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Economic analysis and power management of a stand-alone wind/photovoltaic hybrid energy system using biogeography based optimization algorithm

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ABSTRACT

The stand-alone energy system having a photovoltaic (PV) panels or wind turbines have low reliability and high cost as compared with wind/PV hybrid energy system. In this study, Biogeography Based Optimization (BBO) algorithm is developed for the prediction of the optimal sizing coefficient of wind/PV hybrid energy system in remote areas. BBO algorithm is used to evaluate optimal component sizing and operational strategy by minimizing the total cost of hybrid energy system, while guaranteeing the availability of energy. A diesel generator is added to ensure uninterrupted power supply due to the intermittent nature of wind and solar resources. Due to the complexity of the hybrid energy system design with nonlinear integral planning, BBO algorithm is used to solve the problem. The developed BBO Algorithm has been applied to design the wind/ PV hybrid energy systems to supply a located in the area of Jaipur, Rajasthan (India). Conventional methods require calculation at every single combination of sizing, operation strategy and the data for each variation of component needs to be entered manually and execute separately. Results show that the hybrid energy systems can deliver energy in a stand-alone installation with an acceptable cost. It is clear from the results that the proposed BBO method has excellent convergence property, require less computational time and can avoid the shortcoming of premature convergence of other optimization techniques to obtain the better solution.

1. Introduction

The public attention has remained focused on the renewable technologies as environmentally sustainable and convenient alternatives. Wind and solar power are the two most widely used renewable sources of energy among all renewable sources, since they feature definite merits as compared with the conventional fossil-fuel-fired generation. For instance, wind turbine generators (WTGs) neither generate pollution nor consume depleting fossil fuels. Photovoltaic (PV) systems produce no emissions, are durable, and demand minimal maintenance to operate [1]. Unfortunately, these renewable sources of energy are essentially intermittent and quite variable in their output. In addition, they require high capital costs. Power to off-grid location is usually supplied by a generator using diesel or petrol [2]. These generators are often available at night and only for a certain number of hours as explained by Musseli et al. [3]. During the designing of a hybrid system, it is necessary to select the size of various components with the operation strategy for the long-lasting, reliable and cost-effective system [4]. Many researchers have shown that hybrid energy systems are best suited to diminish dependence on fossil fuel by using available wind speed and solar radiations [5,6].

Hybrid energy system includes photovoltaic (PV) panels and/or wind turbines and batteries, etc. These energy systems are the cost-effective solutions to meet energy requirements of remote areas [7]. Das et al. [8] suggested that Evolutionary Algorithms (EAs), due to their population-based approaches, are able to detect multiple solutions within a population in a single simulation run and have a clear advantage over the classical optimization techniques, which need multiple restarts and multiple runs in the hope that a different solution may be discovered every run, with no guarantee [9]. However, numerous evolutionary optimization techniques have been developed since late 1970s for locating multiple optima (global or local). Due to significant improvement in the capability of computers in recent years [10], evolutionary algorithms (EAs), such as genetic algorithm (GA), evolutionary programming (EP), particle swarm

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optimization (PSO) [11] and differential evolution (DE) are being applied for solving various hybrid energy system optimization problems to overcome some of the drawbacks of conventional techniques [12].

Barley et al. [13] has suggested guidelines regarding main operation strategies, namely frugal discharge, load-following, the state of charge (SOC) set point and the full-power strategy. However, the SOC set point procedure is user-defined, and it is not optimized [14]. Frugal discharge is based on critical load, where if the net load is exceeding the critical load, then it is cost-effective to run the generator set. In load-following strategy, batteries are not charged by the diesel generator. Belfkira et al. [15,16] explained that diesel operating point is set to match the net load. SOC set point strategy is used to charge batteries at the user defined point from the diesel generator. Bernal-Agustin et al. [17] specifies that generator operates at full-power generation with the excess power is used to charge the batteries without dumping power. Otherwise, the generator is set to operate at the maximum point without dumping. In Full power strategy, the diesel generator is operated at full power for a minimum time at a low set point.

Seeling-Hochmuth [18] had investigated the application of the genetic algorithm to solve the optimization problem with various constraints. He further suggested an optimization concept combining system sizing and operation control. Koutroulis et al. [19] used Genetic Algorithm(GA) to minimize the total system cost based on the load energy requirements. Daming et al. [20], Gupta et al. [21] and Sopian et al. [22] explained a methodology of finding optimum component sizing and operational strategy using the genetic algorithm. Dufo-Lopez et al. [23] developed a program based on genetic algorithm, called HOGA, for optimizing the configuration of a PV–diesel hybrid system with AC loads and the control strategy. Hakimi et al. [24] applied PSO for multi-criterion design of the hybrid power generation system. Bansal et al. [25] use Meta Particle Swarm Optimization algorithm for finding the optimal size of the Wind/PV energy system. Ashok developed a reliable system operation model based on Hybrid Optimization Model for Electric Renewable (HOMER) [26] found an optimal hybrid system among different renewable-energy combinations while minimizing the total life-cycle cost. Dufo-Lopez et al. [27] later improved HOGA program to include fuel cell and hydrogen in the hybrid system. However, the control strategies in HOGA are same as used in HOMER. It is focused on maximizing the renewable energy components, while trying minimizing the use of the generator to provide for the load demand.

Very recently, a new optimization concept, based on biogeography has been proposed by Simon [28]. Biogeography Based Optimization (BBO) is a population-based evolutionary algorithm (EA)[29]. Biogeography is the study of the geographical natural distribution of biological organisms. In the BBO algorithm, each solution of the population is represented by a vector of integers. BBO algorithm adopts the migration operator to share information among solutions [30]. This feature is similar to other biology-based algorithms, such as Genetic Algorithm (GA) and Particle Swarm Optimization (PSO). It makes BBO applicable to the majority of problems, where GA and PSO are applicable [31]. Simon [28] compared BBO with many other Evolutionary Algorithms on a wide set of benchmark functions. The results confirmed the excellent performance of BBO. The Markov analysis also proved that BBO outperforms GA on basic unimodal, multimodal and deceptive benchmark functions when used with low mutation rates. The versatile properties of BBO algorithm encouraged the authors to apply this algorithm to solve the non-convex, complex optimal sizing problem of hybrid energy systems.

Hybrid energy system sizing is a nonlinear integral problem, which is a complex problem. The objective of this paper is to explore the application of the BBO algorithm to the hybrid energy system design problem. The combination of components represents the sequence of the suitability index variables (SIVs), which determine the total cost of the system. After the migration operation in BBO, a SIV in the immigrated island (a bad solution) accepts the sharing information from the emigrated island (a better solution). To keep the new solution feasible, adjust the SIV which has the identical component cost [32].

