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Optimal sizing of grid integrated hybrid PV-biomass energy system using artificial bee colony algorithm

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Abstract: This study presents an optimal sizing methodology for a stand-alone and grid connected PV-biomass hybrid energy system that serves the electricity demand of a typical village. However, this method is scalable and can be used in any test system. A recently developed artificial bee colony (ABC) algorithm is used to detect out the optimum hybrid system configuration with the least levelised cost of energy while minimising annualised cost of the system. It has been observed from the results that a grid connected hybrid PV-biomass system is cost effective and reliable choice for rural electrification as compared with stand-alone hybrid PV-biomass energy system. It has been emerged from this study that the proposed system offers reliable and affordable electricity in a sustainable way by harnessing locally available natural resources. A brief comparison of results obtained from the ABC algorithm and hybrid optimisation model for electric renewable (HOMER) has been carried out. Moreover, it is also observed from the results that the ABC algorithm provides better results as compared with HOMER.

1 Introduction

In 2015, India's total installed power generation capacity reached to 258 GW. The major contribution comes from combustion of fossil fuel, which is almost 70% of the entire generation. The share of renewable energy sources (excluding hydro) is almost 12%. According to Ministry of Power, India, almost 5% of the total villages still do not possess access to electricity and mostly electrified villages face scarcity of electricity, especially in summer when electrical demand is at peak [1, 2]. In India, the state of Punjab is one of the largest farming land. Punjab shares only 1.6% of the geographical area of the country, while it produces nearly 10% of rice, 13% of cotton and 22% of wheat of the total production of these crops in the country. From these major crops, a total of 55.39 Metric tons agricultural residues is generated in the state and it is further estimated that 2000–3000 MW of electricity can be generated by using these agricultural residues [3, 4]. Currently biggest drawback with these residues is inefficient usage. Most of agricultural residues are burnt in an open field after harvesting the crop which results air pollution, soil infertility and health hazards [5].

Renewable based hybrid energy systems have received great attention in recent years as they appears one of the clean source of electricity generation. The major issues while designing of renewable based hybrid system are power management, reliability of the system and economic cost of energy. The designed system must be optimal in terms of performance and component selection. Hence, the proper optimal sizing method and control scheme are required to plan an effective and economical hybrid system [6]. Among the available renewable energy sources, solar and biomass based systems have tremendous potential for rural electrification. In recent years, feasibility of various solar and biomass energy based systems have been explored for rural electrification by various researchers [7–13]. Most of the studies have paid much attention on modelling of off-grid renewable hybrid energy systems. Integration of renewable energy sources to the grid is a challenging job because of the intermittent nature of renewable energy sources. The grid connection provides a back up to the hybrid system, which eliminates the need of batteries and diesel generators. A few studies have been reported so far in the literature [14–16] for PV-biomass grid connected system. Most of the works carried out the feasibility studies of grid connected PV-biomass hybrid energy system using software tool hybrid optimisation model for electric renewable (HOMER) [17] for performance and optimisation. Mathematical modelling of grid connected PV-biomass energy system is neglected by the researchers. Therefore, to overcome this shortcoming, this work mainly focuses on detailed mathematical modelling of grid connected PV-biomass hybrid energy system. This study intends to provide a detailed cost analysis of a grid connected PV-biomass hybrid energy system to supply uninterrupted electricity to a village using recently developed artificial bee colony (ABC) algorithm. The ABC algorithm is proposed by Dervis Karaboga and Bahriye Basturk in 2005. This algorithm is inspired by the intelligent behaviour of honey bees and simple to use and also has flexible and robust optimisation process. This algorithm is just similar to other population-based algorithms such as PSO, GA and differential evolution with the advantage of having fewer control parameters. The main objectives of this paper can be summed up as below

- Developing a mathematical model of a grid connected PV-biomass hybrid energy system by exploiting locally available natural resources to fulfil the electricity demands of a small area.
- Performing comparative analysis between a swarm based ABC algorithm and HOMER for cost effectiveness of a grid connected and stand-alone hybrid PV-biomass energy system.
- Finding of optimal sizing of components with the least levelised cost of energy (LCOE) by minimising the annualised cost of the total system (ACS).
- Performing sensitivity analyses for different parameters, such as grid sale capacity with respect to the LCOE and other parameters.

This paper is organised in six sections; Section 2, explains the mathematical modelling of different components. Section 3, describes the problem formulation, operational strategy and brief introduction of the applied algorithm. In Section 4, details of the case study data are presented. In Section 5, results obtained by the applied ABC algorithm and HOMER have been discussed and analysed. Finally, Section 6 presents the conclusion of the work.

2 Mathematical modelling of grid connected hybrid generation system

The proposed grid connected hybrid renewable generation system consists of different components such as solar PV panels, power inverter, biomass gasifier with generator and utility grid as shown in Fig. 1. The diesel generator is kept optional and it will be used as back-up for overcast situations and outages etc. The power generated from renewable sources is assumed to be constant during one hour duration. The mathematical modelling of different components of the proposed hybrid energy system in order to analyse the system performance is presented in this section.

2.1 Solar photovoltaic panel

The output of a solar PV panel depends mainly upon atmospheric conditions and geographical locations. The output power of a particular solar PV panel, (P_{sol}), at any time is a function of solar radiation and atmospheric temperature and it is expressed as

$$P_{sol}(t) = P_{rat} f_{loss} \frac{G_h}{G_S}[1 + \alpha_P(T_c - T_s)] \quad (1)$$

where, P_{rat} is the rated power output capacity of the solar PV panel, f_{loss} is the loss factor of solar PV panel due to dirt, shadow, temp etc., G_h is the hourly solar radiation incident on the solar PV panel (W/m^2), G_S is the standard incident radiation (1000 W/m^2), α_p is the temperature coefficient of power, T_c is the PV cell temperature in the current time step and T_s is the PV cell temperature under standard test conditions [17, 18].

