Clean Technologies and Environmental Policy (2018) 20:1323–1341
https://doi.org/10.1007/s10098-018-1562-y

ORIGINAL PAPER

Distributed polygeneration using local resources for an Indian village: multiobjective optimization using metaheuristic algorithm

Avishek Ray[1] · Kuntal Jana[1] · Mohsen Assadi[2] · Sudipta De[1]

Received: 3 January 2018 / Accepted: 7 June 2018 / Published online: 14 June 2018

Abstract
Introduction of renewable energy systems is an imperative need at present. Hybridization of locally available different renewable resources is required due to intermittency of these resources. A multicriteria optimization using cuckoo search algorithm for simultaneous best combination of economy, land use and GHG emission has been carried out for polygeneration with three utility outputs. These are electricity, heat and high calorific value gas. The levelized cost of electricity at 100% reliability of power supply has come out to be 0.1 USD/kWh. For better economy, a minimum plant life of 20 years is desired. This study is with data for a small hilly village of India with mostly poor people. Methodology and results of this study represent optimization of such sustainable energy systems using local resources in specific sites.

Keywords Polygeneration · Lévy flights · Metaheuristic · Levelized cost of electricity

List of symbols

Abbreviations

AI	Annualized investment (USD)
CSA	Cuckoo search algorithm
CV	Calorific value (kJ/kg)
FC	Fuel cell
GA	Genetic Algorithm
H	Hydrogen
LCOE	Levelized cost of electricity (USD/kWh)
LPSP	Loss of power supply probability
PEM	Proton exchange membrane
PV	Photovoltaic
PSO	Particle swarm optimization
UL	Unmet load
WT	Wind turbine

Symbols

I_T	Total radiation on a tilted surface (W/m^2)
I_b	Total beam radiation on a surface (W/m^2)
r_b	Tilt factor for beam radiation
I_d	Total diffuse radiation on a surface (W/m^2)
r_d	Tilt factor for diffuse radiation (W/m^2)
r_r	Tilt factor for reflected radiation (W/m^2)
θ	Incidence angle of solar radiation (°)
θ_z	Zenith angle (°)
δ	Declination angle (°)
β	Slope of the solar collector (°)
φ	Latitude (°)
ω	Hour angle (°)
ρ	Albedo
α_1	Temperature coefficient of open-circuit voltage (V)
α_2	Temperature coefficient of short-circuit current (V)
$I(t)$	Instantaneous output current of solar module (A)
$I_{incident}$	Solar radiation falling on the module at time t (W/m^2)
BG_{avail}	Availability of biogas per day (m^3/day)
CE_{total}	Total initial cost of the electrolyzer (USD)
CFC_{total}	The total cost of fuel cell installation (USD)
CH_s	Total cost of hydrogen storage (USD)
CM	Annualized maintenance cost (USD/year)
CF	Annualized fuel cost (USD/year)
CP_{elec}	Cost of electrolyzer per watt (CHF)
CP_{fc}	Cost of fuel cell per watt (USD)
CP_{sol}	Cost of PV module per watt (USD)
CP_{total}	Total cost of PV module (USD)

✉ Sudipta De
de_sudipta@rediffmail.com; sde@mech.jdvu.ac.in

[1] Department of Mechanical Engineering, Jadavpur University, Kolkata 700032, India

[2] Faculty of Science and Technology, University of Stavanger, 4036 Stavanger, Norway

$CFC_{installed}$	Total installed capacity of the fuel cell system (kW)
C_{eqb}	Cost of biogas system of capacity b (USD)
C_{eqa}	Cost of biogas system capacity a (USD)
CV_h	Calorific value of hydrogen (kJ/kg)
CV_{bio}	Calorific value of biogas (kJ/m^3)
CV_g	Calorific value of the gaseous mixture (kJ/kg)
C_g	Cost of gaseous mixture (USD/kg)
C_p	Betz limit
CP_{fc}	Cost of fuel cell per watt (USD)
C_{WH}	Annualized cost of waste heat recovery system (USD)
CH_{kg}	Cost incurred to transport 1 kg of hydrogen (USD)
CH_s	Initial cost of hydrogen storage (USD)
CW_{total}	Total initial investment for wind turbine installation (USD)
$W_{installed}$	Installation capacity of wind turbine (kW)
$CW_{inperkW}$	Cost of wind turbine per kW (USD)
E_t	Total units of electricity generated in the life of the plant to cater the local load (kWh)
$EL_{installed}$	Installed capacity of electrolyzer (kW)
E_{fc}	Electricity generated by the fuel cell (kW)
$E_{deficit}$	Yearly electrical energy deficit (kWh/year)
G	Total GHG emission (g-CO_2)
G_s	Emission factor of solar module (g-CO_2)
F_g	Emission factor of fuel cell (g-CO_2)
FC_{ins}	Total installed capacity of the fuel cell system (kW)
G_d	Emission factor of biogas digester (g-CO_2)
G_g	Emission factor of biomass gasifier (g-CO_2)
H_d	Maximum hydrogen required per day (kg)
$H_{elec}(t)$	Instantaneous amount of hydrogen produced (kg)
H_{fc}	Amount of hydrogen fed to fuel cell (kg)
H_{kg}	Cost incurred to store 1 kg of hydrogen in metal hydride tank (USD/kg)
H_y	Total amount of hydrogen transported per year (kg)
i	Bank discount rate (%)
n	Economic life of the system (years)
L	Total land requirement (m^2)
L_{sol}	Land requirement for 1 kW of PV installation (m^2)
L_{bio}	Land requirement for 1 kW of biogas installation (m^2)
L_{wind}	Land requirement for 1 kW of WT installation (m^2)
NF_{LCOE}	Normalization factor for LCOE
NF_L	Normalization factor for land requirement
NF_G	Normalization factor for GHG emission
OP	Operating hours of gas engine per annum (h)
$P_{sol}(t)$	Instantaneous output power of solar module (kW)
P_{load}	Total electrical load in a year (kWh)
$PV_{installed}$	Installed capacity of PV module (kW)
R_y	Revenue earned per year (USD)
R_G	Annualized revenue earned from hydrogen selling (USD)
R_{WH}	Annualized revenue from waste heat (USD)
s	Scale factor for costing of wet biogas systems
$T_{failure}$	Yearly total power failure time (h/year)
T_{total}	Total hours of operation of the plant (h)
$V(t)$	Instantaneous voltage output of solar module (V)
$W_{installed}$	Total capacity of wind turbine (kW)
W_f	Weighing factor for LCOE
W_L	Weighing factor for land requirement
W_G	Weighing factor for GHG emission

Introduction

The consumption of energy and economic development are very closely linked. Developed societies generally have per capita energy consumption higher than that of the developing societies (Toman and Barbora 2003). Presently, the world is mostly dependent on the fossil fuel resources for the supply of energy. Currently, around 78% of electricity need of the world is met by the centralized fossil fuel-based power plants. Out of the fossil fuels, coal is most predominant (around 40%) followed by the natural gas and petroleum, respectively (US Energy Information Administration 2017). There is an expectation of 40% rise in energy consumption by 2040 (USDOE 2016). But fossil fuel reserves are also fast depleting besides having several environmental impacts; most severe is the global warming due to greenhouse gas (GHG) emission. Coal-based power plants emit 50 g-CO_2 equivalent/kWh even with best practices (UK Carbon Footprint 2016).The Intergovernmental Panel of Climate Change (IPCC) has predicted 1.6°–6.3° Fahrenheit rise in global average temperature by 2100 (Climate Change 2016). There is a need to use of renewable sources of energy which are nondepleting and clean in terms of GHG emission. However, these renewable resources are intermittent and dilute in nature. Moreover, limited amount of these resources is available at a particular location depending on the geographical conditions and several other factors including population, livelihood of the local people. So to increase the capacity further technology development with scaled up systems are necessary. Another option is to combine different renewable resources available in a particular locality to increase the capacity of the electricity generation with these limited intermittent resources. This is formally called "hybridization." The technological development of the renewable energy systems is still developing and scaling up of renewable energy systems for large power supply is yet to be matured. Small-scale distributed systems may be a better option at present. These systems reduce the transmission and distribution (T&D) loss and capacity can be optimized with the available resources and local demand. These systems are also good options to electrify the un-electrified hamlets in India where the extension of national grid is impossible due to terrain conditions or other socio-economic factors. Integrating other utility outputs in a single unit formally called "polygeneration" makes it even more beneficial and socioeconomically feasible. So these systems need to be designed matching with the local electricity load and other utility requirements. The process integration and generation of useful chemicals enhance the environmental and economic sustainability of systems (Sadhukhan et al. 2015). The design of the polygeneration systems has several objectives as well as constraints and boundary conditions. It has been observed that even in the conventional coal-fired power plants synthesis of other chemicals through the polygeneration route proves to be beneficial both thermodynamically and economically (Ng et al. 2012). So multicriteria optimization is the only option for designing these systems based on the objectives of policy and planning.

Several optimization algorithms exist but all may not be suitable for optimizing a particular system. Hence, the choice of suitable algorithm is also another important issue in this regard. Chauhan and Saini (2016) used the discrete harmony search-based optimization technique for designing the Integrated Renewable Energy System for supplying electricity to some un-electrified villages of the Uttarakhand state of India. Jana and De (2015a) designed a suitable polygeneration system using biomass as the local resource. They have shown that 20% of the primary energy savings is achieved by the process integration. This also leads to the reduction of 25 kt carbon dioxide emission per annum. Kriakarakos et al. (2011) presented a concept of designing a polygeneration system using a battery bank, proton exchange membrane (PEM) fuel cell, PEM electrolyzer and a metal hydride tank, a reverse osmosis-based desalination unit using heat recovery and control system for the supply of power, potable water and hydrogen as the transportation fuel. They have used the Monte Carlo simulation method to take the uncertainty into account. Results of their study show that the polygeneration is technically feasible and profitable with a probability of 90% at present and 100% in the medium term. The use of renewable energy sources like biogas has proved to be efficient economically in UK perspective (Sadhukhan 2014). Ng et al. proposed a polygeneration scheme producing bio-oil. The bio-oil can be treated as an environmentally benign feedstock but at the same time the economic competitiveness of the bio-oil was yet to be judged. The polygeneration scheme along with the electricity generation (Ng and Sadhukhan 2011). Ng et al. showed that the addition of chemicals in addition to the electricity increases the economic competitiveness of the polygeneration system (Ng et al. 2013). Ng et al. has done a comparative study between the biomass gasification combined cycle (BGCC) and biomass gasification fuel cell system (BGFC). It was found that BGFC system provides twice power than that of the BGFC system. It is observed that increasing power generation from BGFC system decreases the power generation efficiency but at the same time the combined heat and power (CHP) efficiency increases (Sadhukhan et al. 2010). Lam et al. (2016) proposed that process integration is an efficient way for energy savings and energy targeting. This paper has emphasized on the recovery of the industrial process heat. Belgana et al. (2013) designed a hybrid renewable energy system with photovoltaic (PV) panel, wind turbine, diesel generator set and a battery bank using the multiobjective optimization technique to optimize the annualized system cost and the reliability of power supply of the system. So economic feasibility and environmental effect assessment have to be assessed before the introduction of a new renewable energy system. So, optimization of a new small-scale renewable energy system is a multicriteria problem. Kriakarakos et al. (2015) designed a polygeneration system using multicrystalline solar module, fuel cell, electrolyzer unit, desalination unit. In this system, the battery can be replaced by a capacitor bank with more intensive use of hydrogen-based systems. Ng et al. (2012) showed that there is a significant improvement in the thermodynamic and economic potential through suitable balanced polygeneration system.

