Energy Conversion and Management 128 (2016) 178–190

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Feasibility study of an islanded microgrid in rural area consisting of PV, wind, biomass and battery energy storage system

Shakti Singh [a,*], Mukesh Singh [a], Subhash Chandra Kaushik [b]

[a] Department of Electrical and Instrumentation Engineering, Thapar University, Patiala, India
[b] Centre for Energy Studies, Indian Institute of Technology Delhi, India

ARTICLE INFO

Article history:
Received 23 June 2016
Received in revised form 14 September 2016
Accepted 15 September 2016
Available online 28 September 2016

Keywords:
Artificial bee colony algorithm
Battery energy storage system
Biomass energy
Optimization
Solar energy
Wind energy

ABSTRACT

Renewable energy systems are proving to be promising and environment friendly sources of electricity generation, particularly, in countries with inadequate fossil fuel resources. In recent years, wind, solar photovoltaic (PV) and biomass based systems have been drawing more attention to provide electricity to isolated or energy deficient regions. This paper presents a hybrid PV-wind generation system along with biomass and storage to fulfill the electrical load demand of a small area. For optimal sizing of components, a recently introduced swarm based artificial bee colony (ABC) algorithm is applied. To verify the strength of the proposed technique, the results are compared with the results obtained from the standard software tool, hybrid optimization model for electric renewable (HOMER) and particle swarm optimization (PSO) algorithm. It has been verified from the results that the ABC algorithm has good convergence property and ability to provide good quality results. Further, for critical case such as the failure of any source, the behavior of the proposed system has been observed. It is evident from the results that the proposed scheme is able to manage a smooth power flow with the same optimal configuration.

1. Introduction

In the last few years, renewable based hybrid energy system has found attention due to increasing environmental concerns, energy demand, fuel prices and depletion of fossil fuels. In particular, solar and wind based generation systems have become sustainable and environmentally friendly options to supply power in isolated or off grid locations [1]. Solar photovoltaic (PV) energy conversion systems along with storage system have proved to be a very attractive method to provide electricity to the places like remote or off grid locations [2], residential households [3], off-grid location [4] and commercial buildings [5,6]. However, PV generation has a low energy conversion efficiency and cost of electricity per kWh is high. This led to a substantial growth in wind based power generation. Numerous researches focus on feasibility and optimum sizing of the wind based systems [7–9]. However, the major drawbacks for both wind and solar energy sources are their stochastic nature which raises concern about the reliability of power to the user. Therefore, to enhance the reliability, hybridization of both wind and solar energy is a suitable alternative. One's weakness can be compensated by the strengths of another. However, it increases the complexity of the system [10]. Stand alone solar-wind based hybrid energy systems have been analyzed in various researches in terms of cost effectiveness [11–13].

The biggest drawback of a stand alone solar-wind based energy system is its dependency on power back-up due to the irregular nature of both wind and solar resources. In case of a stand-alone hybrid system generally back-up is provided by diesel generator or energy storage devices such as batteries or ultra-capacitors. Usage of a diesel generator in hybrid system raises cost and environmental concerns. Fortunately, continuous advancement in technology, other renewable options such as biomass, bio-gas, mini hydro and fuel cell have been integrated along with solar and wind sources [14]. In the aforementioned renewable energy options, biomass seems to be a more viable option, especially in the case of agriculture rich countries. Biomass can be converted into many forms such as heat, electricity and bio-fuels [15]. Due to advancement in biomass gasification technology, electricity generated by biomass gasifiers is becoming popular especially in the rural areas. Biomass power generation plants have high load factor and cost effective [16]. Biomass power generation has been integrated along with PV, wind and other renewable energy sources. Stand alone and grid connected PV-biomass with or without storage is seen as a viable and cost effective option for electricity, particularly in developing countries [17,18].

* Corresponding author.
E-mail addresses: shakti.singh@thapar.edu (S. Singh), mukesh.singh@thapar.edu (M. Singh), kaushik@ces.iitd.ernet.in (S.C. Kaushik).

http://dx.doi.org/10.1016/j.enconman.2016.09.046
0196-8904/

Thus, utilizing locally available renewable energy sources for generation of electricity can be a possible option at off grid or electricity deficient places. In case of rural areas enough biomass, wind and solar resources are available. Therefore, electricity demands of such areas can be met by intelligently harnessing these resources. Moreover, in the case of renewable hybrid energy system, the power generated needs to be stored in a large battery bank [19]. A typical self-sustainable hybrid energy system could be designed by incorporating renewable energy sources and storage systems. In case of such hybrid systems, various factors such as total cost of system, size and capacity of renewable energy sources plays a crucial role. Optimal power flow between different components of a hybrid system is required due to the intermittent nature of renewable energy sources. Two major parameters such as price of generating energy and reliability of the system are major challenges in hybrid systems. An optimal designed system should have the best selection of components while assuring the reliability of the system [20].

In the existing literature, limited work has been found in PV, wind and biomass based hybrid systems with energy storage. For instance, Balamurgun et al. [21] proposed a PV-biomass-wind hybrid system for rural areas of India. The authors performed economic analysis and component selection with the help of the standard software tool hybrid optimization model for electric renewable (HOMER). Rehman et al. [22] proposed a PV-biomass-wind based hybrid system for a location in Bangladesh. The system sizing was obtained with the help of HOMER. Dhass and Harikrishnan [23] evaluated a PV-wind-biomass hybrid system for rural electrification on the basis of life cycle cost. Ho et al. [24] integrated solar and biomass resources to make a small village self sustainable. To design hybrid system a mixed integer linear programming based model has been developed. Garrido et al. [25] presented techno-economic analysis of hybrid PV-biomass energy system for an off grid location in Mozambique using tool HOMER. It is inferred from the results that agricultural and food processing wastes could play an important role in energy generation, particularly in rural areas.

The aforementioned literature reveals that researchers have used either software tools or conventional optimization methods for performance analysis. However, software tools possess some serious disadvantages such as black box coding, single function minimization and require more computational time as compared to existing optimization techniques. However, many works have been identified in hybrid systems where the different researchers have proposed different conventional and evolutionary algorithms to achieve the optimal size of the components used in hybrid systems. Different research activities have been carried out using conventional techniques such as graphical construction method [26], iterative method [27], trade off method [29] and linear programming [28]. The problem with conventional techniques is that they often trap in local minima. To overcome these shortcoming numerous meta-heuristic evolutionary algorithms, i.e., genetic algorithm [30], particle swarm optimization [31], ant and bee colony algorithm [18], harmony search [32], bio-geography based optimization [33], etc. have been implemented in different hybrid systems. In recent years, a new trend has been observed where researchers are applying widely these evolutionary algorithms for optimal sizing of the hybrid energy system. To the best of authors knowledge, a very limited work is found, where the optimization of hybrid PV-wind-biomass along with the energy storage system has been explored.

From the above mentioned literature, it has been observed that there is a need of a hybrid system which consists of PV, wind and biomass along with an energy storage system especially in isolated or off-grid locations. The sizing of each equipment in any hybrid system is a challenging work. Despite of works in literature under different perspectives, the proposed work focuses on the hybrid energy system which is a combination of PV, wind, biomass and energy storage. The optimal sizing of components for all the above hybrid systems have been identified by using either software tools or by conventional and evolutionary algorithms. But none of the researchers have worked on the optimal sizing of PV-wind-biomass with battery bank as storage using evolutionary algorithms. The biomass resources can be harnessed along with wind and solar sources to enhance the reliability of the hybrid system. Therefore, in this paper, an autonomous hybrid PV-wind-biomass with battery system is proposed to fulfill the electrical demand of a typical village. A swarm based meta-heuristic, artificial bee colony (ABC) algorithm has been applied to realize optimal configurations of the proposed system. The major factor which differentiates ABC algorithm from other algorithms (such as GA and PSO) is that it employs a lesser number of control parameters. Also, it has a good convergence accuracy and potential to provide optimal results, like other evolutionary algorithms [34]. To compare the performance of the applied technique, the results achieved by the ABC algorithm have been compared with PSO and HOMER. A brief comparison is performed on the basis of the levelized cost of energy (LCOE). The configuration with least LCOE is considered the optimal one. The main objectives of this work are outlined as follows.

- To develop a mathematical model of an autonomous PV-wind-biomass energy system with battery bank to provide electricity for an off-grid location.
- To deduce the optimal size of the components used in the proposed system with the least LCOE by minimizing the net present cost (NPC) of the system by applying swarm based ABC algorithm.
- To compare results achieved from the ABC algorithm to results obtained with HOMER and PSO.
- To observe the performance of the hybrid system in the critical cases such as failure of any generating unit.

The major contribution of this paper is to design a cost effective and reliable hybrid PV-wind-biomass energy system with battery storage to meet the electrical load demand of small area which has enough natural resources. The mathematical modeling of various components and operational strategy in the proposed system have been discussed in detail. The detail cost analysis of the proposed hybrid system is performed by applying two evolutionary algorithms and one software tool. For optimal sizing and scheduling, results obtained by applying these different methods have been compared. Moreover, a critical case such as failure of one generating unit has also been performed to test the reliability of the hybrid energy system.