2.2 Biomass gasifier

A biomass gasification technology is used to convert the solid bio-residue into gaseous fuel (producer gas) by partial combustion under controlled air supply. Producer gas is used as input fuel to the combustion engine for electricity generation. In case of a biomass gasifier system, the annual output electricity, E_{bg}, of the rated biomass gasifier system (P_{bg}) depends upon the capacity utilisation factor and can be calculated as,

$$E_{bg} = P_{bg}(8760 * \text{CUF}) \quad (2)$$

The maximum size of a biomass gasifier system, P_{bg}^{max}, that could be installed in a particular area, mainly depends upon factors such as amount of biomass available, calorific value of biomass, number of hours of usage and efficiency of the biomass gasifier system.

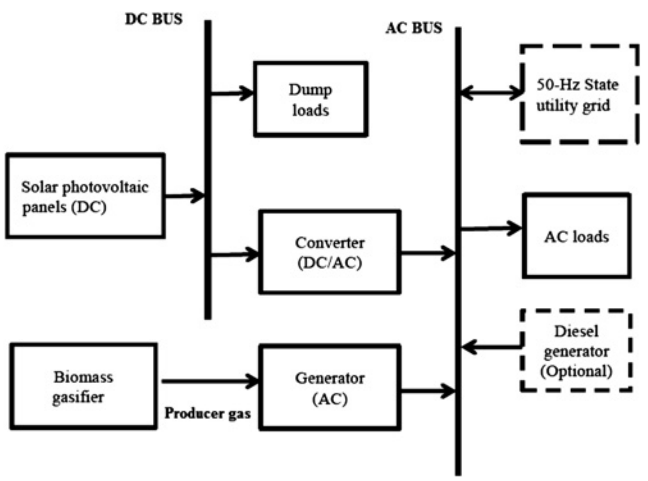

Fig. 1 *Schematic diagram of the proposed hybrid grid connected PV-biomass energy system*

The maximum rating of biomass gasifier can be calculated as

$$P_{bg}^{max} = \frac{M_{bg} * 1000 * \text{CV}_{bm} * \eta_{bg}}{365 * 860 * t_{bg}} \quad (3)$$

where, M_{bg} is the total biomass (Tons/y) available for power generation, η_{bg} is the efficiency of the biomass gasifier system, t_{bg} is the number of operating hours of biomass gasifier system in a day and CV_{bm} is the calorific value of the biomass available [19].

2.3 Power inverter

The power inverter is used to convert DC generated by solar PV panels to AC at the desired frequency to serve the AC load. The maximum power an inverter can convert depends upon the inverter rating (P_{inv}). Further, it can be calculated as

$$P_{inv}(t) = P_{PV}(t)\eta_{inv} \quad (4)$$

where, η_{inv} is the efficiency of the inverter and P_{PV} is the total power generated by solar PV panels and can be calculated as

$$P_{PV}(t) = P_{sol}(t)N_{sol} \quad (5)$$

where, $P_{sol}(t)$ is the power generated by a single solar PV panel and N_{sol} is the number of solar PV panels. In a grid connected system, the maximum size of inverter depends upon grid sale capacity and load served and can be expressed as

$$P_{inv}^{max}(t) = P_L^{max}(t) + P_{gs}^{max} \quad (6)$$

where, $P_L^{max}(t)$ is the peak load demand at day time (kW) and P_{gs}^{max} is the maximum capacity of power sold to the grid (kW).

2.4 Utility grid

In a grid connected system, if the power generated from renewable sources is more than load, then the remaining power can be supplied to the grid. The power which can be supplied to the grid, $P_{gs}(t)$, can be calculated as

$$P_{gs}(t) = [P_{PV}(t)\eta_{inv} + P_{bg}(t)] - P_L(t) \quad (7)$$

The maximum amount of power which can be supplied to the grid should not exceed maximum grid sale capacity (P_{gs}^{max}). At any instant, if the power exceeds from maximum grid sale capacity, the surplus power can be given to the dump load.

If the power generated from renewable energy sources is not enough to meet the electricity demand, then power can be supplied by the grid. The amount of power that can be supplied by the grid, $P_{gp}(t)$, can be calculated as

$$P_{gp}(t) = P_L(t) - [P_{PV}(t)\eta_{inv} + P_{bg}(t)] \quad (8)$$

Further, the maximum amount of power which can be supplied by the grid should not exceed maximum grid purchase capacity (P_{gp}^{max}).

3 Problem formulation

The main objective of this work is to design and model a grid connected PV-biomass hybrid energy system as shown in Fig. 1. To verify the cost effectiveness of the proposed model, the ABC algorithm and HOMER are used to find out the optimal number of solar PV panels and size of the biomass gasifier system. It is also ensured that LCOE of the system is minimised subject to the constraints that electricity demand of the area is completely satisfied. In this work, the concept of the ACS has been adopted [20]. The objective function, operational strategy and implementation of the applied algorithm are hereby explained in brief.

3.1 Objective function

The main objective function considered in this work is the minimisation of total system cost of the proposed hybrid energy system. The total system cost includes total capital cost, replacement cost, operational and maintenance cost, grid sale and purchase power costs. Installation and other costs are included in the capital cost. The system with lowest ACS is considered optimal one while satisfying other constraints. The objective function which has to be minimised can be expressed as follows

$$\min(\mathrm{ACS}) = [N_{\mathrm{sol}}C_{\mathrm{sol}} + P_{\mathrm{bg}}C_{\mathrm{bg}} + P_{\mathrm{inv}}C_{\mathrm{inv}} - C_{\mathrm{gs}} + C_{\mathrm{gp}}] \quad (9)$$

where, C_{sol}, C_{bg} and C_{inv} are the annualised total cost of solar PV panel (per kW), biomass gasifier (per kW) and power inverter (per kW), respectively. C_{gp} is the total price (\$/yr) of electricity purchased from grid annually (refer (19)) and C_{gs} is the total price of electricity sold to the grid (\$/yr) annually (refer (21)).

