Investment-Based Site Selection Model for Interconnected Mini-Grid

Akintunde K. Akinlabi
Department of Industrial and Production Engineering
University of Ibadan, Ibadan Nigeria
tundelabi@yahoo.com

Victor O. Oladokun
Department of Industrial and Production Engineering
University of Ibadan, Ibadan Nigeria
vo.oladokun@mail1.ui.edu.ng

Abstract
Investment decision making by developers of interconnected mini-grid in an underserved electricity distribution network is very critical. This can be achieved by utilizing existing customer data and alternate site characteristics facts available with the utility company. This study developed an investment-based site-selection model (IBSS) that applies the weighted values from pairwise comparison of the criteria and sub-criteria obtained from experts' judgment survey. The criteria for consideration in the study are Customer Lifetime Value (CLTV) and Site Characteristics (SC). The investigation adopts the multi-criteria decision-making tools of the Interval Type-2 Fuzzy Logic and Analytical Hierarchy Process (IT2F-AHP) to rank the potential sites. The aggregate values of both criteria rankings are obtained to get the final rankings of suitable sites that are arranged based on their weightings and suitability. Interconnected mini-grid investors and developers can use this model in deciding on project geographic coverage area within an underserved electricity distribution network and determine a definite return on investment.

Keywords
Interconnected Mini-grid, Underserved Electricity Distribution Network, Investment-based Site-Selection, Customer Lifetime Value, Site Characteristics

1. INTRODUCTION
The diversification and adoption of new technologies to generate electricity in emerging economies are required to achieve sustainable development through energy security and fight against the menace of global warming. Emodi and Ebele (2016) advocated diversification of power sources in all sectors as a way out of the current electricity problem afflicting developing countries, such as Nigeria. One diversification option is the mini-grid solution which is cost-effective to deploy and will bridge the supply gap by providing affordable electricity for the populace. Bhattacharyya (2016) opined that mini-grids solution has not been fully exploited despite being a complementary method to augment insufficient power supply to underserved communities. An underserved area in an electricity distribution network has a poor supply of electricity or an inefficient distribution system and would require a mini-grid solution. Mini-grid is a local, centralized electricity generation system of between 10kW to 10MW and distribution network within one or more communities with less than 10,000 customers (Lilienthal 2013; Greacen *et al*., 2013; Franz *et al.,* 2014). Mini-grids can be interconnected or isolated. 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). 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 an interconnected mini-grid solution within underserved areas of a licensed electricity distribution network. While there are glaring investment opportunities for interconnected mini-grids projects in underserved communities, Yunna Wu *et al.,* (2018) considered optimal project site selection as an important process that will significantly influence investment decisions in the entire life cycle of the projects.

Most studies on site selection for mini-grid do not consider the economic viability of the best optimal site thus creating an investment decision problem. Herrera-Seara *et al.,* (2010) employed Geographical Information System GIS with Analytical Hierarchy Process AHP, Gastli, and Charabi (2011); Khan and Rathi (2014) adopted GIS-based spatial fuzzy multi-criteria evaluation for optimal site selection without reference to an investment decision. Joseph *et al.,* (2016) determined optimum PV plant site selection for selected LGAs in Imo State Nigeria employing United States National Aeronautics and Space Administration - NASA meteorological data, population density, and landmass information from Nigerian Population Commission using PVSyst software. The study, however, does not consider the economic viability of the most optimal site thus creating an investment decision problem. Ighravwe and Babatunde (2017) recommended further research on the appropriate investment-based business model for mini-grid implementation. Ohunakin and Saracoglu (2018) employed five different multi-criteria decision making (MCDM) techniques for selecting a site for a very big concentrated solar power plants in Nigeria. The MCDM used are Elimination and Choice Translating Reality (ELECTRE) III and IV, Consistency-Driven Pairwise Comparisons (CDPC), Decision Expert for Education (DEXi) and Analytic Hierarchy Process (AHP). The results provided quite a few choice sites as substitutes then alongside a major recommendation for further investigation at the investment stage.

Going by the above, mini-grid investors required a workable, investment-based site selection model to guide the decision-making process for the long-term sustainability of mini-grids projects. This study aims to develop an investment-based site selection model for an interconnected mini-grid system in an underserved area, apply the model to the electricity distribution network analysis and evaluate the performance of the model for interconnected mini-grids solution siting.

