

Research paper

Modelling and optimization of an off-grid hybrid renewable energy system for electrification in a rural areas

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ABSTRACT

Energy required by remote village areas can be met quite reliably by hybrid energy technologies. The project under consideration is for electrifying a group of three villages in Kollegal block of Chamarajanagar district, Karnataka State in India using an off-grid hybrid renewable energy system. The process of optimizing such hybrid energy system control, sizing and choice of components is to provide it with a cost effective power solution for the society. The main objective of this paper is to reduce the Total System Net Present Cost (TNPC), Cost of Energy (COE), unmet load, CO₂ emissions using Genetic Algorithm (GA) and HOMER Pro Software. The results of the two methods are compared with four combinations of hybrid renewable energy systems (HRES). A sensitivity analysis is also performed on the best possible solution to the study for changes in annual wind speed and biomass fuel prices. Finally, a comparative analysis is performed between the GA and HOMER. Compared to HOMER, GA based HRES of combination-1(biogas+biomass+solar+ wind+ fuel cell with battery) is found to be the optimal solution supplying energy with 0% unmet load at the least cost of energy, which is at \$ 0.163 per KWH. Thus PV saturation in GA is more cost effective than the HOMER.

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1. Introduction

A more energy efficient economy can be built with sustainable, environmentally friendly and renewable sources such as wind, fuel cells, biogas, and biomass. However, renewable resources experience a number of restrictions while used in a stand-alone, flexible structure. To solve these problems, solar and wind energy sources are pooled with other sources to generate a hybrid renewable energy grid. Therefore, it is possible to obtain higher efficiency in power production by making the best use of their advantages to overcome their limitations (Vendoti et al., 2019b; Rajanna and Saini, 2016b; Vendoti et al., 2018b, 2020). Electrification of rural areas is slowed down by procedural barriers like constrained transmission, hard terrains and highly scattered valleys with low population distinguished by lower the education, load density, and revenues. While developing HOMER based hybrid renewable energy grid to determine the different costs involved in the process like the net present cost and cost of energy.

Rajanna and Saini (2014, 2016c) developed the hybrid system using genetic algorithms. They used genetic algorithm to

achieve energy needs of various load sections inside the villages of Chamarianagar, in the Southern State of Karnataka, India. Chauhan and Saini (2016a) proposed sizing based hybrid renewable energy system to provide uninterrupted power supply to fulfil the energy demands within the area under study. Chauhan and Saini (2016b) also presented a comparative study of demand side management (DSM) based hybrid energy system through load shifting strategy. They suggested the demand side management strategy as the most suitable solution without demand side management strategy.

Different configurations of hybrid energy systems were developed in six geographic zones of Nigeria by Olatomiwa et al. (2015a) and it can be determined economic feasibility solution using HOMER software with sensitivity cases of \$1.1–\$1.3/1 based NPC and COE. Based on the availability of meteorological data, Olatomiwa et al. (2018) presented a statistical analysis of wind and solar energies' potentials for rural areas in Nigeria. It employs design and sizing of an optimal technical and economic hybrid energy system components using HOMER software. Olatomiwa et al. (2015b) also compared the two best optimal system configurations namely PV-diesel-battery and PV-wind-diesel-battery systems with the typical system. From the two configurations, configuration two is the most economically viable option with the TNPC of \$69,811 and COE of 0.409 \$/kWh.

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Mohamed et al. (2016) presented a bi-level system employing decision analysis and multi-objective optimization method for design and analysis of a rural micro grid for developing nations with a perception of sustainable development. Das et al. (2019) compared the performance of two meta-heuristic optimization techniques, namely MFO and WCA algorithms. They evaluated techno-economic optimal design of PV-BG-Battery-PHES based HRES and compared it with GA to obtain for powering a radio transmitter station in India. Zhang et al. (2019) proposed a new hybrid optimization algorithm for optimal sizing of a stand-alone hybrid energy system based on three algorithms such as chaotic search, harmony search and simulated annealing. They are used for reviewing the feasibility study of proposed system with reliability.

Samy et al. (2018) developed a techno-economic feasibility study for off-grid solar PV-fuel cell hybrid energy systems for supplying electricity to remote areas in Egypt. They found the total annual cost using Flower Pollination Algorithm (FPA). The loss of power supply probability is also considered to improve the system performance. Vendoti et al. (2019a) implemented the techno-economic analysis of hybrid renewable energy system for cluster of three villages in India. They are considering two storage devices both can produce electricity as well as storage. But, a battery stores inside it the energy as well as it makes the energy work, like a fuel cell. It makes its electricity from fuel through an external storage tank. For instantaneous use batteries are used for the most part, while for continuing usage hydrogen storage is profitable. Jamshidi and Askarzadeh (2018) presented a multi-objective design of a photovoltaic fuel cell and a diesel generated-hybrid energy system to supply the power of an off-grid rural community in Kerman, South of Iran, with the presence of operating reserve and uncertainties.

1.1. Novelty of the study

Majority of the research scientists developed various configurations of hybrid renewable energy system models. From the available literature and gaps identified in the research recognized above, here a novel hybrid renewable energy system (HRES) model is developed for modelling and optimization of an off-grid HRES for electrification in remote rural areas. The HRES consists of solar-wind-biomass-biogas-fuelcell along with battery. Multi-objective GA and HOMER software is proposed to solve sizing and optimization problems. System performance is evaluated and compared by different combinations of HRES for optimal configurations with minimum value of NPC and COE. Optimized system is economically feasible, has reasonable environmental benefits, attractive payback period and also fewer emissions. Sensitivity analysis is also presented for variation in annual wind speed and biomass fuel prices, with cost of energy and net preset cost.

The main contributions of the paper are listed below:

- i. A novel hybrid renewable energy system (HRES) was developed for size and cost optimization problems in remote areas.
- ii. Multi-objective GA and HOMER Pro software is proposed to solve size and cost problems.
- iii. System performance was evaluated and compared with four combinations of stand-alone HRES with minimum value of NPC and COE.
- iv. Combination of solar-wind-biomass-biogas-fuelcell-battery system leads to having an efficient system.
- v. Sensitivity analysis is also carried out for variation in annual wind speed and biomass fuel price with COE and NPC.
- vi. Proposed system has reasonable environmental benefits, attractive payback period and less emission.

The next section of this paper is organized as follows. Section 2 provides methodology adapted to the study which consists of selection of study area, demand assessment and source assessment. A Section 3 discusses the mathematical modelling. Section 4 explains the problem formulation. Section 5 gives the details the GA and HOMER Pro software. Section 6 shows the results and discussions and Section 7 concludes the paper.