2. Mathematical modeling of proposed hybrid system

This work emphasizes on the formulation of a new hybrid system to supply the reliable power to off-grid or isolated location. Fig. 1 shows the different components of the proposed microgrid. The power generated by wind, solar and biomass is managed with the help of storage devices. As shown in Fig. 1, load, wind turbines and biomass gasifier are connected to AC bus. Moreover, solar PV panels and batteries are connected to the AC bus via converters. A charge controller is also deployed to maintain the smooth flow of power and limit the charging and discharging rate of batteries.

The proposed system is most suitable for off grid locations and agriculture based villages in developing countries where energy crisis is a major concern. However, the proposed system can be integrated to the grid. This system will be helpful in reducing

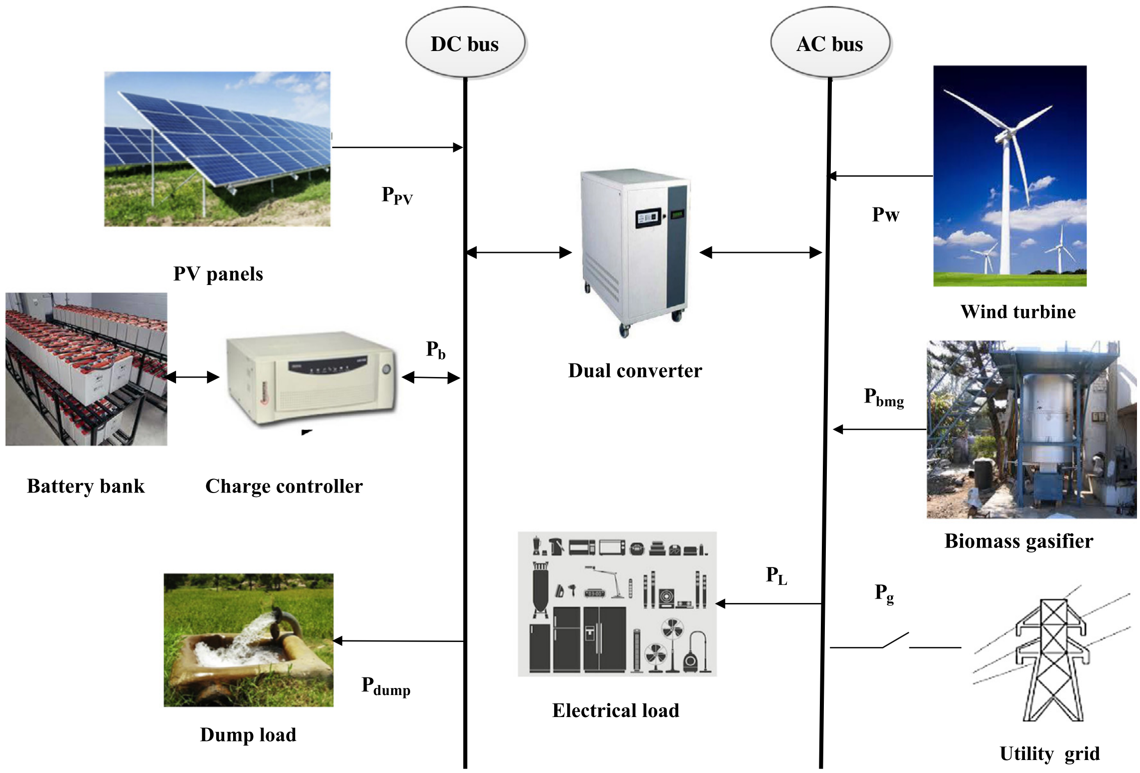

Fig. 1. Different components of the proposed system.

utility grid dependency as it is completely self sustaining with the renewable energy sources. For optimal distribution of power, battery banks are employed, which reduces intermittency of renewable energy sources. This work mainly emphasizes on optimal sizing of each component, while guaranteeing the reliability of the system. The mathematical models of different components are discussed as follows.

2.1. Solar photovoltaic panel

The power output of a solar PV panel ($P_{sol}(t)$) depends upon solar radiation and it can be given as,

$$P_{sol}(t) = P_r^s f_{loss} \frac{G_h(t)}{G_S} \tag{1}$$

where P_r^s represents rating of the solar PV panel, f_{loss} is the derating or loss factor of the solar PV panel because of shadow, dirt and temp etc, $G_h(t)$ is the hourly solar radiation incident at surface of solar PV panel (W/m^2) and G_S is the standard incident radiation (1000 W/m^2). Effect of temperature is not taken in consideration in this study [35].

2.2. Wind power generation

The power generated by a wind turbine ($P_{wt}(t)$) can be calculated as,

$$P_{wt}(t) = \begin{cases} 0 & V(t) \leqslant V_{cin} \text{ or } V(t) \geqslant V_{cout} \\ P_r^w & V_{rat} \leqslant V(t) \leqslant V_{cout} \\ P_r^w \frac{V(t)-V_{cin}}{V_{rat}-V_{cin}} & V_{cin} \leqslant V(t) \leqslant V_{rat} \end{cases} \tag{2}$$

where P_r^w is the rating of a single wind turbine, V_{cin} is the cut in speed, V_{rat} is the rated wind speed, V_{cout} is the furlong speed and $V(t)$ is the wind speed at desired height. The wind speed at the hub height depends upon site and geographical location and it is different from reference height. Further, it is expressed as,

$$V(t) = V_r(t) \left(\frac{H_{WT}}{H_r}\right)^{\gamma} \tag{3}$$

where $V(t)$ is the wind speed at height (H_{WT}), $V_r(t)$ is the wind speed at reference height H_r, and γ is friction coefficient. Typical value of friction coefficient γ is 1/7 for low roughness, surface and well exposed site [13,36].

2.3. Biomass gasifier

In biomass gasification technology, solid bio-residue is transformed into a gaseous fuel which is finally used for electricity generation. Under partial combustion, the producer gas is produced which is a combustible gas with a composition of H_2 (20%), CO (20%), CH_4 (1–2%) and inert gases. In case of biomass gasifier, the producer gas is used as a input fuel. The annual output electricity (E_{bmg}) of a biomass gasifier can be computed as,

$$E_{bmg} = P_{bmg}(8760 * CUF) \tag{4}$$

where P_{bmg} is rating of biomass gasifier system and CUF is the capacity utilization factor. In case of biomass based energy system, few parameters such as calorific value of biomass, availability of biomass (Ton/yr) and usage hours of biomass gasifier play important role. The maximum rating of biomass gasifier installed in a particular area can be defined as follows,

$$P_{bmg}^m = \frac{\text{Total biomass avialable(Ton/yr)} * 1000 * CV_{bm} * \eta_{bmg}}{365 * 860 * \text{Operating hours/day}} \tag{5}$$

where η_{bmg} represents overall biomass to electricity conversion efficiency and CV_{bm} is the biomass's calorific value [37,38].

2.4. Battery bank

Batteries are used in hybrid renewable energy system to store excess energy and to discharge when power from renewable systems is insufficient or absent. The measurement of energy can be achieved with the proper estimation of the state of charge (SOC). The SOC of the battery is a function of time and it can be calculated as,

$$\frac{SOC(t)}{SOC(t-1)} = \int_{T-1}^{T} \frac{P_b(t)\eta_{batt}}{V_{bus}} dt \tag{6}$$

where V_{bus} is the voltage of bus, $P_b(t)$ is battery's input/output power and η_{batt} is the round trip efficiency of the battery. If $P_b(t)$ is positive, battery is charging, else it is discharging. Further, the round trip efficiency of a battery is defined as follows,

$$\eta_{batt} = \sqrt{\eta^c_{batt}\eta^d_{batt}} \tag{7}$$

where η^c_{batt} and η^d_{batt} are charging and discharging efficiency of the battery respectively [35]. The round trip efficiency of the battery bank is considered as 92.2%. Also, it is assumed that charging and discharging efficiencies are different and considered to be 85% and 100% respectively. SOC_{max} is the maximum value of SOC and is equal to the aggregate capacity of the battery bank ($C_n(Ah)$) and it is given as follows,

$$C_n(Ah) = \frac{N_{batt}}{N^s_{batt}} C_b(Ah) \tag{8}$$

where $C_b(Ah)$ is the single battery capacity, N_{batt} is the total number of batteries, N^s_{batt} is the number of batteries connected in series. The battery bank can not discharge beyond a minimum limit which is called SOC_{min}. This limit can be used as system constraints according to the usage of battery bank. To obtain desired bus voltage, batteries are connected in series. The number of batteries connected in series can be calculated as,

$$N^s_{batt} = \frac{V_{bus}}{V_{batt}} \tag{9}$$

where V_{batt} is the voltage of a single battery. Another major factor in battery modeling is the maximum charge or discharge power at any time. It depends upon maximum charge current, and can be calculated by the following equation,

$$P_b^{max} = \frac{N_{batt}V_{batt}I_{max}}{1000} \tag{10}$$

where I_{max} is the battery's maximum charging current in amperes.

2.5. Power converter

DC/AC and AC/DC power converters are required when there are AC and DC components in the system. Solar PV panels and batteries are generating DC output while the considered load is AC. The converter size is chosen based upon peak load demand ($P_L^m(t)$). The inverter rating (P_{inv}) is calculated as follows,

$$P_{inv}(t) = P_L^m(t)/\eta_{inv} \tag{11}$$

where η_{inv} denotes efficiency of the inverter.

3. Problem formulation

The main objective of this study is to formulate a cost effective and reliable hybrid energy system. The rating and sizing of solar PV panels, wind turbine, battery bank and biomass gasifier are main decision variables. In this section, operational strategy of the system, objective function and brief introduction of applied algorithm is presented.

