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Economic sustainability and social inclusion in rural electrical grid design

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ABSTRACT

Electricity access and affordability are critical for sustainable development. A significant global population without access to electricity is in the rural communities of developing countries. Rural grid investments are unattractive to investors due to low electricity demand and poverty of rural consumers. This paper assessed the financial capacity of rural dwellers to pay for electricity installation. The results reveal that rural consumers can barely pay for electricity. We propose a paradigm shift and alternative grid design models that recognize the various economic and social status of rural consumers. One suggested model proposes using agricultural production to drive social inclusion and economic sustainability of microgrid investments.

1. Introduction

Access to electricity continues to set the pace of development and improve human living standards globally. However, according to the World Bank (The World Bank, 2023), more than one billion people cannot access electricity. Whereas most people in developed countries have access to reliable electricity, the vast majority of the rural population living in developing countries has no or limited access to this vital utility. The evolution of electricity infrastructure has brought in islanded microgrid technologies that can solve energy access problems in rural and isolated locations using renewable energy resources, conventional generation technologies, and some energy storage technologies (Ramirez, 2016).

A two-way relationship exists between lack of access to clean and affordable energy and poverty. First, the lack of energy access produces a re-enforced cycle of deprivation and exclusion. Then, as people in energy poverty try to improve their lives by using a substantial part of their income to procure costly and unsafe energy, their poverty level keeps rising, resulting in a poverty trap (Kerekezi et al., 2012).

Investments in rural electrification projects in most developing economies are done as a means of political patronage through top-down decisions. There is no consideration of the economic and occupational peculiarities of the community. These projects end up being unsustainable mainly because of the disconnect between the peoples' sources of livelihood and the project design. Therefore, a bottom-up approach is required in such projects (Akwei et al., 2020).

Considering the concept of the Bottom of the Pyramid (BoP), electrification projects should be designed around economic drivers in rural communities. Microgrids, primarily based on solar photovoltaic power plants and battery storage systems are viable energy access solutions that could be designed to accommodate rural communities' needs without compromising the project's economic sustainability (Mihailova et al., 2022).

Microgrids are flexible electricity solutions that can be adapted to the energy needs of all categories of consumers, both in industrial and residential applications. This electrification can close the gap between energy access and the economic cost of extending conventional electrical grids to rural, isolated, and remote locations (Gómez et al., 2013a).

As much as electrical grids can guarantee energy access, their deployment is limited by economic challenges as most rural, isolated, or remote locations can hardly cater for the cost of installing and running the grids. This results in a need for more economic incentives for such projects (Onu et al., 2023).

The economic sustainability of rural electrical grids has remained elusive despite the promising prospects of microgrids as crucial technologies in mitigating global electricity access challenges, considering their flexibility, efficiency, reliability, and low cost compared to traditional bulk energy systems (Rout et al., 2021a).

There is a need for a unified framework in electrical grid studies and projects comprising energy, information, economic, financial, and social

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issues to diagnose the problems and requirements for the long-term economic sustainability of microgrids in rural, isolated communities (Boche et al., 2022).

The IEEE Smart Village (ISV), an IEEE group that provides systematic solutions for empowering communities (IEEE Smart Village (ISV)), is already using a systematic approach to sustainably tackling energy poverty in rural communities. ISV deploys a unique method to assist global communities enmeshed in energy poverty through an all-inclusive solution that combines renewable energy, community-based education, and entrepreneurial activities. ISV-provided energy solutions and seed funding enable local dwellers to invest in electricity supply and productive energy use. The ISV team also helps train and mentor community members on sustainable business plans. The education component involves programs that enlighten people on income-generating opportunities. Conversely, the entrepreneurship component involves providing seed funding without interest for local entrepreneurs. The result is that local people invest in the success of their community. The success of the energy investment is reinforced by progress in the productive activities of the community members, such as farmers, dressmakers, and others who depend on electricity.

This paper considers three alternative grid design models. Rural grids were classified in this study as mini-grid (more than 500 kW of installed capacity), microgrid (less than 500 kW of installed capacity and at least five users), and nano-grid (less than five users). Such designs should promote social inclusion through electricity access while ensuring the economic sustainability of investment driven by the improvement of local agricultural production.

Productive use of energy will be explored by ensuring that peculiar sources of livelihood and economic resources available in the community are promoted by supporting micro-industries and electricity projects. Typical examples would be a cassava flour plant powered by a rural microgrid in a cassava-producing community or a fish-processing plant in a fishing community alongside a rural electrical grid. Electric energy adds value to rural production, improving communities' income and making electrical grid projects economically viable.

