Modeling and Optimum Capacity Allocation of Micro-Grids Considering Economy and Reliability

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***Abstract*—This paper centers on the modeling and optimum capacity allocation of micro-grids capable of operating autonomously from (or in parallel with) an unreliable grid network. The aim is to estimate the monetary cost of reliable power served, considering the unreliable nature of electric power grid in the developing world. The micro-grid developed consists of the photovoltaic and wind energy conversion systems, the hybrid (super-capacitor/battery) storage and a power conversion system. The grid model utilized a probability-based prediction technique due to the random nature of grid network. The formulated optimization problem was solved using the hybrid Genetic Algorithm and Pattern Search (h-GAPS) based model. The problem objectives were considered in terms of monetary cost while constraining the micro-grid to reliably satisfy the power demand based on the proposed energy management strategy. The process was simulated for a telecommunication system load at Abuja (lat. 9.08°N, long. 7.53°E). The simulation results are presented and discussed.**

***Index Terms*—Electric Power Grid; Genetic Algorithm; Micro-Grids; Pattern Search; Reliability; Renewable Energy.**

I. INTRODUCTION

The rapid growth of cellular mobile telecommunications in developing regions gives rise to a number of setbacks, which include network congestion and poor quality of service delivery. These problems are fast eroding the gains of the telecommunication sector. Operating companies are unable to expand their networks fast enough to meet the ever growing demand by subscribers in most parts of these regions due to lack of a reliable grid network and the cost consequence of a supplementary power source [1].

Nigeria’s electric power grid has been characterized by a high unreliability index for several decades [2]. Numerous attempts have been made by the Nigerian Government in the provision of power infrastructure, yet the electric power grid is unable to ensure a permanent supply of electricity [3]. In spite of the erratic power supply, only about 40% of Nigerians can access the grid. This problem has made entrepreneurs resort to using fossil-fuelled generators [4]. The fossil-powered option has a number of setbacks. First, the cost of electricity served by diesel generators is considerably higher compared to the grid [5]. Second, fossil combustion has added to the concentration of greenhouse gasses in the atmosphere, creating a tendency of global warming of the earth [6]. This drawback has the impetus of creating hazardous climate changes, with overwhelming impacts on the ecosystem [7].

To tackle the dearth of electric power access at different regions worldwide, several micro-grid systems [8], [9], [10], [11], [12], [13] were assessed in comparison with the off-grid, grid-only or grid-tied systems in the literature. In off-grid applications, the practice is through modeling of system components with the control process implemented using iterative search methods or heuristic tools. Conversely, the assumption of an ideal grid distribution system and the subsequent neglect of a grid supply model commonly characterized grid-connected micro-grid designs. A recent release (Pro 3.2.3) of HOMER (Hybrid Optimization Model for Electric Renewable), a computer-based model introduced random outages to account for unreliable grids based on three variables: mean failure frequency, mean repair time and repair time variability. Nevertheless, alternative methods are essential to facilitate comparisons, which can help to verify the applicability of different techniques.

A micro-grid can intelligently control distributed power sources and interconnected loads. It can operate autonomously from (or in parallel with) the grid [7]. Similarly, it can combine different power sources to make best use of individual source's strengths while offsetting for the others' inadequacies [14]. If optimally designed and deployed for developing regions, can be more reliable and cost-effective than the grid network. A reliable and cost-efficient power option can result in the global expansion of telecommunication networks to meet the ever increasing demand of subscribers in the developing world. Perhaps, the micro-grid can improve not only the quality of service delivery but can further increase the mobile market penetration and reduce the cost of cellular mobile services in developing regions. Moreover, pollutant emissions can be reduced and by this means making the atmosphere cleaner and safe.

This paper applies a probability-based prediction technique in the analysis of micro-grids, capable of operating autonomously or in parallel with an unreliable grid network. The objectives are to ascertain the monetary cost of reliable electricity and evaluate the trade-offs between cost and reliability, considering the dynamism and technical viability of various power sources. The next section gives a description of the methods applied in this paper. Results are analyzed and discussed in Section III while Section IV concludes the study.