The BBO algorithm has certain unique features, which overcome several demerits of the conventional methods as mentioned below

(1) In BBO and PSO, the solutions survive forever although their characteristics change as the optimization process progresses. However, solutions of evolutionary-based algorithms like GA, DE etc. "die" at the end of each generation. Due to the presence of crossover operation in evolutionary based algorithms, many solutions, whose fitness is initially favorable, sometimes lose their quality in later stage of the process. In BBO, there is no crossover like operation as the solution gets fine-tuned gradually as the process goes on through migration operation. Elitism operation has made the algorithm more efficient in this aspect and gives an edge to BBO over other techniques.
(2) In PSO, solutions are more likely to clump together in similar groups. While in the case of BBO, solutions do not have the tendency to cluster due to its new mutation operation.
(3) BBO involves fewer computational steps per iteration as compared to other algorithms like GA, PSO, DE etc. Due to this, BBO results are faster in convergence.
(4) In BBO, poor solutions accept a lot of new features from good ones, which may improve the quality of solutions. This is a unique feature of BBO algorithm compared to other techniques. At the same time, this makes constraint satisfaction to be much easier, compared to other algorithms.

In this paper, the BBO optimization algorithm uses the static models of the wind turbine, the PV panel, the battery, the inverter and on the dynamic evaluation of the wind and solar-energy potential. BBO is used to simply solve the size of the hybrid PV/wind energy system by considering economical and reliability constraints of the system. The new method is suitable to deal with the complex design of hybrid energy system and can avoid the local minimum trap. The developed BBO methodology has been applied to design the stand-alone hybrid wind/PV systems to power supply a varying load located in the area of Jaipur, Rajasthan (India) with geographical coordinates defined as: latitude: 26°92 N, longitude: 75°82 E and altitude: 431 m above sea level.

This paler is organized as follows. In Section 2, the hybrid energy system and its components are explained. Section 3 describes the optimization problem of hybrid system and Section 4 explains the simplified BBO. In Section 5, detail of Case study data is presented and Section 6 shows the comparison of Hybrid Optimization Model for Electric Renewable software (HOMER) [26], Biogeography Based Optimization (BBO) [28], Genetic Algorithm (GA) [22], particle swarm optimization (PSO) [23], comprehensive learning particle swarm optimization (CLPSO) [33] and ensemble of mutation and crossover strategies and parameters in DE (EPSDE) algorithm [34] algorithms. In Section 7, the results of proposed BBO algorithm have been explained and discussed.

2. Hybrid energy systems

A hybrid renewable generation system comprises of wind turbine generators (WTGs) of different types, PV panels (PV), storage batteries (SB) with diesel generator are shown in Fig. 1. In the hybrid generation system, they are integrated and complement with each other in order to meet performance targets of the generation systems and access to the most economic power generation.

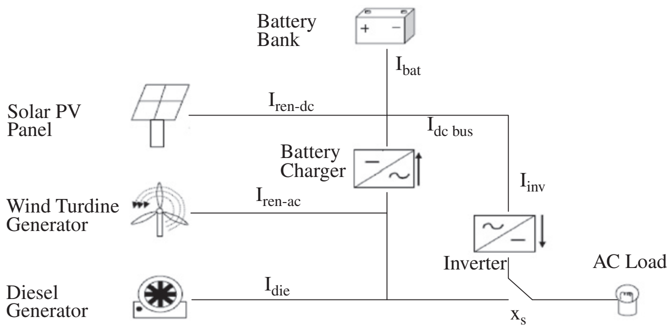

Fig. 1. Hybrid PV/wind Energy System.

2.1. Wind turbine generators (WTG)

The energy and current output of the WTG for each time instant are computed based on local weather conditions and actual installation height of the turbines. Wind turbines are usually connected in parallel, not in a series. Several wind turbines can be connected in parallel to match the system current requirements. Using the wind speed at a reference height h_r from the database, the velocity at a hub height for the location is estimated on an hourly basis are calculated as:

$$v(t) = v_r(t).(h/h_r)^{\gamma} \tag{1}$$

where v is the wind speed at the projected height h, v_r is the wind speed at reference height h_r and γ is the power-law exponent ($\sim$1/7 for open land). The power generated by the wind system at any time 't' can be expressed as:

$$P_W(t) = \eta_W * \eta_g * 0.5 * \rho_a * C_P * A * v_r^2 \tag{2}$$

where P_W is the wind turbine power output, η_W is efficiency of wind turbine, η_g is efficiency of generator, ρ_a is the density of air, C_P is the power coefficient of wind turbine, and A is the wind turbine swept area.

2.2. Photovoltaic generation (PV)

The PV sizing variable comprises of size of a PV panel and the number of strings in a PV array. The necessary number of PV panels to be connected in the series is derived by the number of panels needed to match the bus operating voltage. When matching the current requirements of the system, several PV strings which are connected in series, needs to be installed in parallel. The number of parallel PV strings is a design variable that needs optimization. The output of PV panels must include the impact of geographic location, such as solar radiation and temperature, etc. The output power of photovoltaic panels $P_{PV}(t)$ at any time 't' can be calculated as:

$$P_{PV}(t) = \eta_{PV} * N_{PVP} * N_{PVS} * V_{PV} * I_{PV} \tag{3}$$

where η_{PV} is conversion efficiency of PV panel, N_{PVP} is the number of PV panels in parallel, N_{PVS} is number of PV panels in series, V_{PV} is the operating Voltage of PV panels, and I_{PV} is operating current of PV panels.

2.3. Storage batteries (SB)

The batteries are used to store the excess energy generated by hybrid system and supply energy during the low generation period. The power input to the battery bank is calculated as:

$$\Delta P(t) = P_{total}(t) + P_{DG}(t) - P_{Load}(t) \tag{4}$$

where $P_{total}(t)$ is the total power produced by the renewable resources (PV panels and wind turbines) at hour t, $P_{Load}(t) = P_d(t)/\eta_{bi}$, where $P_d(t)$ is the power demanded by the load at hour t, η_{bi} is inverter efficiency, and $P_{DG}(t)$ is the total power produced by the Diesel generator at hour t.

For the charging process ($\Delta P(t) > 0$) and discharging process ($\Delta P(t) < 0$) of the battery bank, the state of charge (SOC) can be calculated as:

$$P_B(t+1) = P_B(t) + [\Delta P(t)/U_{bus}] * \eta_{bb} * \Delta t \tag{5}$$

where η_{bb} is equal to the round-trip efficiency in the charging process and is equal to the 100% in the discharging process,U_{bus} is the DC bus voltage, and Δt is the time step which is generally 1 h.