Incorporating other community needs like household water supply and irrigation for farming activities could also bring considerable gains from the electrification projects. Regarding energy supplied by utilities, a flexible energy pricing regime should also be considered for all classes of consumers based on their respective load profiles and incomes.

Exploring available renewable energy resources in the communities for energy generation and energy storage, not only solar photovoltaic but also small hydroelectric and small wind turbines, should be considered. Through the creative harnessing of peculiar cultural and economic endowments of rural communities, inclusive and sustainable investments in microgrids could help to bridge the equality gaps globally. Rural dwellers face economic challenges apart from energy poverty. Microgrid design could offer a holistic solution to the problems of energy access and economic deprivation.

Consequently, this paper proposes a paradigm shift in rural electrical grid design that would engender social inclusion and economic sustainability of investments. The paper offers a local economic development model that recognizes most rural dwellers' economic and financial constraints that have hampered investments and the economic sustainability of rural electricity access. The idea is to deploy productive activities like micro-industries and agriculture to drive the economic sustainability of rural grids and, at the same time, improve rural livelihood through energy access. The study also contributes models that support electricity access by low-income rural dwellers while ensuring the economic sustainability of electrical grids through a subsidy model and joint community and commercial ownership of electrical grids.

The rest of the paper is organized as follows: section 2 is dedicated to the literature review, section 3 materials and methods, section 4 covers results and discussion, and section 5 ultimately deals with the key findings and conclusion of the study.

2. Review of related literature

In the late 2000s, Bravo et al. (2008) made an energy access study case in two Buenos Aires slums. They concluded that there is a need for public policies to handle issues related to housing, land tenure, and unemployment to reduce energy poverty and provide social inclusion for low-income slum dwellers. Electricity access is an important facility that can engender social inclusion. Electricity, like every other infrastructure, requires funding for sustainability. Rural areas are usually away from city centres and, as such, lack economic activities that are industry-driven.

Access to electricity can address societal problems in health, education, social welfare, and economic and environmental challenges. In addition, the earning power of rural dwellers could be improved through access to electricity. Model policies and practical changes in the conventional energy supply chain are needed to realize the United Nations Agenda 2030 of universal electricity access (Almeshqab and Ustun, 2019). These changes must be target-driven, emphasizing social, economic, and environmental concerns. The Brazilian government has recognized access to electricity as a citizen's right and expanded electricity by nearly 15 million people over the years through the ''Light for All Program''. However, a significant part of the Amazon region needs access to electricity due to the long distance and other environmental constraints. A hybrid localized energy system using selected renewable energy sources was proposed to address these challenges (Fuso Nerini et al., 2014). This approach emphasizes the need to adopt appropriate models to address various challenges to energy access.

Electricity use has a complex causal relationship with multifaceted socio-economic development, including income generation activities, market, production, revenues, household income, economy, health, education, habits, and social networking (Riva et al., 2018).

Matinga and Annegarn (2013) studied the benefits of electrification in a rural village in South Africa, where the state provides electricity for low-income households without charges. They stated that among the benefits brought by electricity are the spread of information and socialization of people through television and social networks, the reduction in smoke inhalation with the use of electric stoves, the feeling of inclusion provided by the improvement in the living standards of people in the village with electricity, among many others.

Gómes et al. (Gómez et al., 2013b) studied the usefulness of social technology principles for electrifying isolated rural communities. Such a technology is a movement drawing upon the foundations of Gandhi and others. The movement provides a multidisciplinary framework incorporating local resources and knowledge to implement off-grid electricity solutions. The authors argue that it is crucial to consider how locally based knowledge can create a common basis to understand and face all challenges of rural electrification.

Mandelli et al. (2016a) concluded that hybrid systems, consisting of diesel generators, photovoltaic solar panels, and battery banks, are solutions for electrifying isolated rural areas in Sub-Saharan Africa. The conclusion was validated with a case study in Tanzania. Results give credence to the fact that microgrid solutions that integrate renewable energy and energy storage systems are potential solutions for energy access in rural and isolated communities.

Recently, Schmukler (2019) analysed the results of different approaches of neoliberal and developmental governments regarding the rural electrification program in Argentina. The author questioned if local adequacy can be a way of achieving innovation and social inclusion.