The annualised cost of each component comprises several components, that is, annualised capital cost, annualised operational and maintenance cost, annualised replacement cost and salvage value. The cost analysis is further explained in detail in the case of the biomass gasifier system which possess all kinds of costs. Annualised cost of biomass gasifier system, C_{bg}, includes five components and can be expressed as

$$C_{\mathrm{bg}} = C_{\mathrm{acap}}^{\mathrm{bg}} + C_{\mathrm{arep}}^{\mathrm{bg}} + C_{\mathrm{m}}^{\mathrm{bg}} + C_{\mathrm{f}}^{\mathrm{bg}} + C_{\mathrm{sal}}^{\mathrm{bg}} \quad (10)$$

where, $C_{\mathrm{acap}}^{\mathrm{bg}}$ is the annualised capital cost, $C_{\mathrm{arep}}^{\mathrm{bg}}$ is the annualised replacement cost, $C_{\mathrm{m}}^{\mathrm{bg}}$ is the annual maintenance cost, $C_{\mathrm{f}}^{\mathrm{bg}}$ is the operational (fuel) cost and $C_{\mathrm{sal}}^{\mathrm{bg}}$ is the salvage value of the biomass gasifier system.

3.1.1 Annualised capital cost: The capital cost of the component includes the cost of installing and purchasing of components. The annualised capital cost of each component (solar PV panels, biomass gasifier and power inverter) can be calculated by using capacity recovery factor (CRF). For example, in case of biomass gasifier it can be calculated as,

$$C_{\mathrm{acap}}^{\mathrm{bg}} = C_{\mathrm{cap}}^{\mathrm{bg}}\mathrm{CRF}(r, n) \quad (11)$$

where, $C_{\mathrm{cap}}^{\mathrm{bg}}$ is the initial capital cost of the biomass gasifier system, CRF is a capital recovery factor, a ratio to calculate present value of money. For a lifetime of n years and interest rate r, CRF can be calculated as

$$\mathrm{CRF}(r, n) = \frac{r(1+r)^n}{(1+r)^{n-1}} \quad (12)$$

3.1.2 Annualised replacement cost: The annualised replacement cost of the biomass gasifier system is the cost of replacing at the end of life of the biomass gasifier system. The annualised value of total replacement cost, $C_{\mathrm{arep}}^{\mathrm{bg}}$, which occurred during the lifetime of a project life can be given as

$$C_{\mathrm{arep}}^{\mathrm{bg}} = C_{\mathrm{rep}}^{\mathrm{bg}}\mathrm{CRF}(r, n)\frac{1}{(1+r)^y} \quad (13)$$

where, $C_{\mathrm{rep}}^{\mathrm{bg}}$ is the replacement cost of the component and y is the lifetime of the biomass gasifier system in years. The replacements are required if the lifetime of the project is greater than component lifetime. In case of a biomass generator, lifetime is the number of running hours. The lifetime (number of years) of a biomass gasifier can be calculated as

$$N_{\mathrm{bg,l}} = \frac{N_{\mathrm{bg,h}}}{N_{\mathrm{bg}}} \quad (14)$$

where, $N_{\mathrm{bg,h}}$ is the generator lifetime (hours) and N_{bg} is the number of hours operating during one year.

3.1.3 Maintenance cost: The maintenance cost per hours of biomass gasifier system includes labour costs, repairing and other charges to operate the biomass gasifier and can be expressed as

$$C_{\mathrm{m}}^{\mathrm{bg}} = N_{\mathrm{bg}}C_{\mathrm{m}}^{\mathrm{h}} \quad (15)$$

where, N_{bg} is the hours of running of biomass gasifier and $C_{\mathrm{m}}^{\mathrm{h}}$ is the hourly maintenance cost of the biomass gasifier system.

3.1.4 Fuel cost: In case of biomass gasifier system, the biomass cost is equal to the amount of biomass feedstock consumed over a year (in kg) multiplied by the price of biomass (\$/kg). The total cost of biomass used can be calculated as

$$C_{\mathrm{f}}^{\mathrm{bg}} = E_{\mathrm{bg}}C_{\mathrm{b}}q(t) \quad (16)$$

where, C_{b} is the price of biomass per kg, E_{bg} is the total energy generated by biomass gasifier in (kWh/yr) and $q(t)$ is the rate of biomass consumed (kg/kWh) for the biomass gasifier system.

3.1.5 Salvage value: It is defined as the value remaining of a component at the end of project life. The salvage value of the biomass gasifier can be calculated as

$$C_{\mathrm{sal}}^{\mathrm{bg}} = C_{\mathrm{rep}}^{\mathrm{bg}}\frac{R_{\mathrm{rem}}}{N_{\mathrm{bg,l}}} \quad (17)$$

where, $C_{\mathrm{rep}}^{\mathrm{bg}}$ is the replacement cost of the component, R_{rem} is the remaining life of the biomass gasifier system and $N_{\mathrm{bg,l}}$ is the life span of the biomass gasifier system.

In the grid connected systems, apart from the components related costs the price of power exchange between the hybrid system and utility grid are other major economic components as brought up in the main objective function defined in (9). For a grid connected system, the total amount of electricity purchased from the grid, E_{gp}, is expressed as

$$E_{\mathrm{gp}} = \sum_{0}^{8760}(P_{\mathrm{gp}}(t)) \quad (18)$$

For a grid connected system, the total price of electricity purchased from the grid, C_{gp}, can be calculated as

$$C_{\mathrm{gp}} = E_{\mathrm{gp}}C_{\mathrm{g}}^{\mathrm{p}} \quad (19)$$

where, $C_{\mathrm{g}}^{\mathrm{p}}$ is the unit cost of electricity (\$/kWh) purchased from the grid. For a grid connected system, the total amount of electricity supplied to the grid, E_{gs}, is expressed as

$$E_{\mathrm{gs}} = \sum_{0}^{8760}(P_{\mathrm{gs}}(t)) \quad (20)$$

For a grid connected system, the total price of electricity sold to the grid, C_{gs}, can be calculated as

$$C_{\mathrm{gs}} = E_{\mathrm{gs}}C_{\mathrm{g}}^{\mathrm{s}} \quad (21)$$

where, $C_{\mathrm{g}}^{\mathrm{s}}$ is the unit cost of electricity (\$/kWh) sold to the grid.

The major economic parameter which defines cost effectiveness of the proposed hybrid energy system is levelised cost of electricity.

