



# Techno-economic analysis of off-grid solar/wind/biogas/ biomass/fuel cell/battery system for electrification in a cluster of villages by HOMER software

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## Abstract

Electrification of villages is a vital step for improving the techno-economic conditions of rural areas and crucial for the country's overall development. The villages' welfare is one of the main aims of the rural electrification programs. Rural electrification is relatively costly compared to electrification of urban areas. Now, the research question is to find the best combinations of HRES from the available resources in a given village location that can meet the electricity demand in a sustainable manner and to see whether this is a cost-effective solution or not. This study is an attempt to structure a model of electricity generation based on multiple combinations of HRES with the application of HOMER energy software at an identified off-grid village location in India. The main objectives of this study are to analyze the best-suited configuration of a hybrid RE system out of various combinations to meet the village load requirement reliably, continuously and sustainably. The study also reduces the total system net present cost and least cost of energy (COE) using multi-objective HOMER Pro software. In this study, a resource assessment and demand calculation have been carried out and the COE per unit has been ascertained for different systems and configurations. A combination of PV–Wind–Biomass–Biogas–FC along with battery has been identified as the cheapest and most dependable solution with a COE of \$0.214/kWh.

**Keywords** Hybrid renewable energy system · Solar PV · Fuel cell system · Wind system · Biomass/biogas system · HOMER pro software

## Abbreviations

HOMER            Hybrid optimization model of electric renewable  
COE                Cost of energy

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TNPC	Total net present cost
ELE	Electrolyzer
HRES	Hybrid renewable energy system
BATT	Battery
DSM	Demand side management
FC	Fuel cell
LCOE	Least cost of energy
SPV	Solar photo voltaic
BMG	Biomass generator
BGG	Biomass generator
WTG	Wind turbine generator
SOC	State of charge
H <sub>2</sub> Tank	Hydrogen storage tank
DOD	Depth of discharge
CRF	Capital recovery factor
PEM	Polymer electrolyte membrane

### List of symbols

$\gamma$	Annual interest (%)
$h_{BGG}$	No. of hours operated in BGG
$\tau$	Plant life
$\sigma$	Hourly self-discharge rate
\$	US dollars
$h_{BMG}$	No. of hours operated in BMG
C1, C2, C3, C4	Four combinations of HRES model
Egen	Generation of annual energy (kWh)

## 1 Introduction

Sustainable and environmentally friendly renewable sources like solar PV, wind, fuel cells, biogas, and biomass are the most growing energy sources in building a nation with a strong economy. But a renewable source of energy experiences a number of restrictions while used in a stand-alone application. The power produced from wind turbine and solar PV is particularly dependent on environmental factors, while fuel cells need hydrogen-enriched fuel. Biomass/biogas energy generating systems are sophisticated technologies that have been developed newly and are extensively used in stand-alone mode for the rural area energy demands. Fuel cells produce a huge amount of potential in the future green sources as of numerous advantages for example high efficiency, zero emissions, and flexible structure. To conquer these problems, solar and wind energy sources are combined with other sources. A hybrid renewable energy system (HRES) is formed by making more number of renewable resources. Therefore, to obtain higher efficiency by making best use of their characters as overcoming their restrictions (Vendoti et al. 2018; Rajanna and Saini 2016a). Electrification in rural areas is enforced by technical barriers like restricted transmission, hard terrains, and highly dispersed area with low population distinguished by lower education, load density, and revenues.

This paper focuses on designing of rural electrification solutions considering hybrid renewable energy systems for rural remote areas. Off-grid hybrid systems often are the

least-costly; they are a long-term energy solution and capable of delivering the best services of the three alternatives. Adverse environmental effects such as greenhouse gas emission, global warming, and climate change, etc., has promoted focus on alternate energy generations like solar, wind, hydro, tidal, and biogas, etc. In recent years, application of renewable energy sources for electrification is becoming economically feasible due to rapid development of relevant technologies (Halabi et al. 2017).

The remoteness of the majority villages and other physical boundaries make the addition of the electricity grid and different facilities using conservative energy distribution networks almost incomprehensible or uneconomic. Moreover, the absences of the basic facilities in the rural and remote areas are rising rapidly; the rush of urban immigration is immersing the developing world. Such trends have to be arrested and upturned successfully to avoid the dangerous unbalanced growth. To accomplish this, electricity must be provided in the remote and rural area also in sustainable manner (Hossain et al. 2017). For the immediate future, the challenge is to provide electricity at a cost-effective basis to rural remote areas as well to improve the quality of life and slow down the mass migration to the cities. In other words, electricity should migrate to the remote areas instead of the people migrating to the cities where the electricity is available. Engineers have to design size- and cost-based hybrid renewable energy systems and optimize its applications in rural areas for electrification in off-grid manner.

Rajanna and Saini (2014) developed a HOMER-based hybrid renewable energy system to determine the different cost components, for example net present cost and cost of energy. Rajanna and Saini (2016b) also developed the hybrid system using genetic algorithm to fulfill the energy needs of various load sections within the rural villages in Chamarajanagar, Karnataka (India). Chauhan and Saini (2016a) proposed sizing-based hybrid renewable energy system to deliver the uninterrupted power supply to fulfill the energy demands within the study area. They were found in different combinations of resources on optimum cost of the hybrid energy system models using discrete harmony search algorithm. Chauhan and Saini (2016b) also presented a comparative study of DSM-based hybrid energy system through load shifting strategy. They suggested that with demand side management strategy is most cost feasible solution than without demand side management strategy.

Olatomiwa et al. (2015) developed different configurations of hybrid energy system with six geopolitical zones of Nigeria. They determined economic feasibility solution using HOMER software with sensitivity cases of \$1.1–\$1.3/1 based NPC and COE. Olatomiwa et al. (2018) also presented a statistical analysis of wind and solar energies potentials for rural areas in Nigeria based on the availability of meteorological data. It employs design and sizing of an optimal technical and economic hybrid energy system components using HOMER software. Olatomiwa et al. (2015) also compared the two best optimal system configurations namely, PV–diesel–battery and PV–wind–diesel–battery systems with the conventional system. They indicated that PV array (10 kW), DG (5.5 kW), battery (64 units) is the most economically viable option with the TNPC of \$69,811 and COE of 0.409 \$/kWh.