2. Methodology

The selection of study area, and its renewable sources availability; estimation of energy demands allowed by the minimum desirable load in the study area as discussed below:

2.1. Area selection

In Chamarajanagar district, Karnataka state (India) a cluster of three un-electrified village hamlets was selected for the case study (Anon, 2019b). The study consists of a total of 408 households with a population of 1686 (Rajanna, 2016; Anon, 2019a). Majority of the population in these areas live in hilly terrains. To supply the energy to these areas is difficult, so that expansion of the grid is also not a viable solution. Renewable energy source availability is enormous in this study area such as solar, wind, biomass and biogas, and all these are used in stand-alone mode.

2.2. Energy demand estimation

The estimated energy demand is lower in this study apart from the power generation; hence the consumption of energy is increased with respect to time. Therefore, by considering the potential necessities within the area to estimate the required electrical energy demands.

Based on the energy needs within the study, principal data is collected from the locals through surveys with a variety of sections like domestic load, agricultural load, community load, and commercial load sections. Energy demand was mainly constituted as lighting for health centre, primary school, shops, street lighting, water pumping, and small industrial loads. Hourly and monthly load profiles considered within the study are plotted in Fig. 1 (Vendoti et al., 2020). Total energy demand in kWh per day and its peak load within the area were estimated by 724.83 kWh/day, and 149.21 kW.

2.3. Source estimation

Potential availability of renewable energy sources such as solar, wind, biomass, and biogas are vast in this location. The availability of solar irradiation and the average wind speed particulars of study location were taken from the latitude and longitudes of the study area (11°59'N and 77°00'E) (HOMER software). HOMER Pro software was used to work out the daily solar irradiation; average wind speed; and optimal sizing of the system through these latitude and longitudes.

2.3.1. Annual solar radiation

Annual daily solar irradiation available within the study location is shown in Fig. 2 (HOMER software). Highest solar irradiation found as 6.50 kWh/m²/day in the month of March whereas lowest as 4.11 kWh/m²/day was found in November month.

2.3.2. Scaled annual wind speed

Annual average wind speed available within the study location as shown in Fig. 3 and its value is found as 3 m/s.

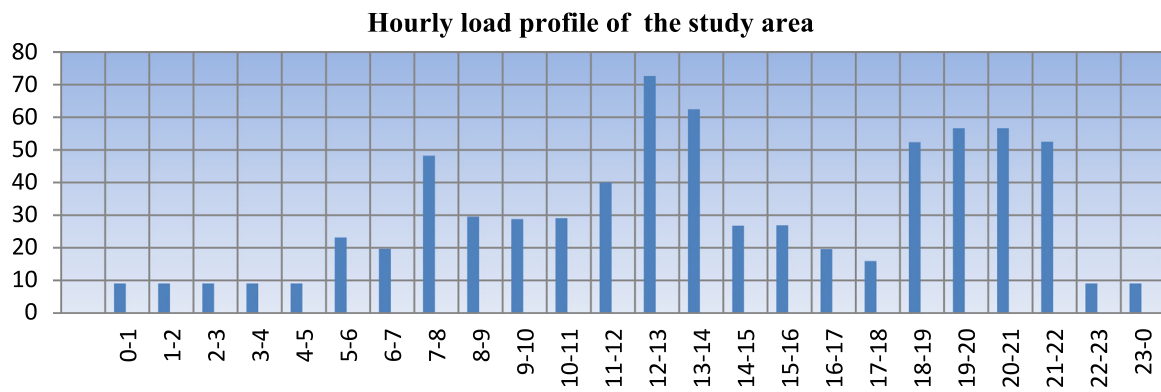


Fig. 1. Hourly load profiles within the study.

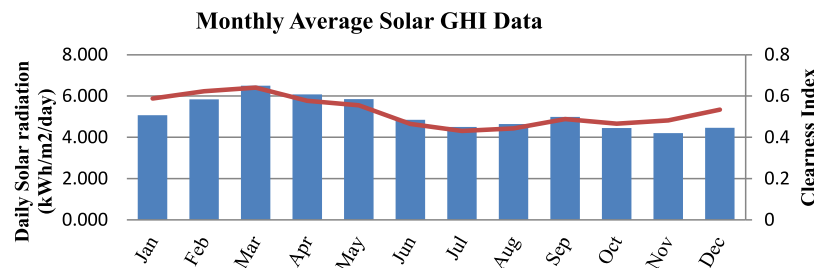


Fig. 2. Monthly solar radiation available.

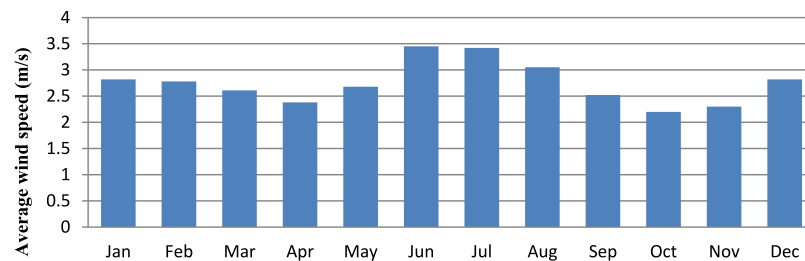


Fig. 3. Monthly average wind speed available.

Table 1

Information regarding the availability of all the renewable energy sources (Rajanna and Saini, 2016b).

Dung availability from biogas	Forest foliage availability from biomass	Wind speed	Solar Irradiance
372 m ³ /d	107.79 ton/yr	Scaled annual wind speed = 3 m/s	Annual average daily solar irradiation = 5.47 kWh/m ² /day

2.3.3. Annual average of biomass and biogas

The availability of biomass and biogas potentials within the study locations are estimated as: Biomass potential from forest foliage is 107.79 tons/yr and biogas potential from cattle dung is 372 m³/day (Rajanna and Saini, 2016b). Monthly available biomass resource in the study location is shown in Fig. 4.

Brief information about all the renewable energy sources availability within the study location are outlined in Table 1.

3. Modelling of system components

For size optimization, modelling of hybrid energy system components is a significant step to providing its performance under

different situations. Mathematical modelling of proposed HRES components is explained below:

3.1. Solar PV system

Single diode solar PV mathematical models are investigated for this study. The value of solar PV module voltage (V_{SPV}) is expressed by Eq. (1) (Thapar et al., 2011):

$$V_{PV} = V_{mppt} [1 + 0.0539 \log(G_{tt}(t)/G_{st})] + \alpha (T_a(t)) + 0.02 G_{tt}(t) \quad (1)$$

where, V_{mppt} as the maximum power point voltage (in Volts), α as the co-efficient of temperature, G_{tt} as the measured value of irradiation (in kW/m²), G_{st} as the standard value of irradiation (in 1 kW/m²), and T_a as the variable temperature (K).

Output current of a solar PV system (I_{SPV}) is obtained by Eq. (2):

$$I_{SPV}(t) = I_{ph}(t) - I_{rs}(t) [\exp(q V_{PV}/N_s K T_a(t) A_i) - 1] \quad (2)$$

where, I_{ph} is the photo current, I_{rs} as the saturation current, q as the charging of the electrons, N_s as the number of series cells, K as the Boltzmann's constant, and A_i as the ideal diode factor.

