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Research Article

Advancing Stand-Alone Photovoltaic Systems in Developing City Outskirts: Technical Solutions and Financing Approaches

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Abstract: This study evaluates the feasibility of electrifying isolated households using stand-alone photovoltaic systems. A technical-economic analysis was conducted in a peri-urban district of Lubumbashi (DRC), characterized by low building density and significant distance from the electricity grid. Surveys of ten households revealed that for an average load of 1,850 Wh/day, the required system includes two 350 Wp PV panels, four 250 Ah batteries, and a 1,000 W inverter. The system's life-cycle analysis estimates an investment cost of 2,542 USD and an energy cost of 0.32 USD/kWh. Additionally, a financing model is proposed, emphasizing flexible government policies and partnerships with photovoltaic equipment producers.

Keywords: stand-alone photovoltaic systems, financing strategies, model of financing, developing countries, lubumbashi

1. Introduction

Reliable and affordable energy access is vital for socio-economic development [1]. Globally, over 850 million people lack electricity, particularly in remote, inaccessible areas [2]. Unlike urban zones with diverse energy sources, rural areas in developing countries face challenges accessing electricity. Extending national grids, while costly, often strains fragile economies [2]. Disparities in electricity access exist across continents, countries, regions, cities, and even neighborhoods [3]. Despite abundant energy resources, Sub-Saharan Africa has the world's lowest electrification rate, where rapid population growth and inefficient systems exacerbate limited energy access.

In the Democratic Republic of Congo (DRC), only 9% of the population has access to electricity, dropping to 1% in rural areas, which make up 76.8% of the population. In Lubumbashi, the second-largest city, urban electricity access is 61.6%, but power outages are frequent and unpredictable [4]. Electrifying remote, low-density neighborhoods requires significant investment, as low building density-ty increases household grid connection costs [5]. The extension of electricity net-works to outlying areas is costly for the state, further strained by limited power plant capacity and an energy deficit in Haut-Katanga province. One proposed solution is to refurbish existing power plants to enhance their capacity and meet the growing energy needs of households and industries. However, such upgrades re-quire significant investment, often reliant on foreign funding. Institutional fragility-ty and a lack of trust from international donors make this approach challenging to implement. The future of universal electricity access in the DRC lies in renewable energy. Prioritizing flexible, localized solutions that align with the country's realities is essential [6]. Stand-alone photovoltaic (PV) systems have proven to be

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reliable, secure, and ideal for remote peri-urban and rural areas in most developing regions. These autonomous systems are often cost-competitive with conventional energy sources and are highly adaptable to decentralized setups of various scales. They can drive societal transformation by reducing poverty, providing clean energy, and combating climate change [7]. To harness this potential, enhancing knowledge of PV technology's implementation, usage, and adaptation to local contexts is critical. For many Congolese living without electricity, PV systems offer a sustainable energy solution. While initial costs are high, they decrease over time, unlike traditional generators whose efficiency declines. Furthermore, PV installations are easy to set up and maintain, offering long-term, renewable energy access. However, their adoption remains hampered by low affordability, particularly for low-income households. More flexible policies and subsidies are essential to democratize this technology. This study therefore aims to propose policies focusing on financing and subsidies, in order to make stand-alone photovoltaic systems accessible to all, even the poorest households.

Off-grid electrification using photovoltaic systems in developing countries is a widely studied topic in the literature. However, this literature focuses mainly on the technical aspects, neglecting the financing strategies that are essential to pro-mote the implementation of this mode of electrification [8]. In this article, we explore in detail the strategies for promoting stand-alone photovoltaic systems as a solution for access to electricity in developing countries. We also analyze the players involved, their roles and the associated financing mechanisms.

The structure of the article is as follows: Section 2 presents the methodology of the study, starting with an introduction to the case study. Section 3 presents the results obtained, with a discussion, and proposes a financing model. Section 4 concludes the study.