This group of authors is studying polygeneration as a sustainable energy solution from different viewpoints over a period. Starting from component design (Jana and De 2015a, b), performance assessment (Jana and De 2015c), economic feasibility study with real data (Jana and De 2015d), environmental impact assessment (Jana and De 2016, 2017) and finally possible optimization with definite objective functions and real boundary conditions (Ray et al. 2017) are reported in their several publications. In this paper, a multicriteria optimization study is carried out using a metaheuristic algorithm "cuckoo search algorithm (CSA)" to determine a possible optimum solution for a distributed generation with three utility outputs and using local renewable resources only. Real data of a typical Indian village of northern hilly area of the state of Uttarakhand have been studied in this work. Extension of national grid to this area is practically not feasible due to terrain conditions. An estimation of the feasibility and possible optimum solution with multiobjectives and several boundary conditions and constraints are done using CSA. A comparison with the other algorithms like genetic algorithm (GA) and particle swarm optimization (PSO) has also been made. The codes of all these algorithms are developed in MATLAB 2013. Methodology is generic for such optimization problems but, the results may vary depending on the type of system, available data, constraints and boundary conditions. In this case, the site-specific study is done. The multiobjective optimization using a metaheuristic algorithm, i.e., cuckoo search algorithm is carried out here. Obtained results may be useful for the policy makers to decide feasibility of future introduction of such distributed polygeneration system using local resources as a possible future sustainable solution.

Materials and methods

In this paper, a distributed polygeneration system has been proposed to meet the local energy needs of a small village in India. This area has solar, wind, cattle dung (biogas resource) and biomass (straw) resources, which can be used to cater to the energy demand of the local people. The optimum capacities of the various components of the polygeneration system for minimized levelized cost of electricity (LCOE), land requirement and greenhouse gas (GHG) emission are estimated by CSA. The three utility outputs are electricity, cooking gas with high calorific value and heat. Till date, no standardized power dispatch strategy is there for the multigeneration system. However, "ideal predictive power dispatch strategy" is used in this hybrid system. This strategy is used as this proves to be economically the best solution for decentralized power plants using hybrid renewable energy systems (Barley and Winn 1996). The electricity is fed to the local microgrid of this polygeneration to meet the local demand matching the load curve. This village is located in a very cold area with occasional snowfall during winter, moderate rainfall during monsoon and a mild summer (National Institute of Disaster Management 2016). In such villages, there is a need for heating which is included as a utility output in this polygeneration system. Excess hydrogen, which is not used to produce electricity, will be mixed with the biogas and thereby enhancing the calorific value of the biogas. The capacities of the components of the proposed polygeneration system are optimized using CSA with three objectives (1) to minimize the LCOE (2) to minimize land requirement (3) to minimize GHG emission. The multiobjective optimization is carried out using weighted sum method. Comparison has also been made with a few other metaheuristic algorithms like genetic algorithm (GA) and particle swarm optimization algorithm (PSO), with number of iterations constant for all the cases.

System description

The proposed renewable energy-based polygeneration system is modeled using solar PV module, wind turbine, gasifier–gas engine, biogas digester, PEM electrolyzer and a PEM fuel cell as shown in Fig. 1. During the daytime, the solar module generates power which is fed to the local microgrid to meet the local load. The domestic and the agricultural load are predominant in this region as industries are practically nonexistent in such rural areas of India. The seasonal variations of loads along with the electricity generation from the solar and wind resources in the four different seasons are shown in Fig. 2a–d. The excess electricity after meeting the load is fed to the PEM electrolyzer to produce hydrogen, which is stored in the metal hydride tanks. The metal hydride storage is used as it is safer and volume efficient than other hydrogen storage options (Muller and Marmejo 2017). The hydrogen stored is used in a PEM fuel cell to produce electricity and waste heat. The capacity of the electrolyzer is estimated so that it can cater to the maximum load even in the absence of solar energy. So when the load is low, there is excess hydrogen. The excess hydrogen is stored in metal hydride tanks. The stored hydrogen is mixed with the biogas for higher calorific value (CV) of the gas mixture. The resultant gaseous mixture contains hydrogen and biogas in the ratio of 2:3. During night hours, the electrical load is met by the electricity coming from the fuel cell, the gas engine and the wind turbine. The quality of fuel cell water is distilled water standard (Tibaquira et al. 2016). It is again fed back to the electrolyzer.

Modeling of the PV system

The solar insolation is incident on the solar panels generating electricity. The module is placed south facing. The total solar radiation on a tilted surface is given by Eq. (1) (Ghribi et al. 2013). The solar system modeling is done in TRNSYS17 as shown in Fig. 3

$$I_T = I_b r_b + I_d r_d + \left(I_b + I_d\right) r_r \tag{1}$$

where I_T is the total radiation on a tilted surface, I_b is the beam radiation on a tilted surface, r_b is the tilt factor for beam radiation, I_d is the diffuse radiation, r_d is the tilt factor for diffuse radiation, r_r is the tilt factor for the reflected radiation. For this case, the reflected radiation is assumed to be negligible.

The tilt factor for the beam radiation r_b for a south facing surface is given by Eq. (2) (Solanki 2009).

$$r_b = \frac{\mathrm{Cos}\theta}{\mathrm{Cos}\theta_Z} \tag{2}$$

where θ is the incidence angle of the solar insolation and θ_Z is the zenith angle.

The angle of incidence θ for a south facing surface is given by Eq. (3) (Solanki 2009)

$$\mathrm{Cos}\theta = \mathrm{Sin}\delta\mathrm{Sin}(\varphi - \beta) + \cos\delta\cos\omega\cos(\varphi - \beta) \tag{3}$$

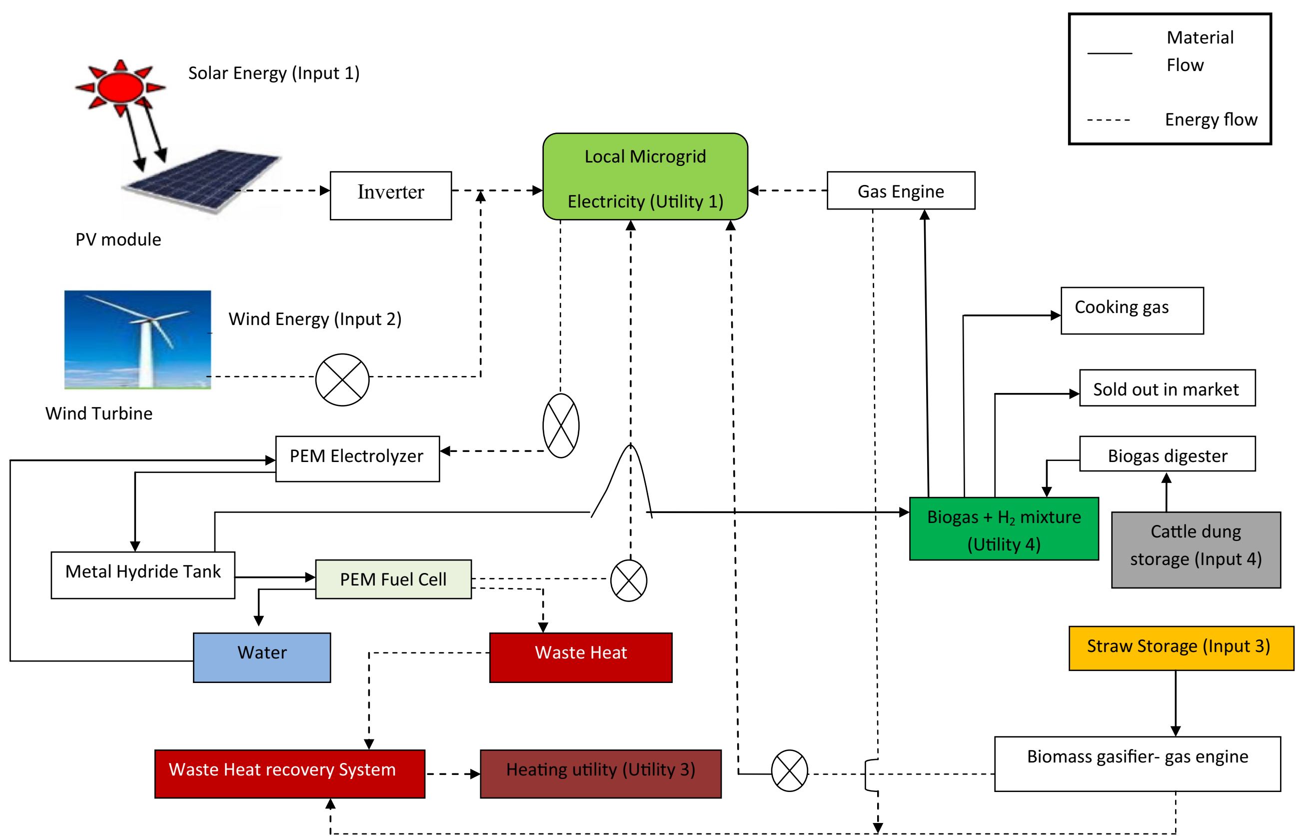


Fig. 1 Schematic of the polygeneration system

where δ is the declination angle, β is the slope of the collector, which is equal to the latitude of the place for this paper, φ is the latitude and ω is the hour angle.