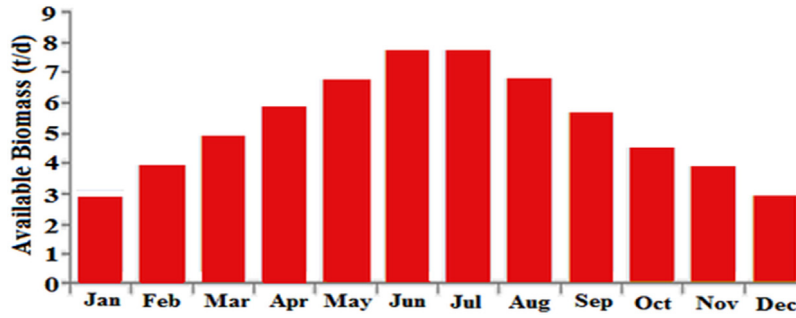


Fig. 4. Monthly available biomass resource in the study area.

Total energy generated by solar PV system (E_{SPV}) is expressed by Eq. (3):

$$E_{SPV}(t) = (N_{PV} \times V_{PV}(t) \times I_{PV}(t) \times \Delta t) / 1000 \quad (3)$$

where N_{SPV} as the number of PV modules and Δt as the step time as 15 min.

3.2. Wind turbine system

A wind turbine system of mathematical model was obtained from the wind turbine power curve produced by the manufacturer. The wind turbine equation is governed by fitting curve method (Kanase-Patil et al., 2011). To determine the power produced from wind turbine (P_{WT}) specified equations are used:

$$\left. \begin{aligned} P_{WT}(t) &= 0, & \text{for } V < V_i \text{ and } V > V_o \\ P_{WT}(t) &= A_1 V^2 + B_1 V + C_1, & \text{for } V_i < V < V_1 \\ P_{WT}(t) &= A_2 V^2 + B_2 V + C_2, & \text{for } V_1 < V < V_2 \\ P_{WT}(t) &= A_3 V^2 + B_3 V + C_3, & \text{for } V_2 < V < V_o \end{aligned} \right\} \quad (4)$$

where, V is the physical value of wind turbine speed, V_i as break in speed; V_o as break out speed, and A, B, C are the co-efficient of a characteristic equations.

Total energy generated by wind turbine system (E_{WT}) is expressed by Eq. (5):

$$E_{WT}(t) = (N_{WT} \times P_{WT}(t) \times \Delta t) / 1000 \quad (5)$$

where N_{WT} as the number of wind turbines

3.3. Biogas system

Based on the cattle dung availability, the output energy generated from biogas generator was determined using the equation expressed by (6) (Chauhan and Saini, 2017);

$$E_{BGG} = \frac{\text{Biogas availability (m}^3/\text{day)} \times CV_{BGG} \times \eta_{BGG} \times \Delta t}{860 \times h_{BGG}} \quad (6)$$

where, E_{BGG} is the energy output of biogas gasifier; η_{BGG} as system conversion efficiency, CV_{BGG} is the biogas digester calorific value (4700 kcal/kg).

3.4. Biomass system model

Based on the forest foliage availability, the hourly energy generated by the biomass generator is determined using the equation expressed by (7) (Chauhan and Saini, 2017);

$$E_{BMG}$$

$$= \frac{\text{Biomass availability (kg/yr)} \times CV_{BMG} \times \eta_{BMG} \times \Delta t}{365 \times 860 \times h_{BGG}} \quad (7)$$

where, E_{BMG} is output energy generated from biomass generator; η_{BMG} as the system conversion efficiency; CV_{BMG} as biomass gasifier calorific value (4015 kcal/kg).

3.5. Fuel Cell (FC) system

For all renewable energy systems, FC system is a potential applicant particularly as backup in rural area applications. These systems are very clean; generates no emissions and are characterized by high efficiency. Hydrogen is the primary fuel of fuel cell systems, that converts the stored energy of fuel directly into electricity with the help of an oxidant used in fuel cells such as methane, ethanol, fuels based on biomass etc. depending on the type of fuel cell system. Out of the different types of FC systems, PEM fuel cell is used in commercial purposes available in industrial applications and has fast dynamic response with time 1–3 s (Garcia and Weisser, 2006). It has a reliable performance under unbalanced supply. Such types of fuel cells are used for large-scale power generation. The output power of an FC was determined by Eq. (8) (Khan and Iqbal, 2005b);

$$P_{FC} = P_{\text{tank-FC}} \times \eta_{FC} \quad (8)$$

Electrolyzer/Hydrogen Tank:

Electrolyzer works under the process of electrolysis; current flows from one electrode to another electrode within water and thus decomposes into hydrogen and oxygen. In most of the surveys, output of the electrolyzer is exactly coupled with the hydrogen storage tank (Khan and Iqbal, 2005a; Vendoti et al., 2018a).

The power transferred from electrolyzer to hydrogen storage tank has been estimated by Eq. (9);

$$P_{\text{elec-tank}} = P_{\text{ren-elec}} \times \eta_{\text{elec}} \quad (9)$$

where, η_{elec} is the electrolyzer efficiency assumed as constant.

The output energy stored by hydrogen tank is expressed by Eq. (10);

$$E_{H2,\text{tank}}(t) = E_{H2,\text{tank}}(t-1) + [P_{\text{elec,tank}}(t) - (P_{\text{tank,FC}}(t) / \eta_{\text{storage}})] \times \Delta t \quad (10)$$

where, $P_{\text{tank-FC}}$ is the output power of a fuel cell, η_{storage} as the efficiency of hydrogen storage as approximately 95% for all operating conditions (El-Shatter et al., 2006).

The mass of hydrogen storage is calculated using Eq. (11);

$$m_{\text{tank}}(t) = E_{\text{tank}}(t) / HHV_{H2} \quad (11)$$

where, HHV_{H2} is hydrogen storage higher-heating value considered as 38.9 kWh/kg (Nelson et al., 2006). Hydrogen storage tank contains several limits of lower and upper portions. When it

exceeds the rated capacity, the total mass of hydrogen tank is not attainable due to some problems like reduction of hydrogen pressure.

The limits of lower and upper portions of the hydrogen storage tank are expressed by the Eqs. (12) and (13):

$$E_{\text{tank-min}} \leq E_{\text{tank}}(t) \leq E_{\text{tank-max}} \quad (12)$$

$$E_{\text{tank}}(t=0) \leq E_{\text{tank}}(8760) \quad (13)$$

3.6. Battery bank system

The energy production and its consumption depending on number of batteries and state of the battery connected at any given time. When the battery is charging, power generation exceeds the load demand. Then availability of power in the battery bank at a specified time is expressed by the given Eq. (14) (Chauhan and Saini, 2017):

$$E_{\text{Batt}}(t) = E_{\text{Batt}}(t-1) + E_{\text{EE}}(t) \times \eta_{\text{CC}} \times \eta_{\text{CHG}} \quad (14)$$

where, $E_{\text{EE}}(t)$ is the extra energy available from all the systems, η_{CC} as the charging controller efficiency, and η_{CHG} as the battery charging efficiency.