Kumar et al. (2017) 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 are evaluated techno-economic optimal design of a PV–BG–Battery–PHES-based HRES and compared 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 to review 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. (2018) implemented the design analysis of hybrid solar PV/fuel cell/battery-based system for cluster of villages in India. Two storage devices are considered; both are producing electricity as well as storage. But, a battery stores energy inside it. It also makes energy like that of a fuel cell making its electricity through an external storage tank. Batteries are used for the most part, for instantaneous use while for continued usage hydrogen storage is profitable. Jamshidi and Askarzadeh (2018) presented a multi-objective design of a photovoltaic, fuel cell and diesel generator 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.

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

The main contributions of the paper are listed below:

1. A novel hybrid renewable energy system (HRES) was developed for size and cost optimization problems in remote areas.
2. The best-suited configuration of a hybrid RE system out of various combinations to meet the village load requirement reliably, continuously and sustainably.
3. The minimized COE generation from the hybrid renewable energy system.
4. System performance is examined and compared with four combinations of stand-alone HRES with minimum value of NPC and COE.
5. Combination of solar–wind–biomass–biogas–fuelcell–battery system leads to having an efficient system.
6. Sensitivity analyses are also carried out for variation in annual wind speed and biomass fuel price with COE and NPC.
7. 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 resource assessment. Sections 3 and 4 explain the mathematical modeling of all system components and problem formulation. Section 5 gives the details of HOMER Pro software. Section 6 shows the results and discussions, and Sect. 7 concludes the paper.

## 2 Methodologies

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

### 2.1 Case study

Chamarajanagar district, Karnataka (India), is selected for the case study, in which a cluster of three un-electrified village-hamlets are established ([http://www.ddugjy.gov.in/portal/state\\_wise\\_summary1.jsp?StateCode=29](http://www.ddugjy.gov.in/portal/state_wise_summary1.jsp?StateCode=29)). The study consists of total 408 households and 1686 populations (Rajanna 2016). Majority of the population in these areas are living in hilly terrains; supplying energy into these areas is difficult so that expansion of the grid is not a viable solution. Renewable energy source availability is enormous in this study area as solar, wind, biomass, and biogas; these are used in stand-alone mode. The plot of geological location is shown in Fig. 1, and information regarding the cluster of three villages is given in supplementary information Table 1 (List of Villages/Towns, Census of India 2011).

### 2.2 Energy demand assessment

The study area has presently low electrical energy demand, but as the electrical power will be generated near to the villages, the energy consumption is expected to increase with time. Therefore, electrical energy demand of the study area has been estimated considering the future requirements of the cluster of village hamlets.

Based on the energy needs within the study, principal data is collected from the locals through surveys with variety of sections like domestic load, agricultural load, community load, and commercial load sections. Energy demands is mainly constituted as lighting for health center, primary school, shops, street lighting, water pumping, and small industries load. The estimation of total load within the study area is specified as supplementary information Table 2. The total load in kWh per day within the area is estimated as 724.83 kWh/

