Optimal Siting of Interconnected Mini-Grid in Electricity Distribution Network Using Interval Type-2 Fuzzy Analytic Hierarchy Process

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Abstract

Siting an interconnected mini-grid project within an electricity distribution network requires a thorough investigation of alternative locations to determine where the solution is optimally required and guarantees quick returns on investment. This study employs location attributes and lifetime value of electricity consumers as decision-making criteria for determining an optimal location for a proposed project. The location attributes criteria are consumer population, hours of supply, and energy consumption, while lifetime value criteria are profit and cost. The paper utilizes an interval type-2 fuzzy analytic hierarchy process as a multi-criteria decision-making methodology for the investigation. The study carried out a pairwise comparison of criteria using the experts' opinion survey to determine the criteria weights. The study developed Location Attributes-Based Model (LABM) and Lifetime Value Model (LTVM) to obtain the weighted value of each alternate location. The cumulative values of LABM and LTVM are used in ranking the alternate locations to determine the optimal location for the interconnected mini-grid siting within an electricity distribution network. This model is recommended for interconnected mini-grid projects decision-making as utility company embraces embedded electricity generation to bridge the supply gap created by the epileptic national grid.

Keywords

Interconnected mini-grid, electricity distribution network, interval type-2 fuzzy analytic hierarchy process, location attributes-based model, lifetime value model

1. INTRODUCTION

Electricity supply from Nigeria's national grid remains unreliable, epileptic, and covers less than 60% of the country's 203 million population over the 923,768km^2 area it covers (Akinlabi and Oladokun 2015) (Oladokun and Asemota 2015) (Aliyu, Ramli & Saleh, 2013) (IEA & World Bank 2017), (CIA, 2019). The instability of electricity supply from the grid resulted in 80% of connected consumers being underserved with only a few hours of supply daily and supply gaps being filled with renewable and non-renewable electricity generation (Oyedepo, 2012) (Akinlabi and Oladokun 2020) (Adebimpe and Oladokun 2020). The electricity supply shortfall from 2000 to 2019 was estimated to be 2.4 billion kWh and has opened up the power sector for both local and foreign mini-grid investors (Oyedepo *et. al*., 2018). Nigeria's growing economy requires several mini-grids solutions to augment her generation capacity of 12,522MW and daily generation which hovers above 4,000MW (Arowolo *et al.,* 2019; USAID 2019).

The Nigeria Electricity Regulatory Commission (NERC) has an operation regulation where a mini-grid is defined as an electricity-generating system with a capacity of not more than 1MW and distribution network infrastructure supplying electricity to customers connected or not connected to the licensed electricity distribution network (NERC, 2016). Some authors described it as local generation and distribution of between 10kW to 10MW electricity for less than 10,000 consumers (Franz *et al.,* 2014; Lilienthal 2013; Greacen *et al*., 2013). Mini-grids can be interconnected or isolated. An interconnected mini-grid is an independent electricity generation and a distribution network that is installed within an existing grid and thereafter, connected to the grid network as part of the licensed electricity distribution network (NERC, 2016). An isolated mini-grid is a localized generation and distribution of electricity to more than one customer that is not connected to the main grid (NERC, 2016). This study focused on the optimal siting of interconnected mini-grid within underserved areas of a licensed distribution network to bridge the supply gap.

One major challenge faced by the utility company and mini-grid investor is decision making on siting interconnected mini-grid projects (Yunna Wu *et al.,* 2018). Several studies have investigated the selection of location for mini-grid utilizing different multi-criteria decision-making methodologies mostly with data that are not readily available, especially in developing countries like Nigeria. Ayodele *et al.,* (2018) developed a geographical information system-based model to determine the optimal site for wind farm using interval type-2 fuzzy analytic hierarchy process (AHP) while Akinlabi and Oladokun (2020) employed the same AHP to develop an investment-based site selection (IBSS) model by utilizing 15 sub-criteria of the site characteristics and customer lifetime value. This study however uses essential criteria like population, hours of supply, energy consumption, profit, and cost. The data is sought from the historical database of the electricity distribution company. The Analytic Hierarchy Process (AHP) is a robust multi-criteria decision-making process that is most used for ascertaining criteria weights in mini-grid or renewable power system site selection assessment Hofer *et al.,* (2016). The study leverages the knowledge and data of alternate locations and existing consumer data with the electricity distribution company to develop models to optimally identify the best site amongst others using the five key criteria – population, hours of supply, energy consumption, profit, and cost incurred at the locations. The profit and cost will determine the lifetime value of consumers in those locations.