II. METHODS

Modeling is a pre-requisite for optimum sizing of micro-grids but the approach differs from one article to another [15]. Besides, information regarding the operating performance of micro-grid components plays a significant role in determining the optimum control strategy. Optimum control enables efficient management of power flow between the different energy sources, storage device and the distribution for reliably supplying the energy demand [16]. The control can allow proper exchange of energy among various components, thereby enhancing the system's performance at optimum cost. The architecture of the proposed micro-grid for cellular mobile telecommunication sites is shown in Fig. 1.

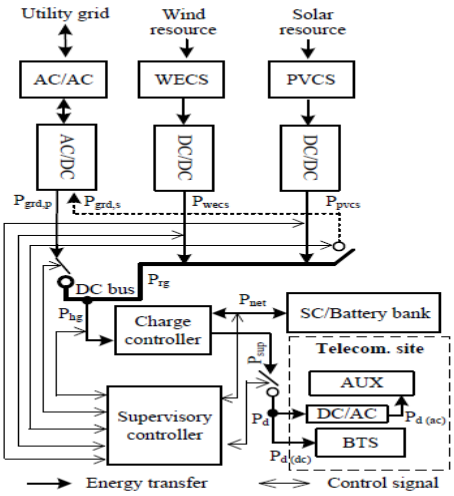

Figure 1: Architecture of proposed micro-power system

The photovoltaic conversion system (PVCS) and wind energy conversion system (WECS) consist of the PV array and a wind turbine generator (WTG) respectively. The utility grid is considered since it is Nigeria's current source of electricity. The storage system is made up of the super-capacitor/battery bank. The super-capacitor (SC) provides the instantaneous power when there are surges since it can be charged or discharged almost immediately, while the battery bank provides the bulk energy to the system over a longer slower time [17]. The choice of a hybrid storage system can be a more feasible option as power surges negatively affect battery lifespan.

The control system consists of the power electronic converters and controllers. The supervisory controller helps in efficient power flow management for improved power quality. The controller coordinates all power electronics. Power electronics technology provides functionalities for optimum energy harvest. This technology is required to adapt the dynamics of renewable resources, transferring suitable and applicable energy to the grid [18], [19]. The control signals are defined by the controller based on the constraints specified by the intended energy management strategy. The net power generation is controlled through the SC/battery using converters. A typical telecommunication site consists of the base transceiver station (BTS) equipment with varying electric power requirement, depending on the site meteorology and configuration [20]. The average hourly electric load observed based on random measurement of an out-door peripheral node sites varies between 1.7 kW and 2.2 kW all through the day due to changes in demand, with a daily average of 2.0kW [1].

A. System Modeling

The operation of the micro-grid design of Fig. 1 is such that only renewable sources can charge the storage unit. The fraction of renewable energy contribution by the micro-grid is expressed as shown in (1). E_{served} ($=E_{sup} + E_{grd,s}$) is the annual electrical load served, E_{sup} is the energy drawn by the load and $E_{grd,s}$ is the energy sold to the grid, all expressed in kWh/y.

$$f_{ren} = 1 - (E_{grd,p} / E_{served}) \; . \tag{1}$$

Photovoltaic conversion system: The solar energy (kWh) generated by the photovoltaic conversion system of Fig. 1 is computed using the following equation:

$$\begin{aligned} E_{sg}(\tau) &= \eta_{mp,stc}\, \eta_{cf}\; S_{pv}\; I_t(\tau)\times \\ &\qquad (1 + t_{po}(T_c(\tau) - T_{c,stc})).\Delta\tau, \\ &= P_{pvcs}(\tau).\Delta\tau \end{aligned} \tag{2}$$

where $\eta_{mp,stc}$ is the photovoltaic generator reference efficiency at the standard test condition (STC), η_{cf} is the efficiency of coupling, S_{pv} (m^2) is the area of the photovoltaic array, I_t (kW/m^2) is the hourly global irradiance incident on the tilted PV, $T_{c,stc}$ (°C) is the cell temperature under STC, t_{po} (%/°C) is the temperature coefficient of power, T_c (°C) is the PV cell temperature and $\Delta\tau$ (= 1h) is the time step. The method for estimating the PV cell temperature is described in [21].