The levelised cost of electricity is defined as the average cost per kWh of the effective electricity produced by the system and it can be expressed as

$$\text{LCOE} = \frac{\text{ACS(\$/yr)}}{\text{Total electrical load served (kWh/yr)}} \tag{22}$$

Further, the minimisation of objective function is subjected to following constraints

$$1 \le N_{\text{sol}} \le N_{\text{sol}}^{\max} \tag{23}$$

$$1 \le P_{\text{bg}} \le P_{\text{bg}}^{\max} \tag{24}$$

$$P_{\text{gp}} \le P_{\text{gp}}^{\max} \tag{25}$$

$$P_{\text{gs}} \le P_{\text{gs}}^{\max} \tag{26}$$

where, $N_{\text{sol}}^{\max}$ is the maximum number of solar PV panels, $P_{\text{bg}}^{\max}$ is the maximum rating of biomass gasifier, $P_{\text{gp}}^{\max}$ is the maximum grid purchase capacity and $P_{\text{gs}}^{\max}$ is the maximum grid sale capacity.

3.2 Operational strategy

The electricity generated by solar PV panels is kept on first priority over biomass gasifier due to environmental issues. The following operational strategy is opted for the power management of the proposed grid connected hybrid system.

- If the power from solar PV panels ($P_{\text{PV}}(t) \ge P_{\text{L}}(t)/\eta_{\text{inv}}$) is adequate and greater than load demand then load can be directly served by solar power and the remaining power can be sold to the grid and can be calculated as

$$P_{\text{gs}}(t) = (P_{\text{PV}}(t)\eta_{\text{inv}} - P_{\text{L}}(t)) \tag{27}$$

- If the $P_{\text{gs}}(t)$ is greater than $P_{\text{gs}}^{\max}$ (maximum grid sales capacity) then excess power is dumped and it can be calculated as

$$P_{\text{d}}(t) = (P_{\text{PV}}(t)\eta_{\text{inv}}) - P_{\text{L}}(t) - P_{\text{gp}}^{\max} \tag{28}$$

- If the power from solar PV panels is not adequate and $P_{\text{L}}(t) \le P_{\text{gp}}^{\max}$ then load can be directly served by the grid power.
- If the power from solar PV panels is not adequate and $P_{\text{L}}(t) \ge P_{\text{gp}}^{\max}$ then biomass gasifier is started and load can be served by biomass gasifier, grid and solar power.
- If $P_{\text{PV}}(t)\eta_{\text{inv}} + P_{\text{bg}}(t) \ge P_{\text{L}}(t)$ then the remaining power can be sold to the grid within maximum limit of grid sale capacity.

3.3 ABC algorithm

The ABC algorithm is based upon an idea of foraging conduct of an ABC. An ABC consists three types of bees: employed, onlooker and scouts. Half of the colony bees are employed and the other half is onlooker bees. The number of food source is equal to the number of employed bees. After food source abandoned the employed bee becomes a scout. The search process of the bees can be summed up as follows,

- First employed bees find out a food source in the search area and remember the location of food sources in their memory.
- After that, employed bees share this information with onlookers bee which are basically waiting bees in the hive.
- Then onlooker bee decides to explore the food source based on information shared by the employed bees.
- After food source abandoned, the employed bee becomes a scout and start searching the area randomly to find a new source [21–23].

The main steps of the implementation of the ABC algorithm to solve the optimisation problem for the above mentioned hybrid system are described as follows,

(i) The first step of optimisation procedures is the input of annual data of the solar radiation and load demand. Initialise the control parameters of the ABC algorithm, that is, max cycle number, colony size, population of food sources, dimension of the problem and limit.

(ii) Consider the number of food sources equals the half of the colony size. For this problem, the colony size is considered 20, hence the initial solutions (food sources) are 10 (half of the colony size). The number of parameters to be optimised are 2 (numbers of solar PV panels and size of the biomass gasifier system).

(iii) Generate a randomly distributed population within the range of boundaries of the parameters ((23) and (24)) by using the following equation

$$P_{ij} = P_j^{\min} + \text{rand}(0, 1)(P_j^{\max} - P_j^{\min}) \tag{29}$$

where, $i = 1\ldots\text{SN}$, here, SN denotes the size of the population and $j = 1\ldots D$, whereas, D is the dimension of the problem or number of optimisation parameter.

(iv) Set trial counters (to store the number of solution trials) to zero.

(v) According to initial guess solutions (number of solar PV panels, size of biomass gasifier) perform the following steps.

- Obtain the solar PV panels output by using (1) and (5).
- According to the solar PV panels and biomass gasifier power output, obtain the grid purchase and sale powers by using (7) and (8). Further, obtain the price of the exchange energy by using (19) and (21).
- Obtain the annualised cost of sizing components by using (11)–(17) for initial population of food sources.

(vi) The objective function as described in (9) is evaluated for initial food source.

(vii) Cycle = 1.

(viii) Repeat.

(ix) Produced a new modified food location for the employed bees by using the following equation

$$P_{ij}^{\text{new}} = P_{ij} + \phi_{ij}(P_{ij} - P_{kj}) \tag{30}$$

where, $k = 1, 2, 3\ldots$ SN is a randomly chosen index, $j = 1, 2, 3\ldots$D is randomly chosen index, k has to be different from j. Whereas, ϕ_{ij} is the random integer between the range of $[-1, 1]$.

(x) If a parameter generated exceeds its predetermined limits, it can be set to an acceptable boundary.

(xi) Evaluate the objective function described in (9) using new solutions by following the procedure mentioned in step 5.

(xii) Apply the greedy selection process for the employed bees.

(xiii) Calculate the probability value, p_i, for the solutions using fitness value by following equation

$$p_i = \frac{\text{fitness}_i}{\Sigma_0^{\text{SN}}\text{fitness}_i} \tag{31}$$

(xiv) Produce the new solutions P_{ij}^{new} by using (30) for the onlookers bees from the solutions selected depending upon the value of p_i.

(xv) Evaluate the objective function described in (9) using new solutions by following the procedure mentioned in step 5.

(xvi) Apply the greedy selection process for the onlookers bees.

(xvii) Determine the abandoned solution for the scout, if exists and replace it with a new randomly produced solution.

(xviii) Memorise the best solution obtained as of now.

(xix) Cycle = cycle + 1.

(xx) Until (cycle = maximum cycle number).