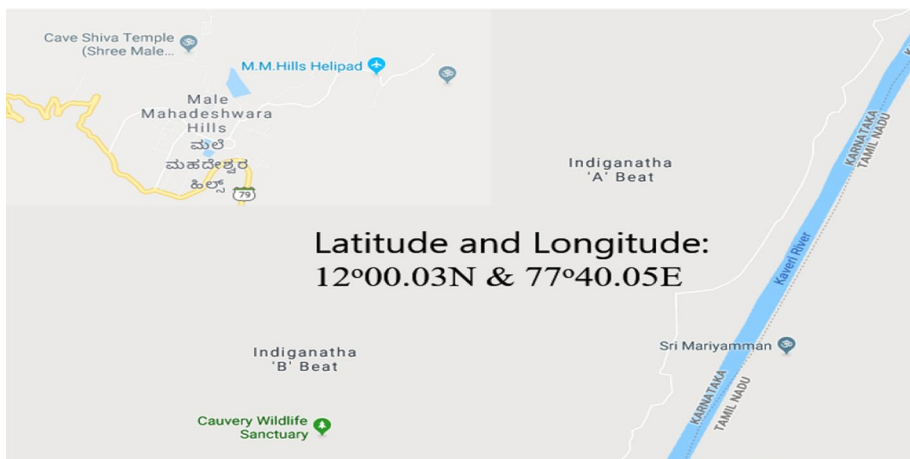


Fig. 1 Geographical location in the study area

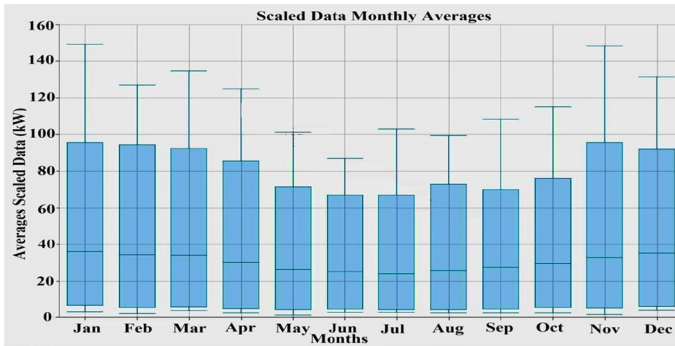


Fig. 2 Monthly load profiles within the study

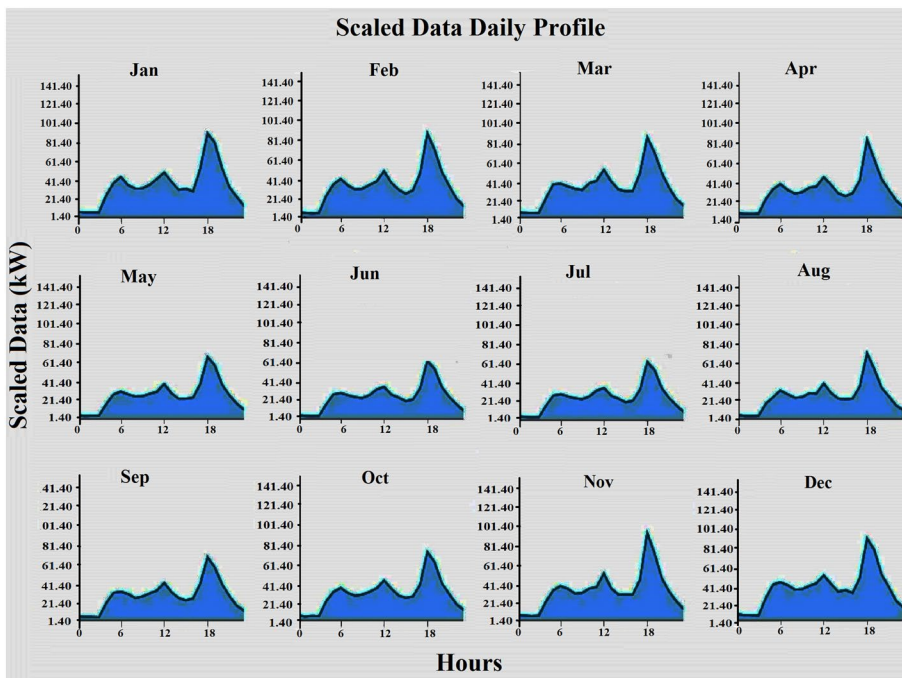


Fig. 3 Hourly load profile within the study

day. The yearly energy consumption was obtained based on hourly load using HOMER pro software as 701,263 kWh/year. Hourly and monthly load profiles in the study area are shown in Figs. 2 and 3.

### 2.3 Source assessment

The study area has enormous potential of renewable energy resources like biomass (forest foliage), biogas (cattle dung), solar irradiation and wind speed. The availability of solar

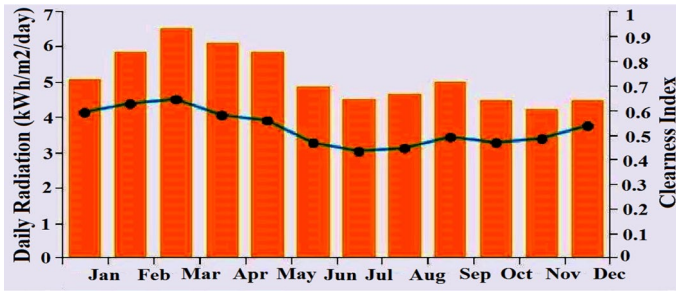


Fig. 4 Monthly solar radiation available (<http://www.nrel.gov/international/homer>)

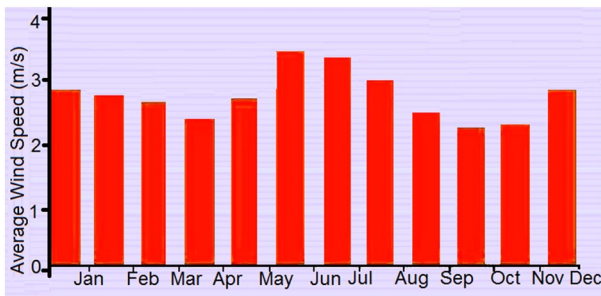


Fig. 5 Monthly average wind speed available (<http://www.nrel.gov/international/homer>)

irradiation and wind speed details of study area are as available for the year 2018. The HOMER Pro software calculates the global horizontal solar radiation, average wind speed and optimum size of the system based on the longitude and latitude of a given geographical location. The selected study area is located at 11°59' N latitude and 77°00' E longitude. The solar irradiation and wind speed data for this location was obtained from HOMER Pro software (<http://www.nrel.gov/international/homer>).

### 2.3.1 Annual solar radiation

Annual daily solar irradiation available within the study location is shown in Fig. 4. Highest solar irradiation is available as 6.43 kWh/m<sup>2</sup>/day in March month, whereas lowest as 4.11 kWh/m<sup>2</sup>/day was found in November month.

### 2.3.2 Scaled annual wind speed

Annual average wind speed available within the study location is given in supplementary information Table 3 and their plot is shown in Fig. 5 (Rajanna 2016). The measured value within the study area was found as 2.85 m/s.

### 2.3.3 Annual average of biomass and biogas

The availability of biomass and biogas potentials within the study location are estimated as: biomass potential from forest foliage is 107.79 tons/year and biogas potential from cattle dung is 372 m<sup>3</sup>/day (Rajanna and Saini 2016b). Monthly available biomass resource in study location is shown in Fig. 6. Brief information about all the renewable energy source availability within the study location is outlined in supplementary information Table 3.

## 3 Mathematical modeling of system components

For size optimization, mathematical modeling of hybrid energy system components is a significant step to providing its performance under different situations. Mathematical modeling 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) (Chauhan and Saini 2017):

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

where  $V_{mppt}$  is the maximum power point voltage (in Volts),  $\alpha$  is the coefficient of temperature,  $G_{tt}$  is the measured value of irradiation (in kW/m<sup>2</sup>),  $G_{st}$  is the standard value of irradiation (in 1 kW/m<sup>2</sup>), and  $T_a$  is the variable temperature (in K).

The output current of a solar PV module ( $I_{SPV}$ ) is calculated by using Eq. (2):

$$I_{SPV}(t) = I_{ph}(t) - I_{rs}(t) [\exp (qV_{PV}/N_sKT_a(t)A_i) - 1] \quad (2)$$

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

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  $N_{SPV}$  is the number of PV modules and  $\Delta t$  is the step time as 15 min.

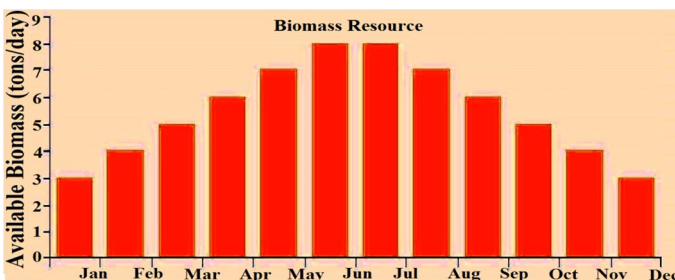


Fig. 6 Monthly available biomass resource (<http://www.nrel.gov/international/homer>)



### 3.2 Wind turbine system

Mathematical model of wind turbine is proposed based on the actual power curve supplied by the manufacturer. The characteristic equations of a wind turbine have been developed by fitting its actual power curve using method of least number of squares (Thapar et al. 2011). Following equations are used to predict the power output of a wind turbine ( $P_{WT}$ ) in kW as:

$$\begin{aligned}
 P_{WT}(t) &= 0, & \text{for } V < V_{ci} \\
 P_{WT}(t) &= aV^2 + bV + c, & \text{for } V_{ci} < V < V_r \\
 P_{WT}(t) &= P_r, & \text{for } V > V_{co}
 \end{aligned}
 \tag{4}$$

where  $V$  is the actual value of wind turbine speed,  $V_{ci}$  is the cut in speed,  $V_{co}$  is the cut out speed,  $V_r$  is the rated speed of the wind turbine, and  $a, b, c$  are the coefficient of quadratic equations.