Molina-Maturano et al. (2020) identified constraint-based innovation as a rapidly growing area of research due to its potential to support sustainable development. However, they noted that recent studies had not given much attention to constraint-based innovation in agriculture. Therefore, the authors advocated for research on frameworks like Technology Adoption Model (TAM) and Sustainable Rural Livelihood (SRL) aimed at deploying constraint-based innovations in driving sustainable development at the rural level.

In recent research, Mihailova et al. (2022) recognized the energy community as a critical stakeholder in the transition to renewable energy. The researchers suggested that energy community members could leverage the opportunities provided by the energy transition to create a sustainable environment and community. Value co-creation between energy citizens and stakeholders was explored in a Positive Energy District (PED). The researchers concluded that positive energy communities are multi-centred business models in which stakeholders determine the changes in the energy community. Most research on Sustainable Business Models (SBM) and Bottom of the Pyramid (BoP) assume that organizations add value to businesses and society based on market-oriented solutions. These schools of thought see the government, at best, as an obstacle when it comes to BoP.

Using the BoP, the Ecoelce project, an SBM in Northeastern Brazil, showed that government regulation could transform challenges into opportunities (Bittencourt Marconatto et al., 2016). Conventional market-oriented approaches to mitigate poverty at the pyramid's base have faced many challenges. Businesses designed around the traditional profit models should be revised to address poverty (Dembek et al., 2018).

Rural energy planning has seen total disregard for social and economic considerations by project managers over the years. There is a need for an all-inclusive energy planning practice that engages all stakeholders to ensure sustainable development. Each community of consumers has its peculiarities that must be considered during the project design phase. The occupation and sources of livelihood of communities determine, to a large extent, their energy requirement. These factors are also linked to their economic status (Herington et al., 2017).

Although India recently achieved universal electricity access, there are growing concerns about the financial sustainability of electricity supply in many rural communities. Between 2018 and 2019, Indian distribution utilities recorded 270 billion Rupees in losses, which poses a sustainability threat to electricity access. A generic mathematical cost model applied to evaluate the financial sustainability of rural grid systems in four provinces of India showed a viability gap in all four provinces. This finding is connected to the low level of economic activity in rural communities (Rout et al., 2021b).

Based on the available literature, economic sustainability and social inclusion in rural electrical grid designs need further consideration to account for the failure to sustain energy access in rural communities due to poverty and the associated economic constraints.

3. Material and methods

This research is part of efforts to improve the economic sustainability and social inclusion of rural grids through the productive use of energy, government subsidies, joint community ownership, and local economic development systems that encourage agricultural production.

3.1. *Rural grid design and assessment*

Mandelli et al. (2016b) have classified electrical systems as centralized, decentralized, and distributed. In a local context, the electric system was classified based on rural energy use, the number of consumers served, and the primary energy sources. Each classification is suitable for application in various economic and social settings.

3.1.1. *Framework for an islanded electrical grid*

A bulk power system consists of an interconnected electrical grid with components that generate, transmit, and distribute electricity to consumers. Electrical grids are divided into three-layered, interconnected networks of generation, transmission, and distribution components. An interconnected electrical grid also needs a sophisticated protection and control system to guarantee reliability and availability (Qazi and Qazi, 2017).

If a small part of a bulk energy system can survive islanded, it has enough generation to supply local loads and an adequate control system, so it can be considered a microgrid. Such electrical grids can also be permanently isolated and without bulk power. Specifically, they can be classified into mini-grids, microgrids, and nano-grids.

A microgrid can be defined as a group of interconnected loads and distributed energy resources (DER) with clearly defined electrical boundaries that act as a single controllable entity that may operate in both grid-connected or island modes (Shahbazitabar et al., 2021). DER includes generators and energy storage technologies when both are not directly connected to the bulk power system.

Only island rural systems are considered in this study, and the following definitions are given. A mini-grid has the same characteristics as a microgrid but with an installed power above 500 kW. Microgrids have a capacity of less than 500 kW. They include at least five users, such as generators, consumers, or even prosumers, who produce and consume electricity at the same connection point. A nano grid is a small grid with less than five users. The following subsection examines the typical load profile of rural households in sub-Saharan Africa to assess the financial capacity of rural dwellers to pay for energy consumed and grid investments.

After this brief introductory section, a typical photovoltaic solar energy project, based on a standard load profile for isolated rural communities, was proposed to allow economic evaluation and provide subsidies for the proposed new approaches to electrical grid design. The objectives of this study will be analysed through energy cost comparisons between the status quo and the proposed grid design models. The system will allow reproducibility based on peculiarities of electrical generations and demand patterns that result in different load profiles with associated costs.