2. METHODOLOGY

Typically, the first step in optimal siting for a mini-grid project is the evaluation of site selection criteria to determine their appropriateness to the locations under investigation. Figure 1 shows the analytic hierarchy process for the optimal siting of interconnected mini-grid. The criteria considered for this study are:

1. Consumer population in selected location - Population
2. Hours of supply of electricity per day (hrs)
3. Energy consumption – (kWh)
4. Profit ‘P’ made by the utility company (Naira)
5. Cost ‘C’ expended in making the profit (Naira)

The parameters are classified into Location Attributes (1 to 3) and Lifetime value (4 & 5).

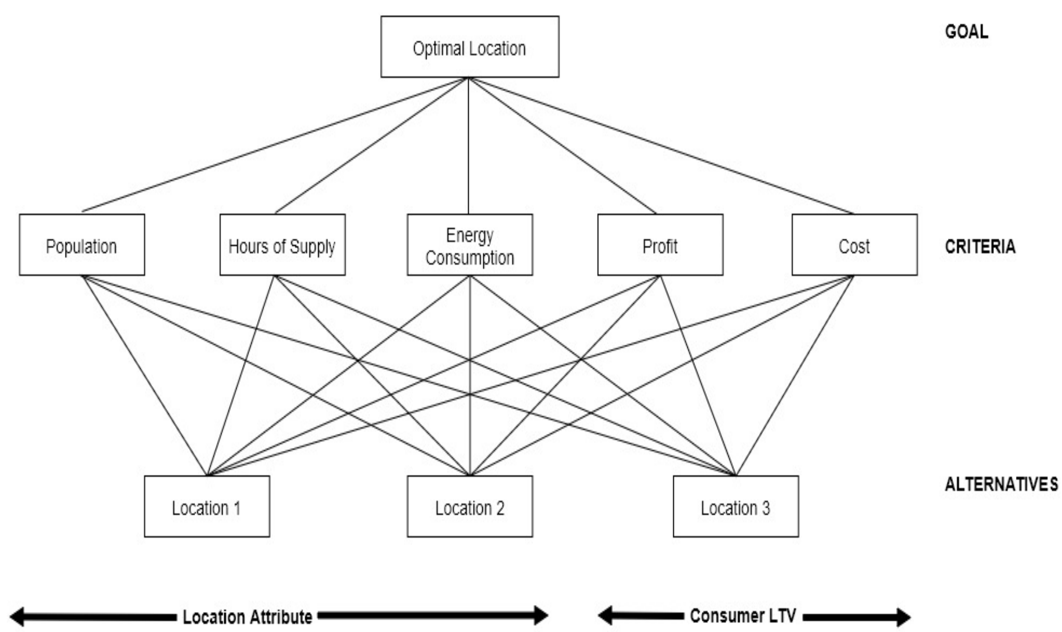

Figure 1. AHP for Optimal Siting of Interconnected Mini-grid (Authors’ conceptualization)

The AHP's apprehension is how to get a better consistency of the judgments by measuring the inconsistency to achieve improvement. Site selection for a mini-grid problem is structured by AHP as a pyramid of the alternatives and criteria (Oztaysi, 2015) as seen in Figure 1. The result of the experts' judgment survey is used as input for interval type-2 Fuzzy sets with AHP to determine the criteria relative weights and alternatives rankings.

2.1 Data Gathering

The study obtained 5-year historical data for the locations within the coverage of an electricity distribution company under consideration for the interconnected mini-grid project. Based on the data, candidate locations were determined using average hours of supply of electricity per day.