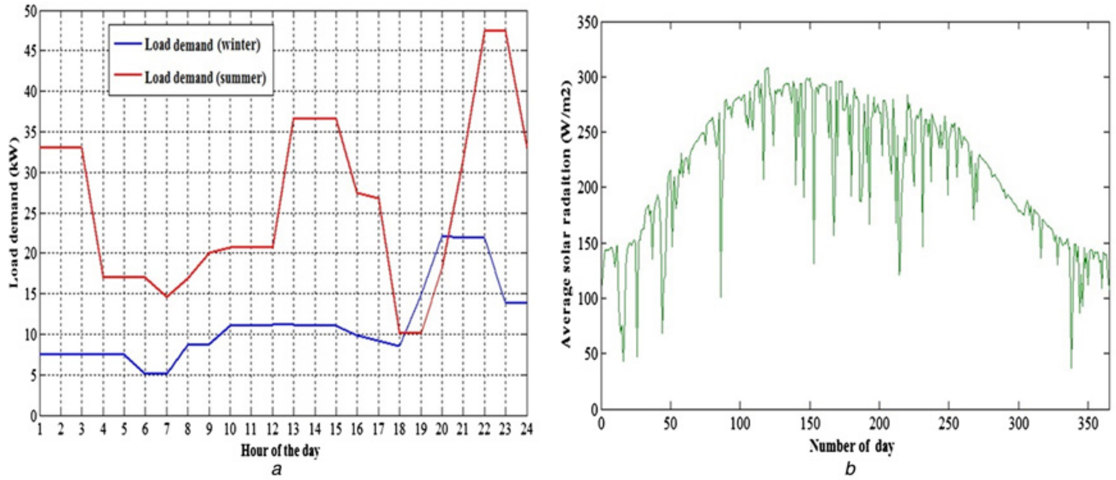

Fig. 2 *Case study of a small typical village located near Patiala, India: load profiles and average solar radiation*

a Load profiles (summer and winter)
b Average solar radiation (Wh/m^2) per day

Table 1 Monthly average solar radiation and clearness index for the case study

Month	Solar radiation, kWh/m^2/day	Clearness index
January	3.134	0.593
February	4.314	0.604
March	5.719	0.607
April	6.660	0.617
May	6.708	0.617
June	6.325	0.602
July	5.990	0.508
August	5.687	0.514
September	5.626	0.608
October	4.784	0.651
November	3.946	0.634
December	3.100	0.573

Table 2 Component cost

Component	Initial cost, per kW, $	Replacement cost, per kW, $	Maintenance cost, per kW	Lifetime
Photovoltaic module [27]	1200	1200	4 $/yr	20 year
Biomass gasifier [13, 28]	1834	1834	0.30 $/h upto 20 kW and 0.50 $/h above 20 kW	15,000 h
Inverter [27]	127	127	1.34 $/yr	15 year
Diesel generator [26]	278	278	0.020 $/h	15,000 h

4 Resource data and component selection

A case study of a small typical village located at a coordinate of 30° 26′ N latitude and 76°12′ E longitudes near Patiala, India is presented in this paper. The average daily electrical demands of this village (both summer and winter) are depicted in Fig. 2*a* [24]. The solar resource data for this location is taken from the NASA surface meteorology website [25]. It is found that average solar radiation for this location is 5.14 kWh/m^2/day. The variation of average solar radiation per day for a year is demonstrated in Fig. 2*b*. Table 1 shows average monthly solar radiation and a clearness index at this location. It is estimated that approximately 1.3–1.5 kg of biomass is required to produce 1kWh of electricity. The price of biomass in the region is approximately 0.025 $/kg, which mainly includes transportation and labour charges. This case study is modelled assuming a lifespan of 20 years while the annual interest rate is considered to be 6%. The rate of electricity purchased from the utility grid in the state is 0.1 $/kWh. The selling price of electricity to the grid is assumed to be 0.15 $/kWh [29]. The maximum grid purchase and sale power capacity considered are 5 kW and 50 kW, respectively. The sensitivity analysis is carried out for different grid sale capacities of 20, 25, 30, 35, 40, 45 and 50 kW. Table 2 demonstrates different costs of the components used for the work.

5 Results and discussions

The ABC algorithm is simulated using MATLAB 2014a program. A simulation is run for one year data with an interval of one hour to examine the behaviour of power exchange in different constellations. In the proposed study, the results obtained by HOMER software have been considered for reference and comparison. The control parameters of the ABC algorithm are considered as shown in Table 3. Two types of configurations, that is, stand-alone and grid connected system have been analysed for cost comparison.

5.1 Standalone system

First, stand-alone system comprises of solar PV panels and biomass gasifier system have been analysed by using HOMER and the ABC algorithm. To design the stand-alone system size of inverter, P_{inv}, is selected according to the peak load demand, $P_{\text{L}}^{\max}(t)$, during daytime. The minimum load ratio for biomass gasifier and diesel generator is considered as 30%. The following two scenarios of stand-alone hybrid system have been considered in this paper (i) Scenario A (without back-up) (ii) Scenario B (with back-up).

5.1.1 Scenario A (without back-up): In this scenario, the hybrid system is designed to meet all electrical load requirements by renewable energy sources only. No storage or back-up or grid connectivity is considered for the study. Table 4 shows the overall

Table 3 Control parameters of the ABC algorithm

NP (Number of colony size (Employed + Onlooker bees))	20
Food number (equal to the half of the colony size, NP/2)	10
Limit	100
Maximum cycle	100
D (Dimension of the problem)	2

Table 4 Optimal sizing result for stand-alone hybrid PV-biomass energy system

		Algorithm	PV, Units	Biomass gasifier, kW	DG, kW	Inverter, kW	Gasifier running, h	DG running, h	ACS, $/yr	NPC, $	LCOE, $/kWh
Scenario A	CASE I	HOMER	76	47	–	37	5687	–	53,141	609,524	0.349
(without back-up)	CASE II	ABC	72	48	–	37	5047	–	47,388	543,814	0.310
Scenario B	CASE I	HOMER	76	47	48	37	5381	306	55,780	639,796	0.366
(with back-up)	CASE II	ABC	72	48	48	37	5759	–	54,891	629,592	0.360