The quantity/state of charging the battery are expressed by the given Eq. (15):

$$\text{SOC}_{\text{min}} \leq \text{SOC}(t) \leq \text{SOC}_{\text{max}} \quad (15)$$

where, SOC_{min} is the value of minimum SOC; and SOC_{max} as the maximum value of SOC assumed as 1. Minimum value of SOC is obtained using the following Eq. (16),

$$\text{SOC}_{\text{min}} = 1 - \text{DOD} \quad (16)$$

3.7. Bi-directional converter system

Major part in the proposed system components is bi-directional converter. The main role of this converter is the regulation of the flow of current into either direction during the time extra power is charged into the battery. The main function of this device is to provide necessary power from DC sources to the load. The size of this converter is based on the minimum or maximum energy levels.

4. Problem formulation

Problem formulation consists of objective function and constraints considered the same as:

4.1. Objective function

Net preset cost contains several costs such as capital, replacement, maintenance & operation, fuel costs etc. Objective function is to determine net present cost by means of genetic algorithm of proposed system and is given by Eq. (17) (El-Sharkh et al., 2006):

$$\text{Total Net Present Cost (TNPC)} = \text{CC} + \text{O\&MC} + \text{RC} + \text{FC} \quad (17)$$

where, CC is the total capital cost, O&MC, the total maintenance & operation, RC, the cost of replacement, FC, the cost of fuel and all the system components.

Total capital cost in all components of the hybrid system was obtained by the given Eq. (18) (El-Sharkh et al., 2006):

$$\begin{aligned} \text{CC} = \{ & (\alpha_{\text{SPV}}, N_{\text{SPV}} + \alpha_{\text{WTG}}, N_{\text{WTG}} + \alpha_{\text{FC}}, N_{\text{FC}} + \alpha_{\text{ELE}}, N_{\text{ELE}} \\ & + \alpha_{\text{H2,Tank}}, N_{\text{H2,Tank}} + \alpha_{\text{Batt}}, N_{\text{Batt}} + \alpha_{\text{Inv}}, N_{\text{Inv}} + \alpha_{\text{BGG}}, N_{\text{BGG}} \\ & + \alpha_{\text{BMG}}, N_{\text{BMG}}) \} \end{aligned} \quad (18)$$

The total maintenance & operation cost in all components of the hybrid system was obtained by the given Eq. (19) as (El-Sharkh et al., 2006):

$$\begin{aligned} \text{O\&MC} = \{ & (\beta_{\text{SPV}}, N_{\text{SPV}} + \beta_{\text{WTG}}, N_{\text{WTG}} + \beta_{\text{FC}}, N_{\text{FC}} + \beta_{\text{ELE}}, N_{\text{ELE}} \\ & + \beta_{\text{HTank}}, N_{\text{H2,Tank}} + \beta_{\text{Batt}}, N_{\text{Batt}} + \beta_{\text{Inv}}, N_{\text{Inv}} + \beta_{\text{BGG}}, N_{\text{BGG}} \\ & + \beta_{\text{BMG}}, N_{\text{BMG}}) \} \times \sum_{j=1}^1 \left(\frac{1+u}{1+i} \right)^j \end{aligned} \quad (19)$$

Main sources of biomass (forest foliage) and biogas (cattle dung) fuels are used in operating the generators of biogas and biomass. The total fuel cost of the proposed system is obtained from availability of fuels, for instance biogas and biomass using Eq. (20) as (Strunz and Brock, 2006):

$$\text{FC} = \sum_{j=1}^1 \left(\frac{1+u}{1+i} \right)^j [\lambda_{\text{AFR}}(\text{CD}_{\text{BGG}} + \text{FF}_{\text{BMG}})] \quad (20)$$

For analysing the hybrid renewable energy system, total net present cost in study area and cost of energy (COE) are determined by using Eq. (21) as (Vendoti et al., 2017):

$$\text{COE} = \text{TNPC} \times \text{CRF} / \sum_{t=1}^{8760} \text{Egen}(t) \quad (21)$$

Capital recovery factor depends on rate of annual interest (γ) and plant life (τ) and is expressed by given Eq. (22) as (Rajanna and Saini, 2016a):

$$\text{Capital Recovery Factor (CRF)} = \frac{\gamma(1+\gamma)^\tau}{\gamma(1+\gamma)^\tau - 1} \quad (22)$$

4.2. Constraints

The following constraints are used to formulate the optimized objective function as:

4.2.1. Battery storage constraint

The capacity of a battery bank at any hour 't' lies in between minimum and maximum capacity. Then, the constraint is expressed as (Chauhan and Saini, 2017):

$$E_{\text{Batt,min}} \leq E_{\text{Batt}}(t) \leq E_{\text{Batt,max}} \quad (23)$$

4.2.2. Bounds constraint

The constraint of lower and upper bounds for solar, wind and battery systems is expressed as (Chauhan and Saini, 2017):

$$N_{\text{WTG}} = \text{Integer}, \quad 0 \leq N_{\text{WTG}} \leq N_{\text{WTG}}^{\text{max}} \quad (24)$$

$$N_{\text{SPV}} = \text{Integer}, \quad 0 \leq N_{\text{SPV}} \leq N_{\text{SPV}}^{\text{max}} \quad (25)$$

$$N_{\text{Batt}} = \text{Integer}, \quad 0 \leq N_{\text{Batt}} \leq N_{\text{Batt}}^{\text{max}} \quad (26)$$

where, $N_{\text{WTG}}^{\text{max}}$ is maximum number of wind turbines, $N_{\text{SPV}}^{\text{max}}$ is maximum number of PV modules and $N_{\text{Batt}}^{\text{max}}$ is maximum number of batteries.

4.2.3. Power reliability constraint

Based on the power reliability, unmet load constraint is included. It is expressed as (Chauhan and Saini, 2017):

$$\text{Unmet Load} = (\text{yearly load supplied}/\text{total load}) \quad (27)$$

In mathematical modelling of HRES components, total cost of the system is varied from component to component with different specifications. The summaries of different parameters considered in the system components are specified in Vendoti et al. (2020), Chauhan and Saini (2017), Barsoum and Petrus (2015) and Saber and Mahdi (2013).

5. Optimization based on GA and HOMER software

5.1. Optimization through HOMER Pro software

HOMER Programming (Created by National Renewable Energy Laboratory, USA) is utilized to build up the hybrid renewable energy system in these studies (HOMER software). It contains design and simulation at the optimized conditions with expected constraints. HOMER is a novel programming to make an advanced model operation for planning of hybrid energy systems as well as grid integrated systems.