2.2 Experts Opinion Survey

An experts' opinion survey was designed to get a linguistic judgment from experts in academics and industry by carrying out criteria pairwise comparison using linguistic variables. The model utilized the output of experts' pairwise comparison of criteria from the opinion survey to outline priority scales that proportionally compute the intangible criteria based on (Saaty, 2008). The inconsistency in experts' opinion was provisioned for by interval type 2 fuzzy logic analytic hierarchy process (AHP) adopted to improve the result of criteria relative weights and provide the fuzzy weight vector showing the relative importance of the criteria. The AHP arranged the goal, criteria, and alternatives as a pyramid structure to obtain the optimal location choice (Oztaysi, 2015). The cumulative weighted average was used to rank the locations to determine the optimal choice.

The flowchart for the Location Attributes-Based Model and Lifetime Value of the consumer model is shown in Figure 2.

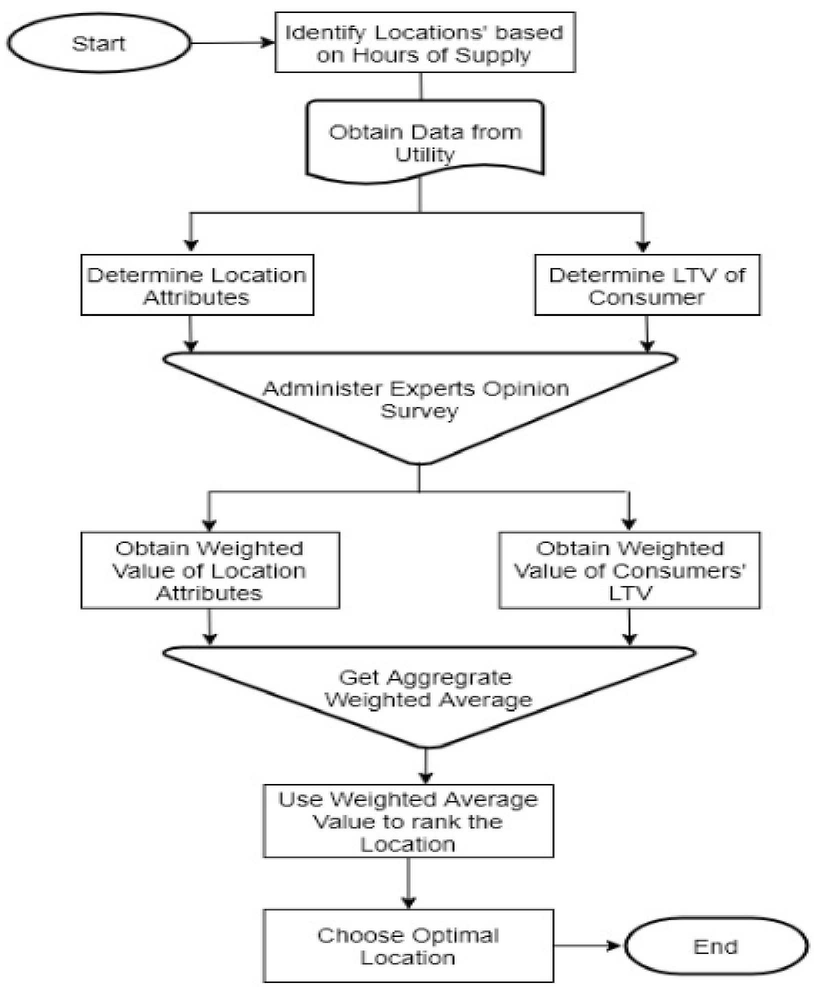

Figure 2: LABM-LTVM Methodological Framework (Authors' conceptualization)

3 MODEL FORMULATION

3.1 Location Attribute-Based Model (LABM)

The attributes of the location are the population, hours of supply, and energy consumption. Since the attributes have different units of measurement, this study adopted the Linear Scale transformation (sum method) by Chakraborty and Yeh (2007) to normalize the criteria value into a compatible unit. The Location Attribute-Based Model (LABM) is a product of normalized criteria value and criteria weights value derived from experts' opinion survey.

