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Techno-Economic Analysis of a Grid-Connected Hybrid Energy System for Developing Regions

M. S. Okundamiya[1]*, J. O. Emagbetere[2], E. A. Ogujor[2]

[1]Department of Electrical and Electronic Engineering, Ambrose Alli University, P. M. B. 14, Ekpoma, Nigeria
[2]Department of Electrical and Electronic Engineering, University of Benin, Benin City, Nigeria

ABSTRACT

This paper examines the viability of a grid-connected hybrid energy system (HES) for domestic electricity generation in the developing world. It aims to determine the techno-economic benefits of operating a wind energy conversion system. The HES consists of the grid power supply, wind energy conversion, power electronics, and storage units. The grid supply unit incorporates a probability-based prediction technique. The wind energy system modelling is based on the piecewise third order polynomial, using wind turbine power profile supplied by the manufacturer. The formulated optimization problem was solved using a hybrid Genetic Algorithm and Pattern Search (h-GAPS) technique. The h-GAPS based approach constrains the generation and distribution of power to ensure efficient operation. Analysis performed for a typical residential area used meteorological data for six sites, which spread across Nigeria. Results showed that the proposed power system could bring benefits of cost saving and improve power reliability, but the range of financial benefits depends on the geographical coordinates. In particular, 10kW/5.40kWh capacity wind/battery system installed in Sokoto can deal with 95.4% of the total electricity demand, save more than 77% of electricity payments and increase the reliability by approximately 140%.

INTRODUCTION

Lack of a reliable and cost efficient power solution is a serious problem hindering the economic growth of most developing countries. Nigeria is a country with an unreliable electric power grid network (utility grid). The reliability of the utility grid varies from 39 to 66 % with an average duration of power access between two power outages of 4.5 h per day. At any period when grid power is available, the supply voltage fluctuates mostly between 160 – 240 Volts with an average of 205 Volts [1]. Only about 40% of Nigerians are connected to the utility grid [2]. As a result, most entrepreneurs have resorted to use diesel generators either as supplements to the utility grid or exclusively in remote areas. The socio-economic and environmental implications associated with the use of fossil-fuelled generators can be very alarming [3].

The rising need for energy sustainability has made green technology a promising energy source. One of the prominent green energy sources commonly used is wind [4-8]. Wind is a clean source of energy that does not emit greenhouse gases. It is ubiquitous and freely available. However, wind energy is intermittent in nature as it depends highly on site meteorology. Energy storage devices such as batteries are required for cancelling out unpredicted power fluctuations, stabilizing voltage and frequency, and improving the power supply quality [6]. The inclusion of a storage device significantly increases the capital cost of micro-grids [7]. And, the initial cost of wind power systems is significantly greater than fossil (diesel) power system.

The hybrid energy system (HES) is widely used in recent times because it combines various power sources to optimize each source's strengths while compensating for the others' shortcomings [8]. Compared to systems comprising of a single energy source, the HES allows improving the system efficiency, reliability of the power supply and reduces the energy storage requirements [9].

* Corresponding author: M. S. Okundamiya
E-mail: msokundamiya@aauekpoma.edu.ng, st_mico@yahoo.com;
Tel: +234 8066263858

Nevertheless, investors should be aware of the optimum configuration, capacity projections and the techno-economic implications of hybrid power systems which include renewable and conventional energy sources. Such indices can enable the investor to decide on the most suitable technology or the combination [6].

This paper examines the impact of unavailability of an electric power grid network and developed a method for inclusion of power outages in the analysis of grid-connected hybrid energy systems. A grid/wind/battery system simulated for a hypothetical residential area, which consists of a population of ten households, was considered. The objectives are to determine the optimum system configurations to provide more reliable electric power; estimate the cost of reliable electricity and under what reliability scenarios can the payment of higher cost of energy be economic. The approach can allow the energy consumer determine the best trade-offs, between cost and reliability, for satisfying the basic energy needs.

The rest of the paper is organized as follows: section 2 describes the methods adopted to achieve the set objectives. This section involves the modelling of the system components, the operation strategy, the techno-economic analysis in determining the system's cost effective components that can reliably satisfy the energy demand. The section ends with a description of the optimization and simulation processes. In section 3, the results are presented and discussed while the paper is concluded in section 4.

METHODS

Model development

The architecture of the proposed grid/wind/battery HES is shown in Figure 1. It consists of the utility grid, wind energy conversion system (WECS), power electronics and energy storage system. The WECS consists of one or more wind turbine generator (WTG) units. Power electronics are included for power conversion and stabilizing of unpredicted voltage and frequency fluctuations. The automatic voltage stabilizer (AVS) is an effective solution to voltage fluctuation problems characterizing the utility grid system in a developing country like Nigeria. The AVS maintains constant output voltage independent of grid supply and the regulation is unaffected by the load power factor.
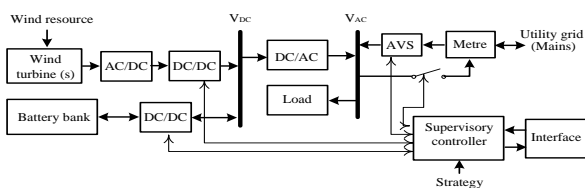

Figure 1. The grid/wind/battery hybrid energy system architecture

The supervisory controller enables the effective management of power flow for improved system stability. The controller coordinates all power electronics. The control signals are defined by the controller based on the constraints specified by the operation strategy. The net power (difference between generation and supply) is controlled through the storage battery using converters. In particular, two DC-DC converters, which connect the DC bus to the battery, allow bidirectional transfer of power. The control ensures the generation of proper power level between power sources, and the distribution for reliably satisfying the energy demand.

System models

The power supplied by the grid at time τ is defined by the following equation [10]:

$$P_{gs}(\tau) = \begin{cases} P_l(\tau)/\eta_r & \text{for } V_{r,\min} \le V_{gs}(\tau) \le V_{r,\max} \\ 0 & \text{else} \end{cases} \quad (1)$$

where, τ (= 1, 2, . . . , 8760) represents each hour of the year, P_l is the load capacity that can response to sudden rise in power demand (kW), V_{gs} is the grid supply voltage (V), η_r is the efficiency of the AVS used in stabilizing the grid-supply, and $V_{r,min}$ and $V_{r,max}$ are the minimum and maximum input voltage of the AVS (V). The energy (kWh) drawn from the grid at time τ is given as follows:

$$E_{ge}(\tau) = P_{gs}(\tau)\Delta\tau \quad (2)$$

where $\Delta\tau$ (= 1 h) is the time step, which is hourly. The power generated during $\Delta\tau$ is assumed constants, which is numerically equal to the energy within $\Delta\tau$.