5.1.1. Simulation analysis

The simulation system is basically subject to the selection of components chosen by the designer. HOMER makes the total operations of the system; along to this procedure, the system develops large quantities of components and its size. Also in this study, the hybrid energy system needs to be assessed as sum total of solar PV, wind turbine, biomass, biogas, fuel cell, battery, and converter. The simulation analysis chooses the best dynamic planning and a system design which is a function of the electrical demand. HOMER also performs the total cost of hybrid system, and determines the capital cost, replacement cost, O&M cost, fuel cost and so on.

5.1.2. Sensitivity analysis

Sensitivity analysis is the variable one that has no control over the designer. The HOMER again integrates the hybrid energy system established on the sensitivity variable chosen by the designer. The sensitivity factors are the world solar radiation, cost of wind turbine, cost of the battery and cost of the fuel in a generator. In development, the list of different components of HRES will be considered from the lower to the higher TNPC. The consequence of the system demonstrates the best components achieved by the lowest TNPC thus obtained (HOMER software).

In the proposed system, availability of renewable energy sources in the study location is evaluated using HOMER Pro software and is shown in Fig. 5. The proposed HRES comprises of biomass generator (BMG), biogas generator (BGG), solar PV system (SPV), wind turbine generator (WTG), fuel cell system (FC), electrolyzer (Elect), hydrogen storage tank (H₂Tank), converter (Conv.), and battery (Batt) systems.

The proposed system consists of two load buses i.e. AC and DC buses. The power generated from AC bus connected to biomass, biogas, and wind generators; whereas the power generated from DC bus connected to solar, and fuelcell systems. The availability of surplus power in the battery when it exceeds the load used to the electrolyzer which energizes to produce hydrogen (H₂) which is stored into hydrogen tanks. The stored energy is used to run the fuelcell generator to meet the required loads during energy shortages to other sources.

5.2. GA based optimization

Genetic algorithm is used for determining constrains based optimization problems. Genetic algorithm accomplishes the number computations in each iteration depending on population size, selection procedure, and crossover & mutation rate to generate the new population (Rajanna and Saini, 2016a). Genetic algorithm is developed into MATLAB software.

In optimization problems, M-file was implemented with constraints, variables and constants as an objective function. The variables considered in the proposed system are WTG, SPV, and Battery. GA toolbox is used to optimize problems to find out the fitness function. Based on the results it was found that, the specified functions are considered in a minimum number of

generations. Also the numbers of components are carried out to find the crossover and mutation rate, and selection process.

For initial generation of population, genetic algorithm is used in the random generation of population numbers. Each potential solution generates the choice vector code based on lower and upper constraints. By evaluating the number components of each generation fitness function is estimated and each generation develops the consecutive iteration. With a lower degree of optimization problems, population size of 50 is adequate and it produces 80 numbers of generations. Therefore, the optimal solution is obtained from the proposed system. Present study considered the crossover and mutation rates as 0.8 and 0.2. These functions are selected based on the Roulette arithmetic. Based on the optimization problem, additional functions are selected.

Initialization of GA optimization is followed on these steps:

Step (1) initially set the cross over and mutation functions.
Step (2) Initialize the population of chromosomes of size N and dimension $DX_{i,j} \forall i \in \{1, 2, \dots, N\}$ and $\forall j \in \{1, 2, \dots, D\}$

Step (3) Determine the fitness value of each chromosome $F_i = f(X_{i,j})$ and calculate the best fit

Step (4) set the iteration number $k = 1$

Step (5) Find the % Reproduction of chromosomes

for $l = 1: 1: N$

$i = \text{randi}(N) \in \{1, 2, \dots, N\}$

$x_{l,j} = X_{i,j}^k$

end for

Step (6) % Crossover of parents (pairs) chromosomes ($x_{l,j,b}$ is $x_{i,j}$ in binary form) and mutation of offspring

for $l = 1: 2: CF \times N$

$c = \text{randi}(\text{bits of chromosome}) \in \{1, 2, \dots (\text{bits of chromosome})\}$

$$X_{l,j,b}^{k+1} = \begin{cases} x_{l,j,b} & \forall j \leq c \\ x_{l+1,j,b} & \forall j > c \end{cases}$$

$$X_{l+1,j,b}^{k+1} = \begin{cases} x_{l+1,j,b} & \forall j \leq c \\ x_{l,j,b} & \forall j > c \end{cases}$$

end for

Step (7) % Mutation of chromosomes $X_{l,j,b}^{k+1}$

for $l = 1: 1: N$,

if $\text{rand}() < MF$

$i = \text{randi}(\text{bits of chromosome})$

$$X_{l,j,b}^{k+1} = \begin{cases} 0 & \text{if } x_{l,j,b} = 1 \\ 1 & \text{if } x_{l,j,b} = 0 \end{cases}$$

end if

end for

Step (8) Evaluate fitness $F_i^{k+1} = f(X_{i,j}^{k+1})$ and find best fit chromosome b ($X_{i,j}^{k+1}$ is $X_{i,j,b}^{k+1}$ in decimal form)

Step (9) If $F_b^{k+1} < F_{b1}^k$ then $b = b1$

Step (10) If $k < \text{max_iteration}$, then $k = k + 1$; and go to step 5 as well go to next

Step (11) Print optimum solution as $X_{b,j}^{k+1}$

6. Results and discussions

The main objective of the study such as the size and cost optimization of the off-grid hybrid energy system for supplying the required energy demand into the study area is already mentioned above. Based on the database available, the proposed configuration is simulated using GA and HOMER Pro software.

6.1. HOMER simulation results

After hourly simulation, different configurations of size and cost parameters are generated as shown in Fig. 6. Out of many, four combinations are proposed and the results of each combination are discussed below:

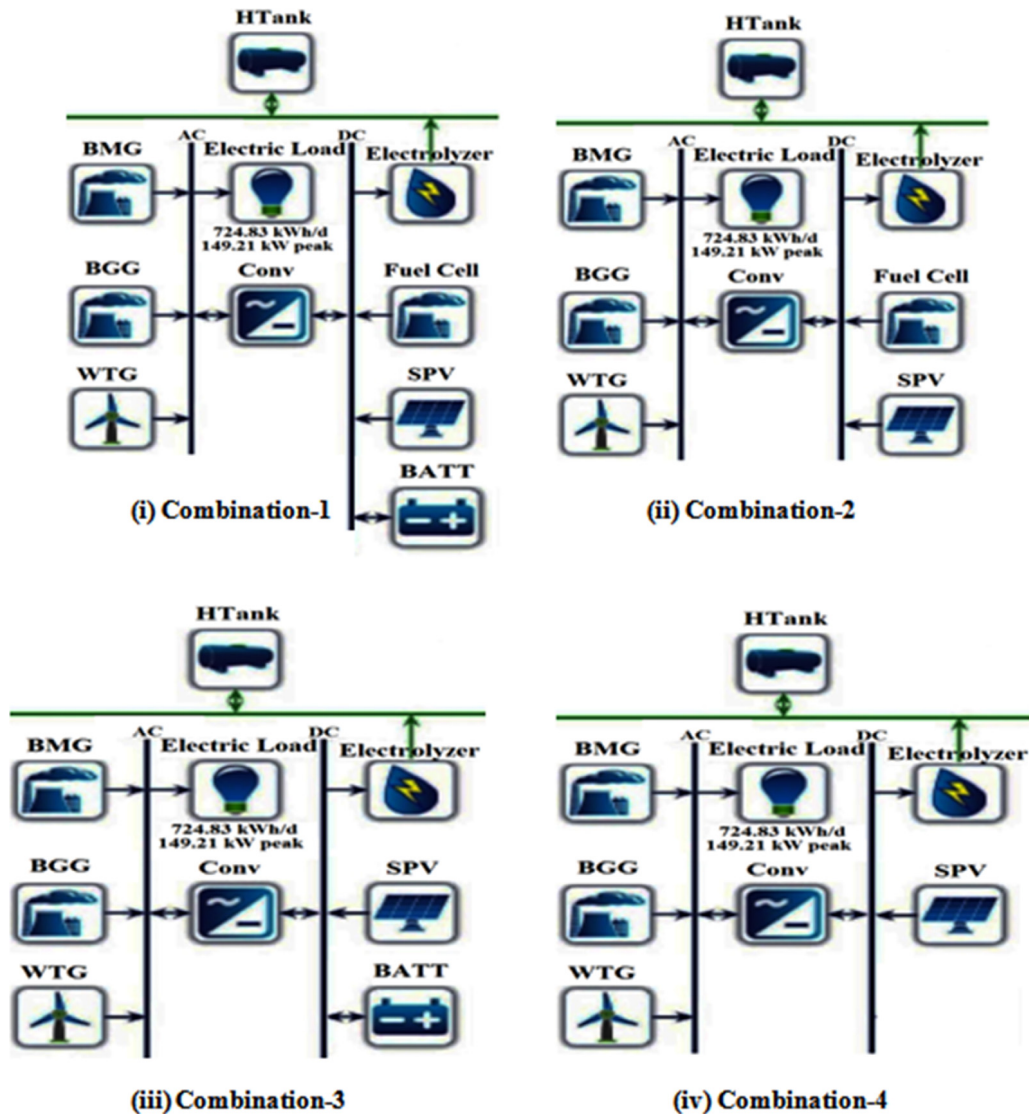


Fig. 5. Proposed HRES.

6.1.1. Combination-1: SPV-WTG-BGG-BMG-FC-BATT

In combination-1, allocation of energy sources for meeting the required energy demand in the study area are SPV, fuel cell, biogas, biomass, and wind turbine generators as shown in Fig. 5(i). The various sizes of the system are considered as SPV, fuel cell, and biogas, biomass, and wind turbine generators was 100 kW, 57 kW, 60 kW, 50 kW, and 50 numbers respectively, whereas the energy demand was estimated at 328 266 kWh/yr; and the availability of excess energy as 6.07%.

6.1.2. Combination-2: SPV-WTG-BGG-BMG-FC without battery

In combination-2, SPV, wind turbine, biogas, biomass, and fuel cell are taken into account and battery is not considered here as shown in Fig. 5(ii). The sizes of the system are considered as SPV, fuel cell, and biogas, biomass, and wind turbine generators was 100 kW, 57 kW, 60 kW, 50 kW, and 50 numbers respectively, whereas the energy demand was estimated at 396 121 kWh/yr; and the availability of excess energy as 4.86%.

6.1.3. Combination-3: SPV-WTG-BGG-BMG-BATT without fuel cell

In combination-3, SPV, biogas, biomass, wind turbine generators, and battery systems are taken into account and fuel cell system are not considered here shown in Fig. 5(iii). The sizes

of the system are considered as SPV, biogas, biomass, and wind turbine generators was 100 kW, 60 kW, 50 kW, 50 Nos., and 200 Nos. respectively, whereas the energy demand was estimated at 277 092 kWh/yr; and the availability of excess energy as 20.65%.

6.1.4. Combination-4: SPV-WTG-BGG-BMG without storage

In combination-4, SPV, biogas, biomass systems, wind turbine generators are taken into account and fuel cell battery systems are not considered here as shown in Fig. 5(iv). The sizes of the system are considered as SPV, biogas, biomass, and wind turbine generators were 100 kW, 60 kW, 50 kW, and 50 Nos. respectively, whereas the energy demand was estimated at 276 755 kWh/yr; and the availability of excess energy as 33.53%.

6.1.5. Cost breakdown of all the components

The overall cost summary of all the components of combination-1 as shown in Fig. 7. Out of certain components, biogas generator offers highest cost as \$3,20,201 and generic electrolyzer system has the lowest total cost of \$9963.

6.1.6. Monthly electricity generation

Monthly electricity generation during the proposed year for HRES are shown Fig. 8. The annual energy generated by biogas

Architecture															
SPV (kW)	WTG	BMG (kW)	BGG (kW)	Fuel Cell (kW)	BATT	Electrolyzer (kW)	HTank (kg)	Conv (kW)	Efficiency1	Dispatch					NPC (\$)
100	50	50.0	60.0	57.0	200	50.0	300	80.0	0	CC					\$890,013
100	50	50.0	60.0	57.0		50.0	300	80.0	0	CC					\$897,847
100	50	50.0	60.0		200	50.0	300	80.0	0	CC					\$929,878
100	50	50.0	60.0			50.0	300	80.0	0	CC					\$1.10M
	50	50.0	60.0	57.0		50.0	300	80.0	0	CC					\$1.14M
	50	50.0	60.0			50.0	300	80.0	0	CC					\$1.18M

Fig. 6. Optimization results.

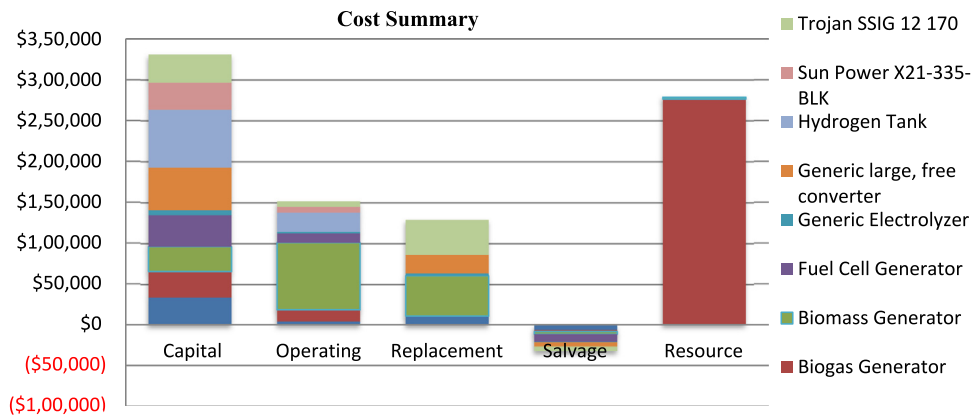


Fig. 7. Overall cost summary of all the components.