The Zenith angle θz for a collector facing south is given by Eq. (4) (Sukhatme 2003)

$$\mathrm{Cos}\theta_Z = \sin\delta\sin(\varphi-\beta) + \cos\delta\cos(\varphi-\beta)\cos\omega \tag{4}$$

The tilt factor for diffuse radiation r_d is given by Eq. (5) (Sukhatme 2003)

$$r_d = \frac{1+\mathrm{Cos}\beta}{2} \tag{5}$$

The tilt factor for the reflected radiation is given by

$$r_r = \frac{(1-\mathrm{Cos}\beta)\rho}{2} \tag{6}$$

where ρ is the albedo.

The instantaneous output voltage $V(t)$ and instantaneous output current $I(t)$ of a PV module is given by Eqs. (7) and (8), respectively (Chauhan and Saini 2016)

$$V(t) = V_{\max}\left[1 + 0.0539\log\left(\frac{I_{\text{incident}}}{I_{\text{standard}}}\right)\right] + \alpha T_a(t) + 0.02 I_{\text{incident}} \tag{7}$$

where $V_{\max}$ is the open-circuit voltage of the module, I_{incident} is the solar insolation falling on the module at time t and I_{standard} is the standard insolation (1000 W/m^2), α is the temperature coefficient of open-circuit voltage and T_a is the ambient temperature.

$$I(t) = \left[I_{sc} + \alpha_1 T_a(t) - T_{(r)}\right] \times \frac{(I_{\text{incident}})}{(I_{\text{standard}})} \tag{8}$$

where I_{sc} is the short-circuit current of the module, α_1 is the temperature coefficient of short-circuit current and T_r is the reference temperature.

The instantaneous power of the solar module $P_{sol}(t)$ is given by

$$P_{sol}(t) = I(t) \times V(t) \tag{9}$$

Modeling of the biogas system

The biogas is produced in an anaerobic biogas digester from the cattle dung available in the village. The biogas is mixed with the hydrogen in a ratio of 2:3. The mixing of hydrogen with biogas results to produce a gaseous mixture which has higher CV than biogas. Less than 50% of the gaseous mixture

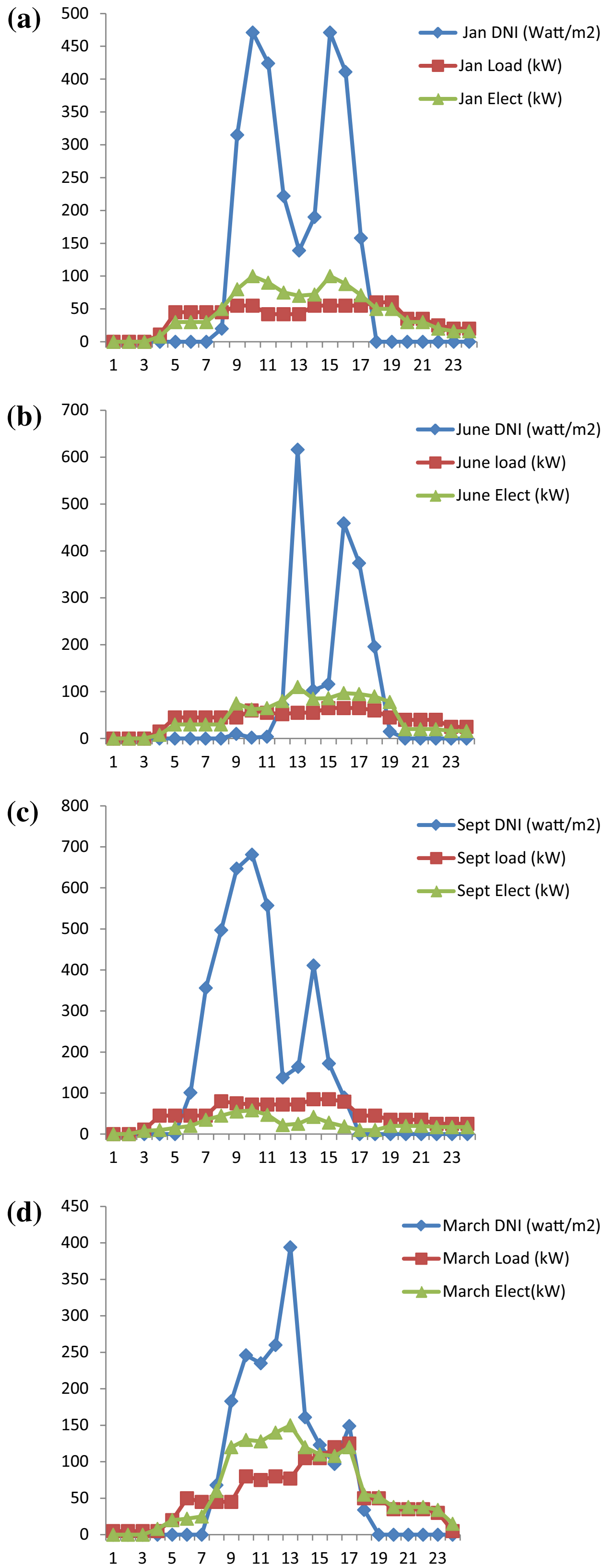


Fig. 2 Load curve and solar radiation pattern of **a** winter, **b** rainy, **c** autumn, **d** summer

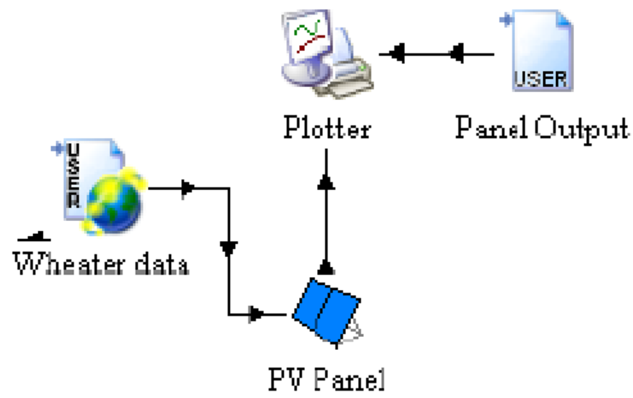


Fig. 3 TRNSYS model for output of a solar PV module

is used by local villagers for cooking purpose and meeting electricity load at night. The excess gas is sold out. The rest is used in the gas engine to produce electricity at night as estimated by Eq. (10).

$$P_{\text{biogas}}(t) = \frac{\text{BG}_{\text{avail}} \times \text{CV}_{\text{bio}} \times \eta_{\text{bio}}}{\text{OP}} \tag{10}$$

where BG_{avail} is the biogas available per day, CV_{bio} is the calorific value of the biogas, η_{bio} is the efficiency of the gas engine and OP is the operating period (in hours) of the engine per day.

Modeling of the PEM electrolyzer

The instantaneous amount of hydrogen $H_{\text{elect}}(t)$ produced by the PEM electrolyzer is given by Eq. 11.

$$H_{\text{elect}}(t) = \frac{E_{\text{elec}}(t) \times \eta_e}{\text{CV}_{\text{h}}} \tag{11}$$

where $E_{\text{elec}}(t)$ is the instantaneous electricity consumed by the electrolyzer, CV_{h} is the calorific value of hydrogen and η_e is the efficiency of the electrolyzer.

Modeling of the PEM fuel cell

The hydrogen generated by the electrolyzer is stored in a metal hydride tank. Then, the hydrogen is fed to the fuel cell to generate electricity. The electricity generated by the fuel cell E_{fc} is given by Eq. 12.

$$E_{\text{fc}} = H_{\text{fc}} \times \text{CV}_{\text{h}} \times \eta_{\text{fc}} \tag{12}$$

where H_{fc} is the amount of hydrogen fed to fuel cell, CV_{h} is the calorific value of hydrogen and η_{fc} is the efficiency of the fuel cell.

The waste heat generated by the fuel cell W_{fc} is given by Eq. 13.

$$W_{fc} = H_{fc} \times CV_h \times \frac{(100 - \eta_{fc})}{100} \quad (13)$$

where H_{fc} is the amount of hydrogen fed to the fuel cell, and η_{fc} is the efficiency of the fuel cell.

Modeling of wind turbine

The instantaneous power output P_{wind} of a wind turbine is given by Eq. 14.

$$P_{wind} = 0.5 \times A \times \sigma \times v^3 \times C_p \quad (14)$$

where A is the area of the wind front intercepted by the rotor blades, σ is the density of air, v is the wind velocity and C_p is Betz limit. The velocity of wind for this location is taken from NASA Web site as shown in Fig. 4 (NASA Surface Meterology 2017). The density of air is assumed as 1 kg/m^3 and the swept area is assumed to be 12.6 m^2.

Formation of the gaseous mixture

The gaseous mixture is formed by the mixture of hydrogen and biogas in the ratio of 2:3. The calorific value of 1 kg of gaseous mixture, CV_g, is given by Eq. 15

$$CV_g = 0.4 \times CV_h + 0.6 \times CV_{bio} \quad (15)$$

where CV_h is the calorific value of hydrogen and CV_{bio} is the calorific value of biogas.

Load curve

The load curve or the electricity demand of this study is taken from the literature as shown in Fig. 2a–d (Kanse-Patil et al. 2011).

Calculation of land requirement

The land requirement L for the entire polygeneration is given by

$$L = L_{sol} \times PV_{installed} + L_{bio} \times BG_{installed} + L_{wind} \times W_{installed} \quad (16)$$

where L_{sol} is the land requirement per kW of PV installation as shown in Table 1, $PV_{installed}$ is the total PV capacity installed, L_{bio} is the land requirement per kW of biogas as shown in Table 1, $BG_{installed}$ is the installed capacity of the biogas plant. The land requirement of the fuel cell is neglected as it is very small compared to the other three. It is also assumed that the two biomass-based systems (biomass gasifier and biogas digester) will have a large area shared.