The wind turbine power output (P_{wt-out}) was computed based on piecewise third order polynomial as described in [6]. The wind speed data were adjusted to WTG hub height according to the power law. Power law is one of the ways to model wind shear [11]. The wind energy (kWh) generation at τ is given by the following equation:

$$E_{wg}(\tau) = \eta_{cf} N_{wt} P_{wt-out}(1 - \alpha_{FOR}).\Delta\tau \quad (3)$$

where η_{cf}, N_{wt}, and P_{wt-out} are the efficiency of coupling, number, and output power (kW) of the WTG respectively. The probability of the WTG being operational is given by ($1 - \alpha_{FOR}$). Forced outage rate is one of the methods used in power system engineering to determine the probability of unavailability of a generating unit at some distant time in the future [12, 13]. This is because the generating unit may be unavailable, for instance, due to maintenance.

The size or total nominal storage capacity (kWh) of the battery bank is expressed as:

$$S_b = N_b E_{bat} \tag{4}$$

where, N_b is the total number of batteries in the battery bank, and E_{bat} is the energy rating (kWh) of a single battery selected. The battery bank life (y) is defined by the following equation [6]:

$$L_b = [L_{bf}, (N_b E_{lt,tp})/E_{ann,tp}]_{min} \tag{5}$$

where $E_{lt,tp}$ is the lifetime throughput of a single battery (kWh), $E_{ann,tp}$ is the annual battery throughput (kWh y^{-1}), and L_{bf} is the battery float life (y). The operation of a micro-grid can influence a battery lifespan. The lifespan of the battery affects the cost of energy of a micro-grid project. As a result, the fixed energy performance model was utilized to model the battery wear. The method described in Eq. (6) is one of the ways for modelling battery degradation when sizing micro-grid [14].

The available battery state of charge (SOC) at time τ is expressed as follows:

$$SOC_b(\tau) = SOC_b(\tau-1) + E_b(\tau)/S_b \tag{6}$$

where, $E_b(\tau)$ is the energy that flows into or out of the battery at any time. Provided the constraints imposed by the operation strategy (described in the following section) are satisfied, the energy flow either charges the battery when $E_b(\tau)$ is positive or discharges the battery when $E_b(\tau)$ is negative.

The energy consumption pattern can be simulated from the daily average load profile P_d (kW), to account for the hourly and daily variations in energy consumption, by the inclusion of noise functions defined as stated below:

$$E_d(\tau) = P_d \times (1+\delta_h \delta_d).\Delta\tau \tag{7}$$

The column ($h \times 1$) matrix of average hourly load profile (P_d) can be represented as $h \times d$ matrix by multiplying P_d with a row ($1 \times d$) matrix of ones, where h (= 1, 2, . . . , 24) is the hour of the day and d (= 1, 2, . . . , 365) is the day of the year. The hourly noise function (δ_h) is $h \times 1$ matrix while the daily noise function (δ_d) is a $1 \times d$ matrix. The hourly and the daily noise input values are randomly drawn from a normal distribution with an average of zero and standard deviation equal to the hourly and the daily noise factor, respectively. These factors (considered here as 0.05 and 0.08, respectively) can be calibrated from the real-time energy consumption pattern using regression techniques [15].

Real time electric load tends to jump around randomly. As a result, an operating reserve is needed to prevent the power system from going down in case of a sudden rise in energy demand [16]. The load capacity required to enable any sudden rise in energy demand is stated in terms of the hourly energy demand as follows:

$$\begin{aligned} E_l(\tau) &= E_d(\tau) + E_{or}(\tau) \\ &= E_d(\tau) \times (1+\beta_d) \end{aligned} \tag{8}$$

where, E_{or} (kWh) is the energy reserve and β_d, which is specified in terms of the hourly energy demand, is used to determine the amount of energy generation to be reserved.

Economic models
If the lifetime L_j (y) of component j is shorter than that of the project (i.e., $L_j < L_N$); it might be necessary to purchase additional component j before the end of the project life span. Given that c_j and $c_{om,j}$ are the capital cost and the annual operation and maintenance (OM) cost per unit size of j respectively, X_j (=L_N/L_j) is the number of times j is needed, $sv_{j,p}$ is the salvage value of j at present and that salvage value of j is assumed to decrease linearly from c_j to sv_j when j operates along its lifetime L_j; the economic cost of investment of an energy system is given as follows [6]:

$$C_{sys} = \sum_{j=1}^{j} S_j.\left(c_j q_{cc,j} + c_{om,j}.q_{om} - sv_{j,p}.q_{L_N} - sv_j.q_{sv,j}\right) \tag{9}$$

S_j is the sizing or design variable, $q_{cc,j}[=\sum_{x=1}^{X_j}(f_e/f_i)^{(x-1).L_j}]$, $q_{sv,j}[=\sum_{x=1}^{X_j-1}(f_f/f_i)^{x.L_j}]$, are coefficients of capital cost and salvage value of component j, and $q_{om}[=\sum_{y=1}^{L_N}(f_e/f_i)^y]$, $q_{L_N}[=(f_f/f_i)^{L_N}]$ are coefficients of OM cost and project lifespan respectively. $f_e = 1+r_e$, $f_f = 1+r_f$, $f_i = 1+r_i$, and r_i, r_f and r_e are the annual interest, inflation and escalation rates respectively.

Inflation involves average change as it is concerned with a group of goods and services. In contrast, escalation deals with the persistent rise in the price of specific goods and services. Therefore, escalation rates, which affects the actual costs and revenues that will be realized for a project, must be accounted for in economic evaluation of investment. Escalation rates are normally based on index numbers. An index number measures the relative change in price, quantity, value, or some other item of interest from one time period to another.

Based on Eq. (9), if the lifetime of the WTG is taken to be equal to the project life span, the total cost of the WECS can be estimated using the following equation:

$$C_{wecs} = (c_{wt} + c_{om,wt} \cdot q_{om} - sv_{wt} \cdot q_{L_N})N_{wt} \quad (10)$$
$$= cc_{wt} \cdot N_{wt}$$

where, c_{wt} is the current cost per WTG unit, $c_{om,wt}$ is the annual OM cost of the WTG, sv_{wt} is the salvage value per unit of WTG at present and cc_{wt} is the cost coefficient of the WECS.