3.1.2. *Typical load profile of a rural household*

Typical rural households' electricity demand is lower than their urban counterparts. The basic needs for electricity in rural areas are lighting, food preservation, mobile communication, television, and a few other loads. Defining the exact load curve, in this case, is a challenging task. However, based on previous studies, a typical load profile of a rural household is presented in Table 1 (Prinsloo et al., 2016) (Ani, 2014). The lamps and television sets were light-emitting diode (LED) bulbs and TVs. Radio sets and some home appliances are also considered. As can be seen, the most significant electrical consumption, more than 27%, of a rural family is for food preservation in the refrigerator that works 24 h daily.

3.1.3. *Standard design for studies*

A standard solar power plant for macroeconomic studies was designed based on the load profile explained in the previous section. As the focus is not on developing a power plant project, some refined details are neglected. According to the National Renewable Energy Laboratory (NREL) solar radiation database, the average of solar global radiation in most tropical developing countries is around 4.5 kWh/m^2 per day (National Renewable Energy Laboratory NREL). The typical power equation for solar plants is shown in 1 (Akpolat et al., 2019).

Table 1
Typical load profile of a rural household (Prinsloo et al., 2016) (Ani, 2014).

Load	Quantity	Power	Total	Use/day	Energy
Bulb	5	10 W	50 W	12 h	0.60 kWh
Charger	3	5 W	15 W	6 h	0.09 kWh
Fan	1	60 W	60 W	10 h	0.60 kWh
Fridge	1	80 W	80 W	24 h	1.92 kWh
TV set	1	80 W	80 W	8 h	0.64 kWh
Laptop	1	60 W	60 W	6 h	0.36 kWh
Others	–	–	–	–	0.25 kWh
Total average daily energy consumption					4.46 kWh

$$P_n = \frac{E_c P_p}{A_p R_m \eta_p} \tag{1}$$

where Ec is the energy consumption from the previous section; Rm is the global solar radiation average in South-West of Nigeria; Pp is the nominal power of a typical solar panel of 300 W; Ap is the typical area of solar panels designed for rooftop installation, 1.6 m^2 on average; and ηp is the electrical yield, considered 20% in this study that represents best-commercialized panels currently (Olofin et al., 2023).

Based on Table 1, the daily peak demand of a single house is 345 W on average, which was used to dimension the nominal power of a solar power plant in this study. Therefore, considering only solar PV to supply the community with an average of 10 h of sunlight a day will need 1.00 kW installed power per house, already considered 40% demand growth in the first years, a typical case of a newly electrified community (Juturu et al., 2023).

de Doile et al. (2021), in a recent study based on NREL and International Electricity Agency (IEA) data, stated that the cost of solar panels, including frequency inverter, is $1,221,10/kW (USD dollars per kW) in average. The authors also say the installation cost is around 20% of investments. Therefore, an installation for a single house will cost $1, 465.32. From the same study, it is possible to infer that adding a 3.5 kW lead-acid battery bank to guarantee the supply during 24 h without sunlight would require an extra $1,000.00 on average, bringing the total installation investment to around $2,500.00 per house.

3.2. Social inclusion in electrical grids design

Realizing social inclusion requires at least two things. The first is people's behaviour within their environment, considering physical and cultural aspects. Secondly, the local economic and financial aspects should be assessed.

3.2.1. Location and population considerations

The term "rural" refers to a diverse group of areas associated with a common characteristic from the peri-urban to the remote communities. Poverty levels are higher in rural areas than in urban areas. The rural areas are homes for the impoverished population in Sub-Saharan Africa and the Amazon region, where more than half of the rural population live in extreme poverty. The World Bank puts $1.90 daily income per person as the extreme poverty line (Jolliffe and Prydz, 2016), (United Nations, 2021).

Most rural communities in developing countries lack good road networks, which results in their inability to access urban centres for commercial purposes. It is estimated that nearly one-third of the world's rural dwellers cannot access paved roads, directly limiting their economic opportunities. A study on the relationship between rural road infrastructure and development revealed that good access roads to rural areas directly impact the prices of goods and services. They also help with the availability of non-local goods, improve the use of agricultural technologies, and improve children's school enrolment (Aggarwal, 2018).

