conducted based on fuel consumption and greenhouse gas emissions. For this evaluation, three scenarios including diesel alone, PV-Diesel and PV-Diesel with energy storage system were studied.

3. Results

3.1. Spatial distribution of alternative sources of electricity in the city of Lubumbashi

The spatial distribution of diesel mini-networks, individual electric generators (generator), solar panels in the city of Lubumbashi is given in Figure 4. The mini-networks are more concentrated in the suburbs and to a lesser extent in some neighborhood's exchanges. The highest density of mini-grids is observed in Kisale, Kalebuka and Kafubu districts. The electric generator as an individual source of access to electricity is more common in Ruashi commune, Gambela and Lufira district. The use of solar panels is more common in the Mampala and Gambela districts. Overall, the density of all sources of electricity studied increases as it moves away from the Lubumbashi urban core to the denser zone of spontaneous peripheral neighborhoods. However, the density of these electricity sources is decreasing considerably in neighborhoods that are increasingly distant from the city center.

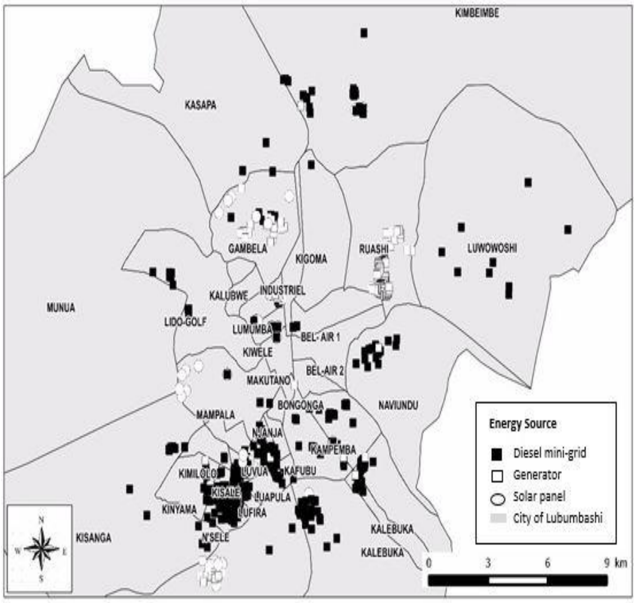


Figure 4. Spatial distribution of alternative sources of electricity in different districts of Lubumbashi (Source: authors' survey).

3.2 Influence of socio-economic factors on access to the mini diesel network

Table 2-Simple correlation Table 2 shows that the monthly income and the agricultural income source are negatively correlated to mini-diesel network subscriptions, but this relationship is not significant ($p > 0.05$). On the other hand, the other sources of income have a positive and not significant correlation with the mini-grid contribution, only households with sources of unspecified "other" income are significantly correlated to the mini-grid. In addition, the number of household managers with a "secondary" level of education increases significantly with the number of subscribers to the mini-grid. Others levels of study are not significantly correlated.

Table 2-Simple correlation between mini-grid connection, educational level, source of income, and monthly income

Figure 5 shows that households with a lower monthly income level tend to have more acceptances to connect to the mini-diesel network, or to opt for a collective solution.

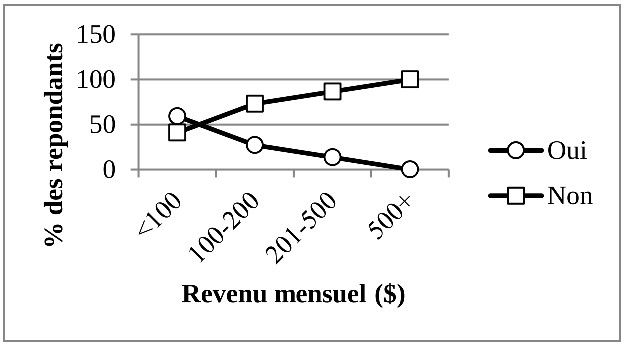


Figure 5. Households connected to the mini-diesel network by monthly income (Source: Authors).

Table 3 shows the average percentage of the learning level variable for the 1143 households connected to mini-diesel grids. For this variable, the secondary education level shows the highest percentage, 54.2% of the households surveyed. Thus, the secondary school level households connected to the mini-diesel network represent more than half (50%) of the households surveyed in all municipalities compared to other levels of education.