If the salvage value of the AVS at the end of the useful lifespan is negligible, then the total cost of energy drawn from the grid is deduced as follows [9]:

$$C_{gs} = C_{grd,int} + 1.05 L_N(n_h C_{fc} + c_{ge,p} E_{grd,p}) + \quad (11)$$
$$(c_r \cdot q_{cc,r} + c_{om,r} \cdot q_{om} - sv_{r,p} \cdot q_{L_N})S_r$$

where, $C_{grd,int}$ is micro-grid interconnection charge (US\$), C_{fc} is the annual fixed charge/cost of meter maintenance (US\$ y^{-1}), n_h is the number of households connected to the micro-grid, and $c_{ge,p}$ is the grid electricity purchase price (US\$ kWh^{-1}). $E_{grd,p}$ is the annual energy drawn/purchased from the grid (kWh y^{-1}), c_r is the capital cost of the AVS per kW (US\$ kW^{-1}), qcc_r is the capital cost coefficient of AVS, $sv_{r,p}$ is the savage value of the AVS per kW at present (US\$ kW^{-1}), S_r is the size or rated power of the AVS (kW), and $c_{om,r}$ (US\$ kW^{-1} y^{-1}) is the annual operation and maintenance cost per kW of AVS. The factor (1.05) accounts for the 5% charged as value added tax (VAT) on the cost of energy drawn from the grid in Nigeria.

If the salvage value of batteries is negligible, the total cost of the energy storage unit is computed by Eq. (12).

$$C_b = (c_b \cdot q_b + c_{om,b} \cdot q_{om} - sv_{b_p} \cdot q_{L_N}) \cdot N_b \quad (12)$$
$$= cc_b \cdot N_b$$

where, c_b is the capital cost per unit size of battery bank (US\$ unit^{-1}), $c_{om,b}$ is the annual OM cost of the battery (US\$ y^{-1} unit^{-1}), sv_{bp} is the salvage value at present (US\$ unit^{-1}), q_b is the capital cost factor, cc_b is the price coefficient per unit size of the battery bank (US\$ unit^{-1}).

The total income from energy sell-back to the grid is expressed as follows:

$$C_{es} = c_{ge,s} E_{grd,s} L_N \quad (13)$$

where, $c_{ge,s}$ (US\$ kWh^{-1}) is the energy sell-back price; from micro-grid to grid, $E_{grd,s}$ is the energy sold to the grid per annum (kWh y^{-1}), and L_N is the project lifespan.

Operation strategy

It is assumed that the control algorithm and the distribution lines are ideal; inverter efficiency η_{inv} is constant, and the battery charge efficiency η_b is set equal to the manufacturers' round-trip efficiency. The generated wind power is constant during $\Delta\tau$ and the power is numerically equal to the energy within the period. The technical constraints imposed on the system operation are as follows:

-If $[E_{wg}(\tau) = E_l(\tau)/\eta_{inv}]$, supply the energy demand [i.e., $E_{out}(\tau) = E_d(\tau)$] using energy generated, with the battery bank operating in the idle mode, i.e., $E_b = 0$.

-If $[E_{wg}(\tau) > E_l(\tau)/\eta_{inv}]$ and $[SOC_b(\tau-1) < SOC_{b,max}]$, supply the energy demand using energy generated, charge the battery bank [using Eq. (6)] with surplus energy $[E_b(\tau) = (E_{wg}(\tau) - E_l(\tau)/\eta_{inv})\eta_b]$. Afterwards check, if $[SOC_b(\tau) \geq SOC_{b,max}]$ stop charging, set $SOC_b(\tau) = SOC_{b,max}$ and sell excess energy $[E_{grd,s}(\tau) = \eta_{inv}E_{wg}(\tau)-(E_l(\tau)+\eta_{inv}S_b(SOC_{b,max}-SOC_b(\tau-1))/\eta_b)]$.

-If $[E_{wg}(\tau) > E_l(\tau)/\eta_{inv}]$ and $[SOC_b(\tau-1) \geq SOC_{b,max}]$ isolate (stop charging) the battery bank, supply the energy demand using generated power and determine the energy sold to the grid using $E_{grd,s}(\tau) = \eta_{inv}E_{wg}(\tau)-E_l(\tau)$.

-If $[E_{wg}(\tau) < E_l(\tau)/\eta_{inv}]$ then compute $SOC_b(\tau)$ [using Eq. (6) with $E_b(\tau) = E_{wg}(\tau) - E_l(\tau)/\eta_{inv}]$. If $[SOC_b(\tau) \geq SOC_{b,min}]$ supply the energy demand by discharging the battery bank to cover the deficit energy and $E_{def}(\tau)=0$; else, if $[(SOC_b(\tau) < SOC_{b,min})$ and $E_{ge}(\tau) > 0]$, stop discharging battery bank, calculate energy drawn/purchased from the grid [using $E_{grd,p}(\tau) = E_l(\tau)-\eta_{inv}(E_{wg}(\tau)+\eta_bS_b(SOC_b(\tau-1)-SOC_{b,min})]$, and satisfy the energy demand; else, if $[(SOC_b(\tau) < SOC_{b,min})$ and $E_{ge}(\tau) \leq 0]$, stop discharging battery bank, and supply the available energy [using $E_{out}(\tau)= \eta_{inv}E_{wg}(\tau)]$.

Reliability considerations

Reliability as defined here is the percentage of energy demand that the power system can deliver. The concept of the *LPSP* (Loss of Power Supply Probability) is used to measure the extent of the power system reliability. The *LPSP* defines the long-term average fraction of the load not supplied by an energy system, expressed as follows [17]:

$$LPSP = \sum_{\tau=1}^{N} E_{def}(\tau)/\sum_{\tau=1}^{N} E_d(\tau) \quad (14)$$
$$= 1 - [\sum_{\tau=1}^{N} E_{out}(\tau)/\sum_{\tau=1}^{N} E_d(\tau)]$$

where E_{out}, and E_{def} are the output and deficit energy supplied by the hybrid energy system respectively, E_d is

the energy demand, and N is the total simulation time (considered here as $N = 8,760$ h).