Unfortunately, rural communities in many developing economies do not have access to good roads. Apart from access roads, electrical grid deployment in rural areas can drive economic development through productive electricity use. The primary source of livelihood in rural areas is agriculture. Therefore, electricity can help improve agricultural investments by driving food storage, processing, and packaging.

3.3. Grid design proposals

Rural electricity access leads us to conclude that there is a need for a change in investment approach to guarantee social inclusion and sustainability of investments. Hence, the following proposals are suggested.

3.3.1. Economic sustainability driven by surplus rural production

Cultural compatibility is relevant to the sustainability of infrastructure investment (Akwei et al., 2020). In this case, a rural electrical grid with a productive economic activity that supports the source of livelihood of the host community will be highly acceptable to the community.

A typical example could be siting a cassava flour plant alongside a community electrical grid in a cassava-producing community. Such an action enables the community members to sell their products to the flour plant with minimal transportation costs, earn a living, and improve the payment compliance level of energy. In this way, the grid investment provides electricity and empowers the community economically through the productive use of energy. Furthermore, this will encourage the community population to embark on large-scale production of cassava roots as they are sure of making financial gains from their investments without transportation constraints imposed by their location.

Herbert and Phimister (2019) reported improved economic benefits from connecting domestic and small rural businesses to a wind-power mini-grid using tea factories as demand anchors.

3.3.2. An alternative payment model for social inclusion and economic sustainability of rural grids

Investment is increasingly shifting to microgrid and nano-grid systems to address the problem of energy access in rural communities and reach the United Nations goal of Sustainable Energy for All (SE4All). However, some challenges that border on the sustainability of the systems include regulatory concerns, low energy demands in rural communities, low payment compliance rates, and oversized demand projections (Peters et al., 2019). Rural microgrid design that can address these identified challenges could offer sustainable and socially inclusive rural electricity access. We proposed using agricultural production to drive social inclusion and economic sustainability of microgrid investments in rural communities.

The proposed model uses the price of one ton of cassava roots as US $55.50 (Ola and Adedayo, 2020). The income adopted in this model is the Nigerian minimum wage of N30,000.00 (U$37.00) per month. The Nigerian energy tariff is N62.33/kWh, according to (BBC News Pidgin, 2020). This model allows consumers of electricity to pay for electricity through any of their preferred options of money, agricultural produce, or labour. It also allows consumers to sell part of their farm produce to the agro-allied industry of the electricity company. Model equations are as follows:

$$Z = A - C \tag{2}$$

$$A = M + X + Y \tag{3}$$

$$C = Ex62.33 \tag{4}$$

$$X = \frac{55.5x414.95xG}{907.185} \tag{5}$$

$$Y = \frac{30000xL}{176} \tag{6}$$

where Z computes the income balance of the consumer paying with cassava roots or labor; A is the total monetary value in Naira arising from a consumer's labor, cash payment, and or cassava produce; C is energy cost in Naira; M is the amount of money in cash paid by the electricity consumer; X converts cassava roots in kilograms to money in Naira; Y converts labor in hours to Naira; E is the electricity need of the consumer in kWh; G is the number of cassava roots in kilograms; and L is labour in hours.

3.3.3. Joint community and commercial ownership

Peters et al. (2019) studied two types of electrical mini-grid ownership and operation, including commercially operated and community-operated mini-grids. Commercially operated mini-grids involve operation by a private company to recover investment and operation costs while making some percentage of profit.

This ownership model faces challenges in covering the cost and ensuring sustainability, such as low electricity demands, low payment ability of rural dwellers, and regulatory barriers. Conversely, community-operated mini-grids are owned by the community that manages, operates, and maintains the mini-grid facility for community use.

This scheme is also confronted with challenges, including the need for a more skilled workforce to manage the maintenance and operation of mini-grids, the low tariff set by the community due to uninformed decisions, and the inability of the community members to enforce payment.

Based on these observed challenges, the present study proposes a joint ownership model in which the community and a company own the mini-grid, microgrid, or nano-grid in rural areas. With this, the private company will have reduced investment costs, a skilled workforce will be employed to operate and maintain the electrical system, and the community will be aware of the grid maintenance and operation costs, encouraging payment compliance. The community will also use part of the profit realized to drive other developmental projects such as water supply, roads, and schools. These extra benefits from the grid operation will serve as sustainability drivers and agents of social inclusion that would bridge the inequality gaps.

Assuming a 40%:60% community and commercial joint ownership, the community will have a 40% stake in the grid investment. The investment cost for the community can be financed through charity donations from wealthy community members, while the profit can be redistributed to all community members, thereby reducing the energy cost using the following algorithm.