2. INVESTMENT-BASED SITE-SELECTION MODEL

For Mini-grid developers, the supply gap is an opportunity to invest in the electricity sector, but the challenge is to decide the optimal location among the alternatives candidates' sites for mini-grids. Mini-grids site selection could be approached from many criteria such as technology, renewable energy sources, business model, solar irradiation, closeness to the grid, consumer population, willingness to pay, etc. Most of the multi-objective methodologies for site selection utilizes different criteria but very few are investment-based. Some of the available methodologies adopted are complex with data that are not readily available, especially in developing countries like Nigeria. Several multi-criteria techniques can be used for determining criteria weights. The most common method for ascertaining criteria weights in mini-grid or renewable power system site selection assessment is the Analytical Hierarchy Process (AHP). This study adopted the AHP multi-criteria decision-making method because of its robustness as shown by Hofer *et al.,* (2016). The Analytic Hierarchy Process (AHP) is a measurement theory using pairwise comparisons and depends on the expert judgments to define priority scales that quantify intangibles in comparative terms (Saaty, 2008). The opinions are decided using a measure of complete judgments that characterize the difference between two elements in relatives to a given attribute.

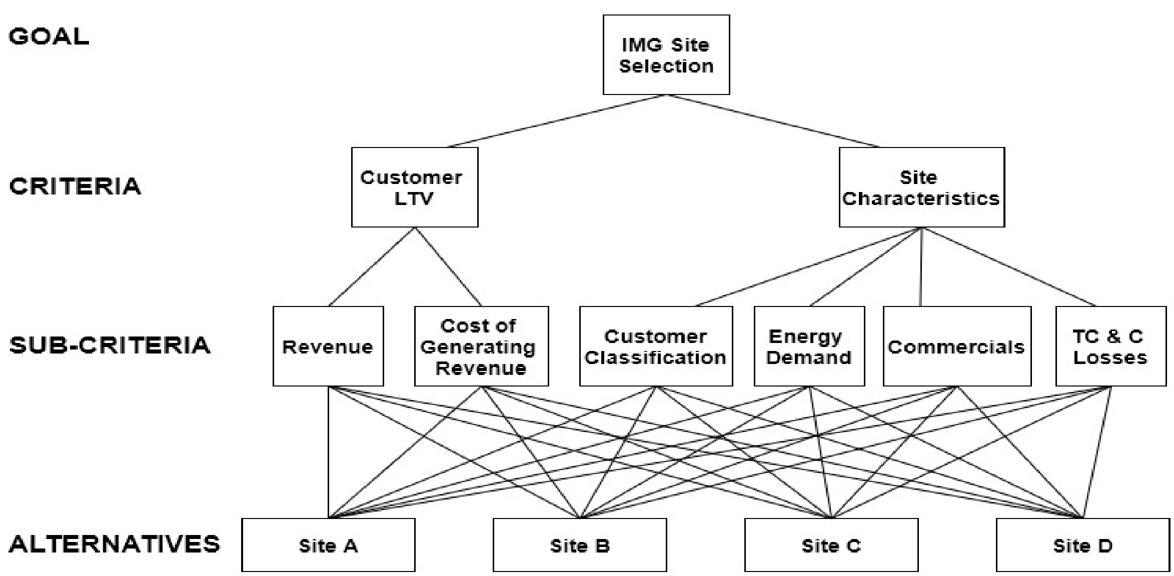

Figure 1. AHP Framework

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 Criteria Definitions

The main criteria for the conceptual framework are Customer Lifetime Value (CLTV) and Site Characteristics (SC). The sub-criteria are Revenue, Cost of Generating Revenue, Cashflow period Discount, Customer classification, Commercials, Energy demand, Technical, Commercial, and Collection losses. The sub-criteria are defined in table 1.