An *LPSP* of zero means the energy demand is always met; while an *LPSP* of 1 means that energy demand is never satisfied. The power system reliability (PSR) is defined by the following equation:

$$PSR = 1 - LPSP \qquad (15)$$

The energy throughput of a power system is defined as follows [6]:

$$k_e = PSR / COE \qquad (16)$$

where COE is the cost of energy (US\$ kWh^{-1}). The cost of energy is defined by Eq. (17).

$$COE = \psi(C_{gs} + cc_{wt}.N_{wt} + cc_b N_b + C_{mgt} - C_{es}) \qquad (17)$$

where ψ (kWh^{-1}) is the reciprocal of the total energy supplied by the power system during the project lifespan, which is equal to $1/(L_N E_{sys,ann})$, and $E_{sys,ann}$ is the annual system energy supplied (kWh y^{-1}). C_{mgt} accounts for the cost of energy system management and control. Other parameters are previously defined.

Optimization procedure
The cost of energy is used as an objective or fitness function. The optimization problem is defined as follows:
1-Minimize the COE:

$$_{min} COE = \psi(C_{gs} + cc_{wt}.N_{wt} + cc_b N_b + C_{mgt} - C_{es}) \qquad (18)$$

2-Subject to the constraint:

$$LPSP \leq \gamma \qquad (19)$$

The loss of power supply probability (LPSP) was computed using Eq. (14) based on the technical constraints specified by the proposed operation strategy described above. Although a no load rejection ratio (i.e., $\gamma = 0$) is desirable, an LPSP set to vary within considerable limits (specified as 0 and 3%) is assumed here for typical applications. Previous analysis [6] showed that a good compromise between reliability and cost of energy can be attained when a hybrid power system is optimized within a reliability limit of greater than or equal to 97% (i.e., LPSP <=0.03).

The Hybrid genetic algorithm and pattern search optimization technique
The hybrid Genetic Algorithm and Pattern Search (h-GAPS) method was applied to solve the formulated optimization problem. The h-GAPS based technique combines the genetic and the pattern search algorithms in the search step. It is well-known that the stochastic population-based algorithms like genetic algorithm (GA) are good at identifying promising areas of the search space (exploration). In contrast, the pattern search (PS) algorithm specifically is a more coordinate search method, which guarantees convergence to stationary points from arbitrary starting points. In addition, pattern search algorithm is useful at improving approximations to the minimum (exploitation). Thus, hybridization of the GA and PS can provide a more efficient trade-off between exploration and exploitation of the search space. The hybridization can help to guarantee that the global optimum solution is selected. The methods for hybridizing a global and a local optimizer are described in literature [18-20].

The proposed h-GAPS based approach is shown in Figure 2. The optimum sizing of the hybrid energy system starts with the GA, which uses three operators (selection, crossover, and mutation). The GA evaluates the initial system design configuration (either chosen or set by default) to determine if the configuration can provide reliable power (defined in terms of LPSP) to the load otherwise new configuration is determined. An arrangement is considered feasible if the power system reliability is greater than or equal to 97%. Next, the GA determines the evaluation qualified configuration with the best (lowest COE) value for a pre-specified number of generations or when a criterion that determines convergence is satisfied. The GA then stores the best configuration (points) and switches to the Pattern search algorithm.

The Pattern search algorithm, at the initial point X_0, begins with the best candidates given by the GA algorithm. At the first iteration, with a scalar =1 called mesh size, the pattern vectors are constructed as: [0 1], [1 0], [-1 0] and [0 -1]. The pattern vectors are added to the initial point X_0 to deduce the mesh points as: X_0 + [0 1], X_0 + [1 0], X_0 + [-1 0] and X_0 + [0 -1]. The algorithm computes the fitness function at the mesh points in the same order. The algorithm polls the mesh points by computing the fitness function values until it finds one whose value is smaller than the fitness function value of X_0. If such point exists, then the poll is successful and the algorithm sets this point equal to X_1; otherwise, the poll is unsuccessful.

After a successful poll, for instance, the PS algorithm doubles the current mesh size and steps to the second iteration. The mesh points at the second iteration are: X_1 + 2 *[0 1], X_1 + 2 * [1 0], X_1 + 2 * [-1 0] and X_1 + 2 * [0 -1]. The algorithm polls the mesh points until it finds one whose value is smaller than the fitness function value of X_1. The first such point it finds is called X_2. And the algorithm doubles the current mesh size to get a mesh size of 4 at the third iteration. If the

third iteration poll, with mesh size = 4, ends up being unsuccessful, the algorithm does not change the current point at the next iteration (i.e., $X_3 = X_2$). At the next iteration, after an unsuccessful poll, the algorithm divides the current mesh size (= 4) by 2, so that the algorithm polls with a smaller mesh size. The point from the previous iteration is replaced by a better point, if any. The procedure illustrated is repeated until the algorithm finds the optimum solution for the minimization of the fitness function. The algorithm stops when a predefined condition or a criterion that determines convergence is satisfied

Unlike other methods, the proposed h-GAPS based approach is capable of minimizing the fitness function (*COE*) while constraining it to safely satisfying the load demand according to the reliability criteria defined by the proposed operation strategy. And the approach maintains the best compromise between system cost and reliability.
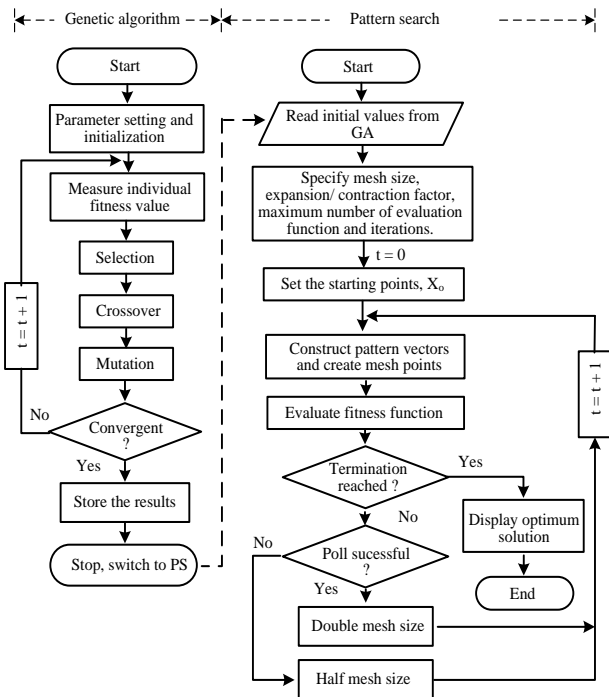
The process simulation employed M-files written in MATLAB code. These files were used in conjunction the GA toolbox to determine the optimum size of the optimization variables.