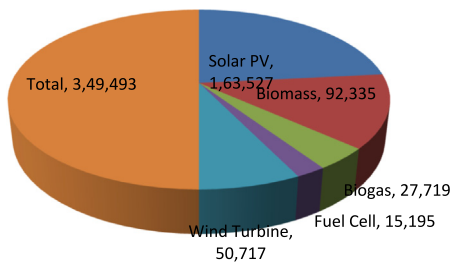


Fig. 8. Monthly electricity generation during a year.

generator, biomass generator, wind turbines, PV system and fuel cell has been arranged as 27 719 kWh/yr, 92 335 kWh/yr, 50 717 kWh/yr, 163 527 kWh/yr, and 15 195 kWh/yr correspondingly.

6.1.7. Emissions generated from the renewable energy sources

To accomplish CO₂ emissions, no costs are considered in this study. Harmful emissions generated by renewable energy sources in combination-1 are specified in a given Table 2. In which, carbon dioxide produces more harmful emissions, and sulphur dioxide produces zero emissions.

6.2. GA based simulation

Different combinations of HRES parameters are considered in the below table, optimization is done by using genetic algorithm (GA) through the procedure mentioned above. Optimization results of NPC, COE and operating cost with different combinations have been achieved using GA and the MATLAB code was developing through MATLAB R2015b environment.

Table 2

Total emissions generated by renewable energy sources for proposed system.

Contaminant	Amount
Carbon dioxide (kg/yr)	4089
Carbon monoxide (kg/yr)	148
Unburned hydrocarbons (kg/yr)	1.35
Particulate matter (kg/yr)	0.186
Sulphur dioxide (kg/yr)	0
Nitrogen oxides (kg/yr)	102

Table 3

Comparison of different HRES with NPC and COE.

Configurations	NPC (\$)	COE (\$/kWh)	Operating cost (\$)
C1	856 013	0.163	34 109
C2	862 428	0.168	36 917
C3	890 013	0.195	39 354
C4	924 637	0.214	52 148

Four combinations of HRES are obtained using GA and its obtained results are given in Table 3. The comparison details of simulation results of possible four combinations are shown in Fig. 9.

6.2.1. Convergence of GA

Convergence process of GA is obtained on the basis of optimal sizes of different sources combination are shown in Fig. 10. The figure shows that, after 75 iterations it is converges into the optimal solution for different sources combinations.

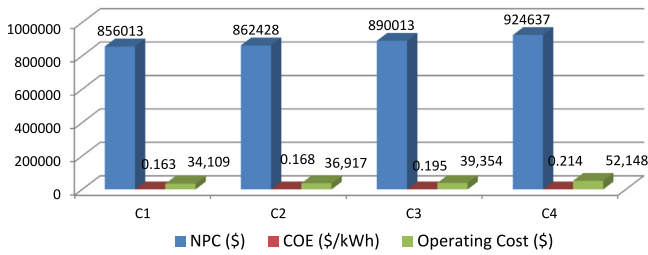


Fig. 9. Comparison of NPC, COE and Operating Cost of different configurations.

6.3. Sensitivity results

The overall system performance with selected combinations of sources is provided by sensitivity analysis. The sensitivity analysis of combination-1 is estimated for variations in annual capacity shortages, mean wind speed and a biomass fuel price using HOMER is shown in Fig. 11.

6.3.1. Variation of wind scaled average

The variation of wind scaled average in the study area is 5–8 m/s and also its effect was analysed with NPC and COE. By varying the wind scaled average from 5–8 m/s; the total NPC of combination-1 is decreased from \$8,33,607 to \$8,06,458. The variation of wind scaled average with NPC and COE are plotted in Fig. 12.

6.3.2. Variation of biomass fuel price

Various charges are included in biomass fuel price such as ventilation, compilation, transportation, labour charges etc. By varying the biomass fuel price from 0.3–0.5 \$/tonne; the COE of

combination-1 is increased from 0.214–0.215 \$/kWh. The variation of biomass fuel price with NPC and COE are plotted in Fig. 13.

6.4. Comparison of Results

The hybrid energy system is calculated based on the hourly simulation under cycle charging strategy and also in load following strategy. The load is supplied by the solar PV and fuel cell generator supplies the load when the batteries are discharged. The schematic diagram of the hybrid energy system utilized in the present study is shown in Fig. 5.

The economic results of different combination of HRES system from HOMER are shown in Fig. 6. Compared to all the other possible configurations, results of combination-1 had the minimum NPC of \$8,90,013 and least COE of 0.214 \$/kWh at 0% capacity shortage. The solar PV produces electrical energy of 1,63,527 kWh/yr from the system. At a total of 3,49,493 kWh/yr, the cost of fuel cell generator is high compared to the cost of battery.

The simulation results from HOMER and GA are given in Table 4 and its comparison is shown in Fig. 14. The results shows that, GA based optimization are more cost effective compared to the HOMER. The cost of energy of GA is 0.163 \$/kWh and HOMER is 0.214 \$/kWh. Also GA based system has more PV penetration than to the HOMER. Further the CO₂ emissions by GA are less compared to the HOMER.

7. Conclusion

The paper presents, modelling and optimization of off-grid hybrid energy system used for electrifying the cluster of three village hamlets in Kollegal block, Chamarajanagar district, Karnataka. Various factors are considered for the development of system operational strategy i.e. energy demand estimation; source

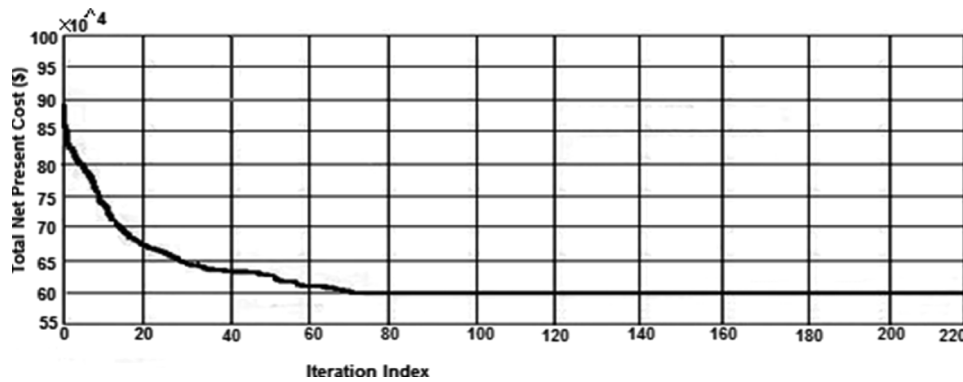


Fig. 10. GA convergence for different sources combination.