Wind energy conversion system: This study intends to mount the WTG on the BTS tower due to land constraint as well as to save additional cost of installing a self-supporting tower. Hence, the WECS of Fig. 1 consists of one WTG. In order to efficiently utilize the available wind energy, four different sizes of turbines (P_{wtj} = 1, 2, 3, and 5 kW) were considered. The wind energy (kWh) generated by the micro-grid is estimated by (3) [22]; where z_f is the altitude factor, $P_{wt\text{-}out}$ and α_{FOR} are power output and forced outage rate of the WTG respectively and (1– α_{FOR}) is the probability of the WTG being operational. S_{wt} (= P_{wtj}), specifies the size of the WTG to be selected.

$$\begin{aligned} E_{wg}(\tau) &= z_f\; P_{wt-out_j}(1-\alpha_{FOR}).\Delta\tau \\ &= P_{wecs}(\tau).\Delta\tau \end{aligned} \; . \tag{3}$$

The output power (kW) of the WTG was computed based on the piecewise 3rd order polynomial described in [9]. Forced outage rate is a known method utilized to ascertain the probability of unavailability of a generating set at some distant time in the future [22].

Grid supply: In order to account for the erratic nature of grid electricity in a developing region like Nigeria, the outcome of the grid is likened to that of a coin, i.e., randomly. Based on this assumption, the probability of grid supply P_s (τ) can be represented as the magnitude of the uniform distribution function and the real-time supply voltage is deduced as follows:

$$V_{gs}(\tau) = n_s\, V_{ave}\, P_s(\tau) \times (1 + \delta_h\, \delta_d) \; . \tag{4}$$

V_{ave} is the average supply voltage, n_s is the number of possible outcome of grid electricity expected for a defined period τ (= 1, 2, . . . , N), representing each hour of the year, δ_h and δ_d are randomly drawn from the normal-distribution function with an average of zero and standard deviation equal to the hourly noise input value and the daily noise input value respectively. The normal-distribution is the most outstanding considered probability distribution with exceptionally broad application [1], [23]. In addition, it is very tractable analytically and a large number of results concerning this distribution can be derived in precise form [24]. The real-time grid supply voltage profile for a reliable grid can be deduced, from the long-term values, using stochastic methods.

The dc power (kW) drawn from the grid is expressed as follows [22]:

$$P_{grd,p}(\tau)=\begin{cases}P_l(\tau)/(\eta_{sta}\eta_{ret}) & \text{for } V_{s,\min}\le V_{gs}(\tau)\le V_{s,\max}\\ 0 & \text{else}\end{cases} \tag{5}$$

P_l (kW) is the required load capacity that can response to a sudden rise in power demand, η_{sta} is the efficiency of the stabilizer used in stabilizing the grid supply, η_{ret} is the rectifying efficiency while $V_{s,min}$ and $V_{s,max}$ are the minimum and maximum input voltages of the stabilizer. The energy (kWh) drawn from the grid is given by the equation:

$$E_{grd,p}(\tau)=D_{grd}\,P_{grd,p}(\tau)\Delta\tau\,. \tag{6}$$

D_{grd} is the decision variable, which specifies the mode of operation while $\Delta\tau$ is the time step. D_{grd} is set to the default value of 0 for off-grid and 1 for grid-connected operation.

The hybrid power, in dc, generated by the micro-grid at time τ is defined by (7), where P_{pvcs}, P_{wecs} and P_{rg} are power generated by the wind, PV and renewable sources respectively while $P_{grd,p}$ is the dc electric power drawn from the grid.

$$\begin{aligned}P_{hg}(\tau) &= P_{pvcs}(\tau)+P_{wecs}(\tau)+P_{grd,p}(\tau)\\ &=P_{rg}(\tau)+P_{grd,p}(\tau)\end{aligned} \tag{7}$$

Energy storage: The energy storage model includes the super-capacitor and battery models, which are linked in parallel to a dc bus. The hybrid energy storage system is chosen due to its ability in reducing battery ageing and the improvement in energy efficiency when the power system operates in critical climate conditions [25], [26]. The size of the SC/battery bank, S_{sb} (kWh) can be expressed as in (8), where S_{sc} and S_b is the size of the SC and battery banks respectively.

$$S_{sb} = S_{sc}+S_b\,. \tag{8}$$

The usable storage capacity (J) of an SC module is estimated using (9) [27], where C (F) is the capacitance and V_{usc} (V) is the upper voltage level of the SC module (1J = 3.6 x 10^{-6} kWh).