2. Methodology

2.1 *Study area*

In order to assess the adaptability of stand-alone PV systems, this study was carried out in the city of Lubumbashi, the second largest city in the DRC, after the capital Kinshasa. The fieldwork was carried out in Kasungami (11°43′51″ S, 27°28′46″ E), an outlying district of the city of Lubumbashi (Figure 1). This site was chosen for the following reasons: its remote position in relation to the city center, its low building density, the absence of electrical infrastructure and the presence of a few households already using photovoltaic systems. These features reflect the typical conditions of many spontaneous neighborhoods on the outskirts of Lubumbashi [5], [9], [10]. Kasungami offers a suitable environment to explore the feasibility of stand-alone PV systems as a solution to the lack of grid electricity, prompting a survey to assess household energy consumption due to the absence of documented data in Lubumbashi. Ten households relying on PV systems were surveyed, and one representative household was selected to analyze PV system potential.

2.2 *Components of a PV system*

Broadly speaking, a stand-alone PV system consists of five essential components (Figure 2), namely [11]:

1. The photovoltaic solar panel that allows to produce the required amount of electricity. The solar charge controller that protects storage batteries against over-charging and deep discharging.

2. The solar batteries that allow to store the energy produced by the photovoltaic solar panel.

3. The inverter transforms the available DC energy (Direct current) in the batteries into 230 V alternating current (AC = Alternating Current) DC and AC consumers (load). Depending on the application, DC (12/24 V) or AC (230 V) applications can be connected to the autonomous system.

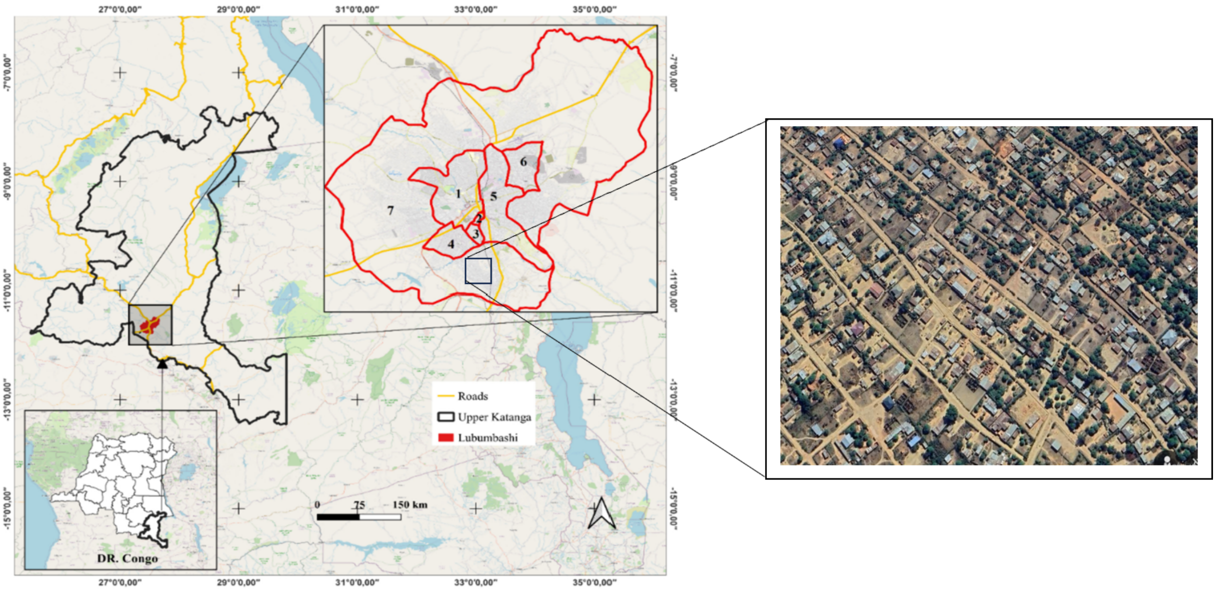

Figure 1. Geographical location and administrative division of the city of Lubumbashi in the province of Haut-Katanga, DRC. Lubumbashi comprises over 80 districts in 7 municipalities, covering a total area of 747 km. These municipalities are Lubumbashi (1), Kamalondo (2), Kenya (3), Katuba (4), Kampemba (5), Ruashi (6), and Annexe (7). The case study is located in the Annexe municipality