Rated power of the wind turbine can be calculated by using Eq. (5) as:

$$Pr = 1/2C_p\rho_a\eta_gA_wV_r^3 \tag{5}$$

where  $A_w$  is the swept area of wind turbine rotor;  $\rho_a$  is the air density;  $C_p$  is the power coefficient of the proposed wind turbine;  $\eta_g$  is the generator efficiency.

Total energy generated by wind turbine system ( $E_{WT}$ ) is expressed by Eq. (6):

$$E_{WT}(t) = (N_{WT} \times P_{WT}(t) \times \Delta t) / 1000 \tag{6}$$

where  $N_{WT}$  is 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 (7) (Kanase-Patil et al. 2011);

$$E_{BGG} = \frac{\text{Biogas availability (m}^3/\text{day)} \times CV_{BGG} \times \eta_{BGG} \times \Delta t}{860 \times h_{BGG}} \tag{7}$$

where  $E_{BGG}$  is the hourly energy output of biogas generator;  $\eta_{BGG}$  is the system conversion efficiency,  $CV_{BGG}$  is the calorific value of biogas digester (4700 kcal/kg).

### 3.4 Biomass system model

Based on the forest foliage availability, the hourly energy generated by the biomass generator was determined using the equation expressed by (8) (Kanase-Patil et al. 2011);

$$E_{BMG} = \frac{\text{Biomass availability (kg/year)} \times CV_{BMG} \times \eta_{BMG} \times \Delta t}{365 \times 860 \times h_{BGG}} \tag{8}$$

where  $E_{BMG}$  is output energy generated from biomass generator;  $\eta_{BMG}$  is the system conversion efficiency;  $CV_{BMG}$  is 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 the backup in rural area applications. These are very clean; it generates nearly no emissions and are characterized by high efficiency. Hydrogen is the primary fuel in fuel cell systems, while oxygenate as the extant. Particular forms of fuels are used in fuel cells such as methane, ethanol, fuels based on biomass, etc., depending on type of fuel cell system. Out of different types FC systems, PEM fuel cell is used in commercial purpose available in industrial applications and also it has a reliable performance under unbalanced supply. Such types of fuel cells are used for large-scale power generation. The output power of a FC was determined by Eq. (9) (Garcia and Weisser 2006);

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

where  $P_{\text{tank-FC}}$  is the power output of fuel cell and  $\eta_{FC}$  efficiency of a fuel cell.

*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, after which hydrogen is collected from the anode. Most of the surveys, output of the electrolyzer exactly coupled the hydrogen storage tank (Khan and Iqbal 2005; El-Shatter et al. 2006; Nelson et al. 2006).

The power transferred from electrolyzer to hydrogen storage tank has been estimated by Eq. (10);

$$P_{\text{elec-tank}} = P_{\text{ren-elec}} \times \eta_{\text{elec}} \quad (10)$$

where  $P_{\text{ren-elec}}$  is the output power from renewable energy system to electrolyser, and  $\eta_{\text{elec}}$  is the electrolyzer efficiency in which assumed as constant.

The output energy of a stored hydrogen at a time step of 't' is expressed by Eq. (11);

$$E_{\text{H2,tank}}(t) = E_{\text{H2,tank}}(t-1) + [P_{\text{elec,tank}}(t) - (P_{\text{tank,FC}}(t) / \eta_{\text{storage}})] \times \Delta t \quad (11)$$

where  $P_{\text{tank-FC}}$  is the output power of a fuel cell,  $\eta_{\text{storage}}$  as the efficiency of hydrogen storage and  $P_{\text{elec,tank}}$  is the power transferred from electrolyzer to hydrogen storage tank.

### 3.6 Battery bank system

The energy production and its consumption from the state of battery are connected at any time from  $(t-1)$  to  $t$ . In the charging process, power generation exceeds the load demand. The availability of power in the battery bank at a specified time expressed by the given Eq. (12) (Kanase-Patil et al. 2011):

$$E_{\text{Batt}}(t) = E_{\text{Batt}}(t-1) + E_{\text{EE}}(t) \times \eta_{\text{CC}} \times \eta_{\text{CHG}} \quad (12)$$

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

The quantity of state of charging in battery is expressed by the given the quantity of state of charging in battery is expressed by the given Eq. (13);

$$\text{SOC}_{\text{min}} < \text{SOC} < \text{SOC}_{\text{max}} \quad (13)$$

where  $SOC_{min}$  is the value of minimum SOC;  $SOC_{max}$  is the maximum value of SOC assumed as 1. Minimum value of SOC is obtained using the following Eq. (14),

$$SOC_{min} = 1 - DOD \tag{14}$$

### 3.7 Bi-directional converter system

One of the important parts in hybrid energy system component is bi-directional converter. The main role of this converter is flow of current into either direction during extra power charging into the battery. Main function of this device is to provide the necessary power from batteries also DC sources into the load. The size of this converter based on the energy levels in minimum or maximum.

## 4 Problem formulation

HOMER simulation is not possible without the financial parameters. This study consists of annual real interest rate, net present cost (NPC), cost of energy (COE), initial capital cost, and replacement cost for the different system configurations.

The net present cost (or life-cycle cost) of a component is the present value of all the costs of installing and operating that component over the project lifetime, minus the present value of all the revenues that it earns over the project lifetime. Net present cost contains several costs such as capital, replacement, maintenance and operation, fuel costs, etc. HOMER calculates the net present cost of each component of the system and of the system as a whole. HOMER calculates the total NPC using the following equation as (Om Krishan and Sathans 2018):

$$C_{NPC} = C_{anc, tot} / CRF(\gamma, \tau) \tag{15}$$

where  $C_{NPC}$  is the total net present cost (\$);  $C_{ann, tot}$  is the total annualized cost in \$/year;  $\gamma$  is the annual interest rate (%); CRF is the capital recovery factor and  $\tau$  is the plant life time (years).

The levelized cost of energy (COE) is defined as average cost per kWh of useful electrical energy produced by the system. The equation of COE used in HOMER is:

$$COE = C_{anc, tot} / (E_{primary} + E_{differable} + E_{gridsales}) \tag{16}$$

where COE is the cost of energy;  $C_{ann, tot}$  is the total annualized cost in \$/year;  $E_{primary}$  is the primary load served (kWh/year);  $E_{differable}$  is the deferrable load served (kWh/year); and  $E_{gridsales}$  is the total grid sales.