Table 1. Criteria Definitions

Customer Lifetime Value	
Criteria	**Definition**
Revenue	Income earned from the customer in period '*i*'
Cost of generating revenue	Amount incurred in getting the income earned from customer
Site Characteristics	
Criteria	**Definition**
Customer Classification	Customer population, tariff classes such as residential, commercial and public
Commercials	Revenue billed and cash collection per annum, collection efficiency and infrastructural investment required
Energy Demand	Average daily consumption, supply availability hours per day, peak power demand and metering rate
Technical, Commercial and Collection Losses	An aggregate of losses arising from technical, commercial and collection activities

2.2 Customer Lifetime Value (CLTV)

Definitions of customer lifetime value by some authors are summarized below:

Table 2. Definition of LTV (H. Hwang et al., 2004)

Definitions	**Article**
The present value of all future profits generated from a customer	Gupta and Lehmann (2003)
The net profit or loss to the firm from a customer over the entire life of transactions of that customer with the firm	Berger and Nasr (1998)
Expected profits from customers, exclusive of costs related to customer management	Blattberg and Deighton (1996)
The total discounted net profit that a customer generates during her life on the house list	Bitran and Mondschein (1996)
The net present value of the stream of contributions to profit that result from customer transactions and contacts with the company	Pearson (1996)
The net present value of a future stream of contributions to overheads and profit expected from the customer	Jackson (1994)
The net present value of all future contributions to overhead and profit	Roberts and Berger (1989)
The net present value of all future contributions to profit and overhead expected from the customer	Courtheoux (1995)

2.3 Customer Lifetime Value Model

The Customer Lifetime Value (CLTV) model offers a context for evaluating and segmenting customers based on their value using the concept of Net Present Value (NPV) obtained from customers over the lifetime of transactions (Hoekstra and Huizingh, 1999). The basic model calculation is written as:

$$CLTV = \sum_{i=1}^{n} \frac{(R_i - C_i)}{(1+d)^{i-0.5}} \tag{1}$$

where R_i

C_i is the total cost of generating the revenue R_i in period i
i is a period of cash flow from customer transactions
n is the total numbers of periods of projected life of customer and
d is the discount

However, this study enhanced equation (1) above by deriving *weighted*-CLTV formula using the weighted value R_i and C_i derived from expert judgment using IT2-AHP. The *wCLTV* is written as:

$$wCLTV = \sum_{i=1}^{n} \frac{(W_r R_i - W_C C_i)}{(1+d)^{i-0.5}} \tag{2}$$

Python programming is used to obtain the CLTV value of several potential sites because of the volume of data involved. The value for each site will be multiplied by their normalized weighted value derived from expert linguistic judgment using IT2-F AHP for a robust result. The final *wCLTV* value for each site will be obtained using equation (2) above. For example, weighted CLTV value for Site A will be written as:

$$wCLTV_a = \sum_{i=1}^{n} \frac{(W_r R_i - W_C C_i)}{(1+d)^{i-0.5}} \tag{3}$$

where $wCLTV_a$ is the weighted CLTV value for Site A,
$W_r R_i$ is the weighted revenue for Site A
$W_c C_i$ is the weighted cost of generating revenue for Site A.

2.4 Site Characteristics Model (SC model)

Site characteristics model clustered customers in potential sites into segments and obtain values for selected criteria used in distinguishing the sites. The criteria values are normalized using Linear Scale transformation (sum method) (Chakraborty and Yeh, 2007) and summed up to get site suitability values for ranking the sites. Criteria used are customer classification, commercials, energy demand, technical, commercial, and collection losses. Each of the Site Characteristic criteria in Table 1 has three or four distinctive sub-criteria and their parameters were extracted and supplied into a preference data collection for Site Characteristic Model in Table 3. The model is a product of criteria weights value derived from expert linguistic judgment using IT2-F AHP and the normalized criteria value. The criteria value is normalized because they are non-linear.

Criteria values X_i are normalized using Linear Scale transformation (sum method).

$$X_i = \sum_{i=1}^{n} \left(\frac{X_i}{\sum X_i} \right) \tag{4}$$

Weighted **Site Characteristics** value for site A will be written as:

$$wSC_a = W_1 X_1 + W_2 X_2 + W_3 X_3 + \cdots + W_n X_n \tag{5}$$

where wSC_a is site characteristics for site A,
$W_1, W_2, W_3 \dots W_n$ are the **Criteria Weights** from expert judgment using IT2-AHP
$X_1, X_2, X_3, \dots X_n$ are the **Normalized Criteria values**

$$wSC_a = \sum_{i=1}^{n}(W_i X_i) \tag{6}$$

Site Suitability value for Site A = aggregation (3) and (6). Chakraborty and Yeh (2007).

$$SS_a = wCLTV_a + wSC_a \tag{7}$$

where SS_a is the site suitability value for Site A,
$wCLTV_a$ is the weighted CLTV value for Site A and
wSC_a is the weighted site characteristics value for site A.