$$E_{sc} = \tfrac{3}{8}C\,V_{U_{sc}}^2\,. \tag{9}$$

The size (kWh) required to enable the SC bank respond to the peak transient power demand (P_{pk}) for a minimum duration considered here as 1 min (= 1/60 h) is given as (10), where η_{sb} is the charge/discharge efficiency and β is a factor used to account for the fractional loss in storage energy due to SC voltage variation.

$$S_{sc} \ge P_{pk}/(60\beta\eta_{sb})\,. \tag{10}$$

The required number of SC modules is given by (11), where N_{sc} is rounded to the greater integer for safety reason.

$$N_{sc} = S_{sc}/E_{sc}\,. \tag{11}$$

The total storage capacity (kWh) of the battery bank is defined by (12), where N_b is the number of batteries and E_{bat} (kWh) is the nominal storage capacity of a single battery selected. The techniques for estimating the battery float life and energy throughput are described in [28].

$$S_b = N_b E_{bat}\,. \tag{12}$$

At time τ, the state of charge of the SB bank, SOC_{sb} (τ) relates to the preceding state, SOC_{sb} (τ – 1) and to the energy generation and utilization state of the system from $\tau - 1$ to τ. During the process of charge/discharge, when net power flows into/out of the storage unit, the available SOC_{sb} (τ) is expressed as (13), where η_{sb} and S_{sb} (kWh) is the charge/discharge efficiency and is the total nominal capacity of the SC/battery respectively.

$$SOC_{sb}(\tau) = SOC_{sb}(\tau-1)+\eta_{sb}E_{net}(\tau)/S_{sb}\,. \tag{13}$$

The net energy E_{net} (τ), computed based on the energy management strategy determines the charge/discharge, provided the constraints imposed by the operation plan are satisfied. To extend the battery life span, the SOC_{sb} is subjected to the constraint defined by (14), where $SOC_{sb,min}$ and $SOC_{sb,max}$ are the lower and upper permissible SOC of the SC/battery bank respectively.

$$SOC_{sb,\min} \le SOC_{sb}(\tau)\le SOC_{sb,\max}\,. \tag{14}$$

Electric load: The required load capacity to enable a sudden rise in energy demand is expressed as (15), where E_d (kWh) is the energy drawn by the load and E_{or} (kWh) is the energy reserve, taken as 10% of E_d.

$$E_l(\tau) = E_d(\tau)+E_{or}(\tau)\,. \tag{15}$$

B. Techno-Economic Analysis

Reliability consideration: Reliability as defined here is the fraction of electricity demand that the power system can deliver. The power system reliability can be deduced in terms of the loss of power supply probability (LPSP) as expressed in (16); where E_d (kWh) and E_{def} (kWh) are the total annual demand and deficit energies respectively while η_{rel} is the power supply reliability.

$$LPSP = E_{def}/E_d = 1-\eta_{rel}\,. \tag{16}$$

Economic consideration: The cost of energy per kWh, COE ($/kWh) is expressed as follows:

$$\begin{aligned}COE = \psi(&cc_{gs}+cc_{wt}.S_{wt}+cc_{pv}.S_{pv}+\\ &cc_{con}.P_{r,con}+cc_{sc}.N_{sc}+cc_b.N_b+\\ &cc_{def}.LPSP+C_{sys,mgt}-C_{grd,sold})\end{aligned} \tag{17}$$

where ψ (1/kWh) is the reciprocal of the total energy drawn by the load during the project life span, cc_h ($/unit) is the cost coefficient per unit of component h, S_{wt} (kW) and S_{pv} (m^2) are the required size of WTG and the PV array respectively, $P_{r,con}$ (kW) is the rated power of the power converter, N_{sc} is the number of SC modules, N_b is the number of batteries, cc_{def} is the cost coefficient of deficit energy supplied, $C_{sys,mgt}$ is the cost of the energy management system and $C_{grd,sold}$ is the total income derived from energy sold to the grid. The COE analysis is described in [1].

