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Performance Investigation of a Solar Photovoltaic/Diesel Generator Based Hybrid System with Cycle Charging Strategy Using BBO Algorithm

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Abstract: In the current scenario, sustainable power generation received greater attention due to the concerns of global warming and climate change. In the present paper, a Solar Photovoltaic/Diesel Generator/ Battery-based hybrid system has been considered to meet the electrical energy demand of a remote location of India. The cost of the energy of hybrid system is minimized using a Biogeography-based Optimization (BBO) algorithm under the constraints of power reliability, carbon emission and renewable energy fraction. Load following and cycle charging strategies have been considered in order to investigate the performance analysis of the proposed hybrid system. Further, different component combinations of specifications available on the market are presented for detail analysis. The minimum cost of energy of the proposed hybrid system is obtained as 0.225 $/kWh.

Keywords: renewable energy; solar; diesel generator; battery; BBO

1. Introduction

In the current scenario, renewable energy has been recognized as the most effective tool in addressing climate change and global warming [1,2]. The installation cost of solar and wind energy is decreasing day by day and becoming competitive with fossil fuels [3,4]. Additionally, the use of renewable energy technologies offers low carbon emission in the environment with reserves of fossil fuels. Further, integration of two or more renewable energy sources ensures continuous power supply and counterbalances the intermittent behavior of renewable sources [5–10].

Baruah et al. [11] investigated the techno-economic feasibility of a hybrid system which consisted of solar photovoltaic, biogas, wind turbine, syngas and hydrokinetic energy. They proposed this system in order to supply the demand of an academic township using HOMER Pro software. They have used Analytical Hierarchy Process in order to optimize the cost of energy generation and area of system. They have also conducted a sensitivity analysis of the system for the changes of different system parameters. Das et al. [12] minimized the net present cost of a hybrid system consisting of PV array, biogas generator, pumped hydro and battery storage using water cycle algorithm and moth-flame algorithms. They have also performed the comparison of statistical characteristics of the net present cost results obtained by water cycle algorithm, moth-flame algorithm and genetic algorithm.

El-houari et al. [13] designed a solar energy, wind energy and biomass-based hybrid system for ten houses located in remote villages in the Moroccan Fez-Meknes region. They found that the proposed hybrid system offered a reduction of 26.48 tons and 28.814 tons of carbon emission in comparison to the utility grid and diesel generator, respectively.

Elkadeem et al. [14] suggested the different combinations of PV array, wind turbines, diesel-based generator and converter for agriculture and irrigation in Dongola, Sudan. They have also performed the sensitivity analysis to evaluate the effect of wind speed, diesel price, interest rate and solar radiation on system economic performance such as net present cost and cost of generation.

Kumar et al. [15] considered three types of battery such as lead acid, nickel iron and lithium ion during the design of hybrid system. They minimized annual cost using Salp Swarm Algorithm and compared the results with other algorithms in obtaining the best optimum solution. Ma et al. [16] proposed the sizing of a hybrid energy system comprised of PV array, wind turbines and battery with consideration of the saturation of renewable sources. They used the saturation factor changing from 0 (only wind system) to 1 (only solar system) in the step of 0.02. Jahangir et al. [17] investigated the economic and environmental assessment of a hybrid system comprised of PV array, wind turbines and biomass generator. They also performed the sensitivity analysis for the changing biomass price, inflation rate and biomass input and evaluated its impacts on the cost of energy and annualized system cost.

Many studies have been performed and investigated the size optimization of the hybrid system. However, many researchers have not considered the battery degradation model during the design of the hybrid system. Additionally, many authors have not accounted for the seasonal changes in the demand and sizes available in market. Renewable fraction and carbon emission in the hybrid system have also not been taken into account by many authors.

The system presented in the work involves a college premises, containing loads of the three hostels and one Sewage Treatment Plant (STP). The design focuses on developing a grid-independent system comprising only SPV and Battery, while diesel generator is working as a backup generator. The maximum number of SPV module is limited depending on the roof area available. The greater size of the SPV system helps to charge the selected size of batteries. The SPV selected through BBO helps to size batteries, which depend on the fulfillment of load primarily during the evening hours. Even then the cumulative usage of the SPV and the batteries are unable to supply the demand due to size constraints of SPV. Hence, sizing of diesel generator is selected to supply the deficit load in case of both load following and cycle charging strategies. In addition, in cycle charging strategy the excess amount of power is fed to charge the batteries. This further reduces the COE of the overall hybrid energy system. The results signify the importance of selecting batteries in place of a diesel generator during the overall operation of the system. This in turn will improve the renewable fraction and reduce the CO_2 emission.

The work also considers number of charging-discharging cycles of the batteries and investment cost, maintenance and operation cost and replacement cost. The parameters that are considered in the work are emission of CO_2, variation of load during summer and winter seasons, Energy index ratio (i.e., a measure that load is fulfilled at all times), renewable fraction, fuel consumption, net present cost.