The power generated from WTG's and PV's at the time 't' i.e. total renewable power is given by following equation

$$P_{total}(t) = \sum_{W=1}^{W_n} P_W(t) + \sum_{PV=1}^{S_n} P_{PV}(t) \tag{6}$$

where W_n, S_n are the total number of wind turbine generators and photovoltaic panels respectively.

3. Description of the problem

For the hybrid energy system design, the objective of optimum design is to minimize $C_t(P_W, P_{PV}, P_B, P_{DG})$, subject to the constraint's explained in Eqs. (14)–(16). The design parameters that should be derived must include WTG capacity (P_W), PV panel capacity (P_{PV}), total battery capacity (P_B), and Diesel generator capacity (P_{DG}).

$$\min C_t(P_W, P_{PV}, P_B, P_{DG}) = \min(C_W + C_{PV} + C_b + C_g + C_r) \tag{7}$$

where C_t is the total system cost, $C_W, C_{PV}, C_b, C_g, C_r$ are the total cost of wind turbine systems, photovoltaic panels, batteries, Diesel Generator and the total cost of considering the power supply reliability respectively.

3.1. The total cost of wind turbines

$$C_W = \sum_{i=1}^{W_n} \left(a_i P_i \frac{r_0(1+r_0)^m}{(1+r_0)^m - 1} + om(P_i) + rep(P_i) \right) \tag{8}$$

3.2. Total cost of photovoltaic panels

$$C_{PV} = \sum_{j=1}^{S_n} \left(b_j P_j \frac{r_0(1+r_0)^m}{(1+r_0)^m - 1} + om(P_j) + rep(P_j) \right) \tag{9}$$

3.3. Total cost of batteries

$$C_b = \sum_{k=1}^{B_n} \left(c_k P_k \frac{r_0(1+r_0)^m}{(1+r_0)^m - 1} + om(P_k) + rep(P_k) \right) \tag{10}$$

3.4. Total cost of diesel generator

$$C_g = \sum_{l=1}^{D_n} \left(d_l P_l \frac{r_0(1+r_0)^m}{(1+r_0)^m - 1} + om(P_l) + rep(P_l) + fuel(P_l) \right) \tag{11}$$

where W_n, S_n, B_n, D_n are the number of wind generators, photovoltaic panels, batteries, diesel generators; a_i, b_j, c_k, d_l are the unit cost (Rs/kW); P_i, P_j, P_k, P_l is the power capacity; $om(P_i)$, $om(P_j), om(P_k), om(P_l)$ are the maintenance and operating costs; $rep(P_i), rep(P_j), rep(P_k), rep(P_l)$ are the replacement costs corresponding to ith wind turbine, jth photovoltaic panels, kth battery, lth Diesel Generator; fuel(P_l) is the cost of fuel used in lth

Diesel Generator; m is the life span of the project and r_0 is the interest rate.

3.5. The total cost of other parameters

The total cost of considering power supply reliability is calculated as:

$$C_r = cco * EENS \tag{12}$$

where cco is the Compensation Coefficient and EENS is the Expected Energy Not Served. In the calculation of C_r, time series and the Monte Carlo method are used. Due to this, time series is divided into many terms i.e. wind speed, light, load, etc. and then the Monte Carlo method is used to calculate the reliability of the randomly selected sample. Within the run-time T (8760 h), the EENS (kWh/year) is calculated as:

$$EENS = \sum_{t=1}^{T} (P_{b_{\min}} + P_{b_{SOC}}(t) - P_{\sup}(t))U(t) \tag{13}$$

where U(t) is a step function that is zero when the supply exceeds or equals to the demand and one if there is insufficient power during hour t; $P_{b_{SOC}}(t)$ is state of charge (SOC) of storage batteries during hour t; $P_{b_{\min}}(t)$ is the minimum permissible storage level of the battery and $P_{\sup}(t) = P_{total}(t) + P_{DG}(t) - P_d(t)$ is the surplus power during hour t.

3.6. Design constraints

Due to the physical or operational limits of the target system, there is a set of constraints that should be satisfied throughout system operations for any feasible solution.

1. For any period t, the total power supplied from the hybrid energy system must supply the total demand P_{d} with a certain reliability criterion. This relation can be represented as:

$$\begin{aligned} &P_W(t) + P_{PV}(t) + P_B(t) + P_{DG}(t) \geq (1-R)P_d(t) \\ &P_W(t) + P_{PV}(t) + P_B(t) + P_{DG}(t) - P_{dump}(t) \leq P_d(t) \end{aligned} \tag{14}$$

   where $P_W, P_{PV}, P_B, P_{DG}, P_{dump}, P_d$ are the wind power, solar power, charged/discharged battery power, diesel generator power, dumped power and total load demand respectively; R is the ratio of the maximum permissible unmet power with respect to the total load demand at each time instant. The transmission losses are not considered because the system is considered as the remotely located isolated system and do not have substantial transmission lines. The dump power is the excess power generated by the system which is not utilized for either supply the load or supplied to charge the battery.
2. The state of charge (SOC) of storage batteries $P_{b_{SOC}}$ should not exceed the capacity of storage batteries $P_{b_{cap}}$ and should be larger than the minimum permissible storage level $P_{b_{\min}}$. The total storage battery capacity should not exceed the allowed storage capacity $P_{b_{cap\,\max}}$. The hourly charge or discharge power P_{bt} should not exceed the hourly inverter capacity $P_{b_{\max}}$. These constraints are defined as:

$$\begin{aligned} &P_{b_{\min}} \leq P_{b_{SOC}} \leq P_{b_{\max}} \\ &0 \leq P_{b_{cap}} \leq P_{b_{cap\max}} \\ &P_{bt} \leq P_{b_{\max}} \end{aligned} \tag{15}$$

3. The number of wind power generation, batteries and photovoltaic panels is subjected to the following constraints respectively

$$\begin{aligned} &0 \leq S_n \leq N_{PV,\,P_{\max}} \\ &0 \leq W_n \leq N_{W,\,P_{\max}} \\ &0 \leq B_n \leq N_{BAT,\,P_{\max}} \end{aligned} \tag{16}$$

   where $N_{PV,\,P_{\max}}$ is maximum capacity of Photovoltaic panel, $N_{W,P_{\max}}$ is maximum capacity of Wind turbine, and $N_{BAT,\,P_{\max}}$ is the maximum capacity of the battery panel.