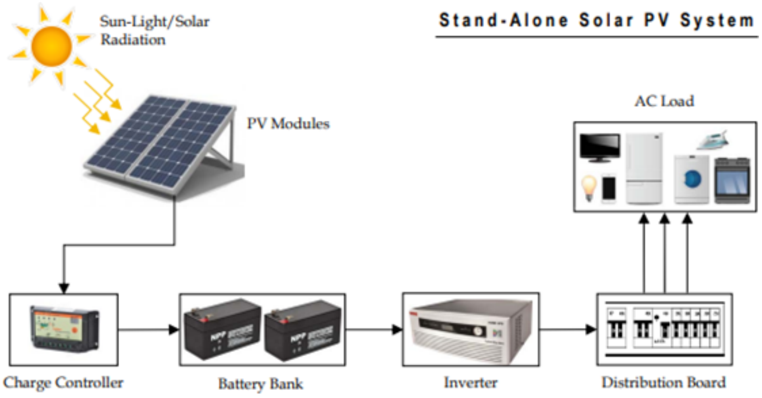

Figure 2. Configuration of a stand-alone solar photovoltaic energy system (Source: [11])

2.3 *Sizing method*

To size a stand-alone PV system, it is necessary to know the temperature and irradiation, consumption profile, and equipment data to be able to determine the power that the PV system can provide [12]. When sizing a photovoltaic system, the first step is to determine when the household needs electricity. Thus, it is necessary to identify the appliances used (the load) in order to quantify the electricity needs of each household and to define the size of the PV station to be set up.

2.3.1 *Sizing of the PV park*

Based on the results on household electricity needs, the number of PV module needed to cover the electricity needs can be calculated. This requires calculating the energy that the modules need to produce each day, as well as knowing the amount of sunshine in the city of Lubumbashi in general. The amount of electricity produced by the photovoltaic modules depends directly on this sunshine and therefore on the region. The average daily solar energy input at the latitude of the site is about 5.5 kWh/m^2/day for the city of Lubumbashi (Figure 3).

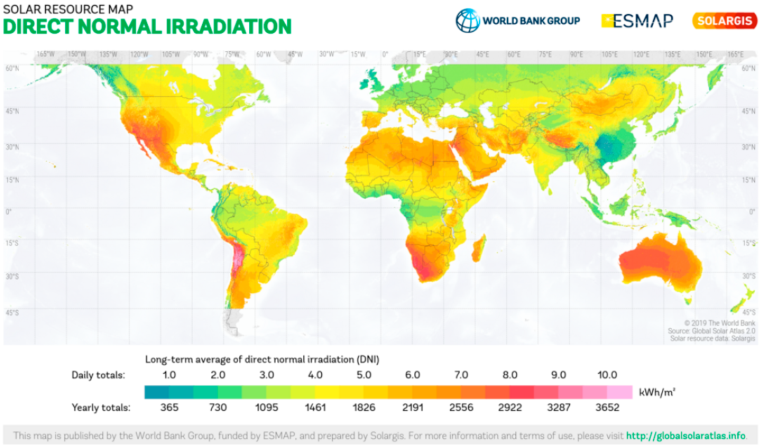

Figure 3. Global DNI map from Global Solar Atlas 2.0, a free application developed by Solargis for the World Bank Group, with financial support from the Energy Sector Management Assistance Program (ESMAP) (Source: [13])

To design a stand-alone PV system for a household, it is essential to determine the number of solar panels and batteries required based on energy consumption patterns and storage needs. Additionally, the charge controller must be sized, and an inverter selected if devices operate on alternating current [14]:

$$\mathrm{PV}_{\text{area}} = \frac{E_L}{G_{av}\eta_{pv}T_{\mathrm{CF}}\eta_{\text{out}}} \tag{1}$$

where:

- $\boldsymbol{G_{av}}$: average daily solar energy
- $\boldsymbol{T_{\mathrm{CF}}}$: temperature correction factor
- $\boldsymbol{\eta_{pv}}$: PV system efficiency
- $\boldsymbol{\eta_{\text{out}}} = \boldsymbol{\eta_b \eta_{\text{inv}}}$, where: $\boldsymbol{\eta_b}$: battery efficiency and $\boldsymbol{\eta_{\text{inv}}}$: inverter efficiency
- E_L: daily load

2.3.2 *Battery capacity sizing*

The storage capacity (SC) of the battery can be calculated according to the following relationship [15]

$$\mathrm{SC} = \frac{\mathrm{Nc}E_L}{\mathrm{DOD}}\eta_{\text{out}} \tag{2}$$

where:

Nc: the number of days of autonomy

DOD: the maximum allowed discharge of the battery

2.3.3 *Design of the battery charge controller (regulator)*

A charge controller regulates battery charging, prevents overcharging, deep discharge, and nighttime discharge, while protecting against faults. Proper design ensures durability, efficient energy storage, and compatibility with the PV array's short-circuit current.