2. Hybrid System Configuration

In the present paper, three hostels and one sewage treatment plant (STP) of the institute Rajkiya Engineering College Banda of India has been taken as the study area. This area is located at the latitude of 25.29° N and longitude of 80.57° E.

This area receives the yearly average daily solar radiation of 5.262 kWh/m^2. Accordingly, a hybrid system comprised of photovoltaic array and diesel generator has been considered as presented in Figure 1. This system is proposed to supply the electrical energy requirements of three hostels and one STP of the institute. Power output of solar panels is connected to direct current bus, and power production of the diesel generator is linked to alternating current bus. A set of battery bank is also used in the system to store the additional electricity produced from the generating sources and supply the shortage of load demand. A bidirectional converter has also been used in the system in order to convert AC to DC and vice-versa.

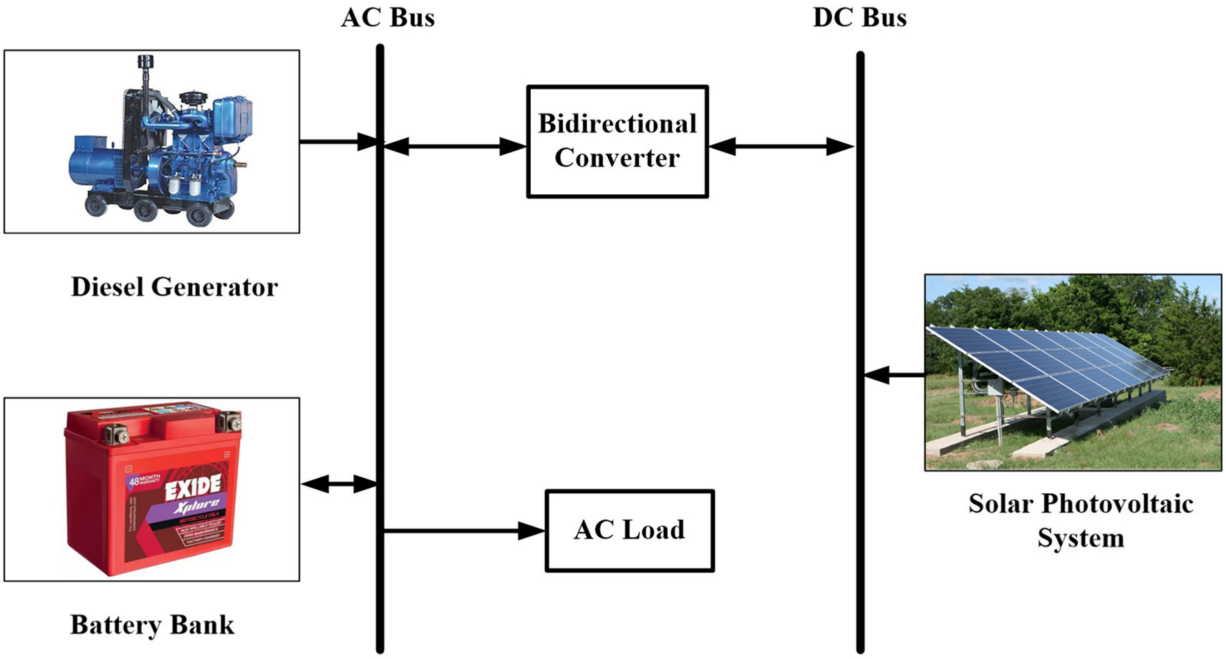

Figure 1. Schematic of Photovoltaic/Diesel Generator/Battery Bank based hybrid system.

A step wise method is required for the performance investigation of the hybrid energy system. It confirms the uninterrupted power supply at the consumer end at minimum system cost. The methodology develops an optimal hybrid system model by addressing all the operational constraints imposed by the user. A step wise description of methodology is summarized as follows:

Step 1: Estimate the electrical energy consumption of each appliance and further, calculate the hourly demand of the selected area.

Step 2: Develop the mathematical model of power output of each generating source and storage system.

Step 3: Choose different configurations of sources.

Step 4: Formulate a framework of objective function and operational constraints of the hybrid system.

Step 5: Take dataset of system components.

Step 6: Perform the simulation of the developed model of the hybrid system for a year.

Step 7: Selection of power dispatch strategy.

Step 8: Show the best optimal configuration of the hybrid system with system sizes and cost parameters.

Step 9: Performance investigation of the best configuration.

A flowchart of methodology is prepared with the steps and depicted in Figure 2.