Capital recovery factor is depending on rate of annual interest ( $\gamma$ ) and plant life ( $\tau$ ) and is expressed by given Eq. (17) as (Rajanna and Saini 2016c):

$$\text{Capital Recovery Factor (CRF)} = \frac{\gamma(1 + \gamma)^\tau}{\gamma(1 + \gamma)^\tau - 1} \tag{17}$$

In this study, the design of the hybrid system is done by entering the required resource parameters into the HOMER software. In mathematical modeling 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 the given supplementary information Tables 4 and 5 (Vendoti et al. 2017; Barsoum and Petrus 2015; Nowdeh and Hajibeigy 2013).

## 5 HOMER software

HOMER Programming (Created by National Renewable Energy Laboratory, USA) is utilized to build up the hybrid renewable energy system in these studies (<http://www.nrel.gov/international/homer>). 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 and as well as grid integrated systems.

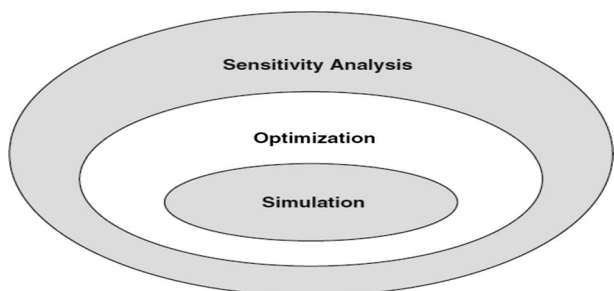
HOMER performs three principal tasks: simulation, optimization, and sensitivity analysis. In the simulation process, HOMER models the performance of a particular micro-power system configuration each hour of the year to determine its technical feasibility and life-cycle cost. In the optimization process, HOMER simulates many different system configurations in search of the one that satisfies the technical constraints at the lowest life-cycle cost. In the sensitivity analysis process, HOMER performs multiple optimizations under a range of input assumptions to gauge the effects of uncertainty or changes in the model inputs. Optimization determines the optimal value of the variables over which the system designer has control such as the mix of components that make up the system and the size or quantity of each. Sensitivity analysis helps assess the effects of uncertainty or changes in the variables over which the designer has no control, such as the average wind speed or the future fuel price.

Figure 7 shows the relationship between simulation, optimization, and sensitivity analysis using HOMER. The optimization oval encloses the simulation oval to signify the fact that a single optimization consists of multiple simulations. Similarly, the sensitivity analysis oval encompasses the optimization oval because a single sensitivity analysis consists of multiple optimizations. The sensitivity factors are the world solar radiation, cost of wind turbine, biomass fuel price, and cost of the battery, etc.

Different combinations of renewable energy sources available in the study area evaluated through HOMER are shown in Fig. 8. The HRES comprises of biomass generator (BMG), biogas generator (BGG), solar PV generator (SPV), wind turbine generator (WTG), fuel cell system (FC), electrolyzer (Elect), hydrogen storage tank (H<sub>2</sub>Tank), converter (Conv.), and battery (Batt) systems.

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 is connected to solar and fuel cell systems. The availability of surplus power in the battery when it exceeds the loads is used to the electrolyzers which energize to produce hydrogen (H<sub>2</sub>) and store it into hydrogen tanks. The stored energy is used to run the fuel cell generator to meet the required loads during energy shortages to other sources.

**Fig. 7** Relationship between simulation, optimization and sensitivity analysis using HOMER



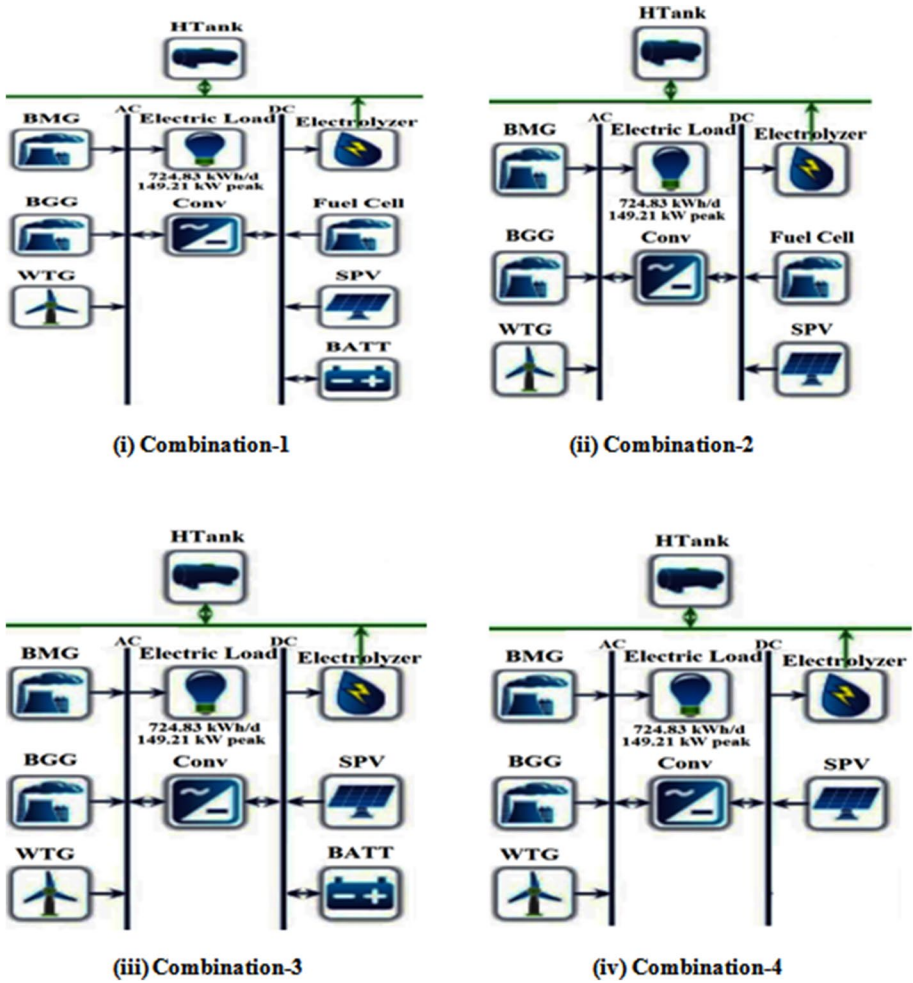


Fig. 8 Different combinations of HRES

## 6 Results and discussions

In the simulation process, HOMER estimates the cost and at the same time determines the feasibility of hybridized energy system over the years with a list of system configurations and their capacities are sorted based on lowest COE and NPC. After hourly simulation, different configurations of HRES generated as shown in Fig. 9. In this study among many configured energy systems, four different scenarios are evaluated to find