Table 3 - Level of study in relation to the different communes (PR: primary, SE: secondary, STC: short high school, STL: long tertiary, UN: university) (Source: authors' survey).

With respect to the source income variable, Table 4 shows that the liberal activity source has the highest total percentage, followed by the source other activities, 31.8% and 26% respectively.

Table 4- Source of income in the different communes (Aa: other activities, Ag: agriculture, Alib: liberal activity, Com: trade with register, Pcom: small business, Sal: salary) (Source: authors' survey).

The Chi-square test shows that there is a link between access to the mini-diesel network and education level and source of income variables ($\chi 2 > \chi c2 = 26.3$ for the level of education and $\chi c2 = 31.4$ for the source of income, at the significance level $p = 0.05$ [57-58]. Figure 6 shows the average monthly income by source of income. The comparison of sources of income with respect to their generated income shows that there is no significant difference between sources of income ($p = 0.123$).

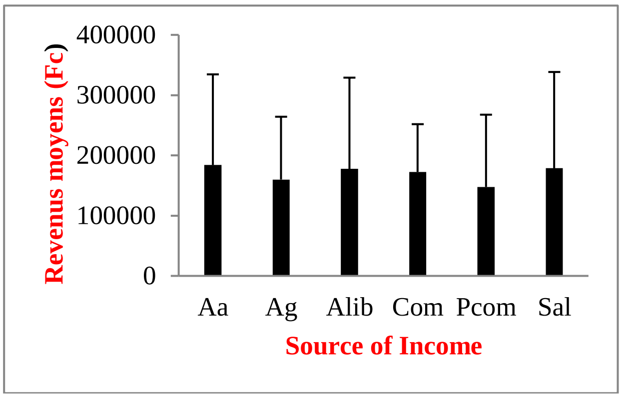


Figure 6-Average Monthly Income by Source of Income (Source: Authors Survey, $ 1 = 1600Fc)

Figure 7 presents the average monthly income in the different municipalities, the analysis of the variance between the communes on the average monthly income shows a highly significant difference ($p < 0.0001$). This difference is more remarkable between the commune of Lubumbashi and the commune of Kenya.

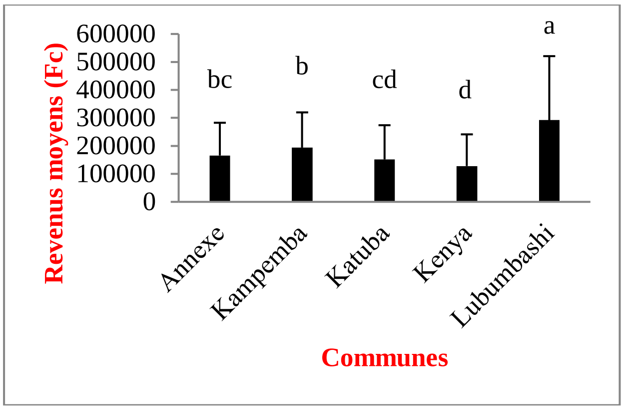


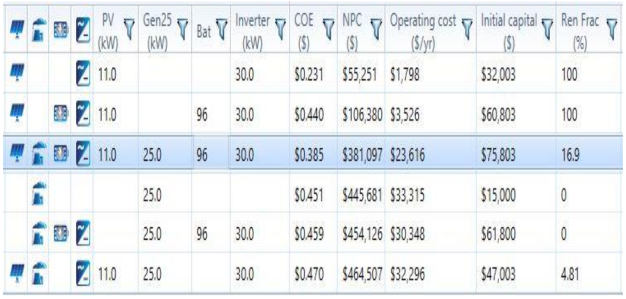
Figure 7-Average monthly income in relation to different municipalities (Source: authors' survey).

Table 5 shows that over 62% of identified mini-diesel grids are located in non-electrified neighborhoods (NEQs), while the presence of mini-diesel grids in electrified neighborhoods (EQs) is explained by hi

Table 5-Presence of mini-grids by type of neighborhood (QE: electrified district, QNE: non-electrified neighborhood, QEM: electrified district + presence of mini-grids, QEAM: electrified district + absence of mini-grids) (Source: authors' survey).