2.5 IBSS Methodological Framework

The Investment-based site selection (IBSS) framework in figure 2 below shows the flow of potential site selection for the study and determining site suitability for investment. This is achieved by investigating the customer lifetime value and site characteristics as shown below:

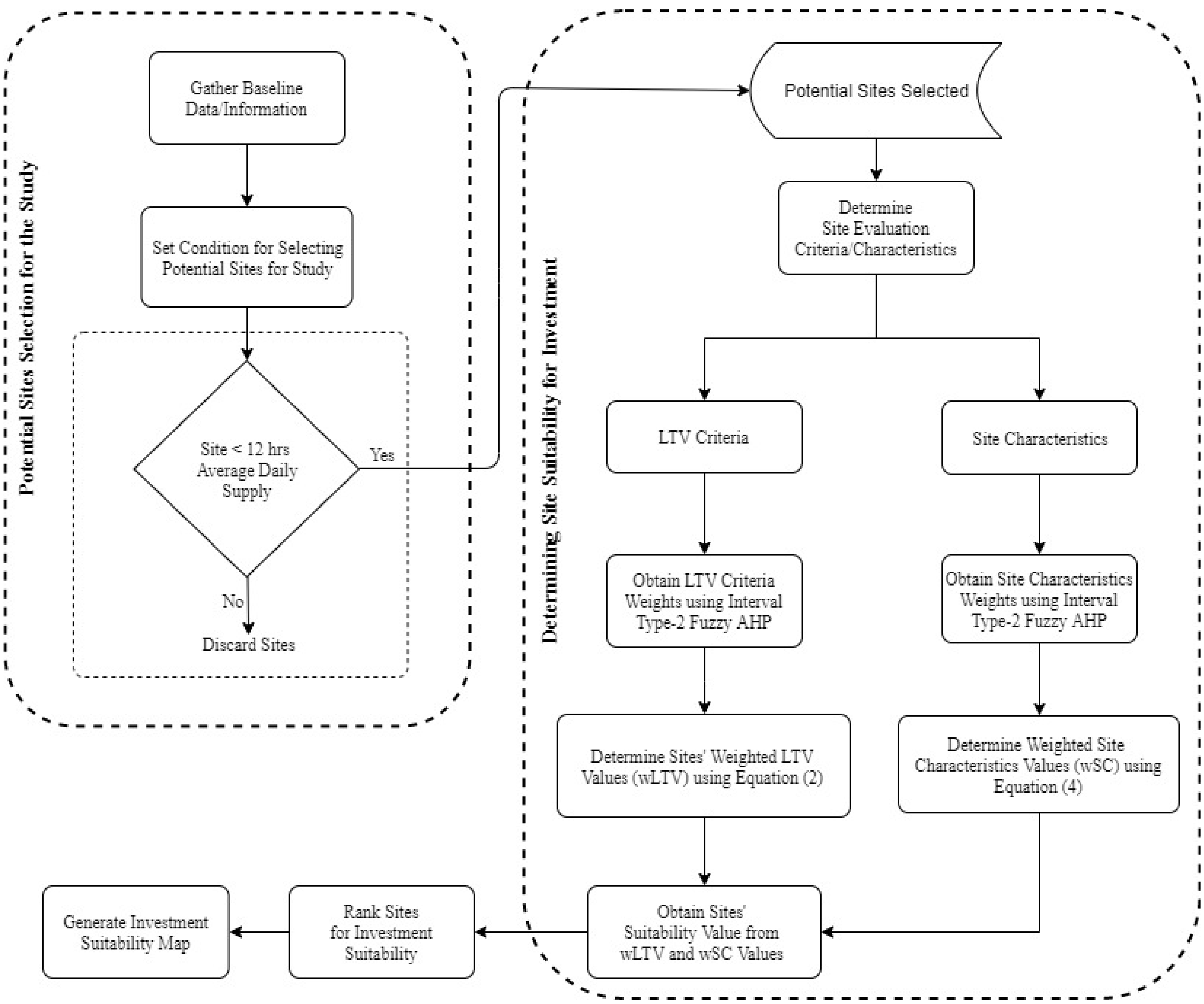

Figure 2. IBSS Methodological Framework

Tables 3 shows the samples of data collected from the Utility for five potential sites (A to E) while Table 4 shows the Normalized Criteria Value for the potential sites A to E.