4. Biogeography-based optimization (BBO)

In the science of biogeography, a habitat is an ecological area that is inhabited by particular plant or animal species and geographically isolated from other habitats. Each habitat is classified by Habitat Suitability Index (HSI). Geographical areas, which are well suited as residences for biological species are said to have a high HSI. Features that correlate with HIS include rainfall, diversity of vegetation, diversity of topographic features, land area, temperature, etc. If each of the features is assigned a value, HSI is a function of these values. Each of these features that characterize habitability is known as Suitability Index Variables (SIV). SIVs are the independent variables while HSI are the dependent variables.

Habitats with high HSI have the large population and have high emigration rate μ, simply by virtue of a large number of species that migrate to other habitats. The immigration rate λ is low for those habitats which are already saturated with species. On the other hand, habitats with low HSI have high immigration rate λ, low emigration rate μ due to sparse population. The value of HIS, for low HSI habitat, may increase with the influx of species from other habitats as suitability of a habitat is the function of its biological diversity. However, if HSI does not increase and remains low, species in that habitat go extinct and this leads to additional immigration. For the sake of simplicity, it is safe to assume a linear relationship between habitats HIS, its immigration and emigration rate. These rates are same for all the habitats and depend upon the number of species in the habitats.

Fig. 2 shows the relationships between fitness of habitats (number of species), emigration rate μ and immigration rate λ. E is the possible maximum value of emigration rate and I is the possible maximum value of immigration rate. S is the number of species in the habitat, which corresponds to fitness. $S_{\max}$ is the maximum number of species the habitat can support. S_0 is the equilibrium value. When $S = S_0$, the emigration rate μ is equal to the immigration rate λ.From Fig. 2, it is clear that island which has outstanding performance like S_2 has a high emigration rate and a low immigration rate. On the other hand, island which has poor performance like S_1 has a high immigration rate and a low emigration rate.

The values of emigration and immigration rates are given as:

$$\lambda_k = \frac{EK}{P} \tag{17}$$

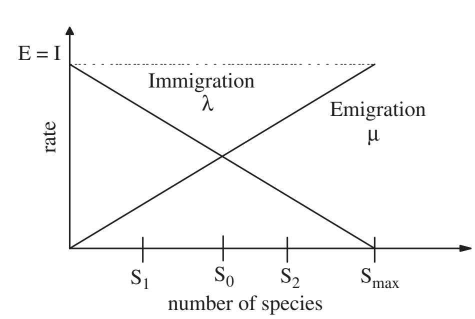

Fig. 2. The model of immigration rate and emigration rate of biology.

$$\mu_k = I(1 - K/P) \tag{18}$$

where K is the number of species of the kth individual, and P is the number of species.

Mathematically, the concept of emigration and immigration can be represented by a probabilistic model. Let us consider the probability P_s in which habitat contains exactly S species at t. P_s changes from time t to time $t+\Delta t$ as:

$$P_s(t+\Delta t) = P_s(t)(1-\lambda_s\Delta t - \mu_s\Delta t) + P_{s-1}(t)\lambda_{s-1}\Delta t + P_{s+1}(t)\mu_{s+1}\Delta t \tag{19}$$

where λ_s and μ_s are the immigration and emigration rates when there are S species in the habitat. This equation holds because in order to have S species at the time t, one of the following conditions must hold

(1) There were S species at the time t, and no immigration or emigration occurred between t and $t+\Delta t$.
(2) There were $(S-1)$ species at the time t, and one species immigrated.
(3) There were $(S+1)$ species at the time t, and one species emigrated.

If time Δt is small enough so that the probability of more than one immigration or emigration can be ignored, then taking the limit of Eq. (19) as $\Delta t \to 0$ given by following equation

$$\dot{P}_s = \begin{cases} -(\lambda_s+\mu_s)P_s + \mu_{s+1}P_{s+1} & S=0 \\ -(\lambda_s+\mu_s)P_s + \mu_{s+1}P_{s+1} + \lambda_{s-1}P_{s-1} & 1 \le S \le S_{\max}-1 \\ -(\lambda_s+\mu_s)P_s + \lambda_{s-1}P_{s-1} & S = S_{\max} \end{cases} \tag{20}$$

Habitat modification (Migration) algorithm is described as:

Habitat modification (Migration) algorithm is described as:

Select H_i with probability α λ_i
If H_i is selected
For j = 1 to P
Select H_j with probability α μ_i
If H_j is selected
Randomly select an SIV σ from H_j
Replace a random SIV in H_i with σ
end
end
end

Habitat mutation algorithm is described as:

Habitat mutation algorithm is described as:

For j = 1to N
Use λ_i and μ_i to compute the probability P_i
Select SIV $H_i(j)$ with probability α P_i
If $H_i(j)$ is selected
Replace $H_i(j)$ with a randomly generated SIV
end
end

For each SIV in each solution, it is decided probabilistically, whether or not to immigrate. If immigration is selected for a given solution feature, the emigrating habitat is selected for a given solution probabilistically, using the roulette wheel normalized by μ. The mutation operator is probabilistically applied to the habitat, which tends to increase the biological diversity of the population. The mutation rate m is inversely proportional to the solution probability, which is given as:

$$m = m_{\max} * \left(1 - \frac{P}{P_{\max}}\right) \tag{21}$$

where $m_{\max}$ is a user-defined parameter.

BBO also follows a migration and mutation step to reach global minima. The flowchart of BBO algorithm application in a hybrid system design is given in Fig. 3. The basic BBO algorithm is described as:Initialize Parameters

P = population size
G = Maximum number of generation
Keep = Elitism parameter
$P_{\max}$ = Island modification probability

Step 1: Initialize P randomly and species count probability of each Habitat.
Step2: Evaluate the fitness for each individual in P.
Step3: *While The* termination criterion is not met do.
Step4: Save the best habitats in a temporary array.
Step5: For each habitat, map the HSI to number of species S, λ and μ.
Step6: Probabilistically choose the immigration island based on the immigration rate μ.
Step7: Migrate randomly selected SIVs based on the selected island in Step 6.
Step8: Mutate the worst half of the population as permutation algorithm.
Step9: Evaluate the fitness for each individual in P.
Step10: Sort the population from best to worst.
Step11: Replace worst with best habitat from temporary array.
Step12: Go to step 2 for the next iteration.
Step13: *end while*