Architecture														Efficiency1	Dispatch	NPC (\$)
SPV (kW)	WTG	BMG (kW)	BGG (kW)	Fuel Cell (kW)	BATT	Electrolyzer (kW)	HTank (kg)	Conv (kW)								
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					
100	50	50.0	60.0	57.0		50.0	300	80.0	0	CC	\$1.14M					
50	50.0	60.0	57.0			50.0	300	80.0	0	CC	\$1.18M					

Fig. 9 Optimization results

the optimized system configuration. They are, both technically and economically, discussed below:

*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. These are shown in Fig. 8(i). In combination, it was found that minimum NPC was \$8,90,013 and least COE of 0.214 \$/kWh at 0% had a capacity shortage. The size of the systems considered by SPV, fuel cell, biogas, biomass, and wind turbine generators was 100 kW, 57 kW, 60 kW, 50 kW, and 50 no’s, respectively, whereas energy demand was estimated at 328,266 kWh/year. The total power generated from this scenario is 163,527 kWh. The contribution from the PV is 46.8% of the total power, and the rest 53.8% comes from the other sources. It is also evident from the result that the excess energy production is 6.07% of the total energy generation, and this system is used to fully satisfy the load requirement. The estimated values of total NPC, COE, and operating cost are given Table 1.

*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 (Fig. 8(ii)). The size of the systems considered by SPV, fuel cell, biogas, biomass, and wind turbine generators was 100 kW, 57 kW, 60 kW, 50 kW, and 50 no’s, respectively, whereas energy demand is estimated as 396,121 kWh/year; the

Table 1 Estimated values of total NPC, COE, and operating cost

Combination-1	TNPC (\$)	COE (\$/kWh)	Operating cost (\$)
<b>C1</b>	890,013	0.214	34,109

Table 2 Estimated values of total NPC, COE, and operating cost

Combination-2	TNPC (\$)	COE (\$/kWh)	Operating cost (\$)
<b>C2</b>	897,847	0.215	36,917

**Table 3** Estimated values of total NPC, COE, and operating cost

Combination-3	TNP (\$)	COE (\$/kWh)	Operating cost (\$)
C3	929,878	0.223	39,354

**Table 4** Estimated values of total NPC, COE, and operating cost

Combination-4	TNPC (\$)	COE (\$/kWh)	Operating cost (\$)
C4	10,95,020	0.263	52,148

availability of excess energy is 4.86%. The estimated values of total NPC, COE, and operating cost are given in Table 2. Although this system is comparable to combination-1 regarding COE, and NPC, this system has slightly higher capital cost. The contribution of energy from PV modules and other systems to the total energy generation are around 39.3% and 60.7%, respectively. From the above discussion, it is evident that the combination-2 is quite similar to combination-1 both economically and environmentally. Ironically, marginally higher capital and replacement cost and a small contribution of fuel cell generator makes combination-2 complicated and not more attractive as combination-1. The estimated values of total NPC, COE, and operating cost are given in Table 2.

*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 (Fig. 8(iii)). The size of the systems considered as SPV, biogas, biomass, and wind turbine generators was 100 kW, 60 kW, 50 kW, 50 no's, and 200 no's, respectively, whereas energy demand is estimated as 277,092 kWh/year. The results also reveal that the SPV–WTG–BGG–BMG–BATT hybrid system generates higher excess energy compared to previous two cases. Additionally, a large number of batteries require frequent maintenance which makes the system infeasible for a remote area like this. The total value of NPC, COE, and operating costs of this combination are listed in Table 3.

*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 (Fig. 8(iv)). The size of the systems of SPV, biogas, biomass, and wind turbine generators considered was 100 kW, 60 kW, 50 kW, and 50 no's, respectively, whereas energy demand is estimated as 276,755 kWh/year; the availability of excess energy is 33.53%. The total NPC (\$10,95,020) is almost 30% higher than the last three configurations. The total value of NPC, COE, and operating costs of this combination is listed in Table 4. From Table 4, it is evident that the COE and NPC are quite comparable with the combination-3 but way higher than the first two combinations.

*Cost breakdown of all the components* The overall cost summary of all the components of combination-1 is shown in Fig. 10. Out of certain components, biogas generator offers high cost as \$3,23,201 and generic electrolyzer system has the lowest total cost of \$9963. The total cash flow analyses of the selected HRES in combination-1 are shown in Fig. 11. From the cash flow analysis, the total capital cost is \$3,52,710 and total replacement cost is \$1,32,421.

*Monthly electricity generation* Monthly electricity generation during a year for proposed HRES are shown Fig. 12. The annual energy generated by biogas generator, biomass generator, wind turbines, PV system and fuel cell has been arranged as 27,719 kWh/