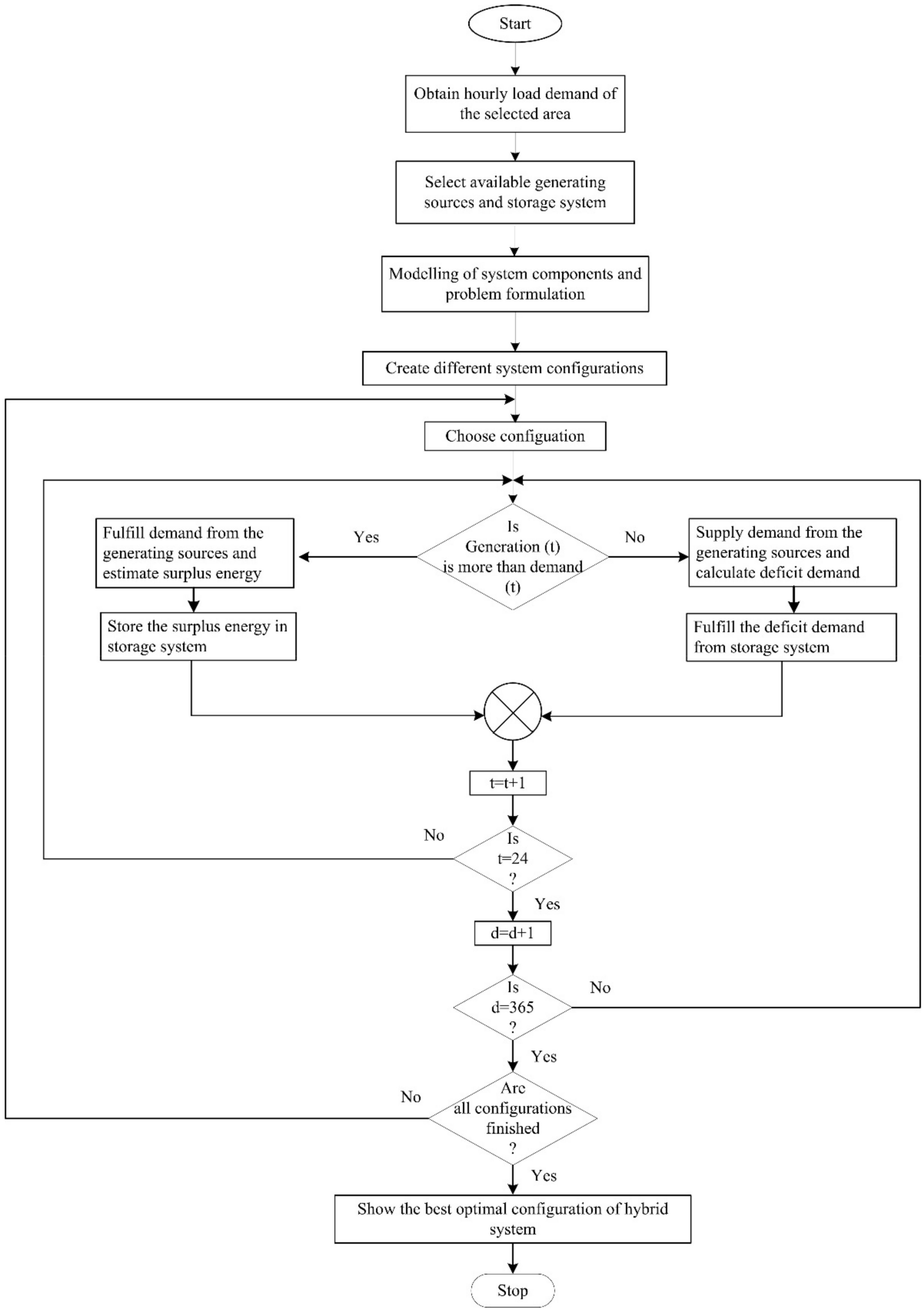

Figure 2. Flowchart of methodology adopted.

3. Mathematical Model

Modelling is an important step before optimization as it gives the static and dynamic characteristics of the component. It relates to the output of the system component in terms of many input variables. The modelling of the hybrid system components is explained as below:

3.1. Model of Solar PV Array

The selected area receives a good amount of daily average solar radiation and therefore PV array has the capability to meet the electricity demand of the area. Power output of a

PV module is the function of open circuit voltage (V_O), short circuit current (I_s) and filling factor (F). It can be modeled as follows [18,19]:

$$P_{PV}^{d}(t) = V_{O}^{d}(t) \times I_{S}^{d}(t) \times F(t) \quad (1)$$

Further, the open circuit voltage and short circuit current of PV module depend upon the different module parameters as provided by the manufacturer, and these can be estimated as follows:

$$I_{S}^{d}(t) = \left\{ I_{S,STC} + C_i \left[T_{cell}^{d}(t) - 25^0 \right] \right\} \frac{\beta^d(t)}{1000}. \quad (2)$$

$$V_{O}^{d}(t) = V_{O,STC} - C_v \times T_{cell}^{d}(t). \quad (3)$$

where $I_{S,STC}$ and $V_{O,STC}$, respectively, represent the short circuit current and open circuit voltage of PV cell at standard test conditions, C_i and C_v, respectively, represent the temperature coefficient of short circuit current and open circuit voltage, β is solar radiation and T_{cell} is PV cell temperature.

