Analysis of Cost-Effectiveness of Grid-Based and Off-Grid Electrification Designs in Nigeria

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Abstract: The significance of electricity access to man's socioeconomic development cannot be overstated. putting competing demands on limited resources. Electrification as one of the demands requires efficient use of these scarce resources using appropriate electrification plans that would improve the attractiveness of policymakers to electrification which in turn brings the development to rural and extending communities. There is a need for a rural-electrification planning structure that considers social equity and balanced regional development through the most cost-effective investment options delivering a reasonable level of service. The objectives of the study were to compare two electrification plans including extending the existing grid distribution system and implementing renewable energy-based rural electrification (RE) for two dissimilar communities. Grid extension, which has a lower initial installation cost and is a suitable option where there are commercial and industrial consumers, is the most economically feasible electrification plan for a community that is close to the existing power grid or one that is growing, according to the study's findings. However, results of the study also show that off-grid electrification model is more cost-effective than a grid extension for electrifying far-from-the-grid un-electrified areas. This model has a higher functional value, economic value, and suitability for remote communities because these areas have fewer infrastructures which are basically lighting and residential applications.

Index Terms: Electrification, On-Grid, Off-Grid, Distribution System, and Grid-Extension

1. Introduction

It is usually said that a lack of energy hinders the growth of the economy. In many ways, electrification helps reduce poverty and benefits every aspect of human endeavors, such as health, agriculture, and education [1]. In most developing countries, particularly in Sub-Saharan Africa, access to electricity has proven elusive. The few resources that are currently available are under additional stress as a result of the rising demand for electricity and the ineffective electrification plans. According to the International Energy Agency (IEA), Sub-Saharan Africa has the 10 least electrified countries in the world with an electrification rate of only 32 percent [2]. As of 2013, around 42 percent of Nigeria's population, or 85 million people, lacked access to electricity [2][1]. If immediate action is not taken to address the problem, the number of people without access to electricity may only slightly decrease to 1.2 billion by 2030 [3]. The problem of limited access to electricity, particularly in Nigeria's rural and emerging areas, is made worse by the absence of cogent electrification plans.

Only 55.4% of the world's population has access to electricity as of 2020, with 24.6% of the rural population being connected to the electricity grid, according to a World Bank global electrification database created by the International Energy Agency, the International Renewable Energy Agency, the United Nations Statistics Division, the World Bank, and the World Health Organization. The report states that 0% of electricity was produced in 2015 from renewable sources, excluding hydroelectricity [4]. Due to the massive energy crisis that has plagued Nigeria for almost 20 years, industrial and commercial activity has been completely halted, which has had a significant impact on the prevalence of poverty. The Nigerian Council for Renewable Energy also claims that power outages cost the nation 126 billion naira (US$ 984.38 million) annually [5].

A reasonably sound electrification strategy should be able to model the electrification technologies that will be used and provide an estimate of the investments needed over a specific period. In some circumstances, grid extension might be practical and economical, especially for populations that are dense and concentrated. Grid extension may not

be practical or cost-effective in other circumstances, such as those with dispersed populations or distant places [6][5] as estimating the shortest routes between existing substations and proposed sites frequently results in longer than necessary and inefficient routes, more resources are used [7][7]. According to the capacity meeting demand five years after the commencement of service for a power distribution transformer's capacity or ten years after the commencement of service for distribution lines, the minimum but necessary configuration and specifications of facilities are chosen for a technically and economically appropriate electrification design [8].

In this study, it is examined whether it is feasible to electrify two different and unconnected communities in Kwara State, Nigeria, using mini-grid-based off-grid solar photovoltaic (PV) systems. The study compares the price of purchasing grid electricity during the same time frame.