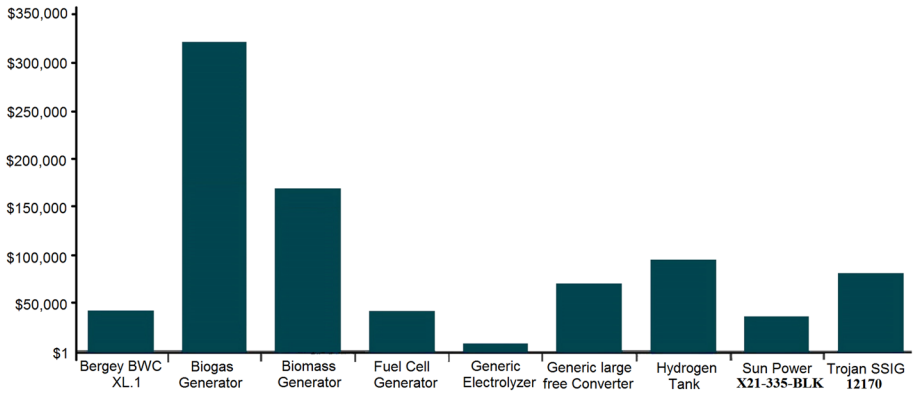


Fig. 10 Overall cost summary of all the components

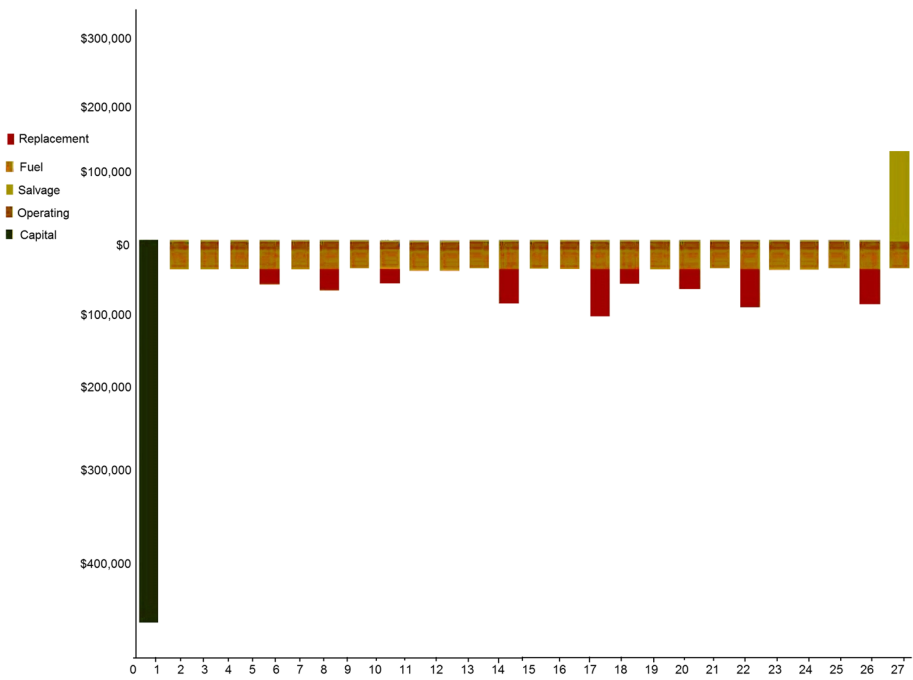


Fig. 11 Cash flow analysis of total cost in combination-1



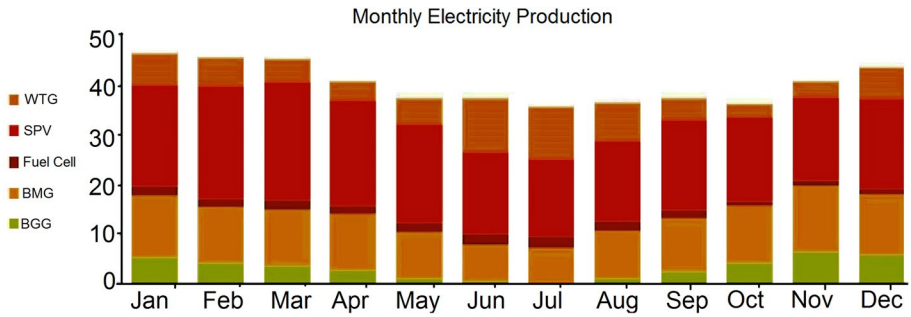


Fig. 12 Monthly electricity generation during a year

Table 5 Total emissions generated by renewable energy sources for proposed system

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

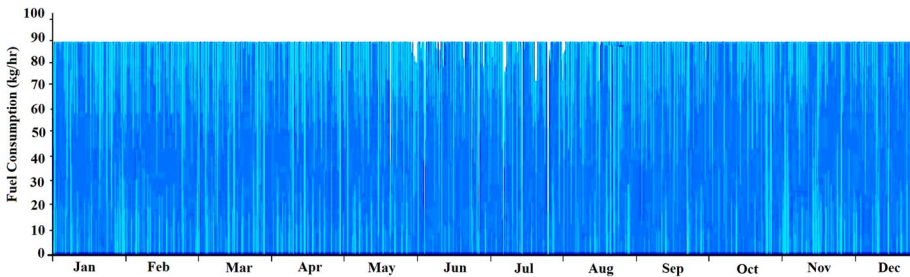
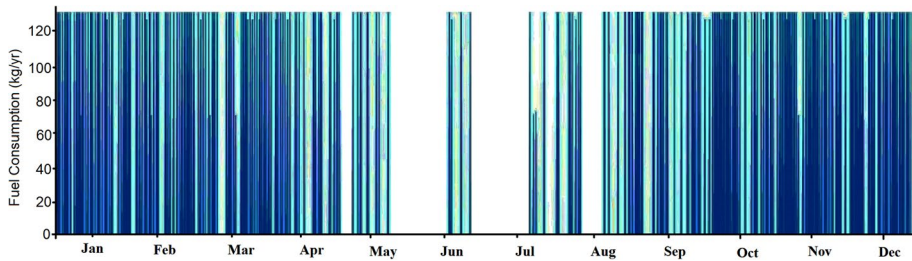


Fig. 13 Monthly fuel summary of biomass



**Fig. 14** Monthly fuel summary of biogas

year, 92,335 kWh/year, 50,717 kWh/year, 163,527 kWh/year, and 15,195 kWh/year correspondingly.

*Emissions generated from the renewable energy sources* To accomplish CO<sub>2</sub> emissions, no costs are considered in this study. Harmful emissions generated by renewable energy sources in combination-1 are specified in a given Table 5. Here, carbon dioxide produces the more harmful emissions, and sulfur dioxide produces the zero emissions.

*Effect of fuel summary* In this study, the fuels are considered as biogas, biomass, and stored hydrogen. The average biomass feedstock consumed per day is 1.28 tons per day and its consumption during the year is shown in Fig. 13. The average consumption of biogas fuel per day is 160 kg/day and monthly consumption of biogas fuel is shown in Fig. 14. The average consumption of stored hydrogen to run the fuel cell generator per day is 3.84 kg/day and monthly consumption of stored hydrogen is shown in Fig. 15.

*Comparison of economic aspects* Comparison of the economic aspects of base system and current system of proposed system with different parameters considered is shown in Fig. 16.

*Optimal configuration (SPV–WTG–BGG–BMG–FC–BATT)* In this study, economic indicators and environmental emissions are the two criteria based on which optimal configuration has been selected. Among the four combinations, the configuration of combination-1 is considered as the most cost-effective hybrid system because of its low cost of energy (COE) of 0.214\$/kWh and NPC of \$890,013. Although, combination-2 gives the appropriate results in terms of COE, the replacement and operating costs and emissions are higher than the combination-1. The comparative analyses of all four configurations are given Table 6 and their graphical representations are shown in Fig. 17.