3.1. Operational strategy

In case of any hybrid energy system, proper power management is required to achieve reliability of the system. In this system, biomass gasifier is kept on least priority, i.e. it is run when solar, wind and batteries are unable to meet the load demand. Simplified steps of operational strategy are as follows

- If the total power produced by solar PV panels and wind turbines is sufficient and also wind power is less than load, then demand can be served by renewable sources only. After satisfying the load, surplus power can be provided to the battery bank and is given as,

$$P_b(t) = P_{PV}(t) - [P_L(t) - P_w(t)]/\eta_{inv} \tag{12}$$

  where $P_L(t)$ denotes load demand at any time and η_{inv} denotes the efficiency of the inverter. If $P_{sol}(t)$ is the power produced by an individual solar PV panel and N_{sol} is the total number of solar PV panels, then the total power produced by solar PV panels ($P_{PV}(t)$) is given as

$$P_{PV}(t) = P_{sol}(t)N_{sol} \tag{13}$$

  Further, if P_{wt} is the power produced by an individual wind turbine and N_{wt} is the total number of wind turbines, then the total power generated by wind turbines ($P_w(t)$) can be given as,

$$P_w(t) = P_{wt}(t)N_{wt} \tag{14}$$

- If power generated solely from wind turbines is enough to supply load demand, the remaining power (solar & wind) can be fed to the battery bank. The battery power in this case can be calculated as,

$$P_b(t) = [P_w(t) - P_L(t)]\eta_{rec} + P_{PV}(t) \tag{15}$$

  where η_{rec} is the rectifier efficiency.
- In both the above mentioned cases, if $P_b(t)$ is greater than the maximum allowable capacity of battery bank (P_b^{max}) then excess energy could be dumped or can be given to deferrable loads. Excess or dump energy is obtained as,

$$P_{dump}(t) = P_b(t) - P_b^{max}(t) \tag{16}$$

- If solar PV panels and wind turbines are not generating adequate power, then balance power can be supplied by the battery and is calculated as,

$$P_b(t) = [P_L(t) - P_w(t)]\eta_{inv} - P_{PV}(t) \tag{17}$$

- If solar and wind power are inadequate and batteries ($SOC(t) \leqslant SOC_{min}$) are also not able to produce the desired power to meet the load demand, then biomass gasifier supplies power to the load. Biomass gasifier can be used in two ways,
  (a) First, load following strategy, i.e. whenever it operates, it generates only required power to meet the primary load demand. The power generated by the biomass gasifier is calculated as,

$$P_{bmg}(t) = P_L(t) - P_w(t) - P_{PV}(t)/\eta_{inv} \tag{18}$$

  (b) In second strategy, it operates at rated capacity or minimum load ratio. In case biomass gasifier is operating at rated capacity, the surplus power is used to charge the batteries and may be expressed as follows,

$$P_b(t) = [P_{bmg}(t) - P_L(t) + P_w(t)]\eta_{rec} + P_{PV}(t) \tag{19}$$

A simplified flow chart of the operating strategy of the proposed hybrid energy system has been demonstrated in Fig. 2.

3.2. Objective function and constraints

The main motive of this study is to minimize total NPC of the proposed hybrid system while maintaining the optimal energy flow. For optimal configuration, four main decision factors, i.e., the number of wind turbines, solar PV panels, batteries and rating of biomass gasifier have been selected. For the economic analysis, annualized system cost (ASC) concept is used. The result with least ASC is observed to be an optimal one while meeting all other constraints and parameters. The objective function considered is the total system cost, which consists of (i) total capital cost (ii) replacement cost and (iii) operational & maintenance cost of the components. Installation and civil works costs are incorporated in the capital costs of the components. The following function is considered as the main objective function which is to be minimized subject to constraints,

$$\begin{aligned} Minimize : ASC \\ = F(N_{sol}C_{sol} + N_{wt}C_{wind} + N_{batt}C_{batt} + P_{inv}C_{inv} + P_{bmg}C_{bmg}) \end{aligned} \tag{20}$$

where $C_{sol}, C_{wind}, C_{batt}$ and C_{inv} are the cost of solar PV panel (per kW), wind turbine (per kW), battery (per unit) and inverter (per kW) respectively. C_{bmg} is the cost of biomass gasifier (per kW) and P_{bmg} is the rating of biomass gasifier. P_{inv} is the rating of the inverter.

The ASC of the installed component has several parts such as capital and installation cost (C_{acap}), replacement cost (C_{arep}), annual maintenance cost (C_m), operation cost (C_f) and salvage cost (C_{sal}). Further, total ASC of each components can be expressed as follows,

$$C_{sol} = C_{sol}^{acap} + C_{sol}^{arep} + C_{sol}^{m} - C_{sol}^{sal} \tag{21}$$

$$C_{wind} = C_{wind}^{acap} + C_{wind}^{arep} + C_{wind}^{m} - C_{wind}^{sal} \tag{22}$$

$$C_{batt} = C_{batt}^{acap} + C_{batt}^{arep} + C_{batt}^{m} - C_{batt}^{sal} \tag{23}$$

$$C_{bmg} = C_{bmg}^{acap} + C_{bmg}^{arep} + C_{bmg}^{m} + C_{bmg}^{f} - C_{bmg}^{sal} \tag{24}$$

$$C_{inv} = C_{inv}^{acap} + C_{inv}^{arep} + C_{inv}^{m} - C_{inv}^{sal} \tag{25}$$

The annualized cost of any component can be calculated with the help of a factor called capacity recovery factor (CRF). CRF is used to compute present value of money and can be given as,

$$CRF(i, N) = \frac{i(1+i)^N}{(1+i)^N - 1} \tag{26}$$

where N is the lifetime in years and i is the annual interest rate. The objective function is minimized enforcing a set of several constraints, which are summarized as

$$1 \leqslant N_{sol} \leqslant N_{sol}^{m} \tag{27}$$

$$1 \leqslant N_{wt} \leqslant N_{wt}^{m} \tag{28}$$

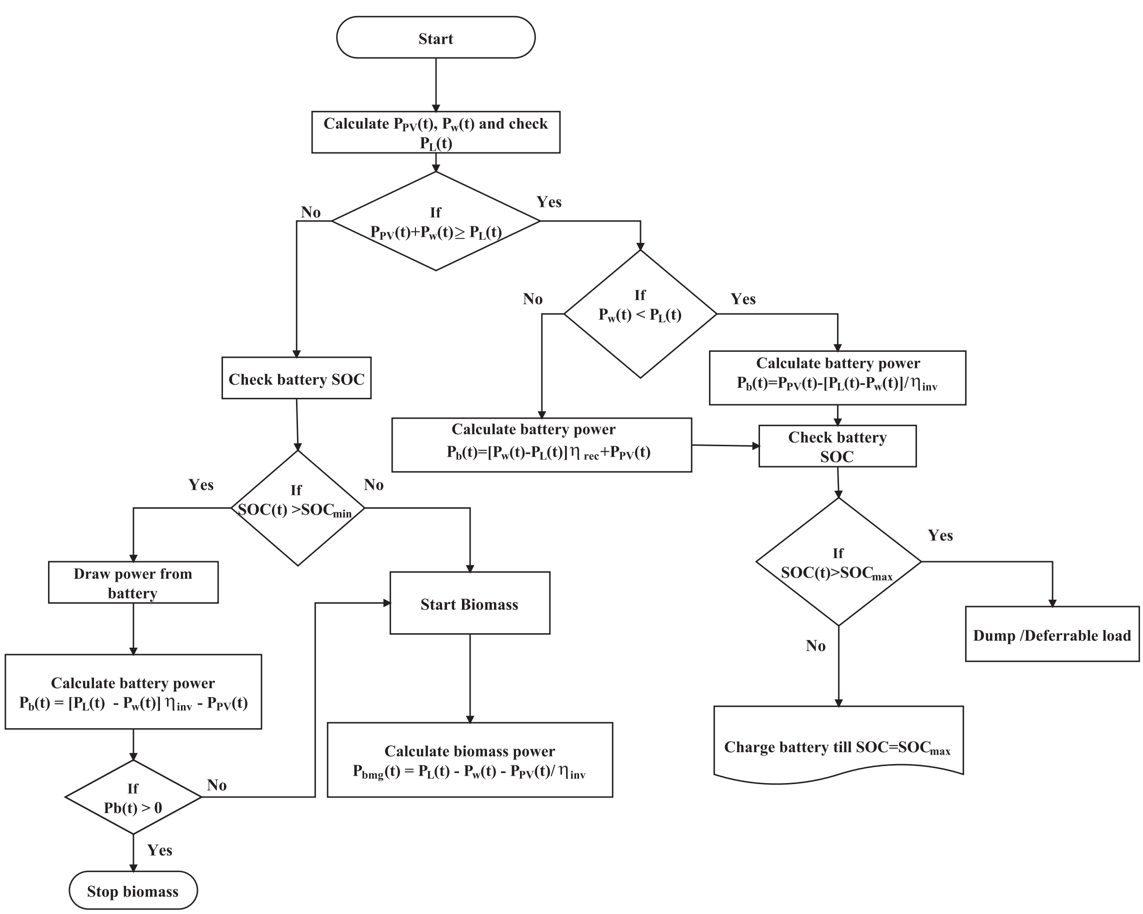

Fig. 2. A simplified flow chart of the operating strategy of the proposed hybrid energy system.

$$1 \leqslant P_{bmg} \leqslant P_{bmg}^{m} \tag{29}$$

$$1 \leqslant N_{batt} \leqslant N_{batt}^{m} \tag{30}$$

$$SOC_{min} \leqslant SOC \leqslant SOC_{max} \tag{31}$$

where N_{sol}^{m} is the maximum number of solar PV panels, N_{batt}^{m} is the maximum number of batteries, N_{wt}^{m} is the maximum number of wind turbines and P_{bmg}^{m} is the maximum rating of biomass gasifier.