2. Literature Review

The feasibility and economic viability of off-grid electrification across states in Nigeria and Africa have been extensively researched. A life-cycle cost estimation for a 25-year life-time cost was used in the study by [9] on the viability of off-grid PV systems in electrifying remote villages in North-Eastern Nigeria. RETScreen was utilized for the analysis. Natural Resources Canada developed the Microsoft Excel-based renewable energy technology (RET) analytical programme called RETScreen. A rural community of 40 households is the subject of the case study, which has an initial electricity demand of 5 kW from both residential and commercial loads. If grid extension was feasible, the financial impact of the off-grid system would contrast with paying electricity bills. The findings indicate that the off-grid system only becomes economically feasible if the cost of the PV system decreases due to the current commercial interest rate.

In a study of microgrid electrification in the eastern Cape of South Africa, [7] performed simulation, optimization, and sensitivity analyses using the Hybrid Optimization Model for Electric Renewable (HOMER) software. In Sub-Saharan Africa, the average cost of grid extension was estimated to be \$25,000/km for an 11 kV line, taking other electrification components into account as well as the rate of inflation. The findings indicated that a microgrid powered by wind, diesel generators, and batteries had the lowest net present cost (NPC) of \$1, 612,679 and \$0.320/kWh. With 0.0057 kg/kWh CO_2 emissions and a 90.5% renewable fraction, the design has a breakeven grid extension distance of -45.38 km, which is less than grid extension. The study came to the conclusion that a hybrid microgrid solution could be a practical choice for illuminating Eastern Cape remote, undeveloped areas.

The research [10], presented focused on the costs and effects of off-grid and on-grid rural electrification in Sub-Saharan African nations like Burkina Faso, Rwanda, Uganda, and Zambia. These African nations' data were contrasted with Indonesia's. Analysis revealed that demand is extremely low in rural Africa, where the majority of households without electricity currently reside. These findings demonstrate that people clearly prefer on-grid connections to decentralized technologies due to their sustainability and the higher costs of technical support incurred by off-grid systems.

The article by [11] described the design of a photovoltaic (PV) system for use in the rural electrification of far-flung communities in the Gambia that are not connected to the electricity grid. The system was modelled using HOMER software, and simulations were run to find the best configuration that would be more affordable and dependable for supplying power to these rural areas by anticipating the rise in load demand and consumption over time. The total NPC calculated by HOMER is equivalent to \$164,192, and a level cost of electricity (COE) as well as the cost of operation are \$1.060/kWh and \$4303 per year, respectively. The authors concluded that using photovoltaic technologies to produce and supply electricity is both feasible and sustainable, and they think that if the plan is put into practise, it will provide a solution for the residents of these villages who are not connected to the national electrical grid.

3. Electrification Designs

Since electricity affects every aspect of our lives, including education, the reduction of poverty, and socioeconomic advancement, rural development occurs through the electrification of rural communities. A rural village in Nigeria has less than 20,000 residents and estimated average household size of 10 [4]. However, good intentions—such as expanding access to electricity—don't always translate into positive outcomes, while a well-designed model undoubtedly does. Historically, grid extension model is the major method used to electrify rural areas throughout time, which contributes to the availability of affordable energy in underdeveloped rural areas. The medium voltage (MV) and low voltage (LV) distribution grids are extended to consumers as part of on-grid electrification, sometimes referred to as grid extension. Grid extension becomes economically unviable when communities are far from existing distribution networks, thus, finding alternative and more environmentally friendly ways to electrify rural areas is necessary. Off-grid solutions allow the deployment of rural electrification (RE) based on renewable energy in off-the-grid locations [5]. Off-grid electrification operates independently of the national grid and has recently become a better option in some cases for electrifying rural areas due to the emphasis being paid to renewable energy and other alternative energy sources. Mini-grids can provide power to several consumers in a densely populated area through an independent distribution grid [12]. Other benefits include the availability of resources that are renewable and naturally abundant in

supply, flexibility, low to medium operation and maintenance costs, ease of use, and low to medium operating costs [13].