2.3.4 *Inverter design*

The selection of the inverter is based on its ability to handle the maximum expected power of the loads used in AC. Therefore, it can be selected to be 20% higher than the rated power of the total loads.

2.3.5 *Life cycle cost analysis*

The Life Cycle Cost (L_{CC}) of an item consists of the total costs of ownership and operation over its lifetime, expressed in current money [16]. The costs of a stand-alone PV system include acquisition, operation, maintenance, and replacement costs.

Considering a lifetime N of all components at 20 years, and 5 years for that of the batteries [15], three additional battery packs need to be purchased after 5 years, 10 years and 15 years, assuming an inflation rate i of 3% and an interest rate d of 10%. After an estimated 5 years of use, the cost of the first additional group of batteries C_{B1} given by [16]:

$$C_{B1} = C_B \left(\frac{1+i}{1+d}\right)^N \tag{3}$$

C_M the cost of maintenance can be calculated using the cost per year method (M/year = 2% of PV cost (PV_C) and system lifetime (N = 20 years) by:

$$C_M = \left(\frac{M}{yr}\right)\left(\frac{1+i}{1+d}\right)\left[\frac{1-\left(\frac{1+i}{1+d}\right)^N}{1-\left(\frac{1-i}{1-d}\right)}\right] \tag{4}$$

Therefore, the L_{CC} of the system obtained for the study case is:

$$L_{CC} = PV_C + C_B + C_{B1} + C_{B2} + C_{B3} + C_C + C_{\text{inv}} + C_{\text{inst}} + C_M \tag{5}$$

It is sometimes useful to calculate L_{CC} of a system on an annual basis. The annualized L_{CC} (AL_{CC}) of the PV system in terms of current US dollars, calculated as follows [2]:

$$AL_{CC} = L_{CC}\frac{\left[1-\left(\frac{1+i}{1+d}\right)\right]}{\left[1-\left(\frac{1+i}{1+d}\right)^N\right]} \tag{6}$$

Once the AL_{CC} is known, the electrical cost (cost per kWh) can be calculated,

$$C_E = \frac{AL_{CC}}{365E_L} \tag{7}$$

3. Results and discussion

3.1 *PV system components*

In order to size the components of the stand-alone PV system, it was first necessary to establish an average consumption profile for the ten households surveyed, and to identify the appliances used by these households (Table 1).

Table 1. Average values of electrical loads used in surveyed households (Source: survey data)

Appliances used	Number	Power (W)	T (Hour/day)	E_L (Wh/day)
Bulbs	5	90	4 et 8*	450
Radio	1	80	2	160
Computer	1	250	2	500
TV	1	80	6	480
DVD	1	10	2	20
Water pump	1	120	2	240
Total		630		1,850

*4 light bulbs are used for 4 h and 1 is used for 8 h.

The daily load obtained (1,850 Wh) is assumed to be identical for all days of the year while the corresponding load profile is given in Figure 4.

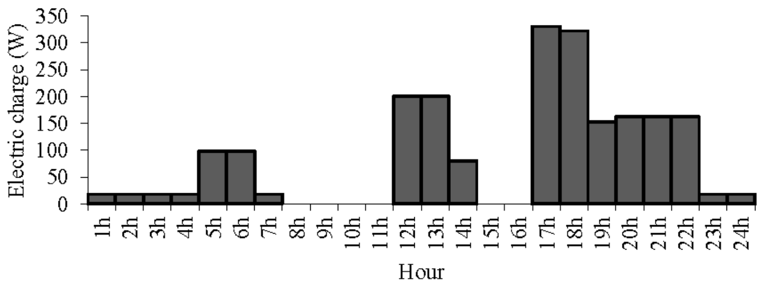

Figure 4. Average load profile for the 10 households surveyed (Source: authors' surveys)

3.1.1 *PV park*

For a 24 V 100 Ah battery, 4 batteries are used and connected in parallel. Assuming $\eta_{pv} = 12\%$ and $\eta_{\text{out}} = 0.85 \times 0.9 = 0.765$. With 0.85 as battery efficiency and 0.9 inverter efficiency.