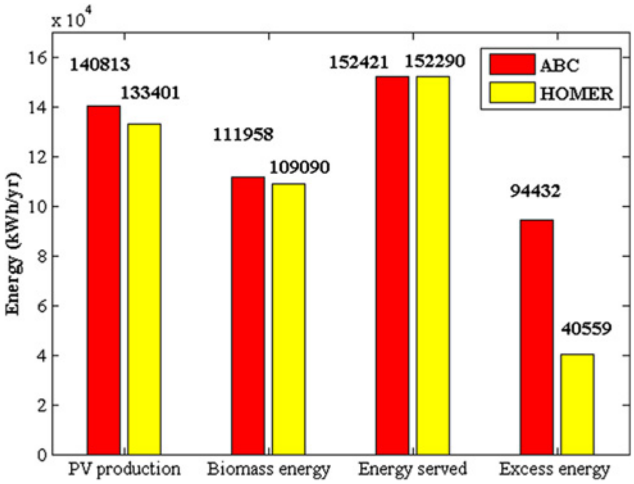

Fig. 3 *Energy produced by the stand-alone hybrid PV-biomass energy system (scenario A)*

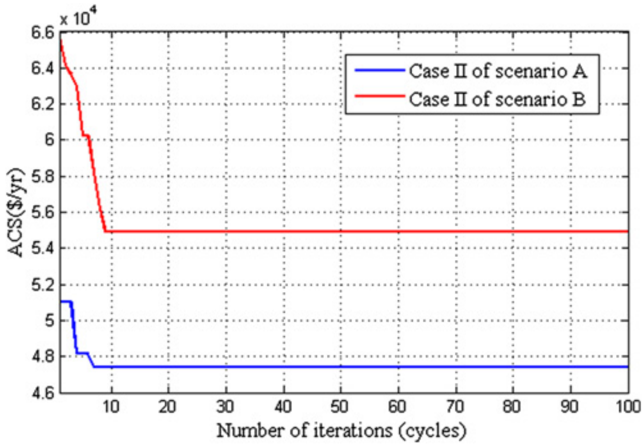

Fig. 4 *Convergence characteristic of the ABC algorithm for the stand-alone system*

Table 5 Optimal sizing result for grid connected hybrid PV-biomass energy system

S. no.	Algorithm	PV, Units	Biomass gasifier, kW	Inverter, kW	Grid sale capacity, kW	Grid purchase capacity, kW	Biomass running, h	ACS, $/yr	NPC, $	LCOE, $/kWh
CASE I	HOMER	100	45	85	50	5	5012	17,916	205,499	0.118
CASE II	ABC	128	43	88	50	5	4915	16,748	192,162	0.110
CASE III	ABC	73	43	88	50	5	5316	21,655	248,014	0.141

optimal results of a stand-alone hybrid system without any storage or grid connectivity for this case study. The case I is generated by using HOMER and case II is obtained by the ABC algorithm. All cases are a feasible solution to meet electrical load. The CRF is found to be 0.08714 for this system for a life span of 20 years and an interest rate of 6% by using (12). Net present cost (NPC) of the total system is calculated using CRF and ACS. Fig. 3 depicts the electricity production of the stand-alone hybrid system. It can be seen from the Fig. 3 that case I does not satisfy total electricity demand. A total of 131 kWh/yr electricity demand is not satisfied with this configuration. It is also observed that the ABC algorithm proved better results as compared with HOMER. As one can note from Fig. 3 that the stand-alone system without any storage and grid connectivity dumps huge amounts of electricity.

5.1.2 Scenario B (with back-up): In case of scenario A of stand-alone system, the biggest challenge is the reliability of power to the consumer. If one of the renewable energy sources (particularly biomass) goes off, the total system collapse. To overcome this shortcoming and enhance the reliability of the stand-alone system, a 48 kW diesel generator is included in the configuration. The current diesel price of 0.8 $/l is considered. The diesel generator prioritised in the last due to harmful gas emissions. Table 4 demonstrates the overall optimal results of a stand-alone hybrid system with diesel generator for this case study. The inclusion of diesel generator improves the reliability of the system while the pollutant emissions as compared with scenario A are increased. The inclusion of diesel generator increases the NPC of the system which result high LCOE of the system. Fig. 4 shows the convergence characteristic of the ABC algorithm for the stand-alone hybrid energy system for both cases. From these simulation results, it can be summarised that from the proposed stand-alone system the LCOE obtained in all cases is more as compared with the existing grid purchase cost (0.1 $/kWh). This stand-alone system may be a suitable choice of reliable electricity in the case of a remote or off grid location where LCOE is not a great concern.

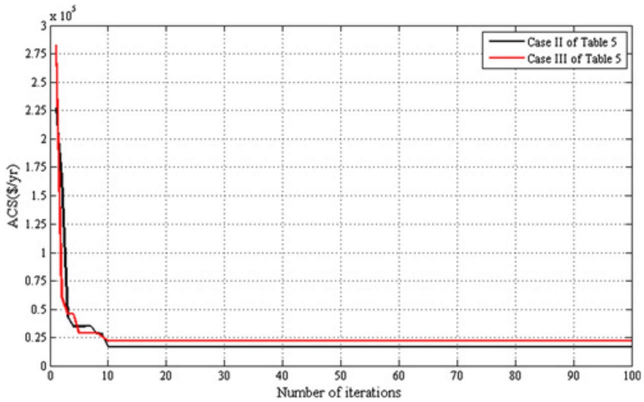

Fig. 5 *Convergence characteristics of the ABC algorithm for grid connected system (case II and III of Table 5)*

Table 6 Electricity production and consumption by HOMER and applied ABC algorithm

	(Case I)		(Case II)		(Case III)	
	kWh/yr	%	kWh/yr	%	kWh/yr	%
Energy production						
PV panels	185,280	45	237,159	52.6	135,050	36.8
Biomass generator	225,540	54.6	211,345	46.9	228,588	62.5
Grid purchases	1719	0.4	2085	0.5	2515	0.7
Total	412,540	100	450,589	100	366,153	100
Energy consumption						
AC load served	152,421	39	152,421	38	152,421	44
Grid sales	234,752	61	247,311	62	194,290	55
Total	387,173	100	399,732	100	346,711	100
Excess electricity	7598		30,155		0	