PV module cell temperature can be calculated with following equation as follows:

$$T_{C}^{d}(t) = T_{A}^{d}(t) + \frac{NOCT - 20^0 C}{800} \times \beta^d(t). \quad (4)$$

where T_A is ambient temperature and NOCT is nominal operating cell temperature.

3.2. Model of Diesel Generator

Diesel generator is operated to serve the peak demand of the area. Fuel required (Q) in order to operate DG depends upon rated power of DG and can be modeled as follows [20,21]:

$$Q_t(t) = \alpha_{DG} P_{DG}(t) + \beta_{DG} P_{DG,rated}. \quad (5)$$

where P_{DG} is power yield of DG at a particular time, $P_{DG,rated}$ is rated power of DG, β_{DG} (0.08145 l/kWh) and α_{DG} (0.246 l/kWh) are constants of DG.

3.3. Model of Storage System

The storage system is essential for energy balance in the hybrid system. It acts as a tool to mitigate the gap between energy generation and demand. In the present system, battery bank has been considered as a storage system. Battery capacity at a particular instant depends upon the previous capacity and difference between total generation and load demand.

A battery mostly works in two states viz. charging and discharging. In charging state, the battery stores surplus power supplied by sources and the current state of battery $E_B(t)$ can be calculated as follows [22–24]:

$$E_B(t) = E_B(t-1) + E_{CCO}(t) \times \eta_{CHG} \quad (6)$$

In discharging state, demand is more than the total electricity generation and the battery bank storage at hour 't' can be estimated as:

$$E_B(t) = (1-\sigma) \times E_B(t-1) - E_{Required}(t) \quad (7)$$

$$E_{Required}(t) = \frac{E_{NL}(t)}{\eta_{INV} \times \eta_{DCHG}} \quad (8)$$

$$E_{NL}(t) = E_{Demand}(t) - [E_{SPVS}(t) \times \eta_{Inv} + E_{DG}(t)] \quad (9)$$

where $E_{Required}(t)$ is hourly energy required from the battery to meet the load (kWh), $E_{NL}(t)$ is net shortfall load, σ is hourly self discharge rate, E_{CCO} is charge controller output, η_{CHG} and η_{DCHG}, respectively, represent charging efficiency and discharging efficiency of battery.

The n_B^S is the series connected batteries, which depends on the nominal DC bus voltage (V_{BUS}) and individual nominal voltage of battery (V_{nom}). Here the V_{BUS} is considered to be 48 V.

$$n_B^S = \frac{V_{BUS}}{V_{nom}} \tag{10}$$

The battery bank nominal capacity (C_n) is directly proportional to the number of batteries (N_{BAT}) and nominal capacity of each battery (C_B), indirectly related to the number of series connected batteries.

$$C_n = \frac{N_{BAT}}{n_B^S} C_B \tag{11}$$

Number of cycles of failure over minimum average depth of discharge for a period of battery bank is depicted in Figure 3. The battery bank replacement hours (N_{BR}) can be calculated by determining the total number of cycles in which a battery (N_{cycles}) can be operated. Here, De is the yearly average minimum capacity of the battery bank achieved over a day and O_{Batt} is the number of days for which the battery should be operated [25]. It is used to determine the life of the battery. A curve fitting toolbox is used to generate the coefficient values of the equation. Battery degradation model equations are described as:

$$O_{Batt} = a_1 \times (D_e)^{b_1} + c_1 \tag{12}$$

$$\begin{gathered} N_{BR} = n \times 365Ncycles\_DOD\% \\ a1 = 1.582 \times 10\bar{5},\ b_2 = -0.9964,\ c_1 = -997.1 \end{gathered} \tag{13}$$

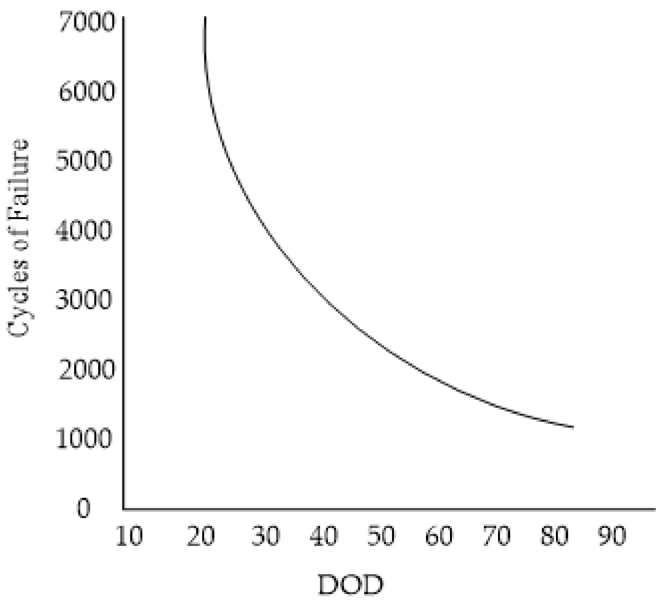

Figure 3. Number of cycles of failure over minimum average depth of discharge for a period of battery bank [25].