The hybrid power system, intended to provide electrical power to a hypothetical area comprising of ten households with average daily power profile similar to Figure 3, was simulated for six sites across Nigeria. The simulation used average hourly wind speed data collected from Nigerian Meteorological Agency, Oshodi, Lagos (Nigeria), and the grid supply voltage profile described in literature [1]. The monthly average daily wind speed data measured at 10 m above sea level for a period of 22 years (1991 – 2012) is shown in Figure 4. For the purpose analysis, a particular (typical) instance of the energy consumption pattern, shown in Figure 5 was deduced from Figure 3 by adopting the method described in Eq. (7).

Figure 2. Flowchart of the proposed h-GAPS technique

Process simulation

The design utilized MATLAB with GA toolbox, version R2012b [21]. It used the default GA toolbox parameter settings with the following changes. The "creation function" was set to "feasible population" and the initial range function varied for different sites. The "mutation function" was set to "adaptive feasible" while hybrid function set to "pattern search". The optimization variables are N_{wt} and N_b. The bounds are entered directly in the dedicated positions of the GA toolbox.
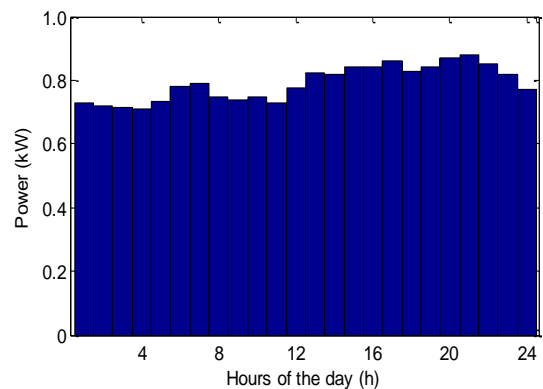

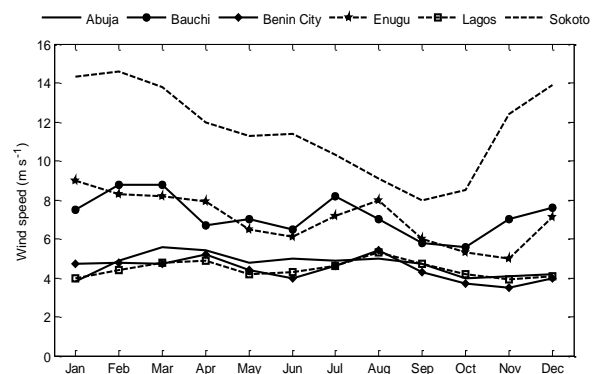**Figure 3.** Daily average load profile during power access in Nigeria [1].

Figure 4. Long-term (22 years) monthly average daily wind speed for various locations across Nigeria
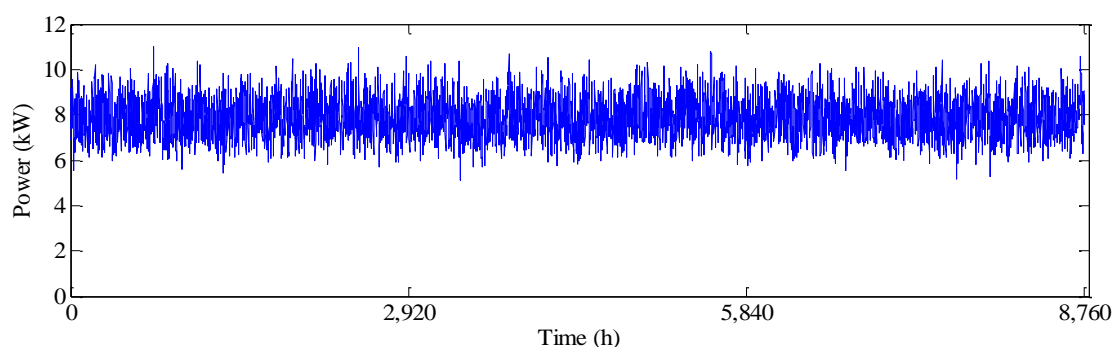
Figure 5. Simulated power consumption pattern for considered residential households

Table 1 shows the main specifications of components used for sizing hybrid power system. The lifespan of the project is taken as that of the wind turbine, which has a longer lifetime (compared to AVS and batteries) of 16 years. The cost of the hybrid energy system management (control) unit is taken to be US$ 1000.

There are four sub-groups (R1, R2, R3, and R4) of residential electricity users in Nigeria [22]. The cost of electricity paid by various sub-groups depends on the type of power connection and the amount of electricity used. The power system described here considers the R2 sub-group. This class of energy users consumes more than 50kWh of electricity per month (or 600kWh of electricity per annum) and is either single or 3-phase connection system. Majority of household electricity consumers in Nigeria fall under the R2 sub-group. Table 2 shows the grid electricity tariffs for R2-residential consumers for various sites in Nigeria.

The micro-grid interconnection fee utilized throughout study locations is US$ 625. The wind energy sell-back price to the grid ($c_{ge,s}$) is taken to be 90% of $c_{ge,p}$. Components installation and operation and maintenance costs are considered to be 10 and 2% of purchase prices, respectively [10]. The minimum and maximum states of charge of battery are taken as 40 and 98%, respectively.

RESULTS AND DISCUSSION

The optimum size of the wind/battery system for different locations in Nigeria is shown in Table 3. The optimum size of the wind/battery system required to supply reliable and cost effective power varies from one city to another, indicating the dependence of renewable (wind) energy sources on site meteorology. Benin City has the largest optimum size of wind turbine (55 kW), which is over five times the lowest optimum capacity realized in Sokoto. It is worth mentioning that Sokoto has the highest average wind speed of 11.6 m s^{-1}

compared to other cities, which varies from 4.4 to 7.2 m s^{-1}.