5. Case study

The developed methodology for BBO Algorithm has been applied to design the stand-alone hybrid wind/PV systems to supply a varying load located in the area of Jaipur in Rajasthan (India) with geographical coordinates defined as: latitude: 26°92 N, longitude: 75°82 E and altitude: 431 m above sea level. The wind speed, solar irradiance, sunshine duration and ambient temperature recorded for every hour, during the period of 1st January, 2010 to 30th December, 2010. The wind speed was measured at 30 m height. In this application, PV panels, wind turbines, battery, diesel generator and inverter have been used. The cluster of colonies is assumed to be located in a remote area with adequate sunshine, moderate to high wind speeds. The average daily load profile of the study area is shown in Fig. 4. The daily energy consumption of load is 2263 kWh/day with a 261 kW peak demand and day to day variation of 30% is introduced in the load profile. The optimal solution is verified by showing the energy profile during the period from 1st January, 2011 to 7th January, 2011. The monthly solar radiation in Jaipur, Rajasthan is between 4 and 7 kWh/m^2/day, with the monthly sunshine duration ranging from 5 h/day to 8 h/day as shown in Table 1. The sunshine hour has been taken for the same duration as for the global solar radiation. These values are essential for sizing of solar energy systems. The monthly solar radiation patterns are shown in Fig. 5. The average wind speed for Jaipur, Rajasthan is between 4 and 11 m/s as shown in Table 2. The average daily wind speeds (m/s) for a year is shown in Fig. 6. The technical, economical data and study assumptions are given in Table 3.

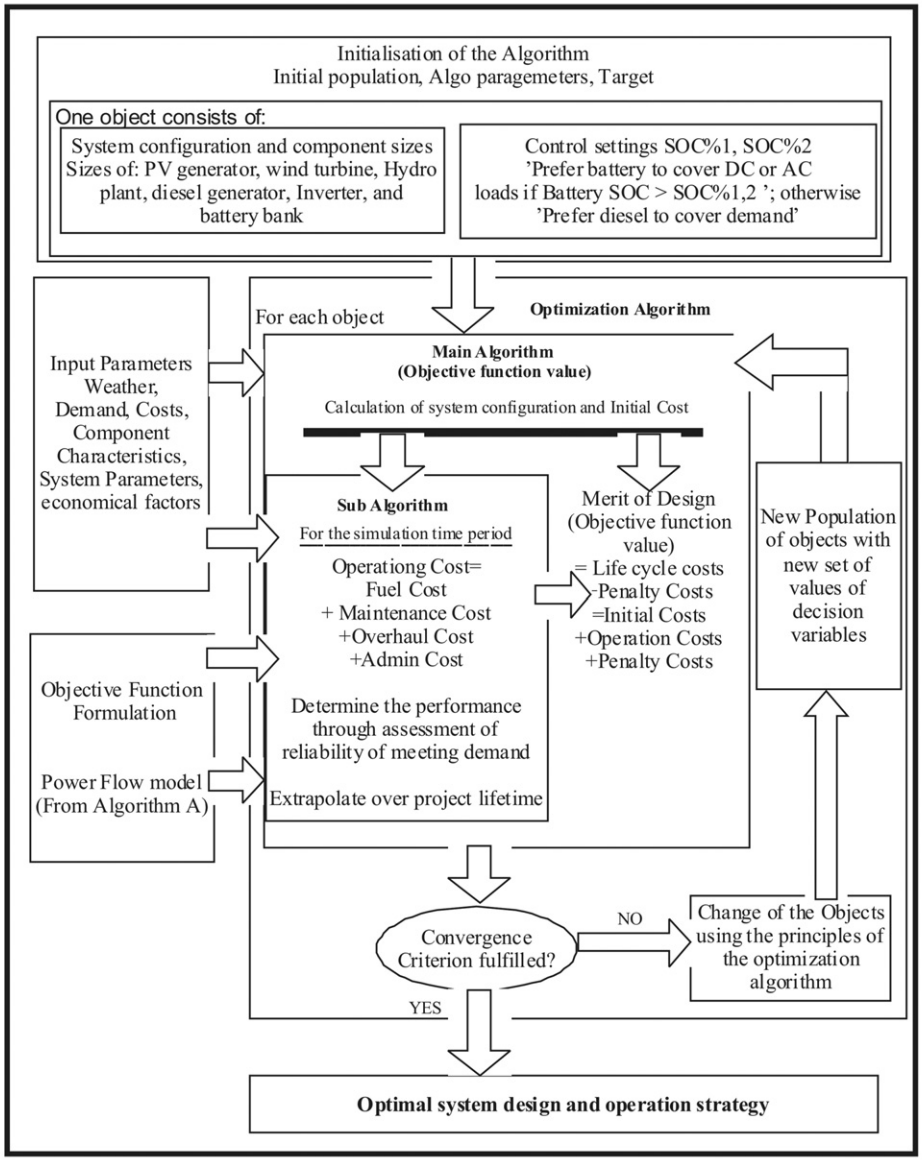

Fig. 3. BBO optimization algorithm for hybrid energy system design.

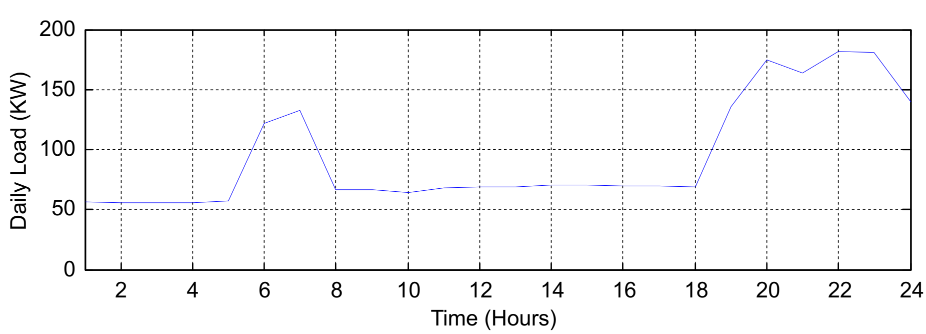

Fig. 4. Daily load profile.

6. Comparison of BBO with other algorithms

The hybrid energy system optimization is performed on an Intel Core 2 Duo PC with 2.1 (GHz) processor speed, 2 (GB) RAM and Windows 7 operating systems. The experiments are performed using the MATLAB R2010b program. The BBO results are compared with the HOMER, GA, PSO, CLPSO and EPSDE.

For the sake of comparison of performance between the various algorithms, the stopping criterion is set at same. Mutation rate = 0.7 and Cross over rate = 0.3 are used to get the best results for GA. For PSO, $C_1 = 1.8$, $C_2 = 2.2$, W starts at 1 and decreases until reaching 0 at the end of the run. In CLPSO, C = 1.5 is selected and in EPSDE, CR = 0.9, F = 0.5 gives the best results. The mating is performed using single point crossover. Fig. 7 depicts convergence of five optimization algorithms for the combination of the hybrid energy system in which PV, WTG, Diesel generator, battery and inverter are present. For comparison of different algorithms, the initial solution points are taken constant. It can be seen that the fitness value decreases rapidly in the first 10 generations. During this stage GA, PSO, CLPSO, EPSDE and BBO concentrate mainly on finding feasible solutions to the problem. Then the value decreases slowly, and they have been converged approximately at around 20 iterations. Consequently, the total system cost, components size has been almost same in BBO, PSO, CLPSO, EPSDE and GA. More details about convergence and optimal solutions are given in Tables 4 and 5.