Calculation of GHG emission

$$G = G_s \times PV_{installed} + F_g \times F_{installed} + G_d \times BG_{installed} + G_g \times G_{installed} + W_g \times W_{installed} \quad (17)$$

where G is the total GHG emission, G_S is the emission factor of solar module, F_g is the emission factor of fuel cell, $F_{installed}$ is the installed capacity of the fuel cell, G_d is the emission factor of the biogas digester, $BG_{installed}$ is

Table 1 Land requirement for solar, biogas and wind systems (Reproduced with permission from Chauhan and Saini 2016)

Serial no.	Name of renewable energy technology	Land required (m^2/kW)
1	Solar PV	30
2	Biogas system	144
3	Wind	110
4	Biomass systems	90.20

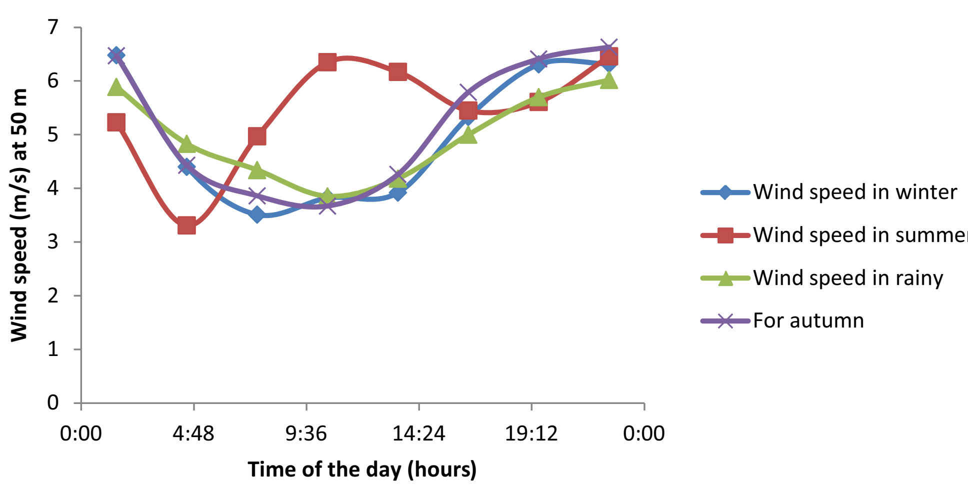


Fig. 4 Variation of wind speed over a day in various seasons

Table 2 Emission potential for solar, wind, biogas, biomass and fuel cell systems (Reproduced with permission from Tester et al. 2006)

Serial No	Name of component	Emission potential (g-CO_2/kWh)
1	SPV	98
2	Biogas system	70
3	Wind	100
4	Fuel cell	20
5	Biomass gasifier systems	65

the installed capacity of the biogas digester, and G_g is the emission factor of biomass gasifier, $G_{installed}$ is the installed capacity of the biomass gasifier, W_g is the emission factor for wind turbine and $W_{installed}$ is the installed capacity of wind turbine. The emission factors are given in Table 2. The emission factors considered here are based on the life cycle assessment of the wind, biomass and the solar systems with on the cradle to grave analysis, i.e., considering the emissions from collecting the raw materials of the product to their final disposal.

Optimization scheme

Cuckoo search

In the present paper, the comparison of cuckoo search algorithm is made with the other metaheuristic algorithm by developing codes in MATLAB 2013. The flowcharts for all the algorithms are shown in Fig. 5. Cuckoo search is a nature-inspired metaheuristic algorithm that has been broadly used for solving complex optimization problems (Tester et al. 2006). CSA is based on the brood parasitism of the cuckoo species. It also uses a balanced composition of a local random walk and global explorative random walks, controlled by a switching parameter p_a. The local random walk can be defined by Eq. (18) (Yang 2014)

$$x_i^{t+1} = x_i^t + \alpha s \emptyset H(u)\left(p_a - \epsilon\right)\emptyset\left(x_j^t - x_k^t\right) \tag{18}$$

x_j^t and x_k^t are two different candidate solutions selected randomly by random permutation, $H(u)$ is a heaviside function, ϵ is a random number drawn from a uniform distribution, α is the step size scaling factor and s is the step size. Here, $\emptyset$ stands for the entry-wise product of two vectors.

On the other hand, the global random walk is carried out by the Lévy flights.

Lévy flights Lévy Flights are capable of maximizing the probability of resource searches in uncertain surroundings. In optical science, Lévy flight can be defined as a term used to designate the motion of light. Sometimes, light follows a random series of shorter and longer steps rather than traveling in a predictable Brownian diffusion. The shorter and longer steps together form a Lévy flights walk. Most of the natural search processes use Lévy flights. Some bee species perform Lévy flights to find the flowers in a new area. Survey says, by performing Lévy flights more area can be covered than normal random search. Performing Lévy flight is additionally informative than the traditional search methods. Lévy flight is defined by Eq. 19 (Yang, 2014):

$$x_i^{t+1} = x_i^t \alpha L(s, \lambda) \tag{19}$$

$$L(s, \lambda) = \frac{\lambda \Gamma(\lambda) \sin\left(\pi\lambda/2\right)}{\pi} \frac{1}{s^{1+\lambda}}, \tag{20}$$

$\left(s \gg s_0 > 0\right)$; $\alpha > 0$ is the step size scaling factor.

In Lévy flights, the Mantegna's algorithm is used to generate the step size for the determination of search space which is given by Eq. (21)

$$s = \frac{U}{|V|^{1/\lambda}} \tag{21}$$

where U and V are the two Gaussian distributions and λ is the characteristic scale of the problem.

Economic modeling

An economic model is a simplified description of reality, designed to yield hypothesis about the economic behavior that can be tested (International Monetary Fund 2016). The economic model is essential to make the polygeneration socially acceptable to the villagers. The economic performance is assessed along with the thermodynamic performance of the system to judge the overall suitability of the system (Khalid et al. 2017). The various input data for economic modeling are shown in Table 3.

Cost of solar PV

The total cost of PV installation, CP_{totall}, is given by Eq. 22

$$CP_{total} = CP_{sol} \times PV_{installed} \times 1000 \tag{22}$$

where CP_{sol} is the cost of PV module per watt at the peak of solar radiation and $PV_{installed}$ is the total installed capacity of the PV module.

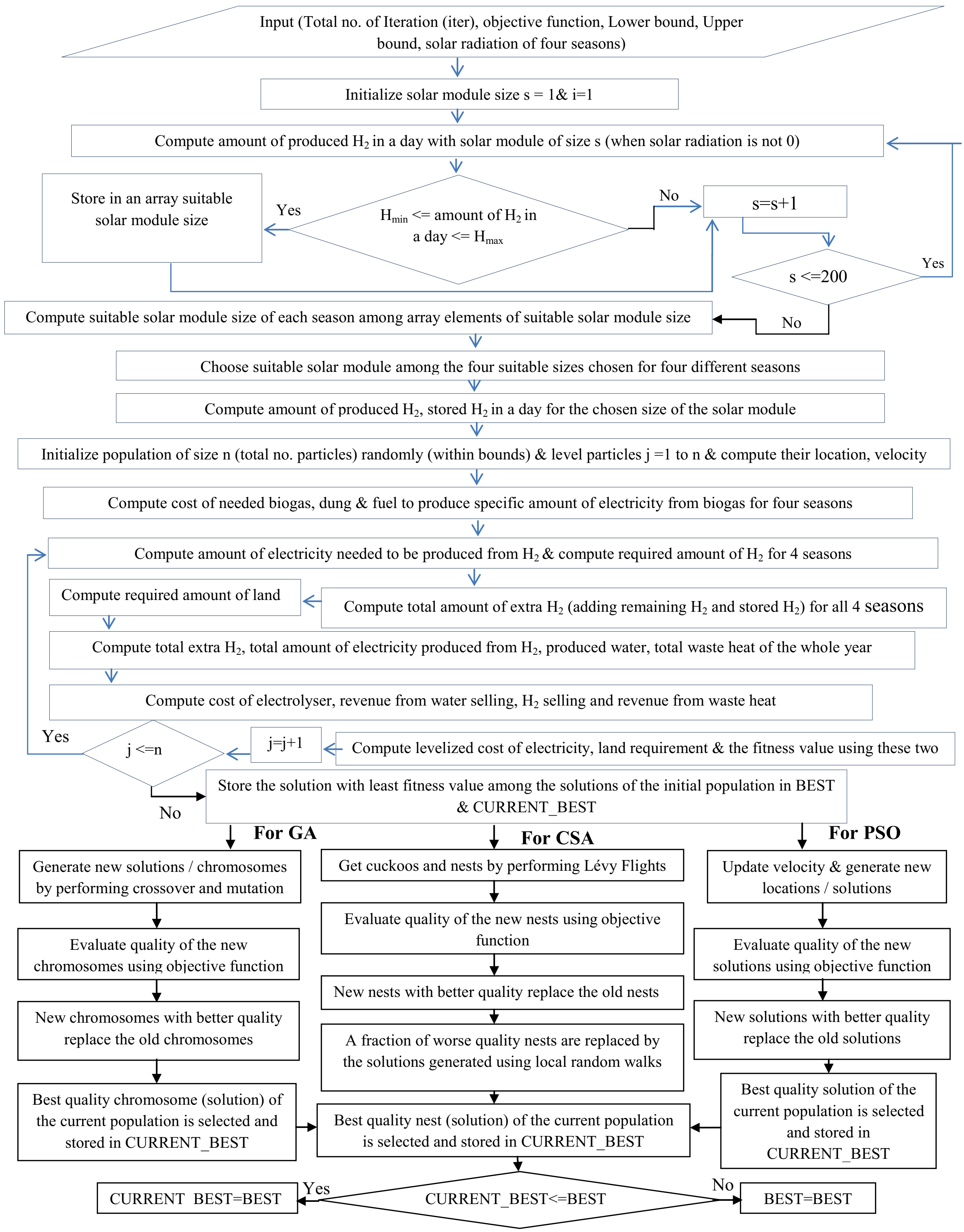


Fig. 5 Flowchart of the optimization scheme using GA, PSO and CSA

Table 3 Input values for economic calculation

Serial No	Name of component	Value
1	1 USD	60 INR
2	1 CHF	70.18 INR (XE Currency Converter 2016)
3	Price of fuel cell per kW	55 USD (DOE 2016)
4	Solar module price per watt	0.64 USD (US photovoltaic prices 2015)
5	Electrolyzer capital cost per kW	1090 CHF (Parra and Patel 2016)
6	Cost of hydrogen storage per kg for metal hydride storage	1.66 USD (Balachandra and Reddy 2017)
8	Cost of hydrogen per kg	3.70 USD (NREL 2014)
9	Price of Solar module per watt with battery	1.64 USD
10	Utility heating price	0.013 USD/kWh (Jana and De 2015d)
11	Cost of cattle dung	0.0033 USD/kg
12	Cost of waste heat recovery systems for heating utility per kW	1.66 USD
13	Plant life	25 years
14	Efficiency of PEM fuel cell	65% (Kreith and Krundieck 2015)
15	Efficiency of gas engine	27% (Chauhan and Saini 2016)
16	Efficiency of PEM electrolyzer	80% (Kreith and Krundieck 2015)
17	Efficiency of solar module	14%
18	Cost of wind turbine per kW	1450 USD (IRENA 2017)
19	Derating factor of PV modules	0.8 (NREL 2017)
20	Bank discount rate	10%
21	Population of the village	400
22	Initial investment with SPV battery systems	640 USD
23	Calorific value of biogas	21 MJ/m^3 (Shane et al. 2017)

Cost of fuel cell

The total cost of fuel cell installation, FC_{total}, is given by Eq. 23

$$CFC_{total} = CP_{fc} \times FC_{ins} \tag{23}$$

where CP_{fc} is the cost of fuel cell per watt and FC_{ins} is the total installed capacity of the fuel cell system.