TABLE 1. Main technical specifications of hybrid system components [6, 10]

Component	Parameter	Specifications
WTG	Model	H6.4-5kW
	Rated/maximum power	5.0/5.6 kW
	Output voltage	110/220/380 V
	Rated/cut-in speed	12/3 m s^{-1}
	Rated rotating rate	240 r min^{-1}
	Working/Survival speed	3–25/50 m s^{-1}
	Blade diameter	6.4 m
	Energy utilizing ratio	0.4
	Generator efficiency	> 0.8
	Over speed regulation	Auto Yawing
	Configuration	3 Blades, Horizontal axis, Upwind
	Blade material	Fibre glass reinforced
	Purchase cost	US$ 7,123 per WTG
	Lifetime	16 y
Battery	Model	USB US-250
	Nominal capacity	225 Ah
	Nominal voltage	6 V
	Round trip efficiency	0.8
	Minimum state of charge	0.4
	Purchase cost	US$ 200 per battery
	Lifetime	Float life:10 y; Lifetime throughput: 845 kWh
AVS	Model	SVC-10000VA
	Phase	Single phase
	Input Voltage	150-260V AC
	Output Voltage	220V±3% AC
	Frequency	50Hz/60Hz;
	Adjusting time	< 0.5 s (with a change of 10%)
	AC-AC	95 %
	Delay	3~8sec
	Loading power factor	0.8
	Humidity	20% to 90%
	Purchase cost	US$ 19.4 per kW
	Lifetime	8 y

TABLE 2. Nigerian grid electricity tariff for R2-residential households [22]

	Abuja	Bauchi	Benin City	Enugu	Lagos	Sokoto
Fixed Charge per Household (US$ y^{-1})	52.66	58.13	56.25	48.75	56.25	58.58
Unit Cost of energy (US$ kWh^{-1})	0.0919	0.1047	0.0926	0.1028	0.0826	0.1063

TABLE 3. System optimum size for various sites

Locations	Number of units		Capacity	
	N_{wt}	N_b	N_{wt}	N_b
Abuja	9	67	45	90.5
Bauchi	5	4	25	5.4
Benin City	11	35	55	47.3
Enugu	5	4	25	5.4
Lagos	10	50	50	67.5
Sokoto	2	4	10	5.4

Table 4 shows the comparison of the annual energy composition of studied hybrid energy system for various cities in Nigeria. The largest proportion of electricity is from wind, with an average of 94.2%. The wind net power generation (difference between wind electricity generation and sell-back to grid) varies from one city to another, depending on the optimum wind turbine ratings and the potential of wind resource. The highest wind electricity input occurs in Bauchi (69,359.3 kWh per annum and accounts for 96.1% of the total electricity drawn by the load). The increase in wind power generation leads to the least quantity of electricity (1,091.0 kWh y^{-1}) per annum drawn from the grid in Bauchi. In contrast, Lagos has the least wind electricity contribution (67,018.3 kWh per annum and accounts for 92.3% of the total electricity drawn by the load). Consequently, grid electricity (3,441.1 kWh per annum) is mostly purchased in Lagos. Although, the highest wind energy input was observed in Bauchi, the wind energy potential in Sokoto is greater than the potential in Bauchi. The reason is that the capacity of wind turb-

-ine installation in Sokoto is less than half of the installation capacity in Bauchi but the wind energy input observed in Bauchi is slightly greater than the observed fraction (95.4%) in Sokoto.

The annual electricity drawn from the utility grid contributes between 1.51 and 4.74% (109.1 and 344.1 kWh per household) of the total energy consumption as shown in Table 4. Sell-back electricity is more than purchased electricity for all sites. The difference suggests that wind energy resource is more viable compared to the electric power grid system in Nigeria. Taking Abuja as an example, the wind electricity generation, electricity purchased from the grid, electricity sell-back to the grid, battery charge/discharge energy and the SOC of the battery bank are shown in Figure 6.

Techno-economic benefits of the grid/wind/ battery system
A comparison of the techno-economic impacts of the proposed grid/wind/battery system for residential electricity consumption is shown in Tables 5 – 7. The inclusion of the wind/battery to the utility grid system improves the power system reliability (PSR) of the grid-only system (an average of 81.41%) across Nigeria. The increase does not depend on the availability (or PSR) of the utility grid. For instance, the highest increase of 140.22% was observed in Bauchi (Table 5), with grid PSR of 0.4063 compared to the lowest increase of 39.91% observed in Lagos (with grid PSR of 0.6933).

TABLE 4. Annual electrical composition of studied hybrid energy system

Locations	Wind energy net generation, (kWh)	Wind energy fraction, (%)	Electricity purchase, $E_{grd, p}$ (kWh)	Electricity sale-back, $E_{grd, s}$ (kWh)
Abuja	67,891.1	92.9	3,099.9	16,428.8
Bauchi	69,359.3	96.1	1,091.0	43,625.0
Benin City	68,897.0	94.8	2,070.9	19,866.3
Enugu	67,558.4	94.0	2,609.5	41,640.3
Lagos	67,018.3	92.3	3,441.1	17,070.7
Sokoto	68,881.0	95.4	1,486.2	5,052.5
Average	68,267.5	94.2	2,299.8	23,947.3

It was observed (Table 6) that the range of economic benefits, derived from the use of grid/wind/battery system, varies from one place to another. Sokoto is the most favourable location for deploying the grid/wind/battery power system. It has the lowest COE (US$ 0.0317 per kWh or ₦ 5.07 per kWh), which account for 77.46% cost saving. In contrast, the