Sensitivity		Architecture												
Wind Scaled Average (m/s)	Biomass Price (\$/tonne)	SPV (kW)	WTG	BMG (kW)	BGG (kW)	Fuel Cell (kW)	BATT	Electrolyzer (kW)	HTank (kg)	Conv (kW)	Efficien			
5.00	0.300	100	50	50.0	60.0	57.0	200	50.0	300	80.0	0			
8.00	0.300	100	50	50.0	60.0	57.0	200	50.0	300	80.0	0			
5.00	0.500	100	50	50.0	60.0	57.0	200	50.0	300	80.0	0			
8.00	0.500	100	50	50.0	60.0	57.0	200	50.0	300	80.0	0			

Fig. 11. Sensitivity analysis of proposed system.

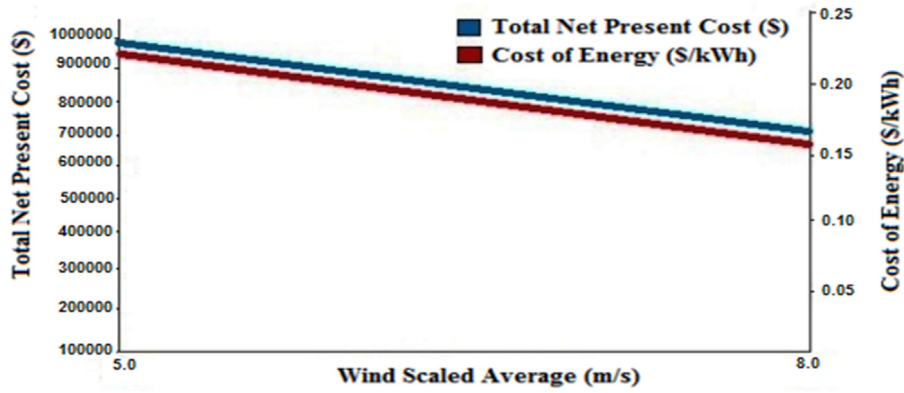


Fig. 12. Variation of annual wind scaled average.

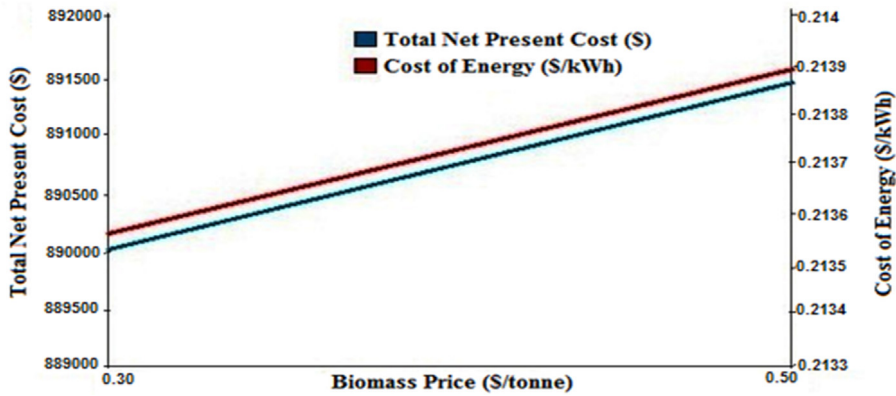


Fig. 13. Variation of biomass fuel price.

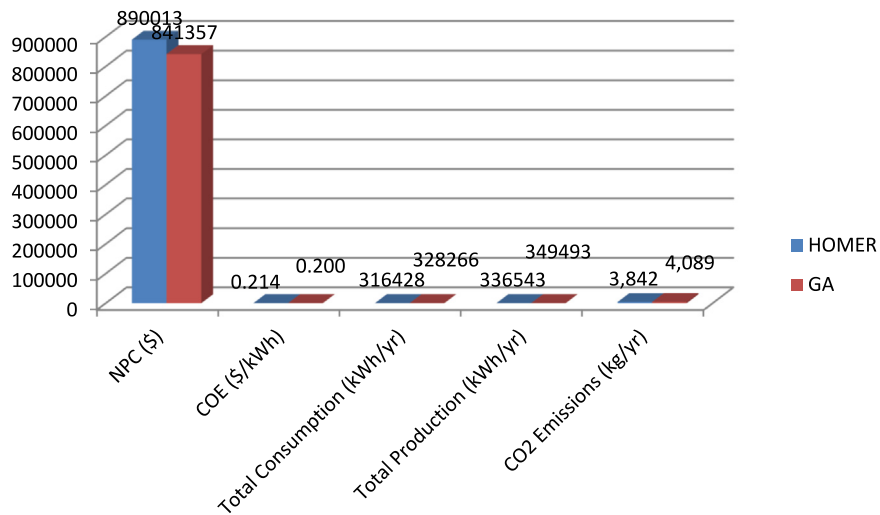


Fig. 14. Comparative analysis of proposed HRES.

Table 4
Comparative analysis of proposed HRES.

Optimization methods	GA	HOMER
Total NPC (\$)	856 013	890 013
COE (\$/kWh)	0.163	0.214
Total production (kWh/yr)	3,36,543	3,49,493
Total consumption (kWh/yr)	3,16,428	3,28,266
CO ₂ emissions (kg/yr)	3842	4089

allocation; emissions generated by the system and comparison of economic aspects. Moreover, four combinations of hybrid energy systems have been evaluated through GA and HOMER Pro software.

Four combinations namely; 1. SPV-WTG-BGG-BMG-FC-BATT, 2. SPV-WTG-BGG-BMG-FC without battery, 3. SPV-WTG-BGG-BMG-BATT without fuel cell, and 4. SPV-WTG-BGG-BMG without storage. These four combinations are considered and evaluated based on the total net present cost and cost of energy in the study area. Firstly, HOMER is evaluated by the four combinations

of HRES. Out of such combinations, the first gives minimum NPC and lowest COE of \$890 013 and 0.425 \$/kWh. Further GA based optimization is run for such four combinations with MATLAB coding, in which combination-1 offers minimum NPC and lowest COE of \$8 560 137 and 0.163 \$/kWh.

Further, a sensitivity analysis is presented for variation in annual wind speed and, biomass fuel price. The proposed system is very sensitive in the variation of biomass price from 0.3–0.5 \$/tone, and the least COE has been deviated from 0.214–0.215 \$/kWh (Ref. from Fig. 13).

Finally, comparative analysis is also presented in the study. On comparing of all the four combinations of HRES using HOMER and GA, GA based optimization is more cost-effective than to the HOMER with least COE 0.163 \$/kWh and 0% unmet load. Also GA based system has more PV penetration and less CO₂ emissions than to the HOMER. .

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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