Cost of biogas system

The cost of biogas systems does not increase linearly with scale. The cost of biogas system is given by Eq. (24) (Jana and De 2015d).

$$C_{eqb}=C_{eqa}\left(\frac{\text{Capacity}_b}{\text{Capacity}_a}\right)^{S} \tag{24}$$

where C_{eqb} is the cost of biogas system of capacity "b," the C_{eqa} is the cost of capacity of another biogas system "a" and "s" is the scale factor for wet biomass systems.

Cost of electrolyzer

The initial cost of electrolyzer, CE_{total}, is given by Eq. 25.

$$CE_{total} = CP_{elec} \times EL_{installed} \tag{25}$$

where CP_{elec} is the cost of electrolyzer per watt and $EL_{installed}$ is the installed capacity of the electrolyzer.

Cost of hydrogen storage

The cost of hydrogen storage CH_s is given by Eq. 26

$$CH_S = H_d \times H_{kg} \tag{26}$$

H_{kg} is the cost incurred to store 1 kg of hydrogen in metal hydride tank and H_d is the maximum hydrogen required per day to meet the night load in a particular season.

Cost of wind turbine

The cost of wind turbine CW_{total} is given by Eq. 27

$$CW_{total} = W_{installed} \times CW_{inperkW} \tag{27}$$

where CW_{total} is the total initial investment for the installation of the wind turbine, $W_{installed}$ is the installation capacity of wind turbine and $CW_{inperkW}$ is the cost of installation of wind turbines per kW.

Cost of gaseous mixture

The cost of 1 kg of gaseous mixture, C_g, is given by Eq. 28

$$C_g = C_H \times \frac{CV_g}{CV_h} \tag{28}$$

where CV_g is the calorific value of the gaseous mixture and CV_h is the calorific value of hydrogen.

Annualized initial investment

The annualized initial investment (AI) is given by Eq. 29

$$\begin{aligned} AI = \{(CP_{total} + CFC_{total} + C_{eqb} + CE_{total} \\ + CH_s + CW_{total} + C_{eqbg} + C_{wh}) \times CRF\} + CH_t \end{aligned} \tag{29}$$

where CP_{total} is the total installation cost of the PV module, CFC_{total} is the total cost of installation of the fuel cell, C_{eqb} is the total cost of installation of the biogas systems,CE_{total} is the total initial cost of the electrolyzer, CH_s is the total initial cost of the hydrogen storage systems, CW_{total} is the total cost for wind turbine installation, C_{eqbg} is the initial cost for the biomass gasifier system C_{wh} is the initial cost of the waste heat recovery system and CRF if the capital recovery factor given by Eq. 30

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{30}$$

where i is the discount rate and n is the economic life of the system. The economic lives of different components may be different and hence annualized cost is considered.

Annualized revenue

The annualized revenue R_y is given by

$$R_y = R_G + R_{wh} \tag{31}$$

where R_G is the revenue earned from selling gaseous mixture of high calorific value and R_{wh} is the revenue earned from utility heat.

Levelized cost of electricity (LCOE)

The LCOE is a convenient tool to assess the competitiveness of different generating technologies. The LCOE is calculated taking into consideration the capital cost, fuel cost, fixed and variable operations and maintenance cost (USEIA 2016). The LCOE is given by Eq. 32.

$$LCOE = \frac{AI + CM + CF - R_y}{E_t} \tag{32}$$

where AI is the annualized initial investment (i.e., capital cost), CM is the annualized maintenance cost, CF is the annualized fuel cost, i.e., cost of cattle dung for the present system, R_y is the total revenue generated by selling utilities other than electricity. E_t is the total units of electricity generated per year. For renewable energy systems, the maintenance cost and the fuel cost are almost negligible with respect to the initial investment (Budischak et al. 2013). Hence, effects of these are neglected for this study.

Analysis of reliability of power supply

Reliability of electricity supply is an important aspect for the design of any renewable energy system. The analysis of reliability of power supply gives a quantitative idea of the amount of power failure for a renewable energy system. Reliability of power supply can be calculated in different ways. In this paper, this is calculated using the Loss of Power Supply Probability method (LPSP) and Unmet Load (UL) probability method. The LPSP method takes into account both the magnitude of the power failure and the total hours of power failure as shown in Eq. (32). The UL probability method takes into account only the hours of power failure as shown in Eq. (33) (Sinha and Chandel 2015).

$$LPSP = \frac{\sum_{i=1}^{i=n} E_{deficit}}{\sum_{i=1}^{i=N} P_{load}} \tag{33}$$

where $E_{deficit}$ is the total electrical energy deficit per year and P_{load} is the total electrical energy required per year.

$$UL = \frac{\sum_{i=1}^{i=N} T_{failure}}{\sum_{i=1}^{i=N} T_{total}} \tag{34}$$

where $T_{failure}$ is the total hours of electricity failure per year and T_{total} is the total hours of operation of the plant per year.

Objective function

The main objective of this work is to optimize the system to simultaneously minimize three required inputs as a combined one. These are LCOE (INR/kWh), land requirement (m^2) and GHG emission (g-CO_2 equivalent). All these inputs are combined into a single-objective function for simultaneous optimization of this using weighted sum method.

The objective function is given by Eq. (35).

Table 4 Constraints for optimization

Serial no.	Parameter	Value
1	Weighing factor for LCOE (W_f)	0.6
2	Weighing factor for land requirement (W_l)	0.2
3	Weighing factor for GHG emission (W_G)	0.2
4	Reliability of power supply	100%
5	Daily availability of biogas	728 m^3/day
6	Yearly availability of biomass	108 tons/year
7	Betz limit	0.59
8	Constant heating load	2 kW

$$S_{obj} = W_f \times NF_{LCOE} \times LCOE + W_L \times NF_L \times L + W_G \times NF_G \times G \quad (35)$$

where W_f is the weighing factor for LCOE, W_L and W_G are the same for land requirement and GHG emission, respectively, and NF_{LCOE}, NF_L and NF_G are the normalization factors for LCOE, land requirement and GHG emission, respectively, to convert the values of each within an order of 10. The values of $NF_{LCOE}, NF_L,$ and NF_G are $1, 10^{-3}$ and 10^{-1} respectively. Values of three weighing factors are given in Table 4. The values of these weighing factors are decided according to the "priority" of these three for optimization. Higher the priority of optimization, higher is the value of weighing factor. The constraints of optimization are given in Table 4.

Results and discussions

In this paper, optimized capacities of the various components of the polygeneration system are shown in Table 5, which is determined by the multiobjective optimization by a program developed in MATLAB 2013. The objective of this optimization is simultaneous minimization of LCOE, land requirement and GHG emission using CSA.

In the present study, a polygeneration system has been proposed with PV module, wind turbine, PEM electrolyzer, PEM fuel cell, metal hydride tank, biogas digester and biomass gasifier. Electricity is the principal output. The other utility outputs are heat and gaseous mixture of hydrogen and biogas with high CV. Decentralized generation using the renewable sources of energy may be a good option for rural electrification of India. Moreover, electricity is not the only need of the villagers. Apart from the electricity, the people in the villages also need other utilities, say, cooking fuel, utility heating, etc. So if more utilities are obtained from a single efficiently integrated unit and catering to the needs of local people it will be even more beneficial for the villagers. With revenue earned through more utilities, LCOE decreases. Hence, the efficient integration of several processes through polygeneration decreases the LCOE. Effects of the system integration on LCOE are studied in this section.

In the present study, it is observed that the revenue shares of electricity and gas are nearly equal as shown in Fig. 6. The simultaneous production of electricity and hydrogen from the same system helps to accommodate the variation in the load curve of this particular location. When there is excess (i.e., the surplus electricity after meeting the instantaneous load) electricity (i.e., the surplus electricity after meeting the instantaneous load) it is diverted toward hydrogen production through electrolysis of water which is a clean fuel with high calorific value. The hydrogen is mixed with the biogas to yield a rich calorific value gas used for cooking and electricity generation purpose. The surplus of this gas is sold out generating revenue. In the present study, the LCOE is the principal indicator of the economic performance of the polygeneration plant. So, effects of changing various parameters on LCOE are to be studied to assess the suitability of the plant in the long run from the economic point of view. This also helps to identify the principal factors affecting the economic performance of the plant. The effects of various parameters on LCOE are shown in Fig. 7a–h. The various parameters for sensitivity analysis are given in Table 6.