improvement of power system reliability in Lagos by 39.91% leads to 13.77% increase in the COE. Hence, the objective of reducing the COE of the power system tends to conflict with that of reducing the LPSP (or increasing the PSR). This conflict in objectives can raise the following question. Under what reliability scenarios will it be economic to pay a high COE?
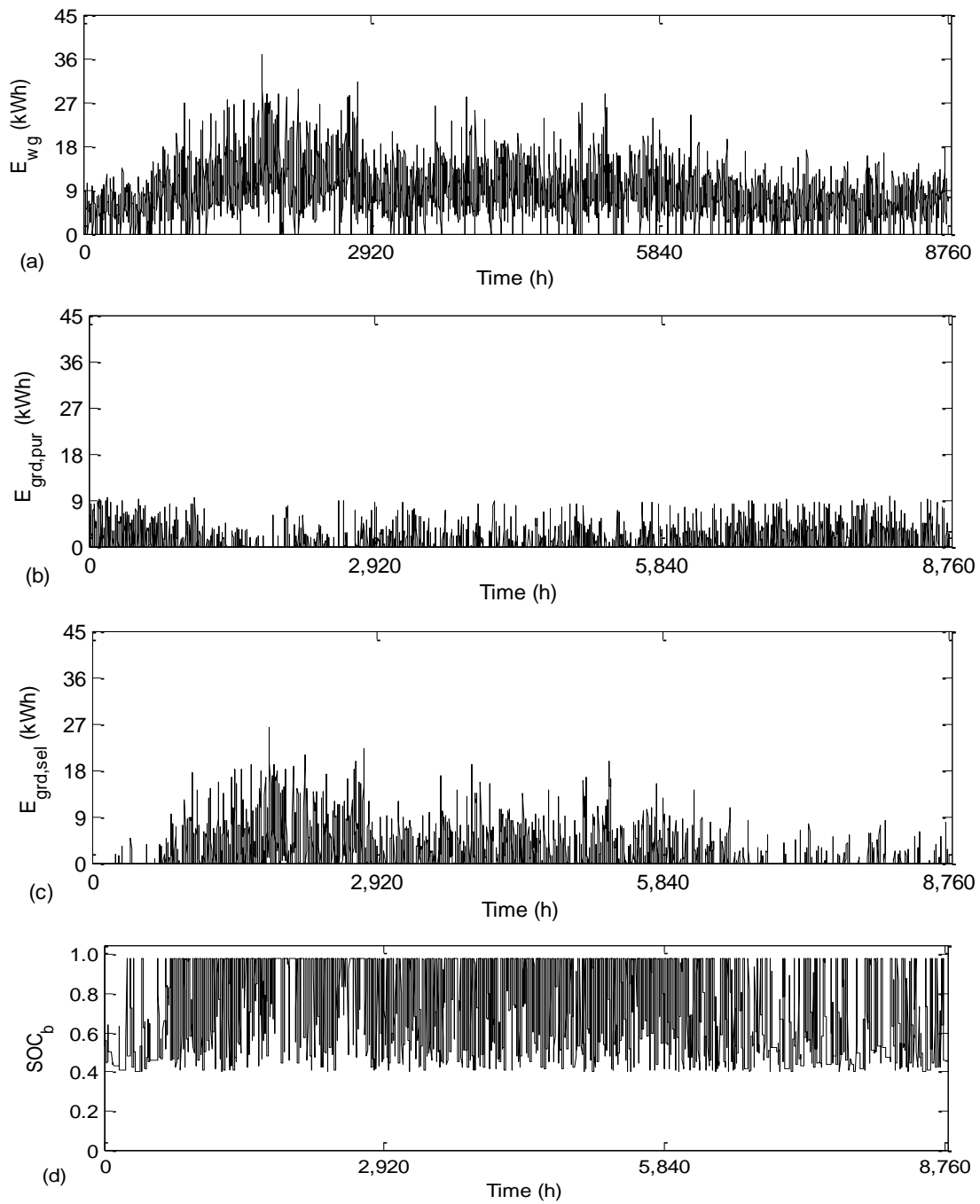
Figure 6. Annual electricity composition for Abuja (a) Wind energy generation, (b) Electricity drawn from the grid, (c) Electricity sell-back to grid, and (d) SOC of the battery bank

TABLE 5. Comparison of reliability of different power system options

Locations	Grid	Grid/Wind/Battery	Improvement (%)
Abuja	63.00	97.14	54.17
Bauchi	40.63	97.61	140.22
Benin City	60.28	97.64	61.98
Enugu	64.06	97.59	52.34
Lagos	69.35	97.02	39.91
Sokoto	40.63	97.45	139.81
Average	56.33	97.41	81.41

TABLE 6. Comparison of COE for different power system options

Locations	Grid (US$ kWh^{-1})	Grid/Wind/Battery (US$ kWh^{-1})	Cost Reduction (%)
Abuja	0.1152	0.1048	8.99
Bauchi	0.1389	0.0522	62.43
Benin City	0.1175	0.1127	4.09
Enugu	0.1260	0.0537	57.40
Lagos	0.1044	0.1188	-13.77
Sokoto	0.1409	0.0317	77.46
Average	0.1195	0.0728	35.86

Note: US$1 ≈ ₦160.0 (Central Bank of Nigeria, accessed August 13, 2014).

The concept of energy throughput defined by Eq. (16) can be applied to answer the above question. As described in literature [6], the energy throughput is an expression of the techno-economic viability of a power generation system measured in terms of power supply reliability and COE supplied. The performance (energy) index, k_e of the grid-only and grid/wind/battery system is compared (Table 7) for six cities across Nigeria.

As observed, the performance index of the grid/wind/battery system is significantly greater than that of the standard (utility) grid system across Nigeria. If the proposed grid/wind/battery system is deployed in Nigeria, an improved energy throughput with an average of 15.61 kWh per US dollar or 0.0976 kWh per Naira investment (compared to 4.69 kWh per dollar or 0.0293 kWh per Naira investment for the utility grid) can be realized. The corresponding improvement of over 300% shows the excellent performance of the grid/wind/battery system over the existing utility grid system in Nigeria. Although the proposed hybrid system COE in Lagos appears to be slightly higher (13.77%) than that of the utility grid, the energy performance is over 23% higher than the energy produced by the utility grid per US$ in Lagos. The implication is that the proposed system can provide an additional 1.53 kWh per US dollar investment in Lagos compared to the utility grid.

TABLE 7. Comparison of performance index of different power systems

Locations	Grid (kWh US^{-1})	Grid/Wind/Battery (kWh US^{-1})	Improvement (kWh US^{-1})	(%)
Abuja	5.47	9.27	3.80	69.47
Bauchi	2.92	18.7	15.78	540.41
Benin City	5.13	8.67	3.54	69.01
Enugu	5.08	18.18	13.10	257.87
Lagos	6.64	8.17	1.53	23.04
Sokoto	2.88	30.69	27.81	965.63
Average	4.69	15.61	10.93	320.90

The effect of different reliability scenarios on the techno-economic performance of the proposed grid/wind/battery HES is illustrated in Figure 7. In particular, the cost versus reliability and the energy index versus reliability curves for Abuja are presented. As shown, a range of reliability scenarios (between 0.90 and 1.00) are considered since a power system with a downtime greater than 0.10 is not desirable. The cost curve (ABCD) can be classified into three distinct regions: AB (lower region), BC (middle or compromise region), and CD (upper region). The COE of a grid/wind/battery designed to operate in region AB can be as low as US$ 0.108 with a corresponding energy index as high as 10.4 kWh per US dollar investment but the system would experience a downtime of approximately 10% (LPSP = 0.10), which perhaps is unreasonable. The COE tends to increase with increasing reliability until a break-away point (point B, with LPSP < = 0.035) is reached. The rise or change in the COE within region BC is negligible compared to other regions. For instance, increasing the system power supply reliability in region BC, from reliability of 0.965 to 0.981, results in 1.85% rise in cost (from US$ 0.108 to US$ 0.110 per kWh), but the increase is as high as between 17.2% (from US$ 0.110 to US$ 0.129) and 21.35% (from US$ 0.089 to US$ 0.108) per kWh of energy drawn in region CD and AB respectively.
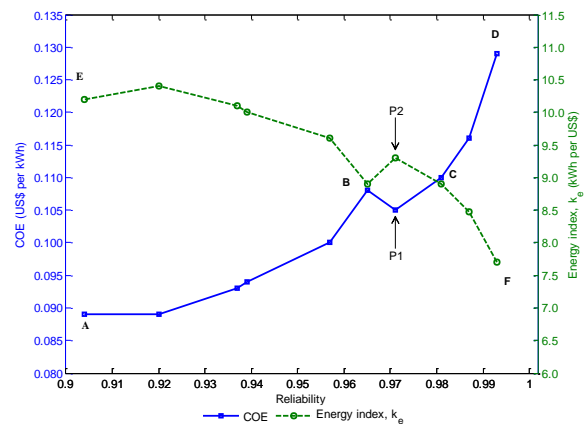
Figure 7. The effect of reliability on the performance of the proposed grid/wind/battery HES at Abuja