3.3. Technico-economic analysis of the proposed hybrid PV-diesel system

Figure 8 shows the results of the economic evaluation of a mini-grid in the Luwowoshi district. The simulation of the system when we are in a scenario in which the entire load is powered only by a generator, indicates that the COE (Cost of Energy) is $ 0.451 which is the cost of energy at kWh, the NPC (Net Preset Cost) is $ 445,681 and the group consumes about 29,779 liters per year. These results are found for an average daily energy consumption of 262 kWh. And for the liter of fuel going back to $ 1.1. In a scenario where the load is powered by a generator and a PV system, the energy cost is $ 0.470 per kWh, the NPC is $ 464.507. The fuel consumption is 27108 liters per year. As for the first scenario, these results are for an average daily consumption of 262 kWh. In the last scenario, the load is powered by a diesel-PV system with storage on 96 batteries of 1kWh, this configuration offers us the lowest cost of energy compared to the other two configurations is 0.385 $ // kWh. It gives an NPC of $ 381,097 and an annual diesel consumption of 19518 liters.



				PV (kW)	Gen25 (kW)	Bat	Inverter (kW)	COE ($)	NPC ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)
●			●	11.0			30.0	$0.231	$55,251	$1,798	$32,003	100
●		●	●	11.0		96	30.0	$0.440	$106,380	$3,526	$60,803	100
●	●	●	●	11.0	25.0	96	30.0	$0.385	$381,097	$23,616	$75,803	16.9
	●				25.0			$0.451	$445,681	$33,315	$15,000	0
	●	●	●		25.0	96	30.0	$0.459	$454,126	$30,348	$61,800	0
●	●		●	11.0	25.0		30.0	$0.470	$464,507	$32,296	$47,003	4.81

Figure 8. Simulation results with HOMER.

It is important to know what impact the change in fuel price may have on the energy cost of the mini-hybrid network. But also, to know if a change on the requested energy.

Figure 9 shows a distribution of the cost of energy according to the demand and the price of fuel. We can understand from this figure that the cost of energy would be the lowest if we had a strong demand and a price of the smaller diesel.

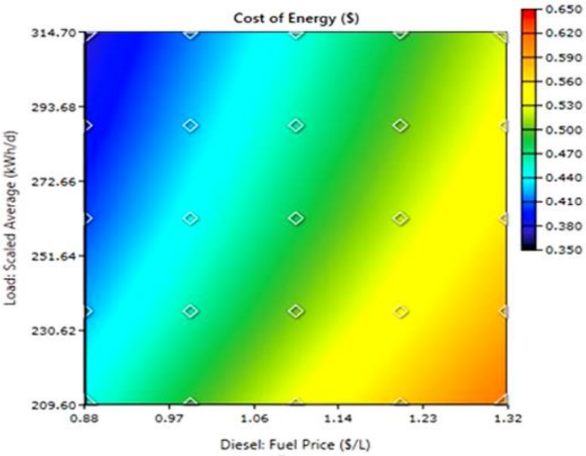
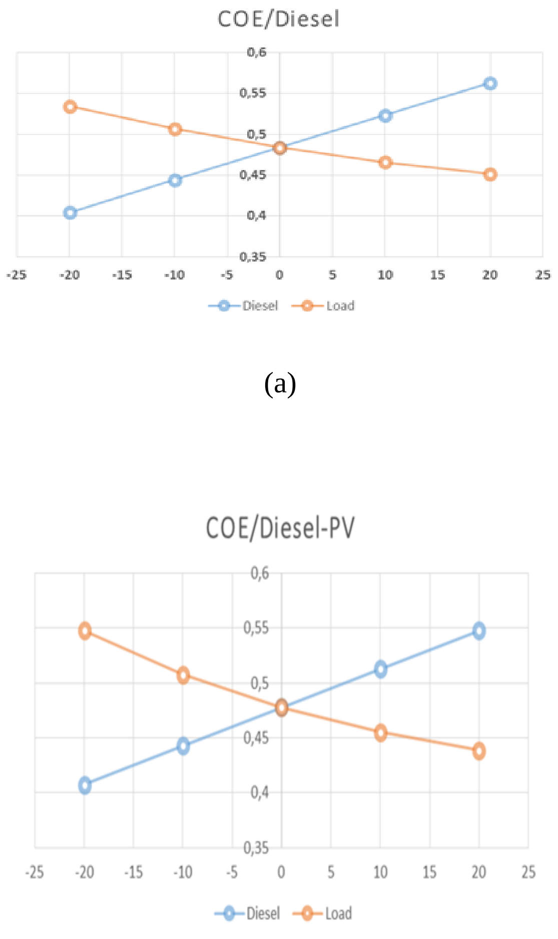