Compared to the all possible configurations, results of combination-1 were found that minimum NPC as \$8,90,013 and least COE of 0.214 \$/kWh at 0% capacity shortage. Hence, the best possible configuration of resources combination-1 (SPV–WTG–BGG–BMG–FC with Battery) has been proposed. This configuration offers minimum cost and fulfills required energy demand in the study area. Figure 11 is the representation of monthly energy generation by the different components of the optimized hybrid energy system (SPV–WTG–BGG–BMG–FC–BATT). The contribution of PV is maximum in every monthly energy generation, whereas the contribution of fuel cell increases slowly from January up to July then it is starts decreasing. It is evident from the maximum share of load demand fulfilled by the PV and in absence of PV; battery bank is used to satisfy the load requirements. However, when neither solar PV nor battery bank is able to meet the demand, the fuel cell generator is introduced to meet the demand. The proposed hybrid system emitted CO<sub>2</sub> approximately 4089/year. It is also

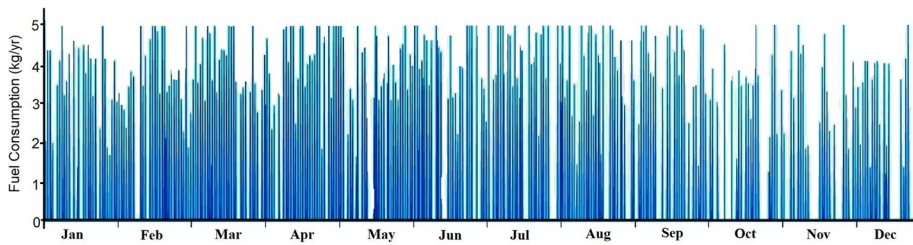


Fig. 15 Monthly fuel summary of stored hydrogen

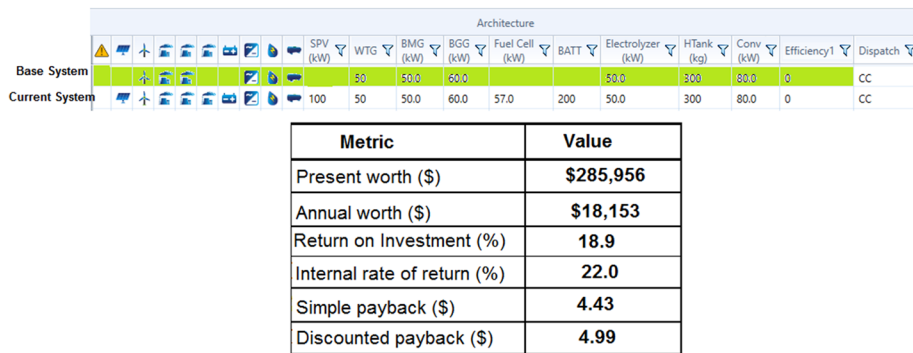


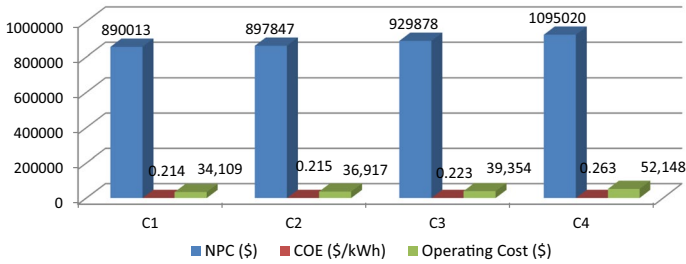
Fig. 16 Comparison of economics

Table 6 Comparison of different HRES with NPC and COE

Configurations	NPC (\$)	COE (\$/kWh)	Operating cost (\$)
C1	890,013	0.214	34,109
C2	897,847	0.215	36,917
C3	929,878	0.223	39,354
C4	1,095,020	0.263	52,148

obvious that CO<sub>2</sub> emission from the optimized system is significantly lower than that of the conventional system.

The hybrid power system can contribute to the rural community with better living standards, raising economic activities, empowering women, safety, employment opportunities, and sustainable development. The hybrid power system will also contribute much more in the case of having a green environment. Finally, the benefits of selling the electricity to the local consumers and the national grid would help to reduce the excess energy substantially. In this regard, government and private organizations should come forward to overcome these hurdles to implement the stand-alone hybrid power system. Integration of renewable energy resources to the conventional system not only reduce the greenhouse gas emissions but also improve the reliability of supplying electricity to meet the required load demand.



**Fig. 17** Comparison of NPC, COE and operating cost of different configurations

## 7 Conclusions

Four different configurations of HRES are compared in this paper comprising of PV–wind–biomass–biogas–fuel cell–battery, PV–wind–biomass–biogas–fuel cell, PV–wind–biomass–biogas–battery and PV–wind–biomass–biogas systems. Various factors are considered for the development of system operational strategy, i.e., energy demand estimation; source allocation; monthly electricity generations; cost breakdown analysis; and emissions generated by the system. Moreover, four combinations of hybrid energy systems have been designed and evaluated through HOMER Pro software.

Comparing all the possible configurations, results of combination-1 was found to have minimum NPC as \$8,90,013 and least COE of 0.214 \$/kWh at 0% capacity shortage. This configuration offers minimum cost and fulfills required energy demand in the study area. In summary, the PV/wind/biomass/biogas/fuel cell/battery have lowest COE and NPC among the system configurations and are fully capable of meeting the load requirements of the studied area. Hence, the best possible configuration of resources combination-1 (SPV–WTG–BGG–BMG–FC with Battery) has been proposed by this study. The size of the proposed systems considered are 60 kW biogas, 50 kW biomass, 50 kW wind turbine, 100 kW solar, 323 kWh battery storage systems and 80 kW converters. The results also shows the monthly electricity generation produced by the proposed HRES, total emissions generated, cash flow analysis, cost breakdown at each system components and comparison of economics in base system and the proposed system.

Based on the environmental constraints and availability of fossil fuels, stand-alone hybrid energy systems are preferred in the near future. Future research would involve the integration of other renewable energy sources. It also seeks to include grid systems, generation expansion planning, and load profiles with other renewable generators. This would provide a wide range for analyzing the economic and technical advantages of different system configurations. The economical comparison between different combinations of hybrid system is presented in Table 6.

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