Let the total cost of investment in the rural grid be I_T; Community investment $= 0.4I_T$; Commercial investment $= 0.6I_T$; Total profit $= P_T$; Community profit $= 0.4P_T$; Commercial profit $= 0.6P_T$; Original cost of energy without joint grid ownership $= T_o$; New cost of energy with joint grid ownership $= T_N$; where $T_N = I_T - 0.4P_T$;

Therefore, the percentage reduction in the cost of energy will be $= 100\left[\frac{T_o - T_N}{T_o}\right]$. As a result of the evident reduction in energy costs due to joint community ownership, the economic sustainability of the rural grid and social inclusion are further guaranteed.

3.3.4. *Income-based subsidies model*

Based on the World Bank poverty index, people living on a daily income below \$1.90 are classified as living in extreme poverty. Such people need more revenue to pay for electricity costs, as assessed in this study. To maintain a socially inclusive society, these people living close to the extreme poverty line must be provided with a sense of belonging. Electricity can be a driver to achieve this goal.

The proposed model is an income-segregated subsidy for rural dwellers based on the citizens' income levels. Let the daily income of citizens $= W$; Subsidy $= S$; Cost of energy without subsidy $= T_o$; Cost of energy with subsidy $= T_s$;

Considering the World Bank poverty index of \$1.90, If $W \leq \$1.90$, then $T_s = 0$, with $S = T_o$; else check if $W \geq 2x\$1.90$, then $T_s = 0.2T_o$; else check if $W \geq 3x\$1.90$, then $T_s = 0.4T_o$; else check if $W \geq 4x\$1.90$, then $T_s = 0.6T_o$; $W \geq 5x\$1.90$, then $T_s = 0.8T_o$; $W \geq 6x\$1.90$, then $T_s = T_o$. Table 4 in section 4 contains income and energy cost data samples based on the proposed subsidy model.

4. Results and discussion

4.1. *Economic assessment*

Based on values found in subsection 3.1.3., a nano-grid will cost \$10,000.00 or less. For example, a microgrid to supply 100 units of a rural household should have 100 kW installed power and cost around \$250,000.00. Mini-grids will cost \$700,000.00. All previously calculated prices include a lead-acid battery bank with one day supply capacity. PV panels have an average useful life of 20 years, whereas lead-acid batteries have a five-year life span (Qazi and Qazi, 2017).

Using the poverty line set by the World Bank of \$1.90 daily income per person and considering a family of five people, the annual household income will be around \$3,500.00. This amount should be used first for basic needs such as housing, food, health, safety, and leisure. Therefore, most of the time, more money is needed to invest in infrastructure, making subsidies necessary. The results of simulations for several income categories are presented in Table 2. A widely used return rate of 5% in long-term economic studies was considered (Hirth and Steckel, 2016).

80% of reinvestment in batteries every five years was considered in the assessment, as this is their life span. Five different annual incomes were considered: the World Bank poverty line for families with three, four, and five people, the Nigerian minimum wage of U\$37.00 (equivalent to 30,000 naira) monthly (Senate, 2019) and the Brazilian minimum wage of U\$250.00 (equivalent to 1,212 reals) monthly (National Congress).

As can be seen, all scenarios are practically unfeasible, as people living close to the poverty line cannot spend these percentages of their incomes on the system installation. Therefore, the government must help with subsidies, low-rate credit lines, and tax exemptions, among other economic or financial incentives, to make social inclusion a reality. The amount to be paid by rural communities for electrical installations cannot enslave them through an unpayable debt.

Table 2
Economic assessment of electrical grids.

Annual income Category	Percent of income needed for payment	
	10 years payment	20 years payment
WB PL 3 people	15.14%	9.78%
WB PL 4 people	11.30%	7.31%
WB PL 5 people	9.01%	5.83%
Nigerian Minimum wage	37.53%	24.16%
Brazilian Minimum wage	10.73%	6.94%

4.2. *Modeling the grid design proposals*

The model in equations (2)–(6) can be adapted to any rural grid with its peculiar production and consumption. The model demonstrates the possibility of driving the economic sustainability of rural grids through agro-allied industries. It also addresses social inclusion by offering local economic development and income generation systems to all categories of consumers. A sample data generated from the proposed local economic development model is shown in Table 3. It shows how a consumer can choose a payment option for money, labour, and agricultural goods. The table also reveals the possibility of earning family income from the consumer's agricultural produce or labour.