Figure 9. Change in COE based on diesel price and HOMER charge.

By varying the two sensitivities parameters, namely the fuel price and the fuel load, by a maximum of 20%, we evaluate the effect they have on the cost of energy in the three scenarios studied. Figures 10a, b and 11 show that an increase in the price of fuel causes an increase in the cost of energy while an increase in the load reduces the cost of energy.



(a)

(b)

Figure 10. Change in COE based on diesel price and load for Diesel (a) and Diesel-PV (b) configuration.

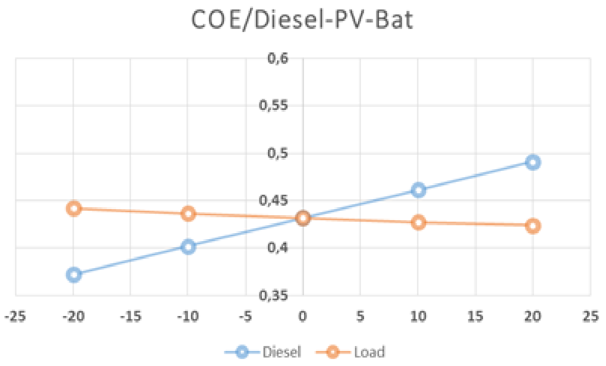


Figure 11. Change in COE as a function of diesel price and load for Diesel-PV-Batteries configuration

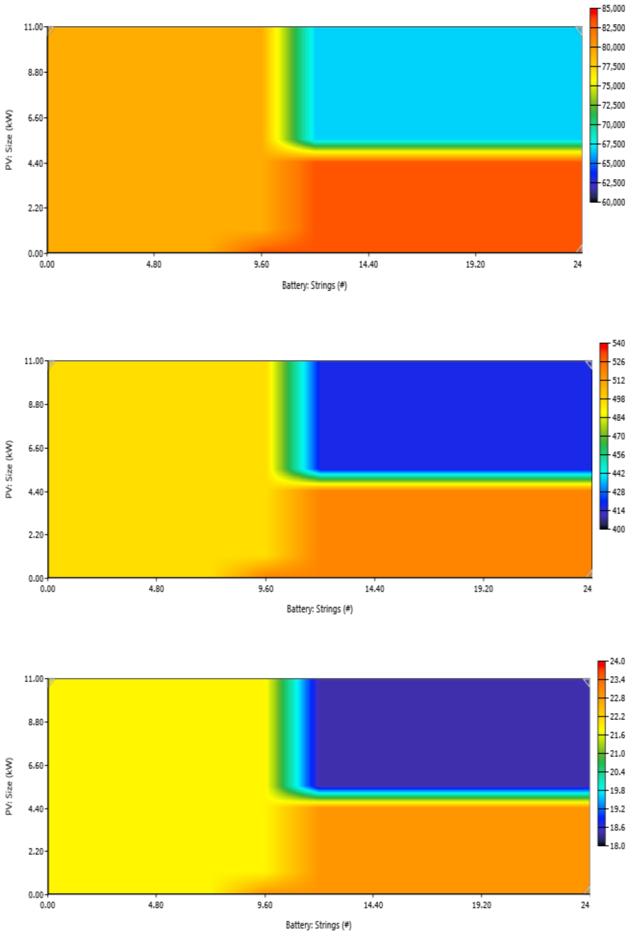
3.4 Environmental Analysis

Total fuel consumption per day per hour is higher when using diesel alone compared to using diesel in combination with photovoltaics. The addition of batteries to PV-Diesel reduces fuel consumption by more than 34% (Table 6).