The optimal configuration is selected on the basis of LCOE and reliability. LCOE is declared as average price per kWh of the energy (useful) generated by the system and it can be given as,

$$LCOE = \frac{ASC(\$/\text{year})}{\text{Total useful energy served}(\text{kW h/year})} \tag{32}$$

3.3. Artificial bee colony algorithm

In 2005, Karaboga and Basturk proposed a new swarm based algorithm named artificial bee colony algorithm. ABC is inspired by the intelligent behavior of honey bees and it can be applied to all types of optimization problems. In a regular bee colony, there are mainly three types of bees, i.e., employed, onlooker and scout bee. In ABC algorithm, the number of employed and onlooker bees are almost equal. Employed bees and food source are equal in number. The employed bees are randomly distributed to exploit food sources and share information with the onlooker bee. The onlooker bees which are normally waiting bees, after receiving the information, decide to explore the food source. If the food source is unrestricted, the employed bees become a scout and start locating a new food source [39]. Algorithm I shows the proposed methodology to implement the ABC algorithm for the problem.

Algorithm 1. Implementation of the ABC algorithm

Input: Solar radiation data, wind speed data, biomass resource, P_L and components prices.
Output: $(N_{sol}, N_{wt}, N_{batt}, P_{bmg})$

1: Store $SOC_{max}, SOC_{min}, NP, D, FoodNumber, Maxcycle, Limit$
2: Store (N_{sol}^{m}=300), (N_{w}^{m} =20), (N_{batt}^{m} =1400) and (P_{bmg}^{m}=50)
3: Compute $P_{sol}(t)$ and $P_{wt}(t)$ by using Eqs. (1) and (2).
4: Generate a randomly initialized population as

$$X_{uv} = X_{v}^{min} + rand[0,1](X_{v}^{max} - X_{v}^{min}) \tag{33}$$

5: Set trial counters to zero.
6: Calculate following for initial randomly generated solution $(N_{sol}, N_{wt}, N_{batt}, P_{bmg})$
- Compute $P_{PV}(t)$ and $P_{w}(t)$ using Eqs. (13) and (14).
- Perform the steps explained in operational strategy.
- Calculate the component costs for initial solution by using Eqs. (21)–(25).

7: Evaluate objetive function F (Eq. (20)) for initial food source.
8: Calculate the fitness value for employed bees in the bee colony

$$fitness_i = \begin{cases} \frac{1}{1+f_i} & 0 \leqslant f_i \\ \frac{1}{1+abs(f_i)} & f_i \leqslant 0 \end{cases} \tag{34}$$

where f_i is the evaluated cost value of the solution X_{uv}.
9: Cycle = 1.
10: Generate modified food location for the employed bees.

$$X_{uv}^{new} = X_{uv} + rand[-1,1](X_{uv} - X_{wv}) \tag{35}$$

where w = 1, 2, 3...SN and v = 1, 2, 3...D are randomly chosen index. w should not be equal to v.
11: Compute objetive function F (Eq. (20)) by following step 6.
12: Apply greedy selection process
13: Compute probability value (p_i)

$$p_i = \frac{fit_i}{\Sigma_0^{SN} fit_i} \tag{36}$$

where fit_i is the fitness value corresponding to i^{th} solution.
14: Generate new solutions (X_{uv}^{new}) by using Eq. (35) for the onlookers bees on the basis of solutions selected according to the value of p_i.
15: Compute objetive function F (Eq. (20)) for new solutions by following step 6.
16: Apply greedy selection prcoess
17: Check if there are any abandoned solution for the scout, Eq. (33) for scouts to generate a new food source.
18: Remember and store the best solution gained so far.
19: Cycle = Cycle + 1.
20: Until, Cycle = *Maxcycle*

4. Results and discussions

Methodology developed in this work has been employed to design a small stand-alone PV-wind-biomass-battery hybrid system as shown in Fig. 1 to meet the electricity requirement of a small village, situated in Patiala, Punjab India. The case study area is situated at latitude 30°26′N and longitude 76°12′E. The scheme is basically designed for household loads of a small microgrid having a peak load demand and load factor of 102 kW and 0.406 respectively. Two different kinds of load profile are considered on the basis of seasons, i.e., winter (October to April) and summer (May to September). This considered location has good availability of solar and wind resources throughout the year. From the existing data, it is found that the yearly average wind speed of this site is 5.9 m/s, while average solar radiation is found to be 5.14 kWh/m^2/day [40]. Fig. 3 shows load profiles (winter and summer both), solar radiation and wind speed data considered for the study area. Table 1 shows detailed load demand for a small community having 110 households. This particular site had enough biomass feedstock to install a biomass gasifier. In Punjab, India the main crop residues are wheat and rice straw. It is estimated that these two crop residues contributes almost 75% of the total crop residues production in the state. The price of biomass, including transportation, storage and labor charges is considered to be $25/ton [15]. Economical and technical parameters associated with components used in this study have been presented in Table 2. The lifetime of the project and the interest rate are considered to be 20 years and 6%, respectively.

4.1. Results analysis

The experimental results were simulated using HOMER and MATLAB 2014a program. The simulation time step is considered for one hour and run on a data for one year. The control parameters

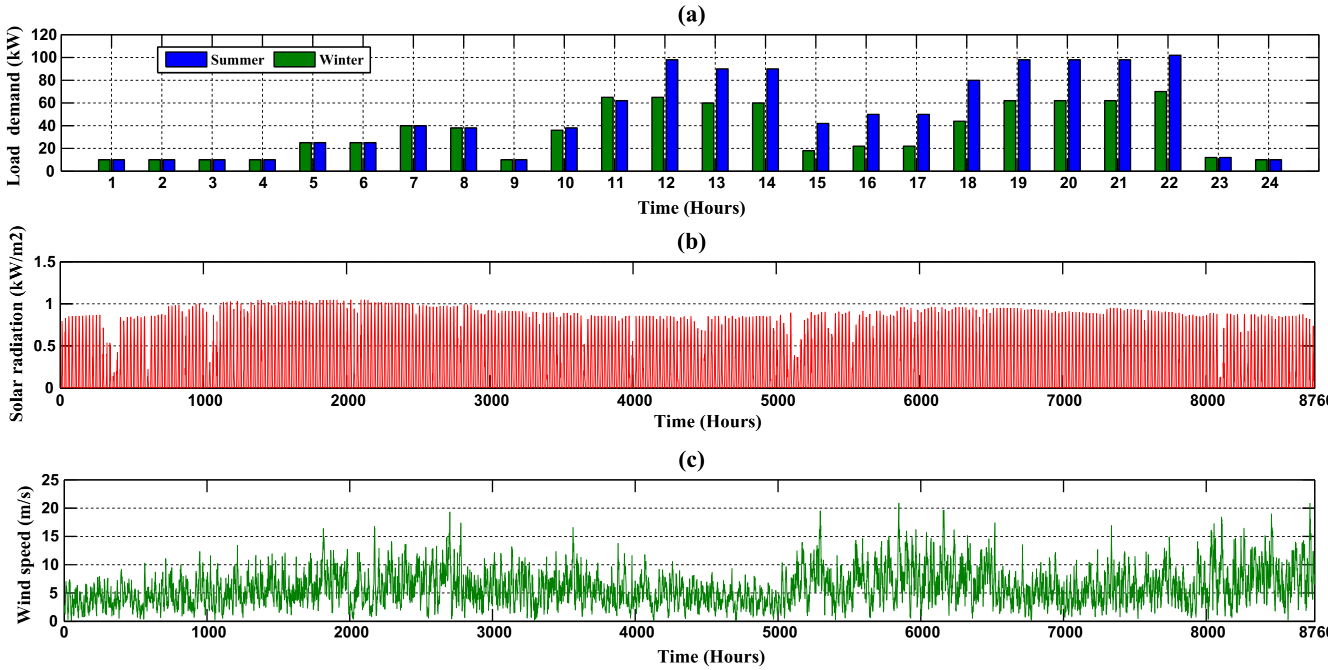

Fig. 3. (a) Daily load profile (winter and summer (kW)). (b) Solar radiation (kW/m^2). (c) Wind speed (m/s).

Table 1
Estimated electricity demand for community.