Table 5 Optimized capacity of the components

Serial No	Name of component	Size
1	Photovoltaic module	120.11 kW
2	Wind turbine	3.745 kW
3	Fuel Cell	57.213 kW
4	Gas Engine	1 kW
5	Land required	3654 m^2
6	Size of biogas digester	800 m^3/day
7	Size of biomass gasifier	41.27 kW_e
8	Size of metal hydride storage tank	2.5 kg/day
9	Size of the electrolyzer	100 kW

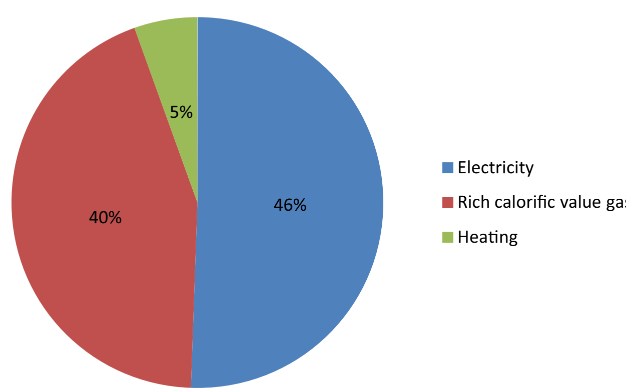


Fig. 6 Pie chart showing the percentage share of annualized income from selling different utilities

Fig. 7 **a** Variation of LCOE with life of the plant. **b** Variation of LCOE with percentage of excess biogas utilization. **c** Variation of LCOE with hybridization of various renewable energy sources. **d** Adding of different utilities. **e** Variation of LCOE with Different algorithms. **f** Variation of LCOE with number of households. **g** Variation of LCOE with Percentage of increase in initial investment. **h** Reliability of power supply

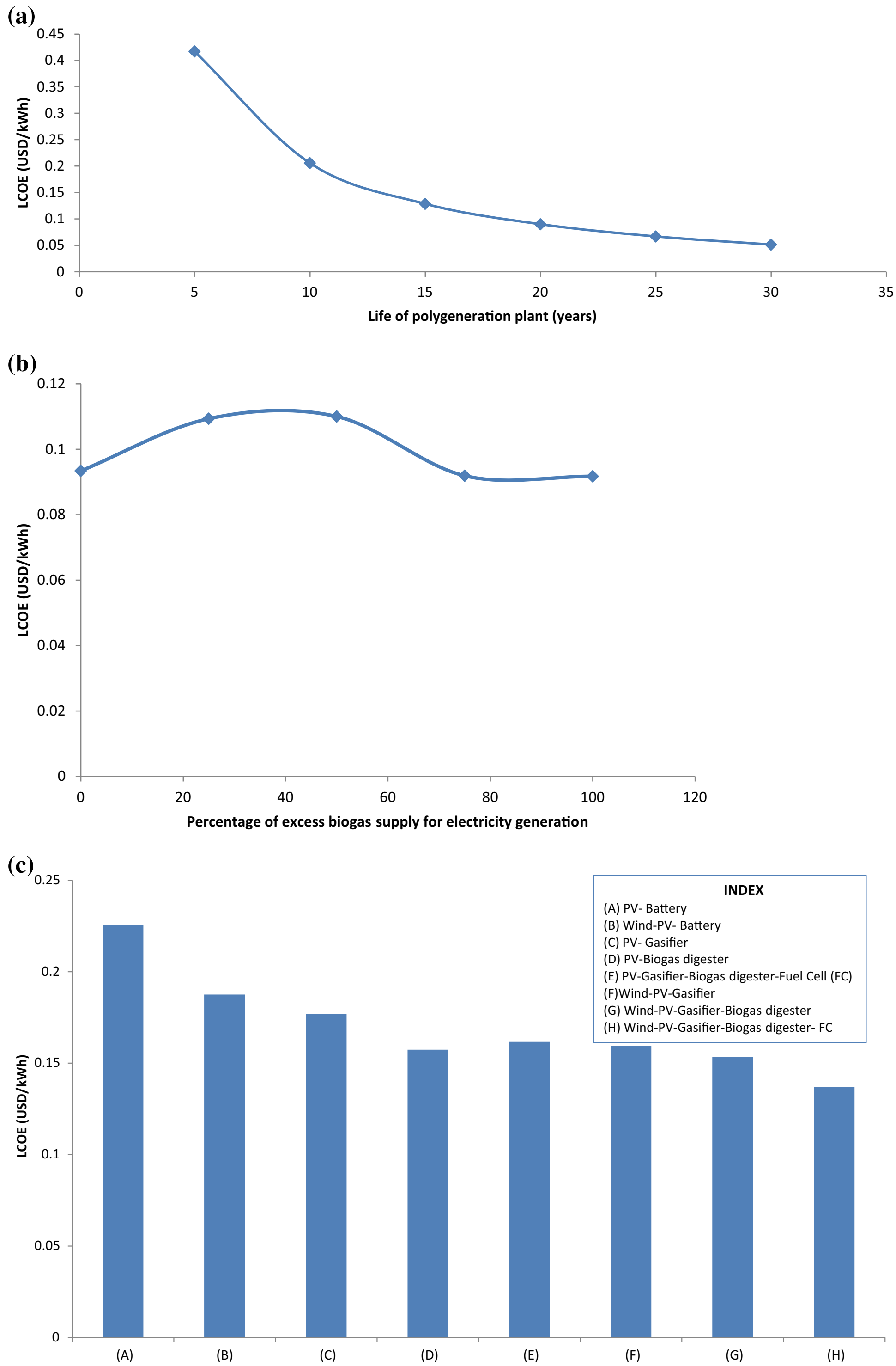
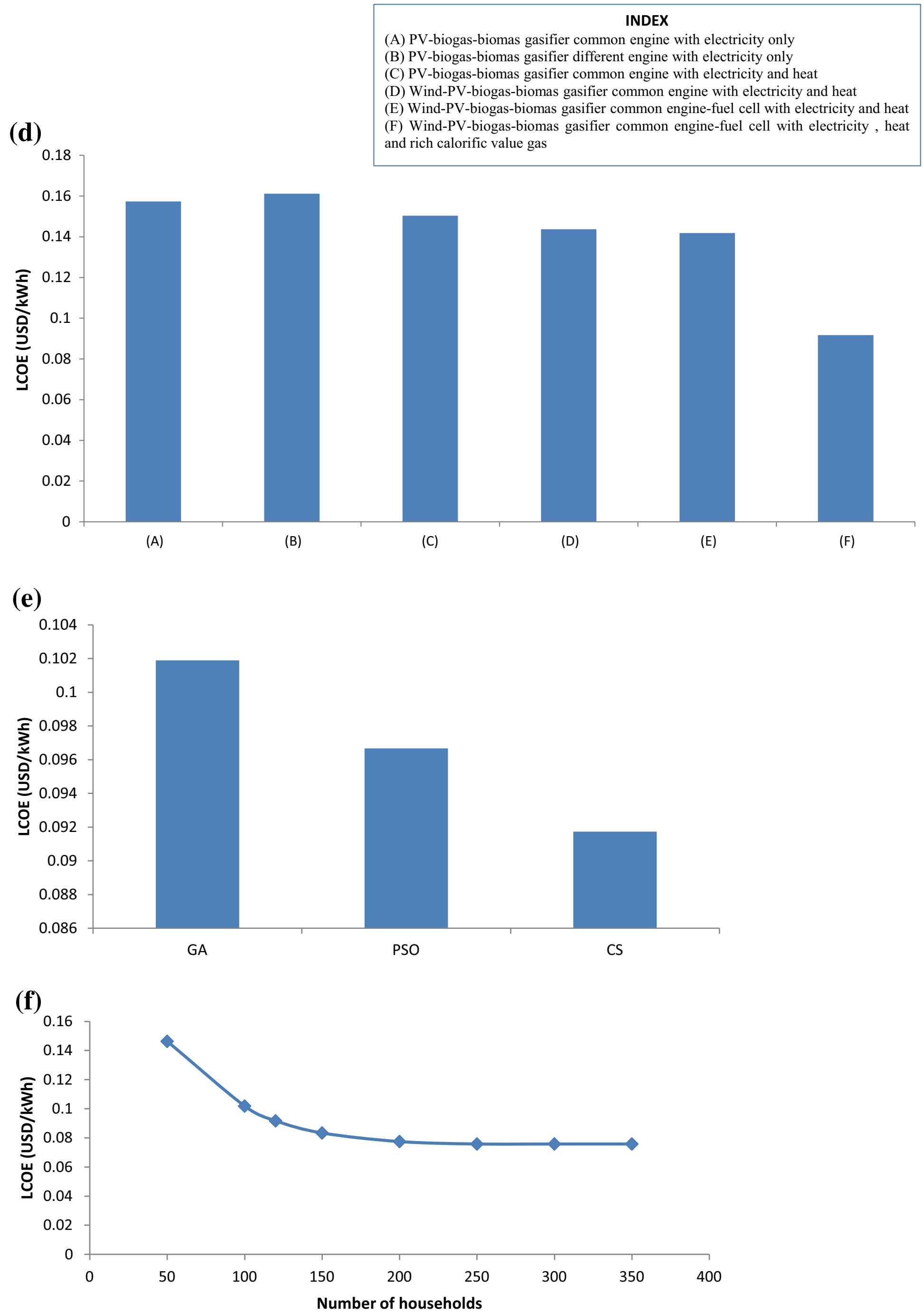


Figure 7a shows the variation of LCOE with the life of the polygeneration plant. The LCOE is high if the life of the plant is below 15 years, and it increases rapidly with decreasing plant life. Higher lifetime of the plant, i.e., more than 15 years decreases the LCOE at a lesser rate, and the LCOE is almost constant if the plant life is above 20 years. So for the better economic operation of the plant, the life of the plant should be 20 years or more.

In India, above 90% of the rural households use firewood as the cooking fuel. Firewood does not burn properly in a conventional way. Rampant use of the firewood for cooking also leads to deforestation causing environmental damages. At the same time, in most of the villages plenty

Fig. 7 (continued)



of cattle are available. The cattle dung has a good potential of biogas production. The biogas can be mixed with hydrogen for increasing its calorific value. This high calorific value gaseous mixture can be used as a better cooking fuel. In the present study, about 65% of the total produced gaseous mixture can be used for the electricity generation which is the surplus amount after cooking requirement of the village. This amount of gaseous mixture is termed as "excess" gas in Fig. 7b. Cooking need has more priority than electricity in the villages. Moreover, the biogas production may also vary due to many reasons. If the percentage of use of the gas for electricity generation drops below 60%, then there is an increase in LCOE. This is due to nonutilization of the total capacity of the biogas digester. Moreover, this will lead to increase in size of the fuel cell and wind turbine systems. Hence, the LCOE increases. The renewable sources of energy generally are intermittent in nature. The resources are not available as per the

Fig. 7 (continued)