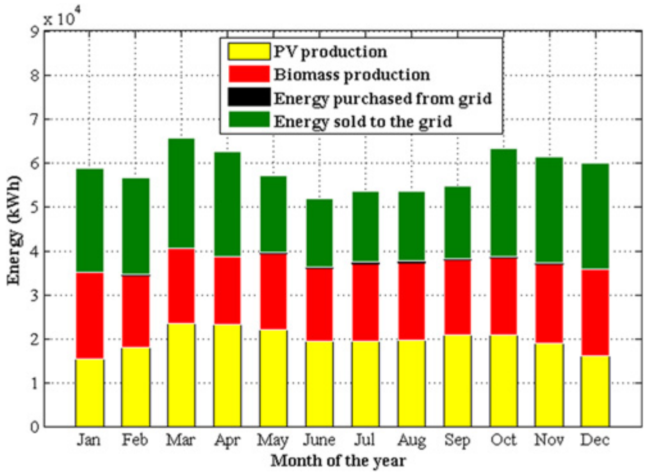

Fig. 6 *Monthly average electricity production during one year for case II (Table 5)*

5.2 Grid connected system

The biggest drawbacks in the case of aforementioned stand-alone system are relatively high LCOE and the intermittent nature of generating power due to high dependency on weather conditions.

Table 7 Cost analysis obtained by the ABC algorithm for case II (Table 5)

Component	Capital, $/yr	Replacement, $/yr	Maintenance cost, $/yr	Fuel, $/yr	Salvage, $/yr	Total, $/yr
PV	13,392	0	512	0	0	13,904
Biomass	6876	23,173	2464	6892	−958	38,440
Grid	0	0	−36,888	0	0	−36,888
Inverter	972	406	117	0	202	1293
Total	21,239	23,579	−33,801	6892	−1160	16,748

Table 5 shows the complete optimisation results obtained by HOMER and ABC algorithm for grid connected hybrid PV-biomass system as shown in Fig. 1. The major drawback with cases I and II (Table 5) is excess or dump energy. These two cases were obtained with the priority of LCOE to be minimised. Further, the simulation is carried out for the third case with the main objective of meeting the load demand and minimising the excess energy. The excess energy which is given to dump load can be minimised by the optimisation algorithm by imposing a high penalty on excess energy in the objective function. This system sales less electricity to the grid as compared with case I and case II therefore the LCOE is high. Fig. 5 depicts the convergence characteristics of the applied ABC algorithm for the case II and III. It has been observed that after almost 10 iterations, the optimisation algorithm converges completely and provide optimal solutions.

Table 6 shows a brief comparison of electricity generation and consumption for grid connected system suggested by HOMER and the ABC algorithm for all three cases. For further discussion the case II of Table 5 is opted as an optimal configuration for this case study. Fig. 6 illustrates the detailed monthly electricity production for the system in the case II of Table 5. It is observed that the energy sold to the grid is more as compared with energy purchased from the grid. This hybrid system purchase electricity from grid mainly in the summer when electrical load is more. Table 7 shows the complete annualised cost analysis for the case II. A complete cash flow summary of the proposed hybrid system during the project lifetime is presented in Fig. 7. It can be observed from Table 7 that biomass gasifier replacement cost has high impact on total ACS of the system. Due to less operational life, the biomass gasifier system replacement cost is high. For configuration in case II of Table 5 the total biomass gasifier system running hours are 4915 in a year, which results 3.05 years