C. Optimization and Simulation

Optimization problem: The objective function is to minimize the COE served, subject to reliable operation. The optimization problem is defined as follows:

- minimize the COE:
-

$$\min COE(S_{wt}, S_{pv}, N_b) = \psi(cc_{gs} + cc_{wt}.S_{wt} + cc_{pv}.S_{pv} + cc_{con}.P_{r,con} + cc_{sc}.N_{sc} + cc_b.N_b + cc_{def}.LPSP + C_{sys,mgt} - C_{grd,sold}) \quad (18)$$

- subject to:

$$\left.\begin{array}{l} LPSP \le \gamma;\ S_{wt,\min} \le S_{wt} \le S_{wt,\max} \\ S_{pv,\min} \le S_{pv} \le S_{pvt,\max};\ N_{b,\min} \le N_b \le N_{b,\max} \end{array}\right\}, \quad (19)$$

S_{wt}, S_{pv}, N_b, are variables to be sized by the h-GAPS-based model (see Fig. 2), which represent the required power capacity (kW) of the WTG, area (m^2) of photovoltaic array and the number of batteries respectively. $S_{h,min}$ and $S_{h,max}$ are the lower and upper acceptable limits of the sizing variable S_h, and γ is the unreliability factor; γ is set to vary within considerable reliability limits (taken to be ≥ 90%) but with the inclusion of cost penalty for unmet loads. The cost penalty can ensure a proper compromise between reliability and monetary cost for optimum sizing of micro-grids in typical applications.

Developed h-GAPS-based simulation model: The h-GAPS-based technique, shown in Fig. 2, is applied to solve the optimization problem. Based on the available load/weather data measured at the telecommunication site, the fixed optimum tilt angle for harnessing solar energy was determined. The method utilized to compute the optimum tilt angle of solar collectors is described in [29]. The wind speed data were adjusted to the BTS tower height using power law [30].

The optimum capacity allocation of the micro-grid begins with the evaluation of the initial design configuration (either chosen or default setting) by the GA, to verify if it can provide reliable power to the load otherwise a new configuration is determined. Thereafter, the GA determines the evaluation qualified configuration with the best value for a pre-specified number of generations or when a condition, which establishes convergence, is satisfied.

The pattern search (PS) algorithm, at the starting point X_0, begins with the best candidates given by the GA. At the first iteration, the pattern vectors as constructed and are summed to the start point X_0 to calculate the mesh points. The algorithm calculates the fitness function at mesh points in the same order and polls these points by evaluating the fitness values until it discovers a smaller fitness value at X_0. If such point exists, the algorithm sets the point to X_1; otherwise, the poll is termed as unsuccessful.

After a successful poll, for instance, the algorithm doubles the current mesh size and moves to the next iteration. The algorithm polls the mesh points until it finds a more suitable value for X_1. The first such point it locates is called X_2. Thereafter, the algorithm doubles the current mesh size at the third iteration. If the third iteration poll ends up being unsuccessful $X_3 = X_2$.

At subsequent iteration, after an unsuccessful poll, the algorithm halves the present mesh size. This process enables the algorithm poll with a lesser mesh size. The point from the previous iteration is replaced by a better point, if any.

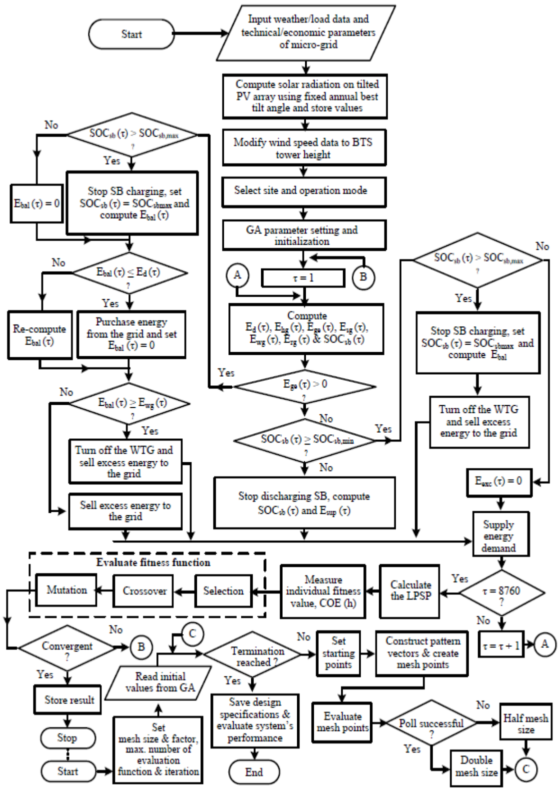

Figure 2: Developed h-GAPS-based simulation model for micro-grid

The procedure is repeated until the algorithm finds the optimum solution for the optimization problem. The process terminates when a pre-defined condition or a criterion that determines convergence is satisfied. The long-term annual hourly solar irradiation, wind speed and load data, and the economic specifications of components utilized in this study are given in [1]. The cost penalty for unmet energy demand is assumed to be the COE (= \$0.50/kWh [9]) of the diesel power system.