Thus, using equation (1) the PV area is 4.6 m^2, the peak PV power at the peak solar insolation (PSI) of 1000 W/m^2 is given by:

$$PV_{\text{peak power}} = PV_{\text{area}} PSI \eta_{pv} = 552\ W_p$$

In this study, the modules selected and present on the market in Lubumbashi are in polycrystalline silicon with the following specifications under standard test conditions:

- Pn = 375 Wp
- No-load voltage = 36 V
- Short circuit current = 10.4 A

To serve a household, 2 PV modules are used. Based on the required DC bus voltage and current, the parallel configuration of the PV array could be readjusted. With a DC bus voltage of 24 V, the two modules are connected in parallel.

3.1.2 *Batteries, charge controller and inverter*

Starting from the equation (2) and considering an average of 3, the number of days of autonomy, for a maximum discharge 80%, the storage capacity becomes 9,069 Wh. Since the selected DC bus voltage is 24 V, then the required ampere hours of the battery will be 378 Ah. For a 24 V 100 Ah battery, 4 batteries are used and connected in parallel.

Since the short circuit current of a solar panel is 10.4 A, in this case we can choose to handle 16 A for the charge controller and keep the DC bus voltage at about 24 V. The total loads presented in Table 1 lead to the choice of an inverter with a power rating of 1000 W. The required inverter specifications will be 1000 W, 24 VDC, 220 VAC and 50 Hz.

3.2 *L_{CC} analysis*

The cost of all components can be calculated as follows:

- $PV_C = 2 \times 100 = 200$ USD
- Initial battery cost $C_B = 4 \times 200 = 800$ USD
- The cost of the first additional battery bank C_{B1} is calculated to be 587 USD (see equation (3)).
- The cost of the second additional battery bank purchased after N = 10 years C_{B2} and the third bank purchased after 15 years C_{B3} are calculated using the above equation as 424 USD and 312 USD respectively.
- The cost of the controller (C_C) = 55 USD
- The cost of the inverter (C_{inv}) = 100 USD
- Installation cost (C_{inst}) = $0.1PV_C = 0.1 \times 200 = 20$ USD
- The maintenance cost (C_M) can be calculated as 44 USD using equation (4).

Therefore, the L_{CC} (Equation (5)) of the system is 2,542 USD and the AL_{CC} (Equation (6)) of the PV system is 218 USD. Based on the data in this study, the electrical cost (Equation (7)) is 0.32 USD/kWh.

The cost per kWh of electricity from photovoltaic (PV) systems in this study is approximately four times higher than the rate charged by National Electricity Company (SNEL) (0.08 USD/kWh). However, while PV electricity costs more than SNEL's grid electricity, it is relatively competitive when compared to costs in other countries. For example, in 2017, the cost per kWh of PV for similar uses was 0.46 USD [3], with a 30% reduction seen by 2024. These findings align with research by Ayik et al. [4] in South Sudan. Notably, this cost reflects basic appliances (e.g., lighting, television, radio) and excludes high-energy appliances like refrigerators or freezers. The study disagrees with the [5], which estimated PV energy costs in Lubumbashi at 0.11–0.12 USD/kWh for larger 20 MWp systems. This cost discrepancy is likely due to system size differences, as larger systems benefit from economies of scale [6] similarly observed that increasing PV system size with energy storage significantly lowers energy costs. Globally, PV costs have declined due to falling module prices, once the primary cost driver. According to [7], the price per PV kWh dropped 70% from 2010 to 2023, from 0.393 USD to 0.117 USD. In Lubumbashi, where PV system costs currently stand at 0.32 USD/kWh, PV installers (under service delegation models) must charge at least this rate to remain profitable. Although this is significantly higher than SNEL's 0.08 USD/kWh, costs could drop to 0.21 USD/kWh if PV module prices fall to 0.08 USD/Wp and battery costs halve. Solar photovoltaic (PV) energy offers significant advantages in terms of reducing carbon emissions. However, its intermittent nature poses challenges in terms of energy supply. This is why batteries are essential for regulating energy production, making it necessary to install high-performance batteries in stand-alone PV systems [8].