User value is crucial to the success of electrification projects design. Some of the value considerations for an electrification project include functional value, economic value, technology appropriateness, and technology uptake [14]. Such projects' dependability, effectiveness, and durability characterize both their performance and quality. These qualities determine the reliability, longevity, and degree to which the power supplied satisfies the demand of the community. The initial cost of installation, the cost of maintenance, and the cost of electricity per unit used, on the other hand, determine the economic value of an electrification plan. Since the government and private sector are worried about the financial benefits of these projects to the communities and the economic returns they would bring, the cost of obtaining electricity is a significant barrier in many communities. How well the availability of electricity satisfies a community's unique needs determines the suitability of the service [14]. For an industrial area that might need a higher power output, a plan made for a primarily residential area would not be appropriate.

A. On-grid Electrification Design Considerations

A detailed feasibility analysis is necessary for successful electrification design to guarantee a service delivery under suitable technical conditions. Getting information on the area to be electrified, particularly for grid extension projects, is a step in the electrical design process for electrification projects. Some of this information includes the kind of line (LV or MV) and the quickest route from the closest distribution substation from a nearby location to the proposed site for optimal design. Additionally, a survey of the region that needs to be electrified is required. This helps establish the distance (in kilometers) and length of line from the adjoining distribution network to the proposed site [16]. Understanding load analysis and configuration allows for the design of the system configuration (including the placement of primary lines and transformer points) to provide the loads represented by the concentrations of future users. The design must adhere to specifications for service quality, especially concerning the current-voltage levels (11kV and 33kV for Nigeria) [16]. The distribution substation's size and location are significant factors in on-grid electrification. The transformer's location and cable routes are selected to ensure that the maximum voltage drops between the transformer and the farthest consumer are less than 5% of the nominal voltage (220V) [[17], [18]]. Because larger cross-sectional areas typically lead to lower resistance and fewer losses, it is safer to select and use oversized line conductors. There might be a need to improve the existing system to permit the extension of the new system to be constructed.

B. Off-grid Electrification Design Considerations

To increase efficiency and long-term sustainability, proper identification of locally accessible renewable energy supplies is a critical issue in the design of off-grid rural electrification systems [19]. Assessments of local renewable energy resources are influenced by a variety of variables, including geography, population, societal demands, and politics. To rank alternatives, a variety of techniques and multi-criteria decision-making frameworks have been developed, including the Analytic Network Process (ANP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), and Elimination Et Choix Traduisant la REalité (ELECTRE) [20]. Energy alternative assessments also considers both intangible and measurable criteria. Cost (investment, maintenance, operating, and other life cycle costs) is one of these characteristics, along with installed capacity, reliability, service life, environmental effects, job generation, and security. Designs must take acceptable business models into account as well as any legislative requirements [21]. Off-grid projects' economic viability is equally dependent on the size of the installed assets, so investments must be supported by a payable demand in the years following commissioning because a poorly configured system will either fail to accomplish its goal or fail to recoup the cost of the investment [22]. This is crucial for the process of choosing the right components in terms of size and specifying the operation mode of the mini-grid. The analysis of local conditions and the consideration of the community's needs at an early stage of the system sizing are advisable.

4. Methodology

Site inspections/surveys, load estimates for the communities to be electrified, model design, and cost estimation for both grid extension and off-grid systems were developed to achieve the study's primary objective of analysing the most cost-effective electrification plans among off-grid and grid extension plans. The initial cost of installation for the two plans was compared for each case study to determine which was the more practical option.

A. Site Surveys

Effective planning and operational decisions were made after conducting site assessments in both communities. The number of homes in the community, the kind of users (religious, industrial, commercial), average energy consumption per category, and peak demand hours were considered in the electrification load study for this task. For the best design, the kind of distribution network from the areas that border the proposed site the closest, as well as the quickest path from the substation, were also determined. These include locating consumer concentrations based on

the project area's actual conditions, which helps determine the line's length and distance (in kilometres) from the neighbouring distribution network to the proposed site.