Table 6. Fuel consumption according to different scenarios

Table 7. Fuel consumption according to different scenarios

Figure 12 presents a sensitivity analysis of greenhouse gas emissions and fuel consumption with increasing power of batteries and PV modules. Overall emissions of all greenhouse gases and fuel consumption drop significantly with the increase in the power of batteries and PV modules. It is also noted in this figure that the emissions decrease little when one puts PV, without storage and when one puts storage for low values of PV, in both cases the diesel group continues to function to cover the rest of the load, which increases emissions.



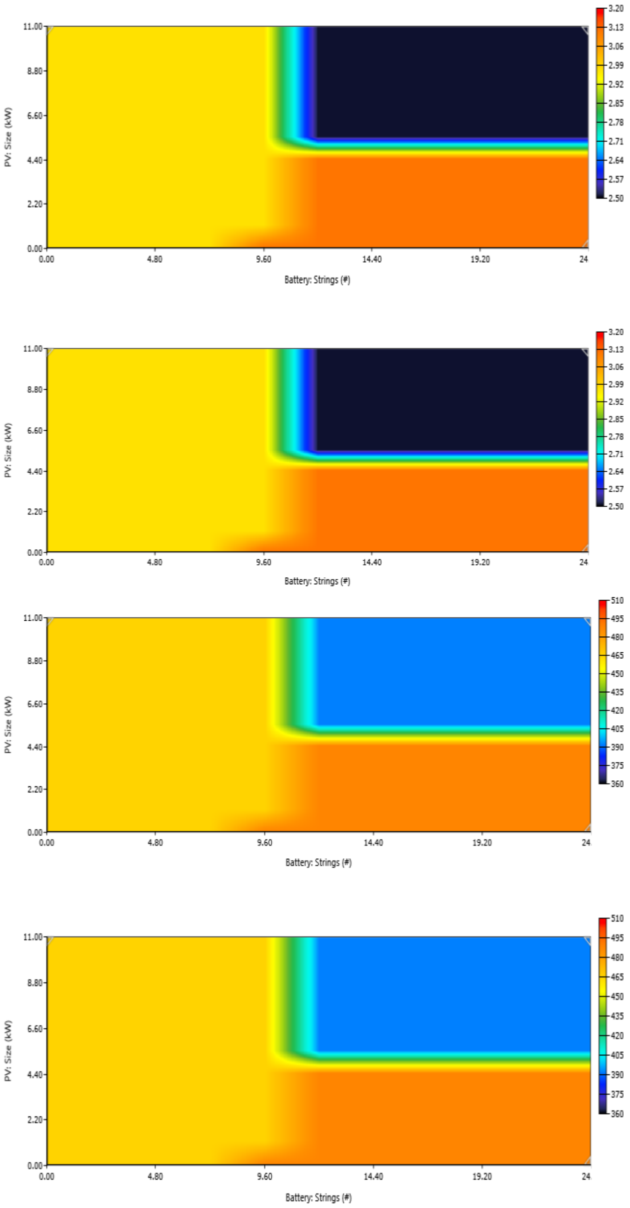


Figure 12. Variation of greenhouse gas emissions by battery power and PV modules calculated with HOMER