3.4. Mathematical Model of Charge Controller

The charge controller makes energy balance among different system components and its model is described as:

$$E_{CCO}(t) = E_{EE}(t) \times \eta_{CC} \tag{14}$$

where E_{CCO} (t) and E_{CCI} (t), respectively, represent the hourly output and hourly input to charge controller (kWh), E_{EE} (t) is amount of excess energy from sources (kWh) after serving the demand and η_{CC} is charge controller efficiency.

4. Problem Formulation

Minimization of system cost of energy is formulated and considered as an objective function for the present paper. Various constraints such as expected energy not supplied, carbon emission, renewable energy fraction and total net present cost have been incorporated during system optimization.

4.1. Objective Function

Cost of generation is the fundamental financial parameter in order to evaluate the techno-economic feasibility of the hybrid system. It can be calculated with annual system cost (ASC) and energy generation (E_{Gen}) as:

$$\mathrm{COE} = \frac{\text{Annual System Cost (ASC)}}{\sum_{t=1}^{8760} E_{Gen}(t)} \quad (15)$$

Annual system cost of hybrid system is a function of net present cost (NPC) and can be estimated as [26]:

$$\mathrm{ASC} = \mathrm{NPC} \times \left[\frac{dr(1+dr)^{\xi}}{(1+dr)^{\xi} - 1}\right] \quad (16)$$

where dr is discount rate and ξ is project lifetime.

4.2. Operational Constraints

System optimization has been investigated under operational economic and reliability constraints which are summarized as follows:

4.2.1. Power Reliability Constraint

At any time, when part of the load demand has not been met from the available generation, energy not supplied is calculated. It is the function of demand not met (NL) and duration of the period (T) as follows [27]:

$$\mathrm{EENS} = \sum_{i=1}^{8760} (\mathrm{NL} \times \mathrm{T}) \quad (17)$$

4.2.2. Economic Parameter Constraint

Constraints of economic parameters have been taken during system analysis. Total net present cost, total recurring cost (TC_{rec}) and non-recurring cost ($TC_{non\text{-}rec}$) of the system have been evaluated. These parameters can be calculated as follows [28]:

$$\mathrm{NPC} = C_{Inv} + TC_{rec} + TC_{non-rec} \quad (18)$$

Total recurring cost of system changes with escalation rate (er) and discount rate. It can be estimated as follows [28]:

$$TC_{rec} = C_{rec}\frac{\left[\frac{1+er}{1+dr}\right]\left\{\left[\frac{1+er}{1+dr}\right]^{\xi} - 1\right\}}{\left[\frac{1+er}{1+dr}\right] - 1} \quad (19)$$

Total non-recurring cost of system can be calculated by using Equation (19) as follows:

$$TC_{non-rec} = \sum_{y=1}^{y=n_{rep}} C_{Inv}\left[\frac{1+er}{1+dr}\right]^{y*n_{frep}} \quad (20)$$

where n_{rep} is total replacement of system component (in Nos.) and n_{frep} is year number of first replacement of system component.

4.2.3. Renewable Energy Fraction

Renewable energy fraction in total system generation ensures the sustainable generation of a hybrid system. It depends on energy generated by diesel generated (E_{DG}) and total energy generation (TE_{Gen}). It can be calculated as:

$$\text{Renewable Energy Fraction}(\%) = \left[1 - \frac{\sum E_{DG}}{\sum TE_{Gen}}\right] \times 100 \tag{21}$$

4.2.4. Total Carbon Emissions

Carbon emission is generated from the use diesel generator in the considered system. Total carbon emission (TE_{Carbon}) can be estimated as:

$$TE_{Carbon} = \sum_{t=1}^{T} \sum_{t=1}^{T} E_{Carbon} \times P_{DG}(t) \tag{22}$$

where E_{Carbon} is carbon emission produced by 1 kWh electricity generation by DG.

5. Energy Management Strategy

5.1. Load Following Strategy

The load following strategy is initiated by determining the demand and solar power generation available in an hour. If the generated solar power in an hour is more than the demand, then the battery state of charge is checked. If the battery bank state of charge is found to be less than the maximum battery state of charge (SOC), the battery bank is charged, otherwise it is fed to the dump loads. In case of demand exceeding the generated solar power, the battery bank is operated until its SOC maximum value is not reached. If the battery bank is unable to fulfill the demand, the diesel generator is operated to supply only the net demand, without charging the battery bank. If any one of these conditions is matched, the iteration as unit time in an hour is updated and the process continuous until the year is complete. Figure 4 shows the methodology of operating load following strategy.