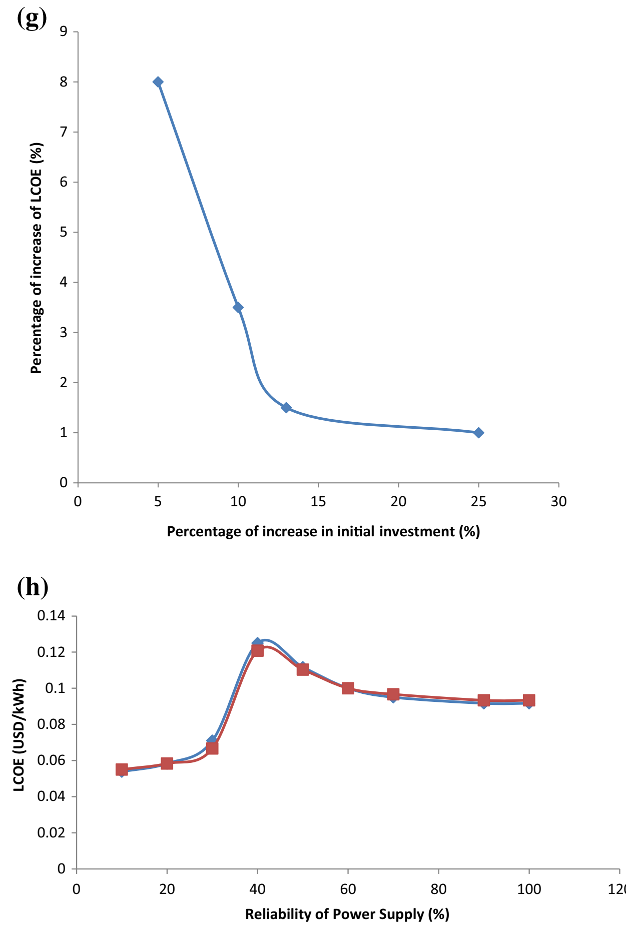


Table 6 Variations considered for sensitivity analysis for variation of LCOE

Serial No	Parameter	Range
1	Life of the polygeneration plant	5–30 years
2	Percentage of supply of excess biogas	0-100
3	Different types of hybridization	–
4	Addition of different utilities	–
5	Application of different optimization algorithms	–
6	Percentage of increase in initial investment	–
7	Reliability of power supply	0–100

human need with time, i.e., following the load curve. To get reliable power supply using the renewable sources of energy, there are two options. These are either storage and/or hybridization. Most common storage option is to store electricity in a battery. On the other hand, hybridization means to integrate two or more sources of renewable energies like solar, biomass, wind to deliver electricity. Figure 7c shows the variation of LCOE with hybridization of the various sources. Bar chart in Fig. 7c shows the LCOE for only electricity generation (i.e., without other utilities) using different possible combinations from solar PV-battery option and subsequently combining with other possible options. Here, battery indicates storage and other adding options without battery indicate more hybridization. Combinations are plotted from maximum to minimum LCOE. The results of this study show that more hybridization combinations are plotted for maximum to minimum LCOE. The LCOE is the highest for a PV-battery storage system. The LCOE decreases with more hybridization. The least LCOE is obtained when wind–PV–fuel cell–gasifier–biogas digester, i.e., almost all the available renewable energy sources considered for this study are hybridized. The variation of the sizes of the different components like solar PV module, wind turbine with different hybridizations is shown in Table 7.

In a polygeneration system, multiple utility outputs are obtained from the same integrated system. Other utilities in addition to electricity are then integrated to study the effect of such integrated system on LCOE in Fig. 7d. Figure 7d shows that the LCOE decreases with adding up of more utilities along with electricity and better process integration. The LCOE is highest for a PV-battery system when the

Table 7 The change of the capacity of the electricity generators on hybridization with other generators

Possible combinations of hybridization	Photovoltaic module (kW)	Biomass gasifier (kW_e)	Biogas digester (m^3/day)	Wind turbine (kW)	Fuel cell (kW)
PV module with battery	400	0	0	0	0
PV module with wind turbine with battery	325	0	0	15	0
PV–gasifier	325	70	0	0	0
Wind–PV–gasifier	318	68	0	10	0
Wind–PV–gasifier–fuel cell	200	55.43	0	7.5	0
Wind–PV–gasifier–fuel cell–biogas digester	120	41.25	800	3.75	58

utility output is only electricity with no hybridization. The LCOE decreases to some extent when PV is hybridized with wind. In wind–PV–gasifier system, there are two utilities, i.e., electricity and waste heat. In this case, the LCOE has even decreased more.

Figure 7e shows the different optimized LCOE for different algorithms (like GA, PSO) after forty iterations. The cuckoo search gives the best results because of the global random walks generated by the Lévy flights. Moreover unlike the other algorithms, the CS performs the global convergence, whereas the other algorithms find out the current best solution. For the multimodal optimization, the other algorithms converge to the current best solution without going for the global best solution for a definite search space.

It is necessary to study the suitability of a renewable energy system with respect to the population size of an area. The design of a renewable energy system depends on the number of consumers. The number of consumers generally increases with the number of the households. Hence, the number of households in a village may serve as an indicator of the population. In the present study, the assumed population of the village is 400 persons and the number of households is assumed to be 100. Figure 7f shows the variation of LCOE with the number of households. It is found that for the economic operation of the plant the number of households must be greater than one hundred and fifty. So the increase in the number of households leads to the decrease in LCOE. Moreover, the capacity utilization of the individual renewable energy devices will also increase. In this study, it is seen that the LCOE decreases if the population in a certain area increases.

Figure 7g shows the percentage of increase in LCOE with the increase in initial investment. Electrification of this area with the PV battery systems is considered as the base for comparing the other optimized hybridized multigeneration system. Renewable energy resources are intermittent in nature. Hence to get uninterrupted power supply, hybridization of one or more renewable resources is necessary. The inclusion of more types of renewable energy generators (like SPV, wind turbine) increases the initial capital investment. It has been observed that when the percentage of increase in the initial investment is 15% then the LCOE is decreased by 4%. This area signifies the inclusion of the wind turbine. The initial investment increases with the incorporation of the wind turbine but the LCOE decreases. There is a sharp decrease in LCOE (nearly 9%) when there is a 25% increase in the initial investment. The rise in the initial investment is due to the incorporation of the hydrogen-based systems like PEM electrolyzer and PEM fuel cell. The LCOE decreases as the excess hydrogen mixed with biogas is sold with a good market price. Thus, hybridization can be viewed as a more efficient way of in situ resource utilization.

Reliability of power supply means assured continuity of power supply without failure. Thus, higher the value of reliability of power supply lower is the chance of power failure. The renewable energy systems are intermittent in nature. These energy can be generated when the resources are available but not when it is actually needed. This is one of the most important issues to address for renewable energy introduction replacing the fossil fuel options. So effect of the reliability of power supply on LCOE is studied here. The reliability of power supply is calculated both by "Loss of Power Supply Probability" and "Unmet load" method as shown in Eqs. (33) and (34), respectively. Figure 7h shows that the increase in reliability of above 40% decreases the LCOE. This is also a socially acceptable solution. This is because for the renewable energy systems the running cost is negligible with respect to the initial cost. During the load shedding hours, no revenue is generated but the initial investment is already done. Hence, the LCOE decreases. As reliable uninterrupted power supply assures better social as well as economic solutions, 100% reliability of supply (i.e., no power failure) is considered as the constraint for this optimization.

The unit prices of components may vary due to many technical as well as socioeconomic factors. So to study the suitability of the system in the varying price environment, the sensitivity analysis is performed by varying the price of each of the components of the polygeneration system, i.e., solar module, wind turbine and the fuel cell as shown in Fig. 8. Here, the price of each of the components is varied within a range of 30% of the base price.

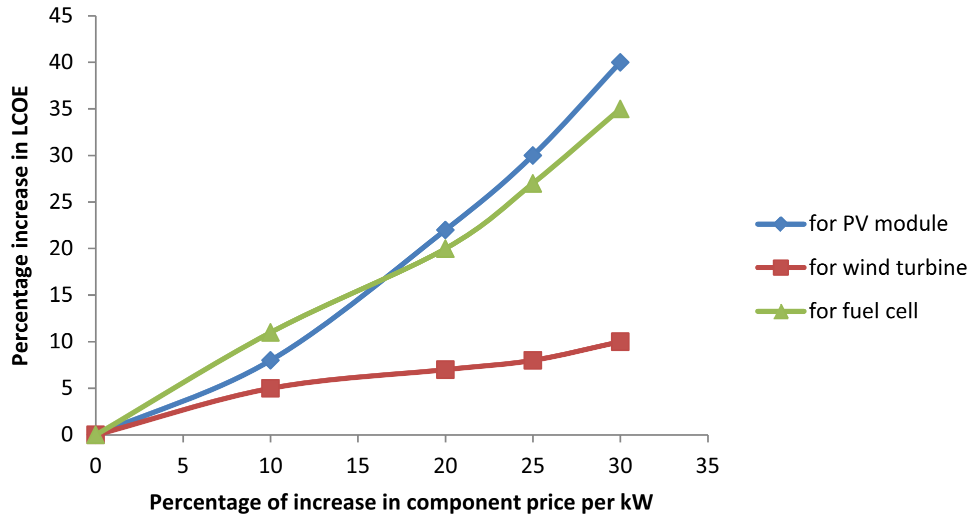


Fig. 8 Variation of percentage of increase in LCOE with the percentage increase in per kW price of the components

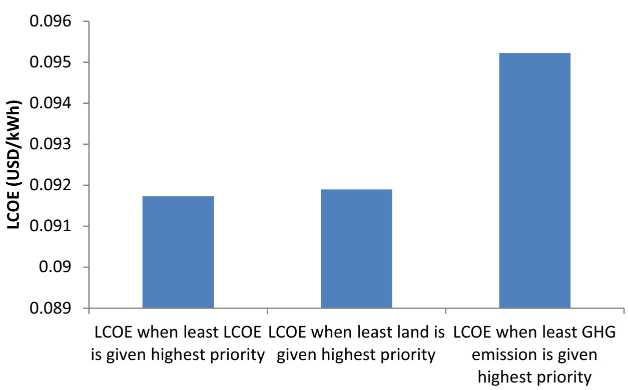


Fig. 9 LCOE with different weightage factors to different factors

The present base price of all these components is shown in Table 3. In Fig. 8, it is observed that the percentage of increase in LCOE is most steep with the rise in the cost of PV module per kW. This is because PV is the principal generator of electricity in this polygeneration system. Moreover, the electricity from PV in excess to that for local consumption also generates hydrogen through electrolysis. Hydrogen is mixed with the biogas to form gaseous mixture with high CV. This lowers the LCOE. But if the unit cost of PV module per kW increases then the hydrogen generation also becomes more costly. This also has a positive effect on the rise of LCOE. Next to PV, the LCOE is sensitive to rise in fuel cell prices per kW. This affects as the unit cost of fuel cell is high and it is the second largest electricity producer in this polygeneration system. The LCOE is least affected by the increase in per kW price of wind turbine. This is because the optimized size of wind turbine is much smaller than the other two. The locally available wind resource is also much less than the solar resource. Hence, the size of the wind turbine is relatively smaller.