III. Results and Discussion

Table 1 shows the simulation result for the micro-grid at Abuja. The optimum capacity, which consists of 33.49m^2 (5.07kW) PV array inclined at 15 degrees, 5kW wind turbines, 0.053/43.20kWh SC/battery bank enables reliable and cost-efficient power supply to the telecommunication site at a cost of \$0.114 (N22.40*) per kWh.

The micro-grid can serve reliable power by generating 56.36% and 40.42% of the total load demand from solar and wind sources respectively, purchasing 3.21% of the demand from the diesel-powered system. It is worthy of note that although the isolated micro-grid has a reliability of 96.78% the opportunity cost of the micro-grid downtime is accounted for by the inclusion of cost penalty in the COE analysis. Therefore, the isolated option can offer reliable power at a cost saving of over 61% compared to the grid-tied option.

This result is indicative of the techno-economic viability of renewable option in Nigeria.

The optimum capacity of the PV array is 33.49m², which is less than one-tenth of the landmass of a plot of land measuring 462.10m². This shows that the implementation of the isolated micro-grid is feasible even with one-tenth size (46.21m²) of a plot of land.

Table 1
Simulation Result of Developed Micro-Grid at Abuja

Option	$E_{grd,p}$ (kWh/y)	Optimum sizes			Performance indices			
		S_{wt} (kW)	S_{pv} (m²)	S_h (kWh)	COE ($/kWh)	LPSP	η_{rel}	f_{ren}
Off-grid	-	5	33.49	43.20	0.114	0.0321	0.9678	1.000
Grid-tied	4,671.79	5	22.79	21.60	0.296	0.0028	0.9972	0.736

*Note: $1 = 196.50 (Central Bank of Nigeria accessed May 9, 2015).

However, the implementation may not be feasible for existing telecommunication sites with a lesser area, unless there is a possibility of site expansion. Where such extension is possible, the cost of an additional land requirement (not considered here) can reduce the monetary cost benefits of the isolated micro-grid. The grid-tied option has smaller PV array and storage capacity but requires 4,671kWh energy per annum from the grid. The grid-tied option can be considered for existing sites with smaller landmass – when site expansion is not feasible, but must have access to the grid. This option offers reliable power at a higher cost compared to the isolated option. Table 2 shows the specifications/optimum capacity allocation of components for the proposed micro-grid options. The availability and mean period of power access between two power outages used for the grid simulation are 0.55 and 4.5h per day respectively [3].

Table 3 shows the COE comparison deduced from the formulated optimization problem based on the h-GAPS-based technique and that of HOMER software, for the same LPSP. The result indicates that the proposed method is preferred to HOMER software, due to the ability of the h-GAPS-based technique to converge to the global optimum rather than the local optimum solution. It is worth mentioning that the stochastic population-based algorithm like GA is good at pinpointing promising regions of the search space.

Conversely, the PS algorithm is a more coordinate search method, which guarantees convergence from arbitrary starting to stationary points. As a result, the h-GAPS-based approach can offer a more efficient trade-off between exploration and exploitation of the search space, which has helped to ensure that the global optimum solution is selected.

Table 2
Specification/Optimum Capacity Allocation of Developed Micro-Grid at Abuja

Power sources	Specification	No of Units
PV	CNSDPV 150 modules: P_{max} = 150Wp, A_{pv} = 0.991m², V_{dc} = 24V, T_{cstc} = 25ºC	34
WTG	Hummer H6.4: v_{ci} =3m/s, v_{co} =25m/s, P_r =5kW, P_{max} =5.6kW	1
Battery	USB US-250 battery: E_{bat} = 1.35kWh (225Ah at 6V)	32
SC	BM0D0165/P048BXX SC: E_{sc} = 0.053kWh (165F SC at 48V)	1

Table 3
Cost Comparison of h-gaps-based technique with Homer software for same LPSP at Abuja

Option	HOMER software COE ($/kWh)	h-GAPS-based COE ($/kWh)	Cost reduction (%)
Off-grid	0.116	0.114	1.72
Grid-tied	0.301	0.296	1.66