S. no	Type of load	Quantity	Power (Watts)	Summer (May-Sep)		Winter (Oct-April)	
				Hrs/day	Watt-hrs/day	Hrs/day	Watt-hrs/day
A. Domestic load demand							
1	CFL	4	23	10	920	6.5	600
2	CFL	1	11	8	88	11	121
3	Ceiling fan	1	120	20	2400	0	0
4	Kitchen fan	1	30	6	180	0	0
5	Cooler	2	120	10.5	2520	0	0
6	Television	1	100	9	900	6	600
7	Computer	1	300	8	2400	9	2700
8	Exhaust fan	1	15	5	75	3	45
9	Table fan	1	15	8	120	0	0
10	Room heater	1	90	0	0	12	1080
11	Room heater	1	150	0	0	7	1050
12	Electric blanket	1	120	0	0	3	360
13	Vacuum cleaner	1	220	2	440	1	220
14	Bulb	1	100	1	100	2	200
	Total (one house)				10,143		6976
	No. of Houses	110					
	Total demand (A) (kWh/day)				1115.73		767.36
B. Community load demand							
1	Shops	4	400	12	4800	12	4800
2	Community shop	2	200	3	600	5	1000
3	Community center	1	1000	7	7000	7	7000
4	Small industry	1	3000	8	24,000	8	24,000
5	Hospital	1	3000	9	27,000	9	27,000
6	Elementary school	1	1500	11	16,500	11	16,500
7	Street light	5	30	9	270	12	360
	Total demand (B) (kWh/day)				80.17		80.66
	Total demand $(A + B)$ (kWh/day)				1195.9		848.02

for ABC and PSO algorithms have been shown in Table 3. For the sake of comparison of results, maximum number of solar PV panels (N_{sol}^m), wind turbines (N_w^m) and batteries (N_{batt}^m) have been considered same for all the cases and taken as 300, 20 and 1400, respectively. The maximum rating of biomass gasifier (P_{bmg}^m) is considered to be 50 kW. The size of inverter has not been included as decision variable. The rating of inverter has been selected on the basis of peak load demand using Eq. (11) and it has been considered as 115 kW. In this proposed system, load following strategy is considered instead of cycle charging.

The results obtained from HOMER are taken as reference for comparison. The optimal results consist of total number of solar PV panels, wind turbines, batteries and a maximum rating of biomass gasifier. The feasible and optimal solution is ranked on

Table 2
Technical and economical data of the components used in proposed hybrid system.

Component	Parameter	Value	Unit
Wind turbine	Rated power (P_r^w)	1	kW
	Cut in speed (V_{cin})	3	m/s
	Cut out speed (V_{co})	20	m/s
	Rated wind speed (V_{rat})	11	m/s
	Capital cost (per kW)	2300	$
	Replacement cost (per kW)	1500	$
	O & M cost (per kW)	2	$/yr
	Hub height	50	m
	Overall efficiency	26	%
	Life time	20	years
Solar PV	Rated power (P_r^s)	1	kW
	Derating factor (f_{loss})	88	%
	Capital cost (per kW)	1200	$
	Replacement cost (per kW)	1200	$
	O & M cost (per kW)	4	$/yr
	Life time	20	years
Battery	Nominal capacity ($C_b(Ah)$)	360	Ah
	Nominal voltage (V_{batt})	6	V
	Max charging current (I_{max})	18	A
	Minimum state of charge (SOC_{min})	30	%
	Maximum state of charge (SOC_{max})	100	%
	Round trip efficiency (η_{batt})	92	%
	Capital cost (per unit)	167	$
	Replacement cost (per unit)	67	$
	O & M cost (per unit)	1.67	$/yr
	Life time	5	years
Biomass gasifier	Rated power (P_{bmg}^m)	50	kW
	Calorific value of biomass (CV_{bm})	18	MJ/kg
	Conversion efficiency (η_{bmg})	21	%
	Capital cost (per kW)	2300	$/kW
	Replacement cost (per kW)	1500	$/kW
	O & M cost (per kW)	2	$/yr
	Life time	15,000	h
Converter	Rated power	115	kW
	Rectifier(η_{rec}) and inverter(η_{inv}) efficiency	90	%
	Replacement cost (per kW)	127	$/kW
	O & M cost (per kW)	1	$/yr
	Life time	20	years
Other	Interest rate (i)	6	%
	Project life (N)	20	years
	Bus voltage (DC) (V_{bus})	120	V
	Batteries in string(N_{batt}^s)	20	units

Table 3
Parameters of the PSO and ABC algorithm.

ABC algorithm	PSO algorithm
Dimension of the problem (D): 4	Dimension of the problem (D): 4
Employed bees = onlooker bees: 10	Population size (N): 20
Colony size (NP): 20	Initial weight (W_{min}): 0.4
Food number: 10 (1/2 of the colony size)	Final weight (W_{max}): 0.9
Maximum cycle: 100	Maximum iterations (It_{max}): 100
Limit: 100	Weighting factors (C_1 and C_2): 2

the basis of ASC and LCOE. Table 4 shows complete optimized results obtained for the case study by HOMER, PSO and ABC algorithms. It is inferred from the results that ABC algorithm predicts minimum ASC of the system with least LCOE. The ABC algorithm predicts 250 kW solar PV, 19 kW wind turbines, 1400 batteries and 40 kW biomass gasifier with ASC of 63,006 $/yr which results a LCOE of 0.173 $/kWh. It can be inferred from the table that both the meta-heuristic algorithms provide almost the same results. The performance of ABC algorithm is satisfactory as compared to PSO in terms of computational time and results. Moreover, both algorithms perform better than HOMER. The LCOE obtained by both algorithms shows that the proposed system provides energy to off grid location with an acceptable cost. The results show that ABC provides an optimal configuration with least LCOE. Therefore, for detailed economic and reliability discussion, results obtained by the ABC algorithm may be chosen as an optimal combination.

Table 5 demonstrates complete and detailed annualized cost analysis of the optimal hybrid system. The annualized costs are calculated with the help of CRF. The lifetime of solar PV panels, wind turbines and inverter are considered same as project lifetime, so no replacement is required in their case. The lifetime of biomass gasifier depends upon the operating hours instead of life in years. Here, the lifetime of biomass gasifier is more than the lifetime of the project, so no replacement is required. The main component which required replacement is battery bank. It is assumed that the set of batteries need replacement in every five years. Therefore, number of replacements of batteries during project life is three. Batteries consist of 44% of the total cost of the system. The results predict that solar PV contributes 43%, wind turbines 6% and biomass gasifier cost 4.5% of total annual costs. Fig. 4 demonstrates a brief comparison between the convergence rates of both algorithms. It can be seen from the figure that both algorithms converge in almost initial 10 iterations. HOMER software took hours to simulate the proposed system, while algorithms reduce simulation time from hours to minutes. Table 6 shows a brief comparison of energy production by all components for the configurations obtained by HOMER, PSO and ABC. It can be noted that major contribution comes from solar energy.

The proposed system satisfies total energy demand with the help of solar, wind and batteries only. Fig. 5 demonstrates the monthly average energy balance for one year. It can be noted that solar and wind powers have been consistent with the available solar and wind resources. In the month of January, when PV panels are generating less power, biomass gasifier is run to fulfill the load demand. During the rest of the month, good amount of solar power is generated due to better availability of natural resources. However, during summers, utilization of battery bank increases, i.e., more power is drawn from the batteries. It can be also seen from the figure that there are only three months, where excess energy is available. This system is designed to minimize the dumped or excess energy. It can be noted from the Table 6 that total excess energy during the complete year is found to be 5,139 kWh/yr, which results in 1.4% of the load served. On the contrary, in case of HOMER, this excess energy is found to be 165,941 KWh/yr, which accounts 45% of total load served.

Table 4
Optimal sizing result received from various techniques.

Algorithm	PV (Units)	Wind turbine (Units)	Biomass gasifier (kW)	Batteries Units	Inverter (kW)	Biomass running (h)	ASC ($/yr)	NPC ($)	LCOE ($/kWh)
HOMER	280	18	50	1200	115	18	65,573	7,52,118	0.181
PSO	251	20	43	1400	115	35	63,584	7,30,011	0.176
ABC	250	19	40	1400	115	10	63,006	7,23,378	0.173

Table 5
Break down of ASC obtained by the ABC algorithm for the proposed system.

Component	Capital ($/yr)	Replacement ($/yr)	Maintenance cost ($/yr)	Fuel ($/yr)	Salvage ($/yr)	Total ($/yr)
PV	26,155	0	1000	–	–	27,155
Biomass	3487	–	80	286	−1071	2782
Wind turbines	3809	–	38	–	–	3847
Batteries	20,384	5111	2338	–	–	27,833
Inverter	1273	–	115	–	–	1388
Total	55,108	5111	3571	286	−1071	63,006

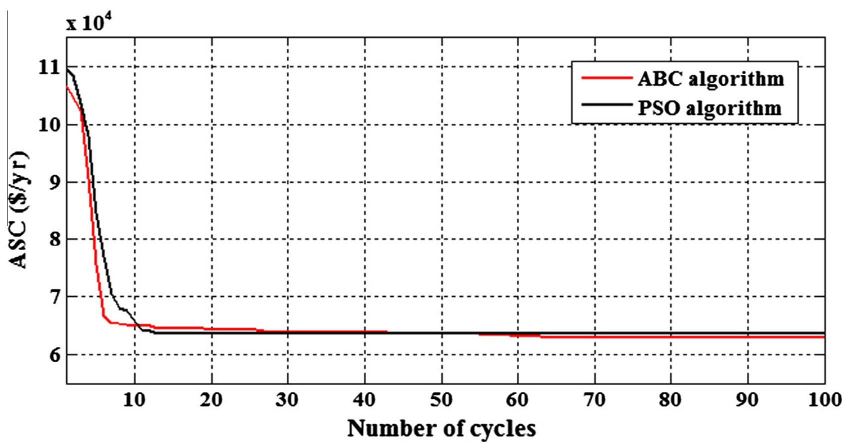

Fig. 4. Comparison of convergence rates for PSO and ABC algorithms.