Normalize criteria value V_i :

$$V_i = \sum_{i=1}^{n} \left(\frac{V_i}{\sum V_i} \right) \tag{1}$$

Location Attributes value (weighted) for Location 1:

$$wLA_1 = V_1 W_1 + V_2 W_2 + V_3 W_3 \tag{2}$$

where wLA_1 is weighted Location Attribute for Location 1,
V_1. V_2, V_3 are the Normalized Criteria values
W_1, W_2, W_3 are the **Criteria Weights**

$$wLA_1 = \sum_{i=1}^{n} (V_i W_i) \tag{3}$$

3.2 Lifetime Value Model (LTVM)

The lifetime value of a consumer is defined as the net present value of all future streams of contributions to overhead and profit from customer transactions with the company (Pearson, 1996; Courtheoux 1995; Jackson, 1989; Roberts and Berger, 1989). It is also defined by Gupta and Lehmann (2003) and Hwang *et al.,* (2004) as the present value of all future profits generated from a customer. The criteria for consumer lifetime value are the profit and cost incurred in making the profit. The Lifetime Value Model (LTVM) proposition is the expected profits (*P*) from consumers, exclusive of costs (*C*) related to consumer management (Blattberg and Deighton, 1999). This is represented with the equation:

$$LTV = \sum_{i=1}^{n} \frac{(P_i - C_i)}{(1+d)^{i-0.5}} \tag{4}$$

where P_i is the profit from the consumer in period i
C_i is the total cost of generating the profit P_i in period i
i is a period of cash flow from consumer transactions
n is the total numbers of periods of projected life of consumer and
d is the discount

To further enhanced equation (1) above, this study deduced the weighted LTV using the weighted value P_i and C_i derived from experts' opinion survey employing interval type 2- fuzzy logic as shown below:

$$wLTV = \sum_{i=1}^{n} \frac{(W_r P_i - W_C C_i)}{(1+d)^{i-0.5}} \tag{5}$$

Weighted LTV for location 1 is written as:

$$wLTV_{L1} = \sum_{i=1}^{n} \frac{(W_r P_i - W_C C_i)}{(1+d)^{i-0.5}} \tag{6}$$

where $wLTV_{L1}$ is the weighted LTV value for Location 1 (L1),
W_rP_i is the weighted profit for Location 1 (L1)
W_cC_i is the weighted cost of generating profit for Location 1 (L1).

3.3 Location Suitability

According to Akinlabi and Oladokun (2020), the Site suitability factor is the aggregation of customer lifetime value and site characteristics value, therefore:
Location Suitability value for Location 1 = equations (3) + (6)

$$LS_{L1} = wLTV_{L1} + wLA_{L1} \tag{7}$$

where LS_a is the Location Suitability value for Location 1,
$wLTV_{L1}$ is the weighted LTV value for Location 1
wLA_{L1} is the weighted Location Attributes value for Location 1.

3.4 Optimal Site Selection

The need to close the shortfall in electricity supply in Nigeria amidst scarce investment in mini-grid requires the usage of a multi-criteria decision-making process to determine the optimal location for the interconnected mini-grid. This study utilizes interval type-2 fuzzy sets in describing uncertainties in the five criteria involved in optimal location selection. Each criterion is represented by a linguistic variable. Candidate locations are represented by L_1, L_2, and L_3 while the criteria are represented by C_1, C_2, C_3, C_4, and C_5. The linguistic judgment of the experts was represented by interval type-2 fuzzy sets scales as shown in Table 1. The table contains the linguistic terms used, the corresponding Saaty linear scale, and the trapezoidal fuzzy sets scale (Ayodele *et al.,* 2018). The terms and their short codes are Exactly Equal EE, Slightly Strong SS, Fairly Strong FS, Very Strong VS, and Absolutely Strong AS.