It observed from the Tables 4 and 5 that HOMER, PSO, GA, CLPSO, EPSDE and BBO are able to find the optimum design parameters of the stochastic simulation model. It can be easily seen that BBO algorithm is more rapid and give minimum cost as compared to GA, PSO, CLPSO and EPSDE. Therefore, the proposed BBO-based optimization procedure can comfortably, rapidly approach the optimum state for a large-scale complex simulation of a hybrid energy system. The total cost of the optimized hybrid energy system showed that the system can deliver energy in a stand-alone installation with an acceptable cost.

The Homer software with a combination of various components and strategies variables of 38 million would require the calculation time of approximately 15 h to evaluate each combination. The proposed BBO algorithm not only reduces the demerits of HOMER but also uses a certain number of combinations. The proposed BBO has reduced 15 h of calculation time around 0.73 h on Intel Core 2 Duo PC for complete hybrid energy system optimization.

7. Results and discussions

The mathematical modeling is driven by HOMER, the results of HOMER software can be used for comparison and point of reference. The optimization results using HOMER software are shown in Table 6.

The biogeography-based optimization algorithm derived the results as shown in Table 7. The total power generated by renewable sources seemed enough, except for its failure to provide the necessary power at peak time, which requires the support of battery and inverter. Optimization calculations obtained by HOMER are slightly different as compared with BBO. However, use of HOMER will be a problem, when the calculation of different types of component needs to be calculated simultaneously. There are three significant disadvantages of HOMER:

1. HOMER requires calculation of every single combination of sizing and operation strategy.
2. The data for each variation of component needs to be entered manually and execute separately.
3. HOMER generally uses diesel generator, so hybrid system cost increases due to increase in fuel intake.

As data involved are large and sensitivity analysis needs to be done for selected components, it is unlikely that HOMER can provide fast and reliable solutions for the optimization. After lot of hit and trial, the following parameters are taken for BBO algorithm:

- No. of habitats or population : 50,
- Generation : 50,

Table 1
Monthly global solar radiation (kWh/m^2/day) and sunshine hours at Jaipur (Rajasthan).

Month	Solar radiation (kWh/m^2/d)	Sunshine hours (h/day)
January	4.128	5.59
February	4.882	6.14
March	5.717	6.13
April	6.427	6.11
May	6.812	5.87
June	6.830	6.09
July	5.748	6.04
August	5.269	5.52
September	5.756	6.77
October	5.329	5.52
November	4.382	6.23
December	3.866	5.82

Table 2
Monthly wind speed at Jaipur (Rajasthan).

Month	Wind speed (m/s)
January	6.312
February	5.433
March	4.627
April	4.993
May	10.335
June	10.717
July	8.413
August	8.754
September	9.776
October	5.850
November	4.443
December	5.931

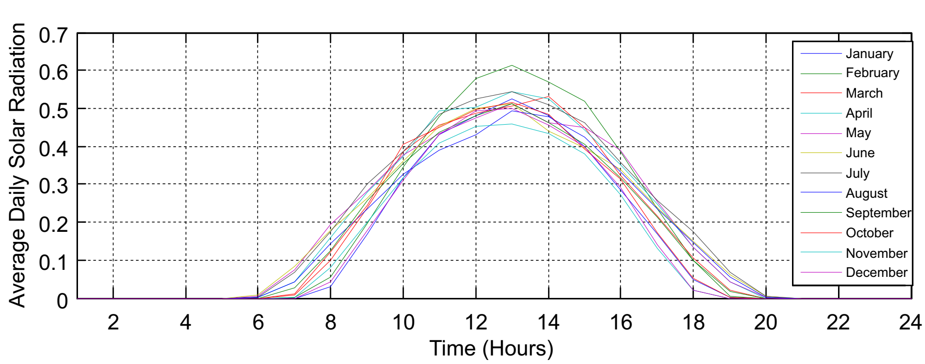

Fig. 5. Average solar radiation monthly data for 1 year.

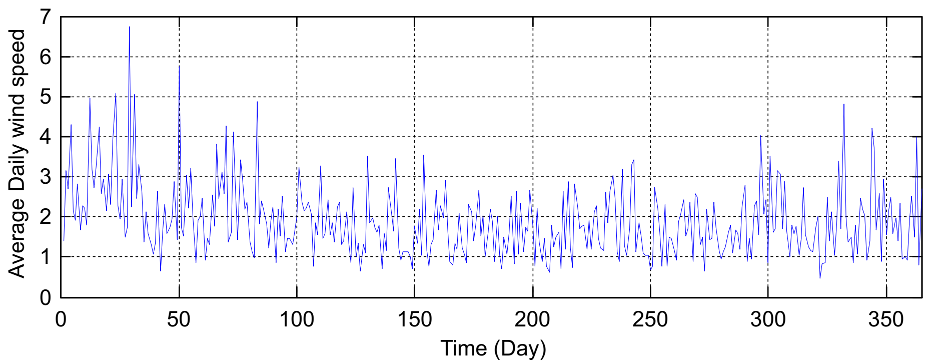

Fig. 6. Average daily wind speed (m/s).

Table 3
Technical data and study assumptions of hybrid energy system.

Description	Data
PV	
Capital cost	200,000 Rs/kW
Lifetime	25 years
Operation and maintenance cost	1000 Rs/kW/year
Replacement cost	200,000 Rs/kW
Wind turbine	
Rated power	Variable (0–300 KW) AC
Capital cost	65,000 Rs/kW
Lifetime	25 years
Operation and maintenance cost	1000 Rs/kw/year
Cut-in speed (m/s) Vci	2–3
Cut-out speed (m/s) Vco	25
Hub height	30 m
Replacement cost	65,000 Rs/kW
Diesel generator units	
Capital cost	20,000 Rs/kW
Rated power of each diesel unit 1 (D1, D2)	Variable (0–100 MW)
Minimum allowed power (min load ratio)	30% of rated power
Operation and maintenance cost	1 Rs/h/kW
Operating hours	16,000 h
Replacement cost	
Batteries	
Type of batteries	Tarjan L16P
Nominal voltage (V)	6 V
Nominal capacity	360 Ah
Nominal energy capacity of each battery	2.16 kWh
Operation and maintenance cost	100 Rs/year
Dispatch/operating strategy	Multiple diesel load following
Capital cost	10,000 Rs
Replacement cost	4000 Rs
Converter	
Capital cost	50,000 Rs/kW
Operation and maintenance cost	100 Rs/year/kW
Lifetime	10 years
Replacement cost	50,000 Rs/kW
Spinning reserve	**10%**
Minimum renewable fraction	**60%**
Annual interest rate	**10%**
Project life time	**25 years**

- Number of SIVs per habitat : 20,
- Habitat modification probability : 1,
- Island Mutation probability : 0.05,
- Elitism parameter : 2,
- Maximum emigration Rate E : 1,
- Maximum immigration Rate I : 1.