In this study, a multiobjective optimization is carried out considering the minimization of LCOE, land requirement and GHG emission. In this study, LCOE is given the maximum weightage. Figure 9 shows the effect of LCOE if the other factors like land requirement and GHG emission are given topmost priority, i.e., the LCOE at least land requirement and least GHG emission are shown.

Conclusion

The extension of national grid across the whole country is difficult due to the terrain conditions and other socio-economic problems of India. In this context, decentralized generation using locally available resources may provide a solution for the electrification of these scattered hamlets. A system is analyzed in this study with solar PV module, wind turbine, PEM electrolyzer, PEM fuel cell, metal hydride tank, biogas digester (using cattle dung) and biomass (straw) gasifier. Here, the suitable sizes of the components are determined using cuckoo search algorithm for optimum economic operation, land use and GHG emission.

Electricity is not the only utility need of the local villagers. In this study, it is observed that if some other utilities can be integrated with the electricity generation through efficient process integration, the overall system performance improves. Addition of economic values to these utilities leads to economic benefit thereby lowering LCOE. Thus, polygeneration beneficially integrates generation of other utility outputs along with electricity. The LCOE lowers when the plant life is above 15 years. The LCOE decreases with hybridization and the addition of other utility outputs. The LCOE also decreases with the increase in reliability of the power supply above 50% which is a better socially acceptable solution too.

Methodology of this study is generic for multicriteria optimization with decided priority. However, data used are site-specific and results obtained representing optimized solutions may vary both with data used as well as priority decided.

Acknowledgements The authors are grateful to the University Grants Commission (UGC) of India and Research Council of Norway (RCN) for the financial support of INCP-2014/10086 project. Mr Kuntal Jana gratefully acknowledges the fellowship provided by Council of Scientific and Industrial Research, New Delhi, for this research work.

References

Balachandra P, Reddy BS (2017). Hydrogen energy for indian transport sector : a well-to-wheel techno-economic and environmental feasibility analysis hydrogen energy for indian transport sector : a well-to-wheel techno-economic and environmental 2007. Retrieved from www.igidr.ac.in/pdf/publication/WP-2007-004.pdf. Accessed 2 Jan 2017

Barley CD, Winn CB (1996) Optimal dispatch strategy in remote hybrid power system. Sol Energy 58:165–169

Belgana S, Alba D, Hasnae B, Mohamed M (2013). Hybrid renewable energy system design using multiobjective optimization. In: International conference on renewable energy research and applications, IEEE, Madrid

Budischak C, Sewell D, Thomson H, Mach L, Veron DE, Kempon W (2013) Cost-minimized combinations of wind power, solar power and electrochemical storage, powering the grid up to 99.9% of the time. J Power Sources 225:60–74

Chauhan A, Saini R (2016) Discrete harmony search based size optimisation of Integrated Renewable Energy System for remote rural areas of Uttarakhand state in India. Renew Energy 94:587–604

Climate Change (2016) http://www.powerscorecard.org/issue_detail.cfm?issue_id=1. Accessed 26 Dec 2016

DOE (2016) Fuel cell technologies office record. Retrieved from https://www.hydrogen.energy.gov/pdfs/14012_fuel_cell_system_cost_2013.pdf. Accessed 20 Dec 2016

Ghribi D, Khelifa A, Diaf S, Belhamel M (2013) Study of hydrogen production by using PV solar energy and PEM electrolyser in Algeris. Int J Hydrogen Energy 38:8480–8490

International Monetary Fund (2016) www.imf.org/external/pubs/ft/fandd/2011/06/basics.htm. Accessed 2 June 2016

IRENA (2017) International Renewable Energy Agency. Renewable Energy Technologies. Cost Analysis Series: Wind Power. Retrieved from https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-WIND_POWER.pdf. Accessed 03 Jan 2017

Jana K, De S (2015a) Sustainable polygeneration design and assessment through combined thermodynamic, economic and environmental analysis. Energy 91:540–555

Jana K, De S (2015b) Polygeneration using agricultural waste: thermodynamic and economic feasibility study. Renew Energy 74:648–660

Jana K, De S (2015c) Polygeneration performance assessments: multidimensional viewpoint. Clean Technol Environ Policy 17–6:1547–1561

Jana K, De S (2015d) Techno-economic evaluation of a polygeneration using agricultural residue–a case study for an Indian district. Bioresour Technol 181:163–173

Jana K, De S (2016) Environmental impact of agro based polygeneration without and with CO_2 storage: life cycle assessment appraoch. Biores Technol 216:931–940

Jana K, De S (2017) Environmental impact of biomass based polygeneration: a case study through life cycle assessment. Biores Technol 227:256–265

Kanse-Patil A, Saini R, Sharma M (2011) Size of integrated renewable energy system based on load profiles and reliability index for the state of Uttarakhand in India. Renew Energy 36:2809–2821

Khalid F, Dincer I, Rosen MA (2017) Thermoeconomic analysis of a solar-biomass integrated multigeneration system for a community. Appl Therm Eng 120:645–653

Kreith F, Krundieck S (2015) Principles of sustainable energy systems. CRC Press, Boca Raton

Kriakarakos G, Dounis A, Rozakis S, Arvantis K (2011) Polygeneration microgrids: a viable solution in remote areas for supplying power, potable water and hydrogen as the transportation fuel. Appl Energy 88:4517–4526

Kriakarakos G, Piromalis DD, Arvantis KG, Dounis AI, Papadakis G (2015) On battery-less autonomus polygeneration microgrids. Investigatio on the combined hybrid capacitors/hydrogen alternative. Energy Convers Manag 91:405–415

Lam HL, Varbanov PS, Klemeš JJ, Yan J (2016) Green applied energy for sustainable development. Appl Energy 161:601–604

Muller J, Marmejo J (2017) Hydrogen storage in hydrides for safe energy systems. Retrieved from https://ec.europa.eu/research/energy/pdf/efchp_hydrogen3.pdf. Accessed 3 Jan 2017

NASA Surface Meterology (2017) https://eosweb.larc.nasa.gov/cgi-bin/sse/grid.cgi. Accessed 2 Jan 2017

National Institute of Disaster Management (2016) Uttarakhand National Disaster Risk Reduction Portal. Retrieved from www.indiaenvironmentportal.org.in/…/national-institute-of-disaster-management/. Accessed 3 Nov 2016

Ng KS, Sadhukhan J (2011) Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power. Biomass Bioenergy 35(3):1153–1169

Ng KS, Zhang N, Sadhukhan J (2012) Decarbonised coal energy system advancement through decarbonisation and polygeneration. Clean Technol Environ Policy 14:443–451

Ng KS, Zhang N, Sadhukhan J (2013) Techno-economic analysis of polygeneration systems with carbon capture and storage and CO_2 reuse. Chem Eng J 219:96–108

NREL (2014) National Renewable Energy Laboratory. Hydrogen and Fuel Cells Research. http://www.nrel.gov/hydrogen/production_cost_analysis.html. Accessed 11 Dec 2016

NREL (2017) http://rredc.nrel.gov/solar/calculators/PVWATTS/derate.cgi. Accessed 3 Jan 2017

Parra D, Patel M (2016) Corringendum to Technological Implications of the electrolyser technology and size for power to gas systems. Int J Hydrogen Energy 2016(41):7527–7528

Ray A, Jana K, De S (2017) Polygeneration for an off-grid Indian village: optimization by economic and reliability analysis. Appl Therm Eng 116:182–196

Sadhukhan J (2014) Distributed and micro-generation from biogas and agricultural sewage sludge: comparative environmental performance and life cycle approaches. Appl Energy 122:196–206

Sadhukhan J, Zhao Y, Shah N, Brandon P (2010) Process integration and economic analysis of bio-oil platform for the production of methanol and combined heat and power. Biomass Bioenergy 35(3):1153–1169

Sadhukhan J, Ng KS, Martinez-Hernandez E (2015) Process systems engineering tools for biomass polygeneration systems with carbon capture and reuse. Process Des Strateg Biomass Convers Syst. https://doi.org/10.1002/9781118699140.ch9

Shane A, Gheewala SH, Phiri S (2017) Rural domestic biogas supply model for Zambia. Renew Sustain Energy Rev 78:683–697

Sinha S, Chandel S (2015) Review of recent trends in optimization techniques for solar photovoltaic–wind based hybrid energy systems. Renew Sustain Energy Rev 50:755–769

Solanki C (2009) Solar photovoltaics fundamentals, technologies and applications. PHI Learning Private Limited, New Delhi

Sukhatme S (2003) Solar energy: principles of thermal collection and storage. Tata Mcgrawhil Publishing Company, New Delhi

Tester JW, Drake E, Golay M, Driscoll M, Peters W (2006) Sustainable energy choosing among options. Prentice Hall, New Delhi

Tibaquira J, Hristovski K, Posner J, Westerhoff P (2016). Generating potable water from fuel cell technology. http://www2.bren.ucsb.edu/~keller/energy-water/Second%20Forum/02_Tibaquira_EWForum09.pdf. Accessed 21 Nov 2016

Toman M, Barbora J (2003) Energy and economic development: an assessment of the state of knowledge. Retrieved from http://pesd.fsi.stanford.edu/publications/energy_and_economic_development_an_assessment_of_the_state_of_knowledge. Accessed 2 Nov 2016

UK Carbon Footprint (2016) http://www.parliament.uk/documents/post/postpn_383-carbon-footprint-electricity-generation.pdf. Accessed 26 Dec 2016

United States Department of Energy (2016) http://www.eia.gov/todayinenergy/detail.php?id=26212. Accessed 26 Dec 2016

U.S Energy Information Administration (2017) https://www.eia.gov/outlooks/ieo/electricity.cfm. Accessed 6 Feb 2017

U.S. Photovoltaic Prices (2015) U.S. photovoltaic prices and cost breakdowns: Q1 2015 benchmarks for residential, commercial, and utility-scale systems. Retrieved from http://www.nrel.gov/docs/fy15osti/64746.pdf. Accessed 20 Dec 2016

USEIA (2016) Independent statistics and analysis U.S. Energy Information Administration. https://www.eia.gov/forecasts/aeo/electricity_generation.cfm. Accessed 22 June 2016

XE Currency Converter (2016) www.xe.com/currencyconverter/current/amount+1 & from CHF to INR. Accessed 20 Dec 2016

Yang XS (2014) Nature-inspired optimization algorithm. Elsevier, Amsterdam