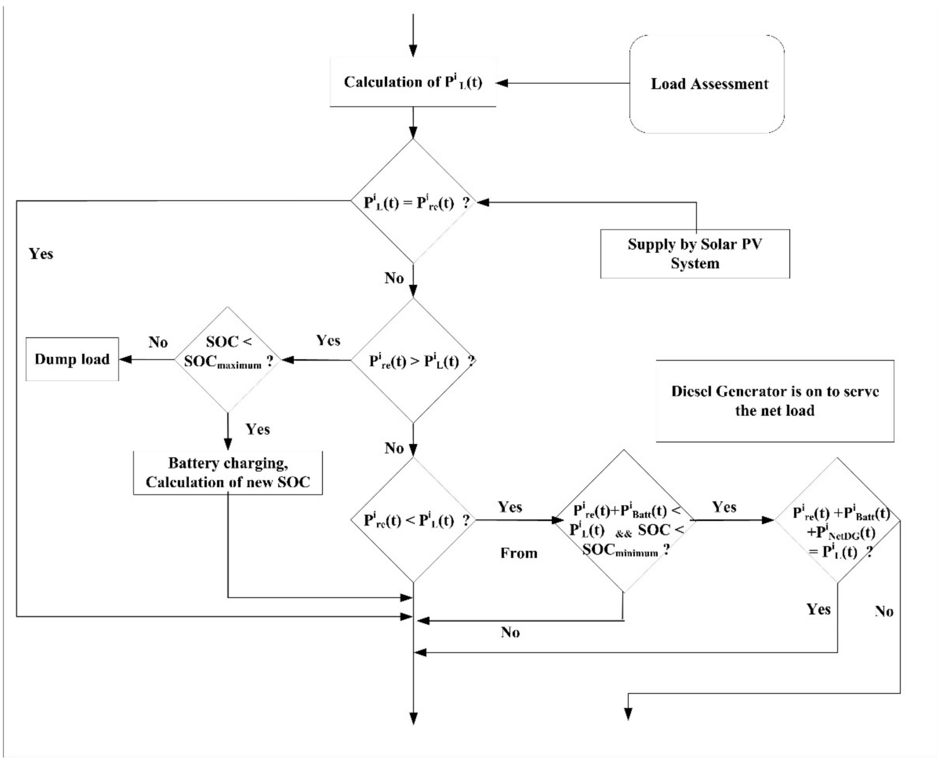

Figure 4. Working of load following strategy.

5.2. Cycle Charging Strategy

In the cycle charging strategy, the hourly load is compared to the available solar power output. If the generated power becomes equal to the demand then the time is updated. If the solar power in an hour is more than the demand then the battery state of charge is checked. If the battery bank state of charge is found to be less than the maximum SOC, the battery bank is charged, otherwise it is fed to the dump loads. In case of demand exceeding the solar power generation, battery bank is operated to fulfill the net demand. If the battery bank is unable to supply the demand, diesel generator is operated. Here the diesel generator is operated to supply the demand as well as charge the battery bank, until the SOC maximum value has not been reached. If any one of these conditions is matched the iteration as unit time in hour is updated and the process continuous until the year is complete. The Figure 5 shows the methodology of operating cycle charging strategy.

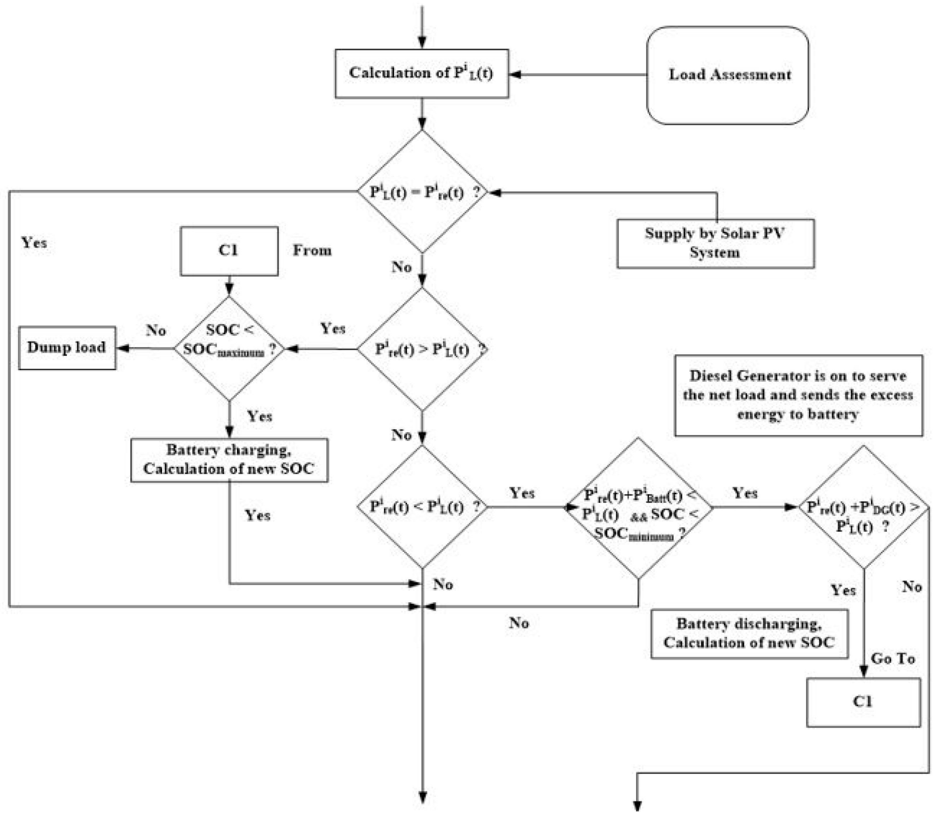

Figure 5. Working of cycle charging strategy.