Compared to other regions, while the reliability of system operating in region AB may be considered unreasonable, the COE of system in region CD is significantly high. Therefore a system optimized to operate beyond the break-away point B can realize a good compromise between reliability and cost. The points, P_1 and P_2, show the optimum cost and the energy throughput the proposed system can supply per unit investment in Abuja (Nigeria).

Performance of proposed h-GAPS versus existing optimum sizing methods

The performance of the proposed h-GAPS technique was assessed by comparison with other stochastic

techniques such as genetic algorithm and pattern search. The performance comparison shown in Table 8 is based on the same objective function of Eq. (18). As observed, proposed method has the best energy throughput compared to other approaches. In other words, the h-GAPS technique gives the best cost versus reliability trade-offs compared to other methods.

It is worth mentioning that the uncertainty related to the energy demand data is not taken into consideration. For instance, the same energy demand profile was considered for all test cases. The variation, perhaps, would not significantly change the findings since the present study is concerned with relative differences in the cost of energy for various micro-grid options. The results presented can be improved if the real-time hourly energy demand profile of the site is utilized.

CONCLUSION

The paper examined the impact of unavailability of an electric grid network and developed a model for optimum capacity allocation of grid-connected HES. The h-GAPS optimization method employed constrains the generation and distribution of power to reliably supply the energy demand while ensuring safe operation of the system. Using the developed model, a grid/wind/battery system intended to provide reliable power to R2 sub-group consumers consisting of ten households, was simulated. Six test cases under varying climatic conditions were examined.

The largest fraction of electricity was from wind, with an average of 94.2%. The grid energy drawn and

proposed hybrid system LPSP constituted negligible fractions, 3.17 and 2.59 % respectively. Sokoto is the most favourable place for deploying the proposed hybrid power system. Specifically, a wind/battery system with installed capacity of 10 kW/ 5.40 kWh at Sokoto can deal with 95.4% of the total electricity demand, save more than 77% of electricity payments and increase the reliability by approximately 140%. This amounts to an energy throughput of 30.69 kWh per US dollar (0.1918 kWh per Naira), compared to the utility grid system with 2.88 kWh per US dollar (0.0180 kWh per Naira) investment in electricity generation at Sokoto.

The method presented allows determining the optimum architecture of a grid-tie hybrid system for any region with an unreliable electric grid network. It enables the user decide on the configuration and mix of resources with the best compromise between cost and reliability. The suggested technique can be further extended to analyze similar problems in energy system design with conflicting objectives or used with different objective functions for different applications. The performance of the proposed design approach was assessed by comparison with other stochastic techniques such as genetic algorithm and pattern search. The results proved that the h-GAPS method is very applicable for techno-economic sizing of power system.

TABLE 8. Performance comparison with different approaches

Locations	COE (US$ kWh^{-1})			PSR			Ke (kWh US$ $^{-1}$)		
	GA	PS	h-GAPS	GA	PS	h-GAPS	GA	PS	h-GAPS
Abuja	0.1225	0.1125	0.1048	0.9903	0.9743	0.9714	8.08	8.66	9.27
Bauchi	0.0658	0.0584	0.0522	0.9976	0.9886	0.9761	15.17	16.93	18.70
Benin City	0.1393	0.1134	0.1127	0.9933	0.9763	0.9764	7.13	8.61	8.67
Enugu	0.0679	0.0537	0.0537	0.9968	0.9759	0.9759	14.68	18.18	18.18
Lagos	0.1422	0.1201	0.1188	0.9891	0.9777	0.9702	6.96	8.14	8.17
Sokoto	0.0348	0.0317	0.0317	0.9950	0.9745	0.9745	28.58	30.69	30.69

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Persian Abstract

چکیده

این مقاله به بررسی عملی بودن یک سیستم انرژی هیبریدی متصل به شبکه (HES) برای تولید برق خانگی در جهان در حال توسعه می‌پردازد. با هدف تعیین مزایای فنی- اقتصادی عامل یک سیستم تبدیل انرژی باد است. HES متشکل از تامین شبکه برق، تبدیل انرژی باد، الکترونیک قدرت، و واحد ذخیره سازی. واحد تامین شبکه شامل یک روش مبتنی بر پیش بینی احتمال. مدلسازی سیستم انرژی باد بر پایه چند جمله ای درجه سوم، با استفاده از مشخصات قدرت توربین بادی عرضه شده توسط تولید کننده است. مشکل بهینه سازی فرموله با استفاده از ترکیبی الگوریتم ژنتیک و جستجوی الگو (GAPS-H) حل شد. رویکرد H- GAPS بر اساس محدودیتهای تولید و توزیع قدرت برای اطمینان از عملکرد کارآمد می باشد. تجزیه و تحلیل برای یک منطقه مسکونی معمولی داده های هواشناسی شش سایت استفاده می شود، که در سراسر نیجریه گسترش یافته است. نتایج نشان داد که سیستم قدرت می تواند ارائه مزایای صرفه جویی در هزینه به ارمغان بیاورد و بهبود قابلیت اطمینان قدرت، اما طیف وسیعی از مزایای مالی بستگی به مختصات جغرافیایی دارد. به طور خاص، ۱۰KW / ظرفیت ۵٬۴۰kWh سیستم باد / باتری نصب شده در سوکوتو می تواند با ۹۵٬۴٪ از کل تقاضای برق را تامین کند ،و در صرفه جویی بیش از ۷۷٪ در هزینه برق و افزایش اطمینان پذیری در حدود ۱۴۰٪ داشته باشد..