The total cost for the minimization of the hybrid system is achieved by selecting an appropriate system configuration. In Table 7, the optimal sizing results consisting of device numbers and the total cost of the hybrid wind/PV system have been presented. The comparison of HOMER and BBO results are shown in Table 8. These results verify that the hybrid energy system has a lower total cost as compared to the stand-alone systems. Reliability of the hybrid energy system is much higher than the other systems, and the output is not very much affected by changes in weather conditions. The combination of wind in a hybrid energy system reduces the battery bank and diesel requirements, and PV array has the high capital cost per kW but very less operating and maintenance cost.

In order to study the hourly behavior of the power exchange in the hybrid energy system, the simulation results were conducted during 1st to 7th January, 2011, for the optimal configuration obtained from BBO algorithm (Case 1 of the Table 7), are shown in Fig. 8. It shows the power supply from the renewable sources, power demand and input/output power to the battery bank. Diesel Generator is used only when the renewable sources and the batteries are not able to satisfy the load demand.

Without much operation reserve, diesel generator can also supply the load demand independently but at much higher cost with Cost of Energy (COE) of Rs. 27.69/kWh. The generator uses 457,100 l of diesel and operating for 8760 h annually, which is almost half of its lifetime operating hours.

In all the calculations, the cycle charging process is selected as operation strategy. Two other operation strategies, load following and set point state of charge at 80% can be considered. Since the initial finding lacking input constraints, cycle charging process is enough to guide the selection and distribution of power.

Fig. 9 shows the annualized cost of the hybrid energy system (Case 2 of Table 7), which have PV, wind turbine, diesel generator, battery and Inverter connected to the system. Wind turbine contributes 31%, battery costs about 11%, PV system contributed 11%, Diesel generator costs 10%, fuel costs around 30% and inverter at 7% of the total annual cost of Rs. 67,877,356. PV panels and Wind system are assumed to last the lifetime of the project, i.e. for 15 years, while the battery and inverter needs to be replaced after a certain number of hours of operation and discharging respectively. The cost of battery and inverter plays an important part for determining the TNPC and COE. Except for three combinations, the system requires battery and inverter as part of the hybrid system for storing the excess energy generated by the system.

As global price of the oil is increasing and the Government of India has indicated that it can no longer provide the oil subsidy. It is important to note that if the true diesel price is used in the calculation, the COE is going up by Rs. 0.1per kWh for 1 Rs/litre increase in diesel price. The sensitivity results for diesel price are shown in Table 9. If diesel price is raised to Rs 50 per litre, the COE is increased by 6%.

To check the sensitivity of the results to variations in average wind speed from year to year, the hybrid energy system in Case

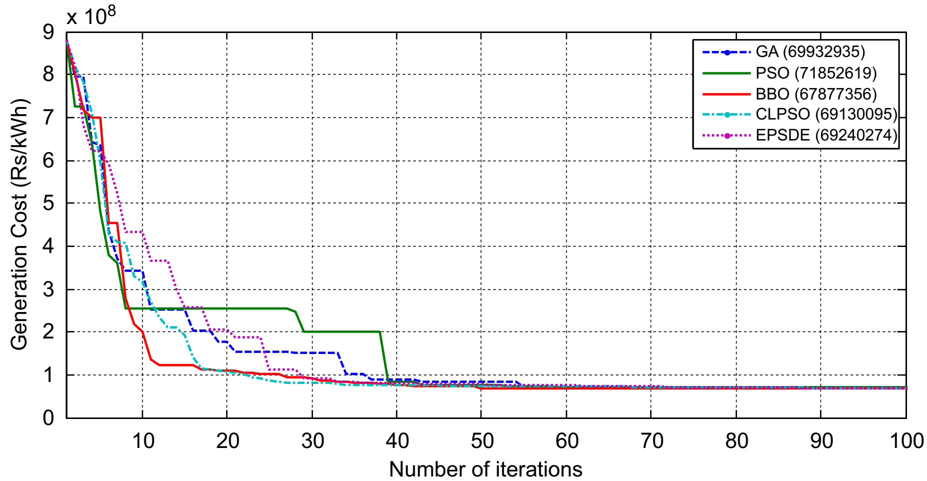

Fig. 7. Convergence characteristics of various optimization algorithms.

Table 4
Optimization results from various optimization algorithms.

Algorithm	PV (kW)	WTG	DG (kW)	Battery	Inverter (kW)	Net present costs	Energy produced	COE
HOMER	55	1	180	800	100	89,352,280	1,243,027	14.23
GA	53	1	168	808	93	71,852,619	1,088,797	11.45
PSO	52	1	165	813	93	69,932,935	1,067,294	11.14
BBO	52	1	163	813	93	67,877,356	1,059,639	10.81
CLPSO	52	1	164	814	93	69,130,095	1,067,894	11.01
EBSDE	52	1	164	813	93	69,240,274	1,068,247	11.03

Table 5
Comparison of optimization algorithms.

Optimization technique	Population size	Iteration number	Number of runs	Average time (s)	Total cost (Rs)	Comments
HOMER	–	21875	10	1648	89,352,280	–
GA	50	100	10	125	71,852,619	Pm=0.7, Pc=0.3
PSO	50	100	10	110	69,932,935	C_1=1.8, C_2=2.2
BBO	50	100	10	82	67,877,356	E=1, I=1
CLPSO	50	100	10	89	69,130,095	C=1.5
EBSDE	50	100	10	102	69,240,274	CR=0.9, F=0.5

Table 6
Complete optimization results received through Homer Software.