6. Biogeography-Based Optimization (BBO) Algorithm

The biogeography-based optimization technique has unique features of longevity in the solutions survival nature as solutions in genetic algorithm die after each iteration. It also adds the merit of mutation, which removes the clustering effect seen while implementing BBO [29,30]. Due to these advantages, BBO is selected over GA and PSO for optimizing the cost of energy of the hybrid energy system.

BBO optimization procedure is as follows:

Step 1: Initialize the generation limit, population size and mutation rate.

Step 2: The fitness function values of all the individuals are evaluated.

Step 3: If the termination criterion is not met.

Step 4: Best habitats are saved in the temporary array.

Step 5: HSI (Habitat suitability index) is mapped using the number of ì, € e and S species for each habitat.

Step 6: Probabilistically choose the immigration island.

Step 7: SIV (Suitability index variables) are randomly migrated based on the island selected in Step 6.

Step 8: The population is randomly mutated.

Step 9: The fitness functions of all the individuals are evaluated.

Step 10: The population is sorted and arranged from best to worst.

Step 11: The best values of habitat as stored in temporary array replaces the worst values.

Step 12: Step 3 is again followed for continuing the next iteration.

Step 13: End the algorithm.

A flowchart of process of BBO algorithm is shown in Figure 6.

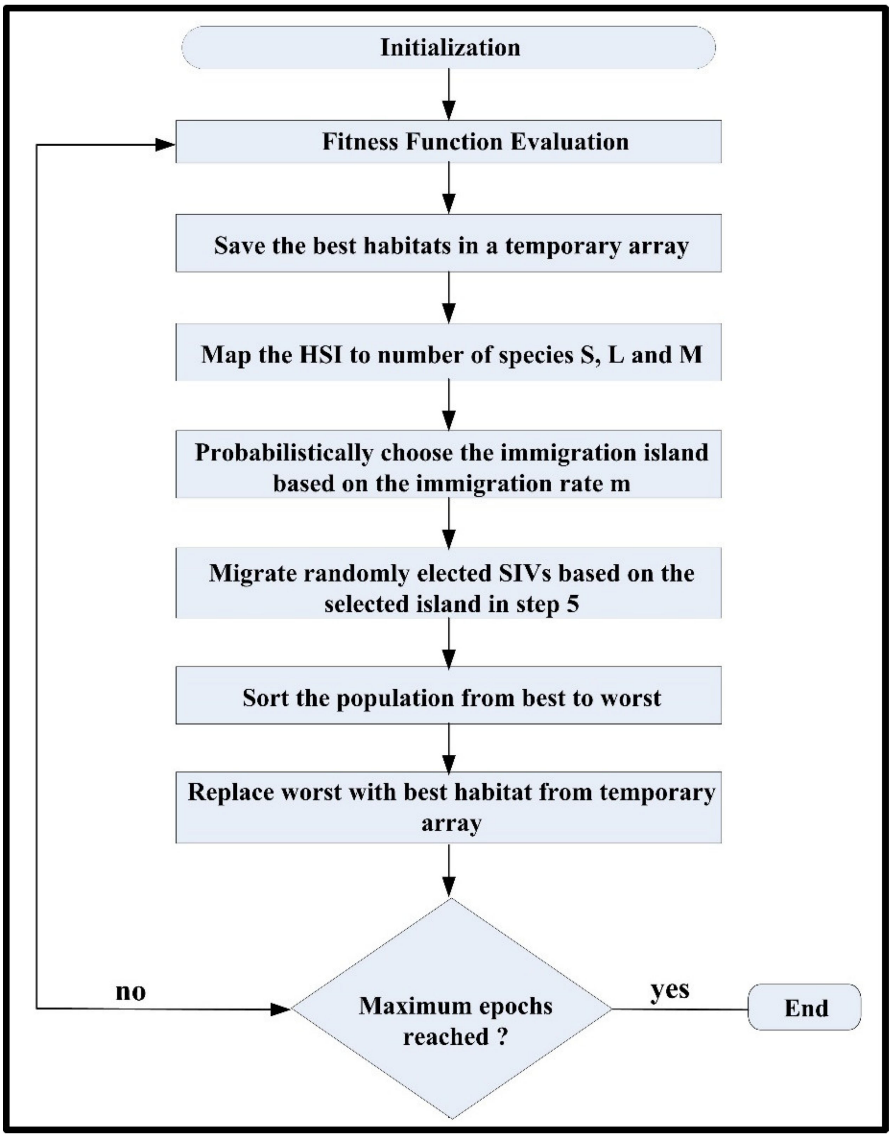

Figure 6. Biogeography based optimization process.