It is important to note that, independently of increasing battery storage capacity, the installed power of the system must also be increased [9]. Thus, the variability of solar irradiation over time offers a wide range of applications, influenced by climatic conditions.

Compared with a system powered by a diesel generator operating at maximum efficiency, the system proposed in this work saves between 0.94 kg and 1.52 kg of CO_2 per kWh produced [10]. To meet a requirement of 1,850 Wh per day, the generator system would have to emit around 1.7 to 2.8 kg of CO_2 per day, representing between 630 kg and 1 tonne of CO_2 per year. Furthermore, if SNEL's grid electricity cost triples due to declining generation capacity and reliance on costly imports from Zambia, PV systems could become a promising solution for electrifying remote households despite initial costs.

3.3 *Financing strategies*

3.3.1 *Actors and their roles*

The Congolese state plays a crucial role in promoting photovoltaic (PV) systems, requiring clear political commitment translated into supportive policies and regulations. Tax incentives could encourage PV adoption, either by complementing or replacing subsidies. For instance, reducing or eliminating duties and taxes on imports and equipment purchases for electrification projects is a widely used approach to boost PV deployment. Government involvement in household solar PV could include:

Allocating public funds for research and development;

Supporting small and medium-sized enterprises (SMEs);

Offering fiscal incentives and ensuring fair competition with conventional solutions;

Providing subsidies to encourage adoption.

In Lubumbashi, multiple stakeholders are engaged in promoting PV systems. Households are central players, with high-income families more likely to adopt PV than lower-income ones. Other actors include international development agencies, donor organizations, NGOs, and technical experts, who can create mechanisms to improve access to stand-alone PV. Meanwhile, SNEL could establish quality standards for PV equipment to ensure reliability and efficiency.

3.3.2 *Model of financing*

Institutional models for the distribution of stand-alone photovoltaic systems: donations, customer self-financing, credit, service charges, etc. are shown in Figure 4. In case of donation, the end user becomes the owner of the whole PV system. The owner's contribution is often less than 10% of the total cost of the equipment.

In case of credit, the customer buys the solar system under a credit agreement (Figure 5). The advantage of credit for the user is that the costs are spread over a period of time. As long as the systems are owned by the financial institution, that institution has the responsibility to ensure that the systems are functioning properly. This will support the use of high-quality systems and service. One problem may be finding a player that is willing to function as a financier. Commercial banks are not yet used to the solar system and may perceive them as a risk. For international financiers, providing credit for solar home systems can be an opportunity to stimulate the introduction of solar energy.

In case of service fees, an energy service company sells the energy service, but retains ownership of the PV system indefinitely. The energy service company can be a private or public company, a cooperative or an NGO. The consumer pays a fixed monthly fee for the service or pays for the amount of energy consumed.

In the case of hire-purchase, one system that can incentivize access to stand-alone PV technology is based on an agreement between an employer and a PV kit provider. In this agreement, the technology provider offers PV kits to be paid for under a hire purchase agreement. The monthly payment is then deducted from each employee's salary for up to three years after the salary is paid [11]. This is a common way of purchasing goods in many sub-Saharan African countries, including Kenya [12]. In the case of the city of Lubumbashi, the various individual mining companies and other private enterprises as well as state utilities could use this arrangement. Thus, most of the employees who do not have access to electricity in their households would benefit from stand-alone PV, which is a sustainable technology. Suppliers, on the other hand, should be encouraged to engage in this form of arrangement only if government policies on PV are flexible and incentive-based. For microfinance, it has long been considered the best single solution for financial inclusion of the poor [11]. For this reason, it has also been tested for the provision of financing for stand-alone PV by international donor agencies in most developing countries [13].

Public subsidies are frequently utilized since PV technologies remain relatively expensive and inaccessible for many low-income households. Establishing special funds can help expand financing channels for stand-alone PV projects while providing preferential interest rates for loans [14]. For example, in 2011, Grameen Shakti (a rural energy organization in Bangladesh) benefited from tax exemptions on imported PV modules and received USD 35 per installed off-grid PV system from the government.