Table 3. Data Collection for Site Characteristic Model

Site Characteristics Model					
Characteristics	***Site A***	***Site B***	***Site C***	***Site D***	***Site E***
Customer Classification					
Customer Population (Nos.)	254	103	212	305	267
Residential Tariff Class (Nos)	212	87	159	249	219
Commercial Tariff Class (Nos)	35	12	39	45	33
Public Tariff Class (Nos)	7	4	14	11	15
Energy Demand					
Peak Power Demand (kW)	75	26	64	83	79
Average Daily Consumption (kWh)	690	230	558	355	478
Metering Rate (%)	0.6	0.7	0.65	0.5	0.4
Supply Availability (hrs/day)	6	5	5.5	4.5	5
Commercials					
Revenue billed/annum (N'm)	8.64	3.51	6.99	10.49	8.91
Cash Collection/annum (N'm)	3.05	1.02	2.31	3.67	3.51
Collection Efficiency (%)	35	29	33	35	39
Infrastructural Investment	19.3	24	13.6	7.5	12
TC & C Losses					
Technical Loss (%)	17	15	15	16	17
Commercial Loss (%)	12	17	16	14	11
Collection Loss (%)	9	10	9	11	12

2.6 Expert Judgment Survey

An Expert Judgment survey was developed for criteria pairwise comparison of the customers' lifetime value and site characteristics. The goal of the survey is to determine the weight for each of the customer lifetime value and site characteristics criteria from the opinion of the experts. The survey was designed to get a linguistic judgment from experts in academics and power industry. The survey was administered to renowned researchers in the field of renewable and alternate energy, industry professional in the electricity distribution business, and mini-grid developers in Nigeria.

Interval Type-2 Fuzzy- Analytical Hierarchy Process (IT2-F AHP) is used to get the criteria weight from the expert judgement. The criteria weight is part of the inputs required for determining the site suitability value for the interconnected hybrid mini-grid project. Criteria pairwise comparison of all criteria affecting the experts' judgment will be evaluated using IT2-F AHP set scale to signify the linguistic judgment of the experts and provide the fuzzy weight vector showing the relative importance of the criteria. The alternatives suitable sites are positioned at the base of the pyramid table (figure 1).

Table 4. Normalized Criteria Value for Alternative Sites

Characteristics	Site A	Site B	Site C	Site D	Site E
Customer Classification					
Customer Population	0.1835	0.1816	0.1847	0.2651	0.2225
Residential Tariff Class	0.1532	0.1534	0.1385	0.2164	0.1825
Commercial Tariff Class	0.0253	0.0212	0.0340	0.0391	0.0275
Public Tariff Class	0.0051	0.0071	0.0122	0.0096	0.0125
Energy Demand					
Peak Power Demand	0.0542	0.0458	0.0557	0.0721	0.0658
Average Daily Consumption	0.4986	0.4054	0.4860	0.3085	0.3983
Metering Rate	0.0004	0.0012	0.0006	0.0004	0.0003
Supply Availability	0.0043	0.0088	0.0048	0.0039	0.0042
Commercials					
Revenue billed/annum	0.0062	0.0062	0.0061	0.0091	0.0074
Cash Collection/annum	0.0022	0.0018	0.0020	0.0032	0.0029
Collection Efficiency	0.0255	0.0512	0.0288	0.0304	0.0328
Infrastructural Investment	0.0139	0.0423	0.0118	0.0065	0.0100
TC & C Losses					
Technical Loss	0.0123	0.0264	0.0131	0.0139	0.0142
Commercial Loss	0.0087	0.0300	0.0139	0.0122	0.0092
Collection Loss	0.0065	0.0176	0.0078	0.0096	0.0100