The algorithm in the income-based subsidy model allocates energy subsidies according to the income levels of consumers, as shown with sample data in Table 4, thereby fostering social inclusion and economic sustainability of the rural grid investment through government subsidy as against the practice of allowing only financially capable consumers to utilize electricity.

Therefore, governments should provide some economic and financial state subsidies on installation costs and energy bills for the low-income people in rural communities. A cross-subsidy in energy bills should be considered, where people from high economic classes pay more than low-income people for the same amount of energy.

4.3. *Results summary*

The proposed grid design models are summarized in Table 5, where

Table 3
Proposed sample rural grid payment system data.

Consumer ID	Payment Option Values			$A = M + X + Y$	E (KWh)	Z (Naira)
	G (kg)	L (Hours)	M (Naira)			
C01	100	37	0	8845.41	134	493.19
C02	300	0	5000	12615.78	134	4263.56
C03	200	20	0	8486.27	134	134.05
C04	250	30	0	11460.12	134	3107.90
C05	100	10	0	4243.14	134	−4109.08
C06	0	70	0	11931.82	134	3579.60
C07	1000	0	0	25385.92	134	17033.70
C08	0	0	15000	15000	134	6647.78
C09	500	5	0	13545.23	134	5193.01
C10	0	0	0	0	134	−8352.22

Table 4
Samples of income and energy cost data based on the proposed subsidy model.

Income W ($)	Original cost of energy without subsidy T_o ($)	New cost of energy with subsidy T_s ($)
0	100	0
1	100	0
1.5	100	0
1.8	100	0
1.9	100	0
3.8	100	20
0.5	100	0
5	100	20
9.5	100	80
9	100	60
10	100	80
11	100	80
12	100	100
13	100	100
14	100	100
15	100	100
0.8	100	0
17	100	100
1.9	100	0
19	100	100
20	100	100

Table 5
Summary of proposed grid design models.

	Current Practice	Proposed Grid Design Models
A	Rural grids are built without accompanying rural industries	Local economic development model. Rural grids should be based on rural industries tailored toward the primary source of livelihood for the community. This approach would increase the community members' earning power and increase social inclusion.
B	Separate ownership of rural grid, either Community or Commercial Investment	Joint community and commercial ownership model. This approach would reduce the cost imposed by the full commercial ownership model. The result would entail affordable energy and social inclusion.
C	No subsidy consideration for low-income electricity consumers in rural communities	Income-based subsidies model. People living close to the World Bank's poverty line with incomes of less than $1.90 per day should be considered for some level of subsidy from the state. In this way, the low-income population would benefit from the opportunities offered by access to electricity.

Grid Design A proposed as a "local economic development" model, Grid Design B is the "joint community and commercial ownership" model, and Grid Design C is the "Income-based subsidies" model.

Arising from data for Grid Design A, the electricity consumer who does not have sufficient money to pay for electricity costs may decide to earn money from the grid-allied industry by providing raw materials like cassava roots and or labour. In this way, the purchasing power of the consumer is improved. The consumer can pay for electricity consumption due to the extra income earned from productive activities. The grid investor gains from this activity and the electricity delivery to the rural population is sustained. This approach contrasts with the present practice, where low-income consumers are only expected to pay for energy consumption through monetary values. This proposal aims to mitigate poverty through electricity access by using energy to sustainably drive productive activities in rural areas. The proposal targets the social inclusion of the rural population and the economic sustainability of the investments.

The data in Table 3 demonstrate the ability of the model to generate income through labour and or goods. For instance, consumer C07 made an additional income of 17033.70 Naira for the month for consuming 134 kWh of electricity and supplying 1000 kg of cassava roots only. On the other hand, consumer C06 earned an extra income of 3579.60 Naira after consuming 134 kWh of electricity and putting in a total of 70 h of labour for the month. Consumer C08 was buoyant enough to have paid for all monthly energy needs, leaving a positive balance of 6647.78 Naira. These data reveal that the actual energy cost for 134 kWh in the simulation is (15000–6647.78 = 8352.22 Naira). Consumers C07 and C06 do not have this amount to pay for their energy needs; they opted for the alternative of goods and labour to pay and earn extra income from the grid-allied industry.