Table 1. Interval Type 2 Fuzzy Preferences

Linguistic terms	Saaty linear scale	Trapezoidal Fuzzy sets scale
Exactly Equal (EE)	1	(1,1,1,1;1,1) (1,1,1,1;1,1)
Slightly Strong (SS)	3	(1,2,4,5;1,1) (1.2,2.2,3.8,4.8;0.8,0.8)
Fairly Strong (FS)	5	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)
Very Strong (VS)	7	(5,6,8,9;1,1) (5.2,6.2,7.8,8.8;0.8,0.8)
Absolutely Strong (AS)	9	(7,8,9,9;1,1) (7.2,8.2,8.8,9;0.8,0.8)

The fuzzy preferences for the three candidate locations are shown in Table 2. The weights of the criteria are calculated after fuzzy preferences have been derived.

Table 2. Fuzzy Preferences For The Three Candidates Locations

	L_1	L_2	L_3
C_1	(1,2,4,5;1,1) (1.2,2.2,3.8,4.8;0.8,0.8)	(5,6,8,9;1,1) (5.2,6.2,7.8,8.8;0.8,0.8)	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)
C_2	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)	(5,6,8,9;1,1) (5.2,6.2,7.8,8.8;0.8,0.8)
C_3	(1,2,4,5;1,1) (1.2,2.2,3.8,4.8;0.8,0.8)	(1,2,4,5;1,1) (1.2,2.2,3.8,4.8;0.8,0.8)	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)
C_4	(5,6,8,9;1,1) (5.2,6.2,7.8,8.8;0.8,0.8)	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)
C_5	(3,4,6,7;1,1) (3.2,4.2,5.8,6.8;0.8,0.8)	(5,6,8,9;1,1) (5.2,6.2,7.8,8.8;0.8,0.8)	(1,2,4,5;1,1) (1.2,2.2,3.8,4.8;0.8,0.8)

The pairwise comparisons and calculation of the analytic hierarchy process are carried out following the steps below:

Step 1: Compose the pairwise comparison decision matrices (C) using each element of the expert opinion as an interval type-2 fuzzy set.
Step 2: Normalize the decision matrix
Step 3: Check for consistency

The AHP calculations are summarized in Table 3. The consistency ratio is 0.092 and less than 0.1, this shows that the derived calculations for AHP are consistent. If CR exceeds the 0.1 thresholds, the matrix will need to be modified until a consistent value is arrived at.

4. RESULTS AND DISCUSSION

The weights of the weighted criteria were obtained by inputting the experts' opinion data into the mathematical model. The level of inconsistencies in the experts' opinion was found to be ok with the consistency ration CR less than 0.1 and within the acceptable limit. The CR obtained is 0.092. From the experts' opinion points of view on the criteria influencing the optimal siting of interconnected mini-grid in Nigeria, the results of the criteria weight result reveal that hours of supply (C_2 = 0.4813) has the highest influence of 48%, followed by Profit (C_4 = 0.2623) at 26% and Cost (C_5 = 0.1592) at 16%. Population has the least influence at just 4% (C_1 = 0.0345).
It is observed that other criteria, aside from hours of supply, accounted for 52% of the calculated weight as adjudged by the experts. This implies that hours of supply being the highest influencer in this study should not be taken as a sole decision criterion for optimal siting of interconnected mini-grid. Other criteria should also be taken into consideration when deciding on siting the project.

5. RECOMMENDATION AND CONCLUSION

Location Attributes-Based Model (LABM) and Lifetime Value Model (LTVM) developed in this study is recommended for quick decision making on the optimal siting of interconnected mini-grid. It will be a willing tool for mini-grid investors, utility companies, international development agencies when swift decision-making is required for the interconnected mini-grid project. The use of LABM and LTVM to obtain the weighted values of criteria in determining the optimal siting of interconnected mini-grid is faster than the investment-based site selection model developed by Akinlabi and Oladokun (2020). The volume of data required is lesser and easily available, unlike similar models. The model is remarkable for its swiftness in decision making for the optimal location for a mini-grid. One of the limitations of this study is that other factors like the infrastructural investment required, collection efficiency, customer tariff classification, technical, commercial, and collection losses were not considered due to difficulties in getting their data from the utility company. Future studies can employ other multi-criteria decision-making techniques and compare the outcome with the result of this study.

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