3. CASE STUDY – NIGERIA

Nigeria is a developing nation with a population of 203 million over the 923,768km^2 area it covers (CIA, 2019). The International Energy Agency and World Bank reported in 2017 that 58% of Nigeria's population is connected to electricity through the national grid. Oyedepo (2012) opined that the instability of electricity supply from the national grid resulted in 80% of consumers being underserved with only a few hours of supply daily. Thus, consumers have resulted in self-generation of electricity from renewable and non-renewable sources to be able to meet their energy needs but at a cost higher than average kilowatt-hour (kWh) tariff by the electricity distribution companies. The gap between power production and consumption in Nigeria between the years 2000 and 2014 is about 2.35 billion kWh (Oyedepo *et. al*., 2018) despite the privatization of the power sector. In 2019, the United States Agency for International Development (USAID) estimated the installed electricity generation capacity in Nigeria to be 12,522MW with daily generation hovering above 4,000MW. To bridge the apparent supply gap, Sambo (2008) recommended the deployment of all Nigeria's energy resources and involvement of private and foreign investors while Arowolo *et al.,* (2019) proposed the use of Mini-grids like other developing nations such as Mozambique and India with similar problems like Nigeria (Uamusse *et al*., 2019; Kater *et al*., 2019). Adeleke (2016) opined that successful operations of Mini-grids will require the adoption of verified business models, community inclusiveness, and cooperation of other stakeholders.

IBSS model is a suitable tool for Interconnected Mini-grid investors in Nigeria. It will help them decide on the best segment of the network that guarantees quick returns on investment. Six years after the privatization exercise, the licensed electricity distribution companies (DISCO) are yet to improve their services to many underserved locations in the country (UNDP 2016; Oyedepo *et al*., 2018). The DISCOs could not provide uninterrupted electricity supply for consumers leaving many communities underserved with only a few hours of supply daily with no immediate plan to improve availability by bridging the supply gap. Interconnected Mini-grid investors have great opportunities given the current state of the Nigeria Electricity Supply Industry. Although customers will embrace the mini-grid solution, the revenue collection could be difficult due to customers' apathy to payments of currently subsidized tariffs from the main grid.

In terms of data gathering for the model utilization, the investors will approach the licensed electricity distribution company (DISCOs) for the data for preliminary investigation. The underserved areas will be determined using historical data from daily interruption reports while other data will be required from the technical and commercial management systems and enterprise resource planning systems of the utility company.

4. RECOMMENDATION AND CONCLUSION

4.1 Recommendation

Investment-Based Site-Selection model developed in this study is recommended for electricity distribution companies, mini-grid investors, and other government agencies in the decision-making process for the interconnected mini-grid project. It is highly recommended that the Electricity Distribution Company (utility) should support investors and government agencies by providing the required data as inputs for the model. To encourage diversification of electricity generation through mini-grid, regular updating of the IBSS model would also help the utility company in determining the most optimal site for network expansion and resource allocation which will guarantee quick returns on investments.

4.2 Conclusion, Limitation and Future Research

This study analyzed the customer lifetime value and potential site characteristics for the Interconnected Mini-grid project. This approach is novel to investment decision making for mini-grid projects. An important element for the model is accurate data from the utility company. In Nigeria, the regulatory body for the electricity supply industry is NERC – Nigeria Electricity Regulator Commission, constantly overseeing the performance of all the stakeholders in the sector with data-driven reports and investigation. A major limitation of this study is access to customer data from the utility company as they might be unwilling to provide such a large volume of data. Further study is recommended using other criteria with variants of MCDM processes within the same study area to validate this model.

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Biographies

Akintunde K. Akinlabi, BEng, MSc, MBA, PMP is a doctoral student in the Department of Industrial and Production Engineering, University of Ibadan, Nigeria. He is an ICT inclined Business Operations Management Professional, a COREN® Engineer, and a member of the Nigeria Society of Engineer. His research interests include captive power, mini-grids and renewable hybrid power system as a solution to electricity poverty in Nigeria. He is currently working on cost modeling for interconnected mini-grid projects.

Victor O. Oladokun, Professor, Department of Industrial and Production Engineering, University of Ibadan, Nigeria. Professor Oladokun a Fulbright African Research Scholar, a Commonwealth Academic Fellow, a certified SAP trainer, and SAP ERP consultant is the Deputy Director, University of Ibadan School of Business. His research interest involves applying engineering optimization and soft computing for modeling some emerging socio-economic and techno-ecological challenges in Nigeria. He is currently working on flood risk management and resilient system development.