As for Grid Design B, this model allows the community to be part of the grid investment and enjoy profits, which ultimately reflects a reduction in energy costs. For example, if the community invests in the sum of forty million Naira, while the commercial ownership invests sixty million Naira. If the total profit is ten million Naira, the community is entitled to four million Naira in profit based on the investment ratio of 40:60; thus, the old tariff without community joint ownership will be reduced by four million Naira.

Finally, Grid Design C makes it possible to classify consumers based on income levels to offer subsidies appropriate for social inclusion and economic sustainability. This algorithm is shown in Table 4, where samples of incomes and associated subsidized energy costs based on individual income levels are presented. Consumers earning $1.90 or less in daily income enjoy a 100% subsidy. The subsidy amount keeps reducing as the income increases until a supposed high income is reached; at this point, there is no subsidy for the consumer because of the improved ability to pay for energy consumed.

Each of the three grid design models proposed in this study has its strengths. For instance, Grid Design A encourages a production-driven rural economy that deploys electricity access as a tool for social inclusion and economic empowerment. Grid Design B allows the community to be part of the grid ownership, resulting in shares in investments and profits and thereby reducing energy costs. Grid Design C recognizes differences in income levels and offers subsidies based on income levels. This approach bridges the gap between high- and low-income earners and ensures social inclusion while sustaining the investments.

For better results in ensuring economic sustainability and social inclusion in rural electricity access, proposals can be combined depending on the targeted outcomes, as highlighted.

5. Conclusion

Rural electricity access in developing countries is a major driver of development. A significant population of rural dwellers in developing economies cannot access electricity. In most cases, the extension of the national electrical grids to rural areas is limited by economic and geographic factors. Small electric networks such as nano-grids, mini-grids, and microgrids are alternative technologies for rural electricity access. However, these solutions face the challenges of simultaneously ensuring economic sustainability and social inclusion for a rural population enmeshed in poverty.

Some remedies to the problems of economic sustainability and social inclusion are proposed in this study. The remedies include the use of production in driving economic sustainability and social inclusion through a local economic development model that encourages rural output of goods and services and government subsidy for consumers close to the World Bank poverty line of $1.90 daily income.

The economic assessment shows that a family of three with an average daily income of $1.90 per person would need 15.14% of their income over ten years to pay the capital cost of a nano-grid system capable of supplying a typical rural house. A family of four with the same income level would need 11.30% of their income to pay off within the same ten years, while a family of five with the same income level would use 9.01% of their income to pay off within ten years. Conversely, a 20-year repayment period would require 9.79%, 7.31%, and 5.83% of annual incomes from each listed family, respectively.

Again, it was observed that an individual earning the Nigerian minimum wage of N30,000.00 monthly needs almost 38% of their annual income to pay off a nano-grid for a typical rural house in ten years. The Brazilian counterpart earning R$1,212.00 (the national minimum wage) needs approximately 11% of their income to pay off in the same ten years. We recommend that the government subsidise households close to the World Bank poverty line to ensure social inclusion and economic sustainability of rural electricity investments.

This paper proposes a paradigm shift and three models to engender social inclusion and economic sustainability of rural electricity access. These models include local economic development models, subsidies, and joint community/commercial ownership of rural electrical grids.

The results obtained from the simulation of the proposed models show that it is possible to improve electricity access in low-income rural communities while ensuring the economic sustainability of the investment. Again, the income status of rural dwellers can be improved through productive activities driven by electricity access. The energy cost can be reduced through joint community and commercial ownership of electricity investment and government subsidies anchored on consumer income levels.

The minimum wage and cassava sales data were limited to Brazil and Nigeria. In future studies, some regions, such as rural Nigerian communities, should be evaluated in detail to determine the amounts the community can pay, the amounts that should be shared with utilities, and whether any subsidy will be required. Future research should consider economic analysis using the Hybrid Optimization of Multiple Energy Resources software (HOMER) on sample rural communities in developing countries to obtain each community's most economical generation source. Also to be considered is the future cost of energy and income growth from using electricity.

As other limitations, it should be noted that these proposals are limited to electrical grids in rural, isolated communities with high poverty index and inadequate transportation and market infrastructure. Other energy sources could be studied in future works, as only solar photovoltaics were considered here.

CRediT authorship contribution statement

Uchenna Godswill Onu: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Gabriel Nasser Doyle de Doile:** Writing – review & editing, Writing – original draft, Formal analysis. **Antonio Carlos Zambroni de Souza:** Writing – review & editing, Supervision. **Pedro Paulo Balestrassi:** Writing – review & editing, Supervision.

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

No data was used for the research described in the article.

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