4. Discussion

4.1. Relationship between socio-economic status of households and spatial distribution of energy sources

This study showed that mini-diesel networks are more concentrated in outlying neighborhoods (62.8%) and to a lesser extent in some central neighborhoods (37.2%). This observation is mainly due either to the absence of the electric utility network of the National Electricity Company (SNEL) in the outlying districts and in the central districts by a service characterized by long-term interruptions (14 hours / days) [14]. Banza et al. [15] revealed that between 1996 and 2014, the distribution of electric cabins did not follow urban sprawl. The electric generator (generator) as an individual source of access to electricity is more common in Ruashi commune, Gambela district and Lufira district. In addition, this solution is more expensive than the direct connection to the electricity grid [59-61]. The cost of electricity produced by electric generators in Sub-Saharan Africa is estimated at between 0.35 and 0.40 $ / kWh [61], this is four to five times higher than the price of kWh sold by SNEL. The use of solar panels is more common in Mampala and Gambela districts. Overall, the density of all alternative sources of electricity studied increases as it moves away from the urban core [5, 62-63] from Lubumbashi to the zone of higher density consisting of spontaneous peripheral neighborhoods. The high density of diesel mini-grids and solar panels in the peripheral neighborhood belt is motivated by the inaction of the public authorities in the viabilization of these neighbourhoods [15]. On the other hand, in the neighborhoods that are more and more distant from the city center, the collective sources of access to electricity such as the mini-diesel network are limited by the very low density of the building. This situation offers the unique possibility of using individual solutions such as photovoltaics (PV) and the individual electrical generator [61].

Monthly income and farm income source are negatively correlated to mini-diesel subscriptions. On the other hand, the other (diversified) source of income is positively correlated to the mini-diesel network subscription. This study corroborates Muhoza and Johnson's [65] claim that to improve the payment capacity of users of mini-grids, it is necessary to diversify their sources of income. With respect to the monthly income variable, the finding in this study shows that higher-income households do not use collective solutions such as mini-diesel. Typically, these households live in serviced central neighborhoods using the personal diesel generator and / or the PV system as an alternative source of electricity in the event of a power outage [66]. Other high-income households show the least satisfaction with the use of fossil fuel for the PV system, this has also been shown in Bangladesh by Alam and Bhattacharyya [13]. The number of household managers with a "secondary" level of education increases significantly with the number of subscribers to the mini-diesel network.

Other levels of study are not significantly correlated. This link indicates that the level of education determines household access to the mini-grid. The level of education of the household plays an important role in the selection and consumption of various types of fuels [67]. It has an impact on the willingness to pay for the energy consumed when the household is connected to the mini-grid [68]. Highly educated households are less and less connected to the mini-diesel network. This may be justified by the fact that people with a higher level of education generally adopt the autonomic PV system than those with a lower level of education [66, 69-71]. This study also showed that the high numbers of households subscribing to the mini-diesel network are particularly installed in Katuba commune. Their sources of revenue are mainly small businesses and other activities. In addition, the secondary level of education characterizes the households connected to the mini-network in Katuba commune. While the township and Kampemba are respectively characterized by the level of primary education and university less subscribers to the mini-network. The level of education and the level of income next to the location of the household, are the factors that determine the most access of a household to the mini-diesel network.

4.2. Technical-economic and environmental analysis of the hybrid PV-generator mini-grid

According to our previous work [14], a large proportion of households in Lubumbashi (29.2%) use generators to meet their electrical energy needs. And only 3% of households surveyed use the photovoltaic system. The hybrid system as studied in this work presents an alternative solution to the high cost represented by an extension of the conventional network for the outlying districts of Lubumbashi. The important indicator of the durability of this type of mini-grid is the cost of energy. Evaluating a particular energy system for its techno-economic feasibility is of utmost importance if the system is to function satisfactorily at a given location [72]. The optimal solution found in this study involves an energy cost of $ 0.385 / kWh. This value is close to those found by Batha [73] and Lao [74] for similar applications respectively in Ethiopia and Cambodia, and lower than the cost found by Abanda et al. [75] in Cameroon. The cost found in this study is much higher than the price of electricity sold by SNEL ($ 0.087 / kWh). The high unit cost of electricity found in this study could be associated with the high cost of photovoltaic solar modules [24]. From an economic point of view, the hybrid PV system is therefore less competitive than the electricity supplied to homes by the conventional grid.

The lower competitiveness of photovoltaic solar systems, regardless of the country's solar potential, could be explained by the fact that government policies to increase the amount of electricity produced have been largely concentrated on hydroelectric power stations [75]. In the outlying districts, where the extension of the electricity grid is less likely due to the shortage of electricity in the city, the current cost of energy, as found in this study remains affordable and reliable especially in the long term. The African Development Bank [77] has shown that for electricity from their mini-diesel networks SNEL would apply tariffs ranging from $ 0.32 / kWh to $ 0.40 / kWh [78] and EDC (Electricity of Congo) 0, $ 48 / kWh in Tshikapa, DR Congo. While independent power producers such as Hydro-force and Enerkac in Kananga in DR Congo sell their electricity to the local grid at a price of $ 0.31 / kWh and $ 0.39 / kWh respectively [77].