The end-use approach to load demand estimating and forecasting was used. This method directly estimates energy consumption by utilizing substantial information on end use and end users, such as appliances, customer use, their age, house size, and other factors. The many ways that energy is used in the residential, commercial, and industrial sectors are the main emphasis of end-use models. As a result, the model clarifies how the quantity of appliances on the market affects energy demand [23]. To account for the increasing load, future effective electricity demands for the neighborhoods were taken into consideration. For this study, a 30% growth that is suggested in [4] was chosen. The total load demand for each community is therefore equal to the sum of the current load demands for all categories of electricity consumers within the community plus the percentage load allowance for load increase. Mathematically, this is written as:

$$P_{total} = 1.3 \sum_{i=1}^{N} P_i \tag{1}$$

Where P_i is the load demand per category.

B. *Design and cost estimation for on-grid electrification*

The distribution plan must comply with service quality standards, especially considering the current distribution voltage levels (which are 11kV and 33kV for Nigeria). The following factors were taken into account when developing the transformer substations;

a. *Substation sizing and siting*

Transformer size, load growth, sizing flexibility, load distribution flexibility, and other factors affect the size and placement of the substation. According to Kelvin's Law, the most cost-effective transformer size is one whose annual winding cost (copper or aluminum losses) equals the thermal running cost or charges of the installed transformer plus the annual core cost [24]. For better voltage regulation and minimal losses, locations were chosen to be very close to the center of the loads in their service area. Crossing between cables was also avoided as much as possible. The locations support the addition of load easily and in proximity to the substation. Accessibility for fuse replacement, general maintenance, and servicing of switchgear and panels was also considered. The transformer size is calculated using the equation in (2) and a power factor of 80%.

$$S = \frac{P_{total}}{\cos \theta} \tag{2}$$

The size of the transformer feeder pillar connecting the substation to the areas to be fed is determined by the transformer's rated current in amperes, which is calculated by equation (3):

$$I = \frac{S}{\sqrt{3} V_{L-L}} \tag{3}$$

Where V_{L-L} is the line-to-line voltage for a three-phase system

b. *Line equipment sizing*

It is crucial to choose the overhead line conductor that is the most cost-effective size. According to Kelvin's law, the most cost-effective conductor size is one for which the annual charges on the investment are equal to the energy losses [24]. Because larger cross-sectional areas typically lead to lower resistance and fewer losses, it is safer to select and use oversized line conductors. It plays a crucial role in both the design of high tension (HT) and low tension (LT) lines because it keeps the conductor's tension within the safe range if it varies due to seasonal change. The primary and secondary current ratings of the distribution transformers served as the main determinant of the sizes of the conductors and cables in this work. In order to determine the overall length of the overhead conductor, equation (4) was used:

$$Length\ of\ conductor = L \times 3(or\ 4) \times s \cdot f \tag{4}$$

Where L is the length of overhead conductors per phase and s.f is the sagging factor of the cable

The use of constants 3 or 4 in equation (4) are for HT (11 or 33 kV) lines, which typically have three sets of conductors (3-phase), and LT (0.415 kV) lines, which have four sets of conductors, respectively.

C. *Design and cost estimation for off-grid electrification*

Kwara State and Nigeria as a whole is rich in terms of solar energy resources. Based on the monthly averaged daily global solar radiation, a photovoltaic (PV) mini-grid is considered viable (Figure 1). To supply safe, dependable, and cost-effective energy services that satisfy the needs of the consumers, the components and configurations for each sub-system must be chosen carefully [25].
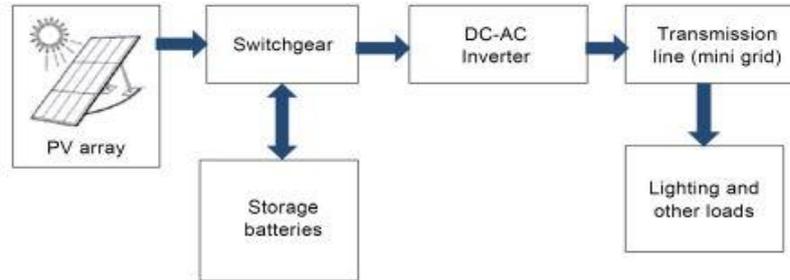