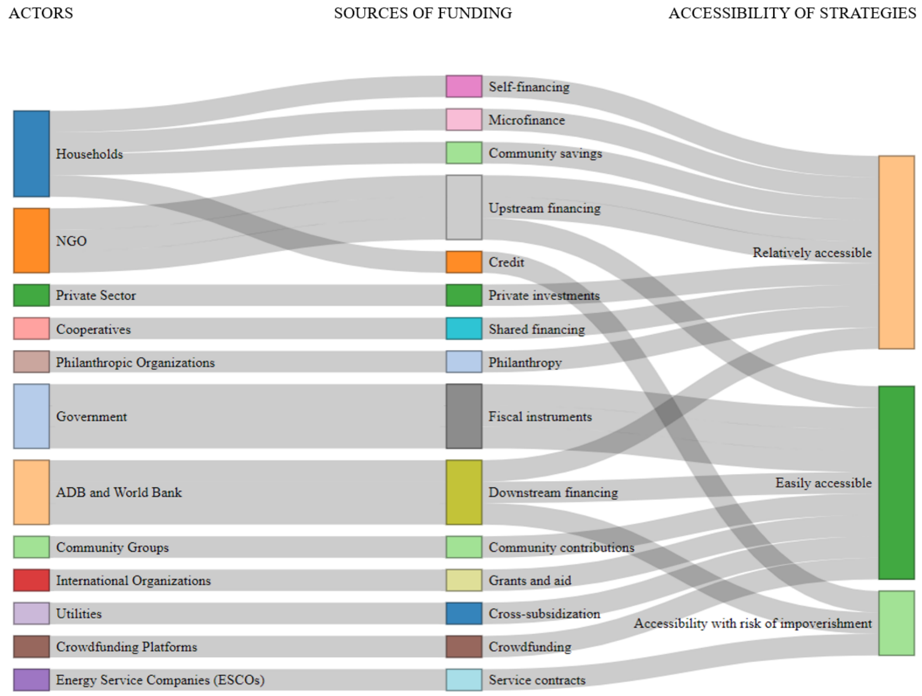

Figure 5. Model of financing, a tool for technology adoption (Source: authors)

A "capital subsidy" is one of the most common policy tools to overcome the initial investment barrier for households. Furthermore, several developing countries have significantly reduced or even abolished taxes on PV markets, creating effective incentives. Self-financing is a widely used conventional financing model where buyers acquire assets using their own funds. Under this model, owners shoulder the full costs of installation and maintenance for solar PV systems, which can result in high upfront expenses, limiting adoption. Maintenance is often provided by private providers on a fee-for-service basis. Unfortunately, this model excludes low-income households and primarily benefits high-income groups. An example from Thailand highlights solar leasing services, which expand the PV market by enabling customers to pay for solar systems over time and avoid high initial costs [15]. Across all financing models, government subsidies remain essential to reduce costs for households. To increase the adoption rate of photovoltaic (PV) systems at household level, the government plays an essential role as the main source of policy and regulatory frameworks, especially in remote areas [16]. However, the absence of favorable legislation has a significant impact on the barriers to adoption of these systems.

This confirms the findings of Mustafa et al. [17], who point out that in the absence of specific governmental support in terms of policies and regulations, barriers to the adoption of PV systems cannot be easily overcome. For instance, the fee-for-service system spreads costs over long periods (up to 10 years). Additionally, incentive structures open access to PV systems in areas reliant on generators due to frequent grid outages. This hybrid approach complements the conventional grid, enabling the progressive replacement of generators. Over time, surplus electricity generated by PV systems can be injected back into the grid, promoting sustainability and energy efficiency.

4. Conclusions

The aim of this work was to study the feasibility of electrifying households in remote areas with stand-alone photovoltaic systems. To this end, stand-alone photovoltaic systems proved to be a safe and feasible means of serving the population in remote areas, particularly in outlying districts where low building density and distance from the city center make grid extension almost impossible. Ten households were surveyed in an outlying district of Lubumbashi, DRC. The results showed that an average load of 1850 Wh/day requires two 350 Wp photovoltaic panels, four 250 Ah batteries and a 1000

W inverter. Life-cycle cost analysis of the system gave an investment cost of 2,542 USD and an energy cost of 0.32 USD per kWh. A financing model for stand-alone photovoltaic systems and their dissemination among different segments of society was also proposed. This model would be possible if the government's renewable energy policies were flexible and incentive-based, and if a partnership were established with certain partners developed in the production of photovoltaic equipment.

Conflicts of interest

The authors declare no conflict of interest.

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