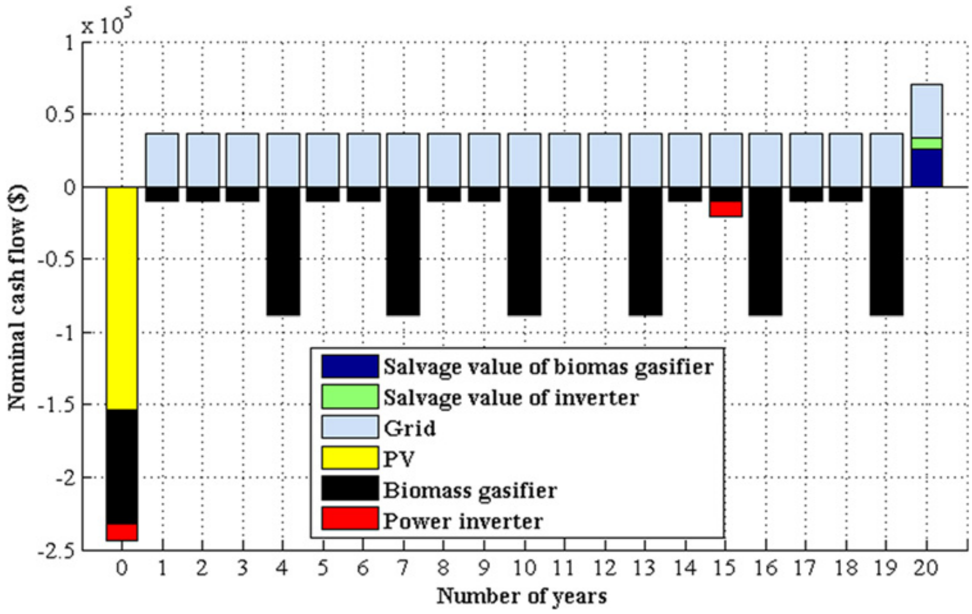

Fig. 7 *Nominal cash flow during the project lifetime for case II (Table 5)*

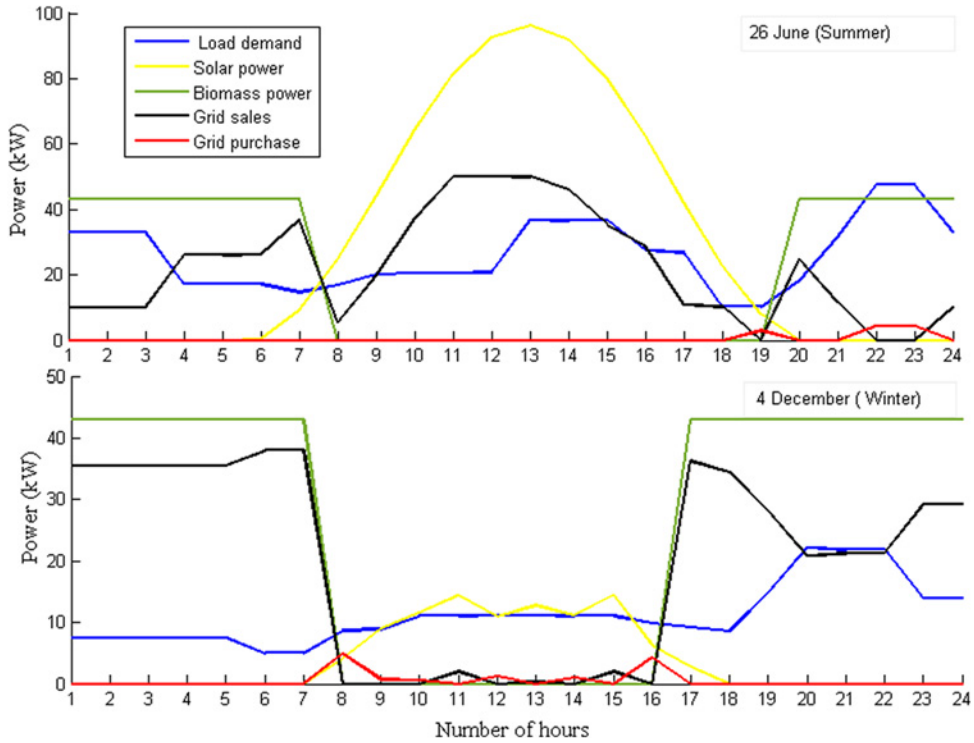

Fig. 8 *Power management indicating load demand, biomass, solar, grid sales and purchased powers in the case II (Table 5)*

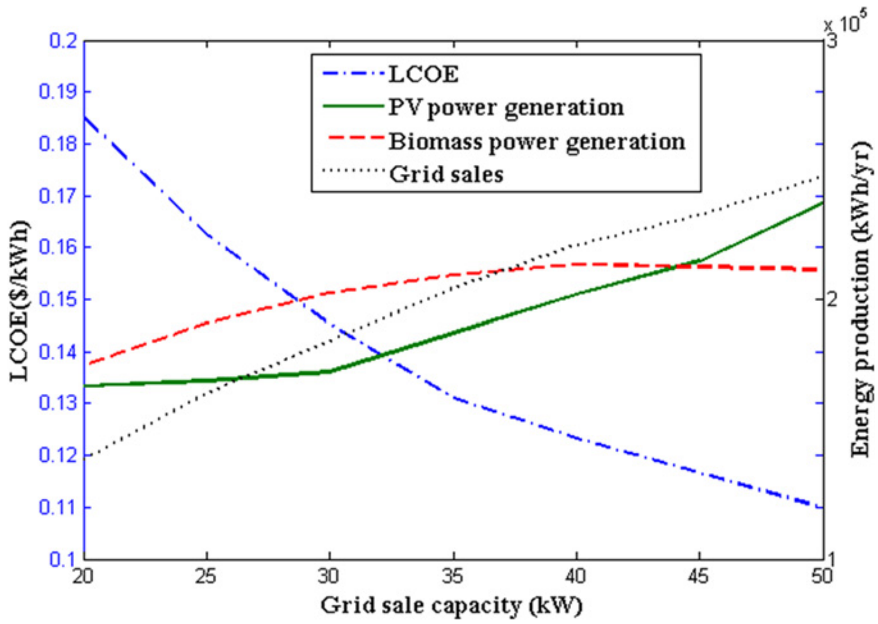

Fig. 9 *Effect of grid sale capacity on PV production, biomass power, grid sales and LCOE for case II (Table 5)*

operational life of the biomass gasifier system by using (14). Therefore, approximately six replacements are required during the project lifetime.

Fig. 8 demonstrates the optimal power management of the proposed system (case II of Table 5) in order to study the hourly power exchange between PV, biomass and grid. The simulation is conducted for two days where one day in winter and the other day of summer is taken for validation of the scheme. The first part of the Fig. 8 shows the optimised power management in a typical sunny day of summer. It is observed that in the summer season PV power contribution is more. Second part of the Fig. 8 illustrates the power management of a typical winter cloudy day, it has been observed that even during overcast of the cloud, the proposed system has optimised the generation of the biomass and grid purchased power. In the cases of outage conditions (grid failure), the system behaves in stand-alone (with back-up) mode.

In the sensitivity analysis, one major parameter such as grid sale capacity has been considered in this study. Fig. 9 illustrates the effect of grid sale capacity on annual PV power generation, biomass power generation, LCOE and electricity sold to the grid. It can be seen from the Fig. 9 that as grid sale capacity increases the contribution of PV and biomass power generation increases almost linearly. Moreover, after 40 kW of grid sale capacity, the biomass power contribution decrease and utilisation of solar power increases. It is found that if grid sale capacity increases, the LCOE decreases. It can also be observed from the Fig. 9 that LCOE of the system is minimum when grid sale capacity is maximum. LCOE is highly dependent on grid sale capacity. The main findings of the paper can be summarised as,

- For a stand-alone PV-biomass system the LCOE is found to be 0.349 $/kWh, while for a grid connected PV-biomass system LCOE is obtained to be 0.110 $/kWh by the ABC algorithm (Tables 4 and 5).
- A total of 2085 kWh/yr energy is purchased from the grid and 247,311 kWh/yr energy is sold back to the grid in the grid connected system (Table 6).
- A total of 276 tons of biomass feedstock has been utilised for power generation in the grid connected system (Table 5).
- Effect of grid sale capacity has been investigated on LCOE of the system and it is observed that LCOE decreases as grid sale capacity increases (Fig. 9).
- As compared with the stand-alone system, the grid connected system can achieve a higher power supply reliability.
- The applied ABC algorithm reduces hours of calculation time as compared with HOMER to few minutes.

6 Conclusion

This paper explored a methodology for optimal sizing of a grid connected PV-biomass hybrid energy system using the ABC algorithm and HOMER. First, a mathematical model of hybrid system was presented. Then optimisation algorithm and operational strategy were explained. Finally, the optimal sizing method was applied to find out the optimal configuration in case of stand-alone and grid connected PV-biomass hybrid system. The results obtained clearly show that grid connected hybrid system may be a cost effective electrification solution for numerous villages in developing countries. It is also perceived from the obtained results that grid connected PV-biomass system shows better results in terms of cost effectiveness and reliability as compared with stand-alone PV-biomass system.

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