According to Halabi et al. [79], the hybrid PV-diesel-battery system has the best technical characteristics and very good economic characteristics based on the overall cost of the system. According to our study, the cost of energy is high by using PV alone compared to using the diesel engine alone. The environmental analysis has shown that regardless of the greenhouse gas considered, its emission is higher if the diesel is used alone and decreases with the adoption of hybrid solutions. The use of PV-diesel-batteries reduces emissions by more than 34%. Jamil et al. [72] estimated the reduction in carbon emissions using the hybrid system above at about 24% compared to the scenario using only the diesel engine. The use of a hybrid PV-diesel battery system can significantly reduce dependence on available diesel resources only if the design of the diesel generator and PV array is done and demonstrated [80].

5. Conclusion

The objective of this research was to evaluate the feasibility of a mini hybrid PV-diesel network to electrify peri-urban areas in Lubumbashi. This research presents in its first part the spatial distribution of alternative sources of electricity by identifying the socioeconomic factors of households explaining this distribution. Socio-economic survey data from 5,270 households across the city of Lubumbashi revealed 163 mini-grids fueled by diesel generators serving 1143 households, or 21.6 % of households surveyed. The results of this study showed an increase in the density of solar panels, electric generators and mini-diesel networks with distance from downtown Lubumbashi. This study also revealed that there is a link between access to the mini-diesel network and household socio-economic variables and this link is different for different variables. This link is positive and more significant with the secondary education and other income source variables (the combination of several identified sources of income). The variable monthly income, however, shows a negative but not significant link with the ac

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Table 2: Simple correlation between mini-grid connection, educational level, source of income, and monthly income

Source of income and monthly income							
	Salary	Registry	Small Commerce	Liberal	Agriculture	Others	Monthly Income
Index	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 long term	Superior long term	University		
Index	0,397	0,935	0,682	0,347	-0,186		
p value	0,508	**0,02**	0,205	0,567	0,765		

Table 3: Level of study in relation to the different communes (PR: primary, SE: secondary, STC: short high school, STL: long tertiary, UN: university) (Source: authors' survey).

Township		Level of Study (%)					
	n	PR	SE	STC	STL	UN	Total
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
Chi-square	χ^2= 83,9141, *dl* = 16, *p-value* = 3,254e-11						

Table 4: Source of income in the different communes (Aa: other activities, Ag: agriculture, Alib: liberal activity, Com: trade with register, Pcom: small business, Sal: salary) (Source: authors' survey).

Township	Source of Incomes (%)							
	n	Aa	Ag	Alib	Com	Pcom	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
Chi-square	χ^2= 185,0028, *dl* = 20, *p-value* < 2,2e-16							

Table 5: Presence of mini-grids by type of neighbourhood (QE: electrified district, QNE: non-electrified neighbourhood, QEM: electrified district + presence of mini-grids, QEAM: electrified district + absence of mini-grids) (Source: authors' survey).

Mini-grids (%)		**Nb of breaks/day**	
QE	**QNE**	**QEM**	**QEAM**
37,2	62,8	14	9

Table 6: Fuel consumption according to different scenarios

Quantity	Fuel Consumption (L)		
	Diesel	PV-Diesel	PV-Diesel-Batteries
Total consumption	29779	27108	19518
Daily average consumption	81,6	74,3	53,5
Hourly average consumption	3,4	3,09	2,23

Table 7: Quantity of Greenhouse Gases Emitted for Different Scenarios

Type of gases	Emission of greenhouse gases (kg/an)		
	Diesel	PV-Diesel	PV-Diesel-Batteries
Carbon dioxide (CO_2)	77959	70966	51095
Carbon monoxide (CO)	487	443	319
Unburned hydrocarbons (HC)	21,4	19,5	14,1
Volatile particle (PVo)	2,92	2,66	1,91
Sulphur dioxide (SO_2)	191	174	125
Nitrogen oxides (NOx)	457	416	300