Table 6
Energy analysis by HOMER, PSO and ABC algorithm.

	HOMER kWh/yr	PSO kWh/yr	ABC kWh/yr
Solar	518,786	465,054	463,201
Biomass	572	891	326
Wind	72,009	80,010	76,009
Battery in	198,910	292,780	302,796
Battery out	169,348	167,712	169,766
Total demand served	362,795	362,795	362,795
Excess electricity	165,941	3513	5139

To verify the optimal operation of the proposed system for one year a total period of two weeks have been selected, i.e., one week in January where the load is less and second week in June where load demand is more. Fig. 6 shows a complete power exchange for one week in the month of January in order to understand the power exchange between different components of the system. As discussed in the operational methodology, a biomass gasifier is run when power from solar and wind is deficient and batteries are equal or below *SOCmin* (30%). It can be seen from figure that in the month of January, for a few hours (0050–0091) solar and wind power generation is less and also battery SOC are approaching *SOCmin*. So during these hours, biomass gasifier is run to provide power to the system. Fig. 7 demonstrates the energy management for the last week of June. It can be inferred from the Fig. 7 that enough solar power is generated due to better availability of the solar resource. No biomass power is required as the total load demand is met with the help of batteries, solar and wind only.

Particularly, in systems using battery as storage, battery SOC measurement becomes an important issue. Fig. 8 shows variations of the state of charge of the battery bank and also input and output energy throughout the year. The initial SOC level and minimum allowable SOC have been considered as 100% and 30%, respectively. Fig. 8 demonstrates that battery SOC always remains in predefined limit. On Ist January, at hour 0000, initial SOC of the battery bank is considered to be 3,014 kWh (100%). It is evident from the Fig. 8 that SOC reached a minimum of 907.2 kWh (30%) during a few hours in the whole year. Fig. 8 also shows that most of time battery SOC is good, except a few instances, such as in the month of January when natural resources are low, and in the case of the months June-July when the load demand is more. The charging and discharging rates of battery are other factors which required to be monitored continuously. For effective charging and discharging of the battery bank, maximum charging or discharging power (P_b^{max} for one hour interval) is 151.2 kW and it is calculated using Eq. (10). If the energy is available to charge beyond the charging rate it can be used as deferred load or it can be dumped. If discharging energy is more than discharging rates of batteries, a biomass gasifier will be used as generating source.

4.2. Robustness test

In order to verify the effectiveness of ABC and PSO algorithms, total 30 number of independent runs have been performed for each algorithm. Table 7 shows mean, maximum and minimum value of ASC and standard deviation for 30 runs. It is evident from the table that the ABC algorithm shows minimum deviation, which makes ABC better than the PSO algorithm. Further, paired student's *t*-test is performed to validate the effectiveness of results at 5% confidence level. The ASC achieved by the ABC algorithm is significantly less than ASC achieved using PSO algorithm. The reason being that the *p*-value ($4.22 * 10^{-10}$) is less than 0.05, when paired student's *t*-test is performed on both the algorithms (Table 8). The *p*-value less than 0.05 indicates that there is a substantial difference between the outcomes of the ABC and PSO algorithms.

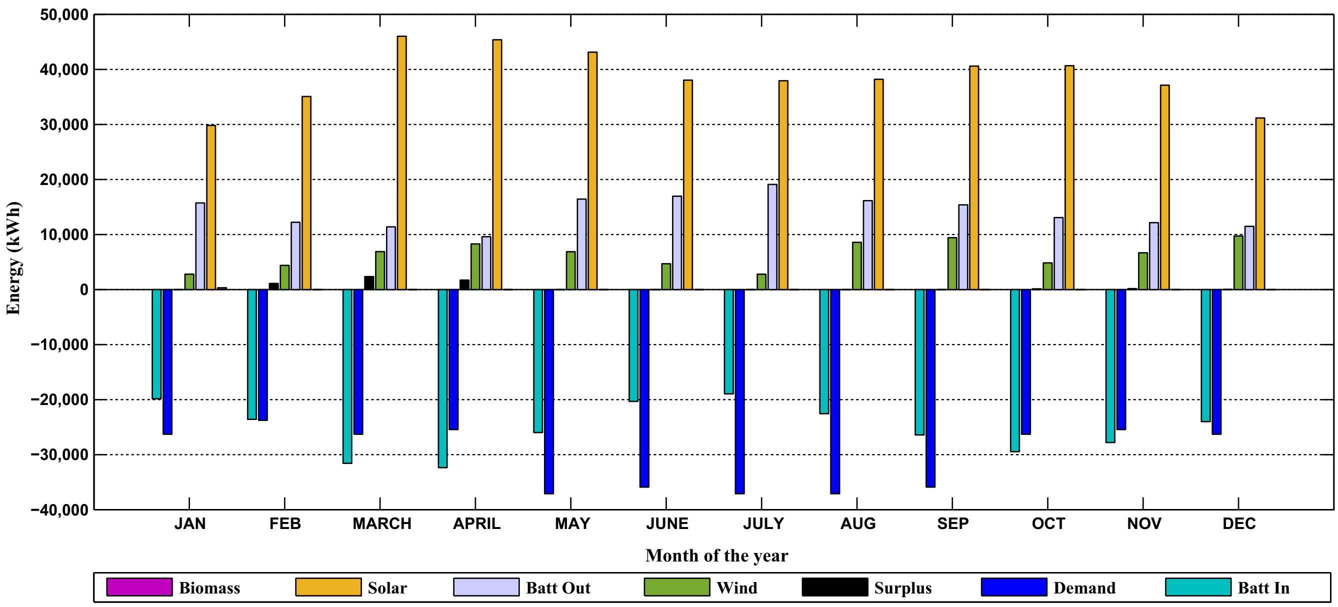

Fig. 5. Monthly energy analysis for the proposed case study.

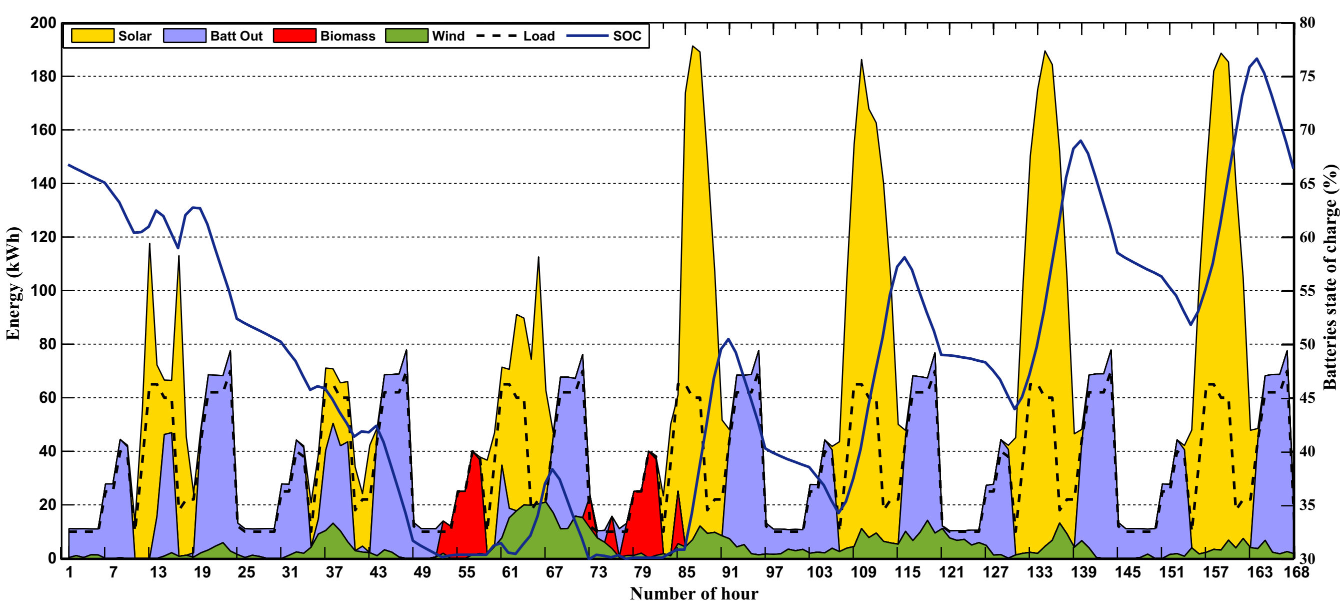

Fig. 6. Energy balance and battery SOC for the third week of January.

4.3. A special case: failure of one source

In this subsection, the effect of failure of any generating unit of the system is discussed to analyze the performance and reliability of the system. For instance, failure of wind source in the month of June is considered. The failure of any generating unit creates a supply-load imbalance in any system. Fig. 9 shows a complete power exchange for one week in the last week of June, while keeping optimized parameters same. It can be seen from the Fig. 7 that previously biomass gasifier was not run in the month of June, while failure of wind power forces biomass gasifier to run several times. It can be noted from the Fig. 9 that if SOCs of the batteries are less than their critical values, i.e. 30%, the biomass gasifier starts and provides power. The biomass running hours increase from 10 to 45 h and total power generated by biomass also increase from 325 kWh to 1,091 kWh. Also, due to more usages of biomass gasifier, total ASC of system increases from 63,006 $/yr to 63,416 $/yr, which makes LCOE slightly costlier.