SN	PV (kW)	Wind (units)	Diesel (kW)	Battery (units)	Inverter (kW)	Net present costs (Rs)	Energy produced (kWh)	COE (Rs/kWh)
1	0	1	160	900	100	89,295,624	1,195,797	14.21
2	55	1	180	800	100	89,352,280	1,243,027	14.23
3	350	0	200	1300	200	125,044,944	1,130,267	19.9
4	0	2	220	0	0	128,571,824	1,995,859	20.46
5	60	2	220	0	100	136,609,248	2,093,897	21.74
6	600	0	0	4700	250	138,103,712	1,271,608	21.99
7	0	0	250	0	0	153,526,384	888,155	24.44
8	450	0	240	0	100	170,852,800	1,588,055	27.19
9	0	6	0	24,000	300	357,250,624	4,612,242	56.86

Table 7
Complete optimization results received through proposed BBO algorithm.

SN	PV (kW)	Wind (units)	Diesel(kW)	Battery (units)	Inverter (kW)	Net present costs (Rs)	Energy produced (kWh)	COE (Rs/kWh)
1	0	1	147	906	92	65,408,516	1,135,910	10.42
2	52	1	163	813	93	67,877,356	1,059,639	10.81
3	284	0	176	1239	212	131,414,657	929,470	20.94
4	0	1	210	0	0	85,046,660	1,110,834	13.55
5	51	1	201	0	104	83,891,664	1,140,773	13.37
6	557	0	0	4289	261	129,015,885	1,180,840	20.55
7	0	0	260	0	0	173,812,087	931,781	27.69
8	437	0	245	0	103	125,171,224	1,182,069	19.94
9	0	4	0	28,926	321	347,414,450	3,074,832	55.35

Table 8
Comparison of optimization results received through HOMER and proposed BBO algorithm.

SN	Components	NPC by HOMER (Rs)	Energy produced (kWh)	COE (Rs/kWh)	NPC by HOMER (Rs)	Energy produced (kWh)	COE Rs/kWh
1	Wind+DG+Battery	89,295,624	1,195,797	14.21	65,408,516	1,135,910	10.42
2	PV+Wind+DG+Battery	89,352,280	1,243,027	14.23	67,877,356	1,059,639	10.81
3	PV+DG+Battery	125,044,944	1,130,267	19.9	131,414,657	929,470	20.94
4	Wind+DG	128,571,824	1,995,859	20.46	85,046,660	1,110,834	13.55
5	PV+Wind+DG	136,609,248	2,093,897	21.74	83,891,664	1,140,773	13.37
6	PV+Battery	138,103,712	1,271,608	21.99	129,015,885	1,180,840	20.55
7	DG	153,526,384	888,155	24.44	173,812,087	931,781	27.69
8	PV+DG	170,852,800	1,588,055	27.19	125,171,224	1,182,069	19.94
9	Wind+Battery	357,250,624	4,612,242	56.86	347,414,450	3,074,832	55.35

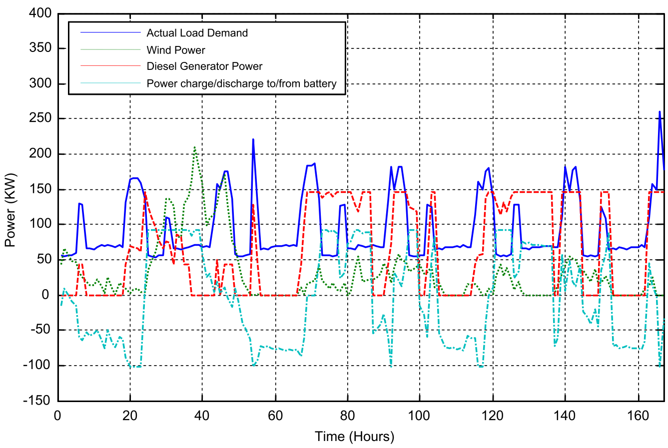

Fig. 8. Power management indicating load power, wind power output, diesel generator output, input/output power of the battery bank of the hybrid System in Case 1 of Table 6.

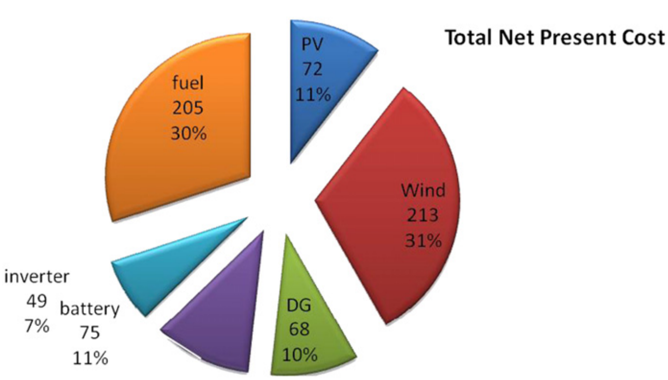

Fig. 9. Percentage share of components cost in Total net present cost for Hybrid energy system as given in Case 2 of Table 6.

Table 9
Economic sensitivity of diesel cost in Case 1 of Table 7.

Diesel price (Rs)	Tot NPC (Rs)	COE (Rs/kWh)
43	65,408,516	10.42
46	67,084,720	10.69
50	69,319,658	11.04
55	72,113,332	11.49

1 of Table 7 is run with the wind speeds adjusted upward and downward by 17.5%, which is the inter-annual variability (one standard deviation) found in the historical wind measurements. The results are shown in Table 10. With the wind speed 17.5% lower than the present measurement year, COE rose by 11.6%. With the wind speed 17.5% higher, COE dropped by 8.06%.

Table 10
Economic sensitivity to wind speed variations in Case 1 of Table 7.

Case	Average wind speed (m/s)	Diesel saving (kl)	COE (Rs/kWh)
−17.5%	6.0	179	11.63
Baseline	7.2	265	10.42
+17.5%	8.4	336	9.58

8. Conclusion

Stand-alone hybrid energy systems are more suitable than stand-alone systems that only have one energy source for the supply of electricity to off-grid applications, especially in remote areas with difficult access. However, the design, control, and optimization of the hybrid energy systems are usually very complex tasks.

Power supply reliability under varying weather conditions and the corresponding system cost are the two major concerns in designing PV and/or wind turbine systems. In order to utilize renewable energy resources efficiently and economically, one optimum sizing method is developed in this paper based on a Biogeography Based Optimization (BBO), which has the ability to attain the global optimum with relative computational simplicity compared to the conventional optimization methods. The system configuration, characteristics of the main components, overall sizing, control and power management strategy for the hybrid energy system have been presented. The wind and PV generation systems are the main power generation devices, and the battery acts as a storage device for excess power. The developed methodology is based on the use of long-term data of wind speed, solar irradiance and ambient temperature. The BBO algorithm manages to optimize the size and the operation strategy for a simple daily load. Furthermore, a numerical example (Case study) is used to demonstrate the applicability, power management and usefulness of the proposed method.

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