Fig. 1. A typical PV Microgrid [11]

The remaining PV system components, including the number of parallel-operating PV modules, the size of the storage battery bank, and the transmission lines (mini-grid) for the anticipated loads, must all be sized properly after the community's required load has been determined [11]. To ensure that the battery can be recharged from its maximum depth of discharge in a reasonable amount of time while still being able to fulfill the daily load requirements, any renewable energy source of electricity must be large [11]. The number of PV modules needed is calculated by dividing the installation's total power by the solar module's rated power in equation (5):

$$N_{Module} = \frac{P_{total}}{P_{Module}} \qquad (5)$$

The switchgear system, which houses the charge controller and other switching and protection components, is typically sized so that it can support the open-circuit voltage of the PV array and carry at least 125 percent of the array short circuit current [11]. The likelihood that all of the loads could turn on simultaneously and run continuously is taken into account while sizing the inverter. However, this indicates that the inverter is typically operating at a lower load than its rated load while it is operating [11]. Using the expression from equation (6) and an oversize factor of 1.15, the size of the inverter was determined.

$$Inverter\ size = Total\ load \times Oversize\ factor \qquad (6)$$

The daily energy requirement, days of autonomy, battery safe depth of drain, battery efficiency, inverter efficiency, and system voltage are the key design factors for battery systems. Equation (7) determines the overall design load based on the DC bus or battery bank's observed load;

$$E_{total} = \frac{E_{AC}}{\eta_{inverter}} \qquad (7)$$

Where:
E_{total} = total daily energy demand from the DC bus in kWh;
E_{AC} = design daily energy AC load in kWh; and
$\eta_{inverter}$ = average energy efficiency of the inverter.

5. Results and Discussions

Case Study A

ASUU estate owned by the Academic Staff Union of Universities (ASUU), University of Ilorin branch, is just a few kilometers from the University's main gate. It is an extension of the nearby community of Jalala. Only 50 units of the estate's residential, that is three-bedroom apartments have been constructed, and more of the same size are still being built. .

A. Electricity Demand Assessment

By interviewing certain people, primary data on energy demand were gathered. Electrical appliances found in residential buildings made up the bulk of the loads. When all of the equipment was in use, the morning and evening hours saw the highest load demand in the area. The overall amount of power needed for the estate's structures was also determined using the average consumption and power ratings of each item. Since access to all structures was not feasible, assumptions were made on the size of a typical residential building to determine the residential electricity demand.

The total electricity demand for 50, 3-bedroom flats is then 8,552,500Wh. Current electricity demands for the estate are given by the expressions in (8).

$$kW = \frac{kWh}{hour\ of\ the\ day} \simeq 355kW \qquad (8)$$

For an expected load growth of 30%, the future effective electricity demand of the estate stands at approximately 463kW.

Table 1. Electricity consumption of a typical flat in the Estate

S/N	Description	Rating(W)	Quantity	Average hours of usage	Load demand (Wh)
1	Lighting Point	100	24	15	36000
2	Television Set	80	1	15	1200
3	Refrigerator	150	1	24	3600
4	Ceiling Fan	50	3	15	2250
5	Radio/Music Centre	50	2	8	800
6	Boiling Ring	1000	4	2	8000
7	Pressing Iron	1000	1	2	2000
8	Air Conditioner	1500	5	8	60000
9	Cooker	5000	1	5	25000
10	Security Lighting	100 per unit	8	10	8000
11	Computer set	220	1	10	2200
12	Oven	1500	1	2	3000
13	Microwave Oven	1000	1	2	2000
14	Electric Grinder/Blender	1000	1	1	1000
15	Clothes Dryer	4000	1	2	8000
16	Washing Machine	1000	1	2	2000
17	Deep Freezer	500	1	12	6000
Total					171050

B. Proposed on-grid system

A 500kVA, 11/0.415kV transformer substation with accessories at a cost implication of seven million, eight hundred and seventy-six thousand, two hundred and forty-eight naira (#7,876,248.00) is proposed.