4.4. Effect of the battery's efficiency on LCOE

In this subsection, the effect of battery's round trip efficiency on LCOE has been performed. In the previous section the results were obtained with a round trip efficiency of 92.2% while the charging and discharging efficiencies were considered as 85% and 100% for results analysis. However, to make the study more realistic the charging and discharging efficiencies have been considered to be same. The results for different round trip efficiency by keeping similar charging and discharging efficiencies has been plotted in the Fig. 10. It has been found that as the round trip efficiency increases the LCOE decreases drastically.

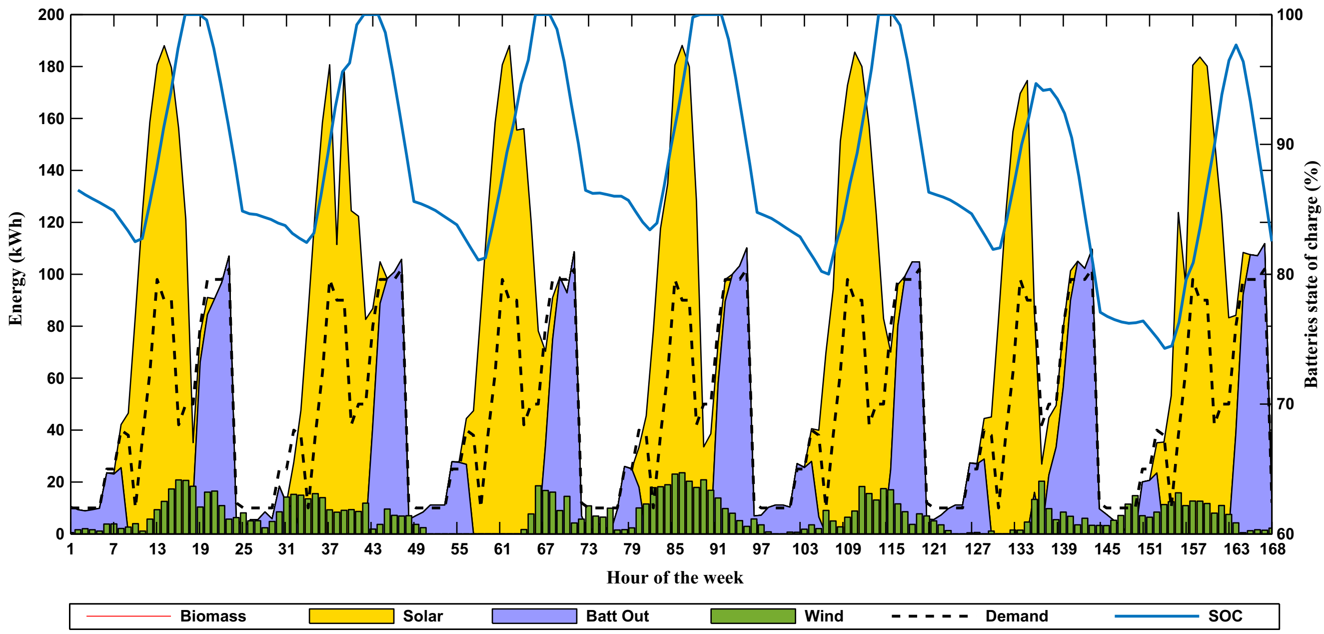

Fig. 7. Energy balance (on left y axis) and battery SOC (on right y axis) for the last week of June.

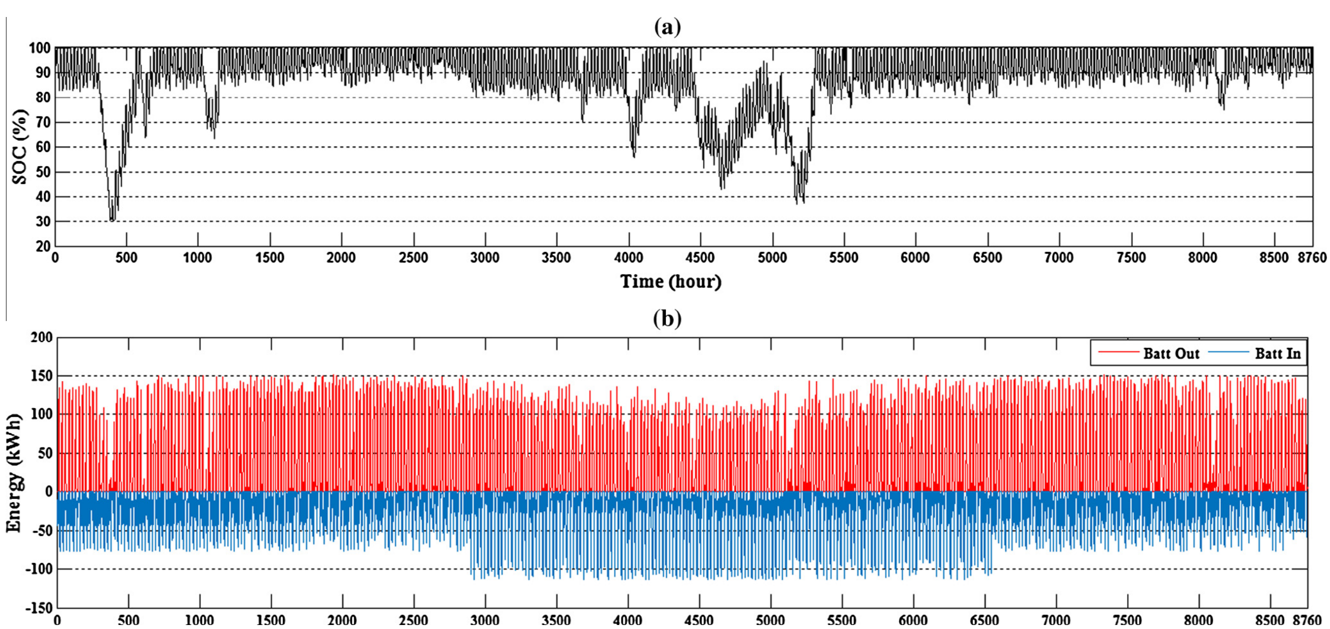

Fig. 8. (a) Battery state of charge (%). (b) Battery input and output energy for one complete year.

Table 7
Statistics of the results.

Algorithm	Mean value	Minimum value	Maximum value	Standard deviation
ABC	64,180.05	63,006	64,755.6	293.44
PSO	64,855.00	63,584	65,345.9	359.04

Table 8
Paired student's t-test results for sample mean (p-value = 0.05).

Statistics	System
p-value	$4.22 * 10^{-10}$
t-calculated	7.26
t-critical	1.67

5. Conclusion

A hybrid energy system is more reliable, economical and suitable source of electricity, particularly for off grid locations. In this paper, a mathematical model has been developed to find the optimal size of components of a hybrid PV-wind-battery with biomass by applying the ABC algorithm. Initially, mathematical modeling of

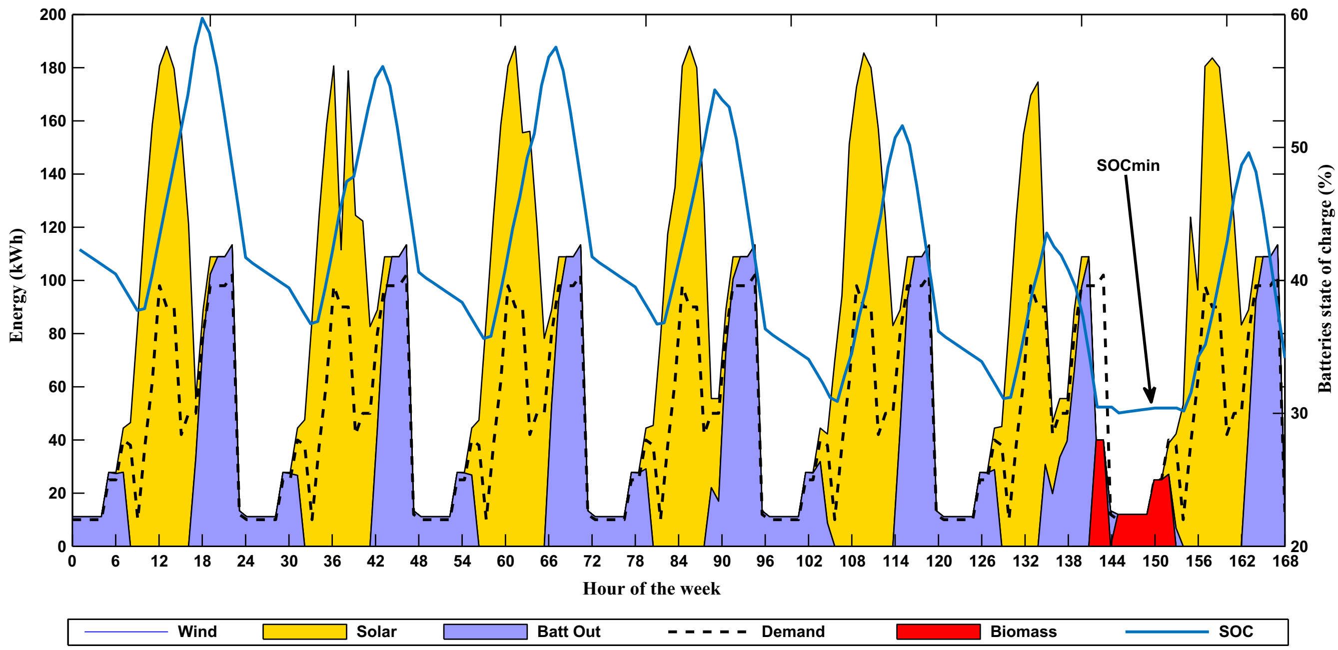

Fig. 9. Solar, wind, battery, biomass energy, load demand and battery SOC (on right y axis) for the last week of June.