Table 4
Comparison of Performance indices of Different Power Options under same Reliability Scenarios at Abuja

Grid type	Option	COE ($/kWh)	K_e (kWh/$)
Baseline (Reliable grid)	Grid-only	0.124	8.06
Typical (Unreliable grid)	Grid-only	0.204	2.59
Typical (Unreliable grid)	Isolated micro-grid	0.114	8.77
Typical (Unreliable grid)	Grid-tied micro-grid	0.296	3.38

A. Baseline Comparison

First, the ideal grid – business-as-usual (BAU) scenario that considers reliable operation of the grid and ignores power outages was assumed. Based on the assumption, the grid can supply the energy demand at any time when renewable power is unavailable or when there is a shortfall. The micro-grid simulated based on the BAU scenario is used as the baseline for comparison to study the impact of an unreliable grid on the results from this study. The impact of unreliable grid on the optimum costs of different power options is shown in Table 4. The analysis is based on the monetary cost of energy and energy index. The energy index is the energy throughput of a power system measured in terms of per unit cost of energy served, which is defined as K_e (= η_{rel}/COE) [9].

As observed, the unreliable nature of the grid has a considerable impact on the cost of energy served and the energy throughput of the power system. The optimum system from the baseline (reliable grid) scenario is the grid-only power system, offering power at $0.124 (₦24.37*) per kWh. The cost of reliable power served by an unreliable grid-tied system is over 2.3 times that of a reliable grid at Abuja. Therefore, the energy throughput per dollar investment offered by the micro-grid connected to an unreliable network over 58% less than that of a reliable grid.

The grid-only solution is still available with an unreliable grid, but is only optimal (at a cost of $0.204 per kWh) if 47% or more unmet load is allowed. In this case, increasing the power supply reliability of the unreliable grid by 47% requires 45% increase (from $0.204 to $0.296) in the COE offered. It should be noted that the increased cost of reliable energy offered by the grid-tied micro-grid is due to additional equipment to the system, which raises the cost of the entire system. The increase in the monetary cost of energy is justifiable given the enhanced reliability of power supply to the electric load. Moreover, the optimum cost of reliable power offered by the isolated micro-grid option is lower (8.10% lesser) than that of a reliable grid at the study location. The cost saving is perhaps due to the relatively high cost of grid electricity compared to green sources and the high unreliability index that characterizes grid electricity in Nigeria. It is worthy of note that the cost of the renewable energy has significantly reduced over the years due to advances in green energy technology.

The results deduced in this study are based on 22 years data for the study location as the long-term average value is believed to be adequate. However, when there are abrupt changes in the climatic conditions, the developed h-GAPS-based model, based on the new geographical parameter can re-establish a new optimum configuration. An improved meteorology (increase in irradiance and wind speed) will enhance the monetary cost benefit for the site and vice versa. But in general, the range of the monetary benefit within the useful lifespan of the project may not be significant since the long-term values were used.

It is important to note that unlike other models, although the developed h-GAPS-based model (Fig. 2) was simulated for Abuja, it can be applied to any location with an unreliable grid, provided the meteorological data are available. One of the unique features of the developed model is that it accounts for the dynamic nature of electricity grids especially in developing regions where there are frequent power outages.

IV. CONCLUSION

This paper applied a probability-based prediction method in the analysis of micro-grids, which can operate in parallel with (or independently from) an unreliable grid network. The developed h-GAPS-based optimum capacity allocation model was utilized to solve the analytical shortfall in the techno-economic analysis of unreliable grid networks at Abuja (Nigeria). Compared to a reliable grid network, analysis showed that the cost of power offered by the isolated micro-grid reduced by 8.01% but the cost of the grid-tied micro-grid increased by over 130%.

This study is useful as it can allow the energy consumer verify the trade-offs between cost and reliability for satisfying the basic energy needs. Prospective investors can be informed of the optimum capacity allocations/projections and the techno-economic impacts of the renewable technology. This information enables the investor to decide on the most appropriate option or the energy mix for harvesting reliable and cost-efficient power. The method discussed can be used to find the optimum architecture of both isolated and grid-tied micro-grids for any region with an unreliable grid. This method can further be extended to analyze similar problems in energy system designs or used with different objective functions for other purposes.

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