C. Proposed off-grid system

A solar mini-grid with a 450kVA / 48V Growatt Inverter, 9,004 Nos of 320 W PV modules, 2, 346 Nos of 24V, 300 Ah batteries at a cost of one hundred and fourteen million, seven hundred and two thousand naira only (#114,720.00) is proposed for the solar system.

Case Study B

Olorundara Community, Ganmo in Ifelodun Local Government Area (LGA) is equally a growing community but quite dissimilar to the first case study. It is quite undeveloped and could pass as an extension of Ganmo community, a bigger town in the same LGA.

A. Electricity Demand Assessment

The community has a residential, commercial, and religious buildings that were assessed for their energy demand. Two types of residential buildings include face-to-face rooms and 3-bedroom flats. Table 2 is the electricity demand of the community

Table 2. The electricity demand of Olorundara Community, Ganmo

S/N	Type of Consumer	Number of Houses	Load demand (Wh) per flat	Total load demand (Wh)
		A	B	C=AB
1	Residential (3-bedroom flats)	20	101,050	2,021,000
2	Residential (8 rooms face-to-face)	30	95,400	2,862,000
3	Shops	6	95,600	573,600
4	Religious Centres	4	54900	219,600
	TOTAL			5,676,200

B. Proposed on-grid system

A 300kVA, 11/0.415kV transformer substation with accessories at a cost implication of thirteen million, three hundred and eighty thousand, two hundred and thirty naira, and seventy-two kobo (#13,380,230.72) is proposed.

C. Proposed off-grid system

A solar mini-grid with a 356kVA / 48V Growatt Inverter, 4,183 Nos of 320 W PV modules, 1,974 Nos. of 24V, 300 Ah batteries at eighty-six million, seven hundred and thirty thousand naira (#86,730,00.00) was selected for the solar system.

The study's findings indicate that off-grid electrification is more economically feasible for the remote community of Olorundara than on-grid electrification which is for the urban community of ASUU estate. Grid extension is more appropriate for these users because urban settlements are predicted to expand more quickly and may contain numerous commercial and/or industrial users. While a grid extension project's overhead cable could easily be vandalized in rural areas, coupled with voltage drops along the network, an off-grid system's security is guaranteed within the community, which is why rural communities would benefit more from it.

6. Conclusion

As the study reveals, off-grid design has higher cost impacts. This is hardly surprising given how pricey the components are right now. Grid extension and mini-grid have different economies of scale, with grid extension being considerably more affordable with greater capacity and off-grid having less of an economy of scale. Grid expansion is probably going to end up being the least expensive option at some point. Off-grid systems are more practical from the perspective of return on investment when combined with additional benefits of distributed generations, such as autonomous operation, reliability, and nearly maintenance-free operation.

From a more comprehensive planning perspective, the issue is not which form of electricity to use—grid extension or off-grid electrification—but rather how and when to combine the two. Mini-grids can be configured to run independently so they can join the main grid when grid expansion happens. Hence, off-grid electrification is becoming more cost-competitive than grid extension and is therefore being considered a viable option for those locations where main grid expansion is either impossible or has no economic justification. To achieve this, nations should create a framework for planning rural electrification that assesses the cost-effectiveness of various investment options when providing adequate levels of service and then considers social equality and balanced regional development.

Nigeria needs to develop national electrification plans to include off-grid energy development with investments from private organizations giving priority to remote communities by creating stand-alone renewable energy-based programs while speeding up the spread of distribution from the national grid into rural areas where this is practical. This will relieve the already burdened National Grid. The operation and maintenance of the mini-grids may be handled by the private sector.

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