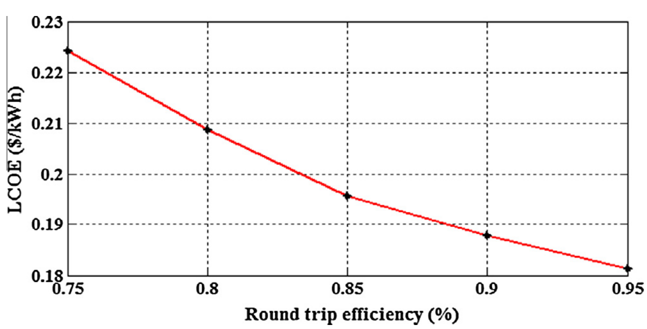

Fig. 10. Effect of battery's round trip efficiency on LCOE.

different components used in the study is discussed in brief, later on operational strategy and implementation steps of the ABC algorithm has been presented. Finally, results deduced by ABC algorithm have been compared with results obtained by software tool HOMER and other meta-heuristic algorithm PSO. The proposed algorithm proved better results as compared to HOMER and PSO. The performance of the proposed hybrid system is analyzed by considering failure of one generation unit. It can be concluded from the study that optimal hybrid system satisfactorily satisfy the load demand without violating any constraints.

References

[1] Zhou W, Lou C, Li Z, Lu L, Yang H. Current status of research on optimum sizing of stand-alone hybrid solar-wind power generation systems. Appl Energy 2010;87(2):380–9.
[2] Agarwal N, Kumar A, Varun. Optimization of grid independent hybrid PV-diesel-battery system for power generation in remote villages of Uttar Pradesh, India. Energy Sustain Develop 2013;17(3):210–9.
[3] Lazou A, Papatsoris A. The economics of photovoltaic standalone residential households: a case study for various European and Mediterranean locations. Sol Energy Mater Solar Cells 2000;62:411–27.
[4] Yamegueu D, Azoumah Y, Py X, Zongo N. Experimental study of electricity generation by solar PV/diesel hybrid systems without battery storage for off-grid areas. Renew Energy 2011;36:1780–7.
[5] Shaahid SM, Elhadidy MA. Prospects of autonomous/stand-alone hybrid (photo-voltaic+diesel+battery) power systems in commercial applications in hot regions. Renew Energy 2004;29:165–77.
[6] Kazem H, Khatib T, Sopian K. Sizing of a standalone photovoltaic/battery system at minimum cost for remote housing electrification in Sohar, Oman. Energy Build 2013;61:108–15.
[7] Abouzahr I, Ramakumar R. Loss of power supply probability of stand alone wind electric conversion system. IEEE Trans Energy Convers 1990;5(3):445–51.
[8] Elhadidy MA, Shaahid SM. Role of hybrid (wind+diesel) power systems in meeting commercial loads. Renew Energy 2004;29:109–18.
[9] Elhadidy MA, Shaahid S. Optimal sizing of battery storage for hybrid (wind+diesel) power systems. Renew Energy 1999;18:77–86.
[10] Yang H, Zhou W, Lu L, Fang Z. Optimal sizing method for stand-alone hybrid solar-wind system with LPSP technology by using genetic algorithm. Sol Energy 2008;82:354–67.
[11] Bhattacharjee S, Acharya S. PV-wind hybrid power option for a low wind topography. Energy Convers Manage 2015;89:942–54.
[12] Tina G, Gaglianom S, Raiti S. Hybrid solar/wind power system probabilistic modeling for long term performance assessment. Sol Energy 2006;80:578–88.
[13] Wu K, Zhou H, An S, Huang T. Optimal coordinate operation control for wind-photovoltaic-battery storage power generation units. Energy Convers Manage 2015;90:466–75.
[14] Patil ABK, Saini RP, Sharma MP. Integrated renewable energy systems for off grid rural electrification of remote area. Renew Energy 2010;35(6):1342–9.
[15] Singh J, Panesar BS, Sharma SK. Energy potential through agricultural biomass using geographical information system: a case study of Punjab. Biomass Bioenergy 2008;32:301–17.
[16] Patil ABK, Saini RP, Sharma MP. Sizing of integrated renewable energy system based on load profiles and reliability index for the state of Uttarakhand in India. Renew Energy 2011;36(11):2809–21.
[17] Bhattacharjee S, Dey A. Techno-economic performance evaluation of grid integrated PV-biomass hybrid power generation for rice mill. Sustain Energy Tech Assessments 2014;7:6–16.
[18] Singh S, Kaushik SC. Optimal sizing of grid integrated hybrid PV-Biomass energy system using artificial bee colony algorithm. IET Renew Power Generation 2016;10(5):642–50.
[19] Mahapatra S, Dasappa S. Rural electrification: optimizing the choice between decentralized renewable energy sources and grid extension. Energy Sustain Devel 2012;16(2):146–54.
[20] Nehrir MH, Wang C, Strunz K, Aki H, Ramakumar R, Bing J, et al. A review of hybrid renewable/alternative energy systems for electric power generation. IEEE Trans Sustain Energy 2011;2(4):392–403.
[21] Balamurugan P, Ashok S, Jose TL. Optimal operation of biomass/wind/PV hybrid energy system for rural areas. Int J Green Energy 2009;6:104–16.
[22] Rahman MW, Hossain S, Aziz A, Mohammedy FM. Prospect of decentralized hybrid power generation in Bangladesh using biomass, solar PV & wind. In: 3rd International conference on the development in renewable energy technology. Dhaka, Bangladesh: IEEE; 2010. p. 2–7.
[23] Dhass AD, Harikrishnan S. Cost effective hybrid energy system employing solar-wind-biomass resources for rural electrification. Int J Renew Energy Res 2013;3(1):222–9.
[24] Ho WS, Hashim H, Lim JS. Integrated biomass and solar town concept for a smart eco-village in Iskandar Malaysia (IM). Renew Energy 2014;69:190–201.

[25] Garrido H, Vendeirinho V, Brito MC. Feasibility of KUDURA hybrid generation system in Mozambique: sensitivity study of the small-scale PV-biomass and PV-diesel power generation hybrid system. Renew Energy 2016;92:47–57.
[26] Borowy BS, Salameh ZM. Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PV hybrid system. IEEE Trans Energy Convers 1996;11(2):367–75.
[27] Diaf S, Diaf D, Belhamel M, Haddadi M, Louche A. A methodology for optimal sizing of autonomous hybrid PV/wind system. Energy Policy 2007;35:5708–18.
[28] Chedid R, Rahman S. Unit sizing and control of hybrid wind-solar power systems. IEEE Trans Energy Convers 1997;12(1):79–85.
[29] Gavanidou ES, Bakirtzis AG. Design of a standalone system with renewable energy sources using trade off methods. IEEE Trans Energy Convers 1992;7(1):42–8.
[30] Nafeh AE-S. Optimal economical sizing of a PV-wind hybrid energy system using genetic algorithm. Int J Green Energy 2011;8:25–43.
[31] Upadhyay S, Sharma MP. Development of hybrid energy system with cycle charging strategy using particle swarm optimization for a remote area in India. Renew Energy 2015;77:586–98.
[32] Heydari A, Askarzadeh A. Optimization of a biomass-based photovoltaic power plant for an off-grid application subject to loss of power supply probability concept. Appl Energy 2016;165:601–11.
[33] Kumar R, Gupta RA, Bansal AK. Economic analysis and power management of a stand-alone wind/photovoltaic hybrid energy system using biogeography based optimization algorithm. Swarm Evol Comp 2013;8:33–43.
[34] Karaboga D, Basturk B. A powerful and efficient algorithm for numerical function optimization: artificial bee colony (ABC) algorithm. J Global Opt 2007;39(3):459–671.
[35] National Renewable Energy Laboratory (USA). <www.nrel.gov/homer> [last accessed April, 2016].
[36] Malheiro A, Castro PM, Lima RM, Estanqueiro A. Integrated sizing and scheduling of wind/PV/diesel/battery isolated systems. Renew Energy 2015;83:646–57.
[37] Gupta A, Saini RP, Sharma MP. Steady-state modelling of hybrid energy system for off grid electrification of cluster of villages. Renew Energy 2010;35(2):520–35.
[38] Nouni MR, Mullick SC, Kandpal TC. Biomass gasifier projects for decentralized power supply in India: a financial evaluation. Energy Pol 2007;35(2):1373–85.
[39] Karaboga D, Akay B. A comparative study of artificial bee colony algorithm. Appl Math Comp 2009;214(1):108–32.
[40] 'Surface Meteorology and Solar Energy'. <http://eosweb.larc.nasa.gov/sse/RETScreen> NASA [accessed April, 2015].