The parameters-chosen BBO technique have mutation probability of 0.4, population size is 50 selected due to better convergence of the objective function, and problem dimension is 3, while the available rooftop area limits the maximum number of solar modules to 500 modules. The variations of the total number of batteries and diesel generator to be selected are limited by 500 and 50, respectively.

7. Results and Discussions

7.1. Input Technical and Economical Dataset

Study area receives the annual average solar radiation of 5.26 kWh/m^2 per day. Peak solar radiation of 7.05 kWh/m^2 is found during the month of May and minimum solar radiation of 4.08 kWh/m^2 has been received during the month of December. A maximum temperature of 45 °C is recorded in the month of May and the lowest temperature of 12 °C is observed during the month of January. Monthly solar radiation and monthly temperature distribution of the selected site are depicted in the Figures 7 and 8, respectively.

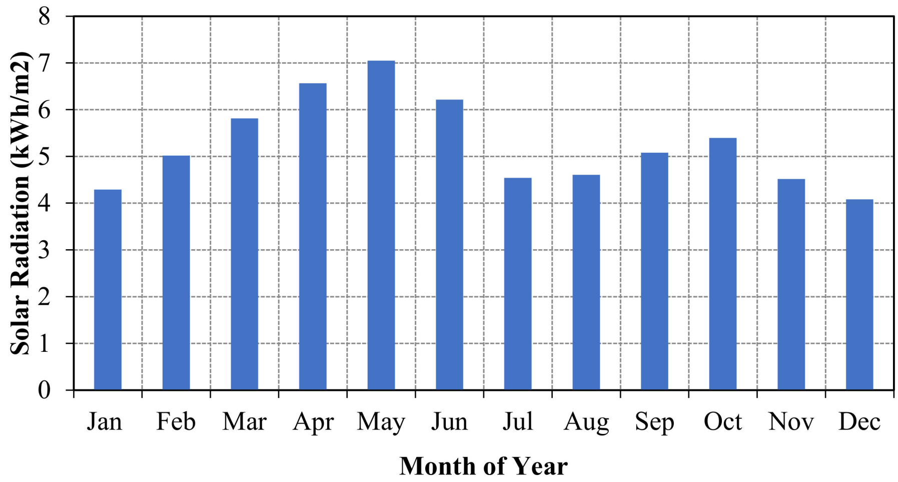

Figure 7. Monthly solar radiation of the selected site.

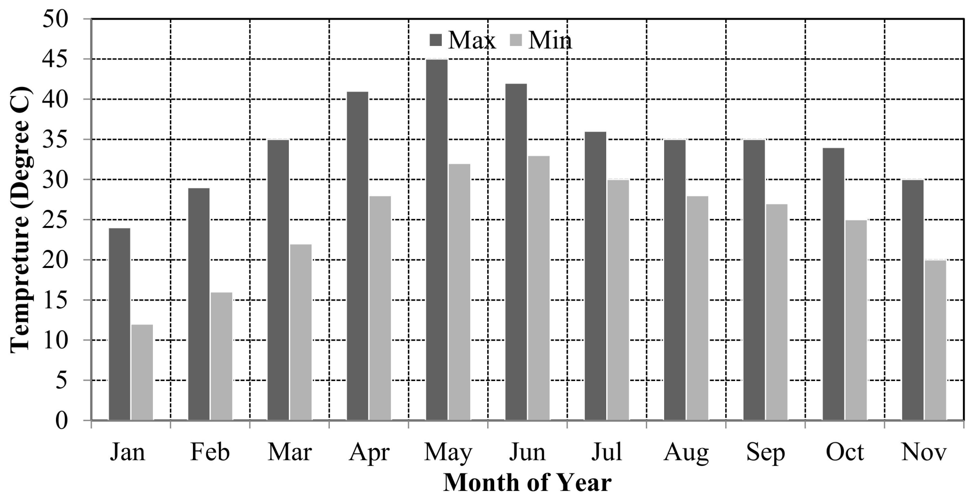

Figure 8. Monthly temperature of the selected site.

Load profile on an hourly basis is shown in Figure 9. Peak electrical load of 89.80 kW and 59.60 kW are estimated during summer season and winter season, respectively. Meanwhile, a minimum load demand of 14.5 kW and 5.43 kW is observed during the summer season and winter season, respectively.

Detailed specifications of system components available in market have been considered in the present paper as given in Table 1. Three types of DG (20 kVA, 30 kVA and 50 kVA) have been taken during the analysis. However, diesel price of $1.05 per Litre is same for all three DG. Two types of PV module (0.375 kW and 0.32 kW) have been used in the study. Capital cost of these modules is $273.79 and $205.34, respectively. Three types of battery sizes, 100 Ah, 150 Ah and 250 Ah have been considered during the performance analysis. Capital cost of these battery types is $96, $130 and $219, respectively. Specifications of charge controller and bidirectional converter are also given in Table 1.

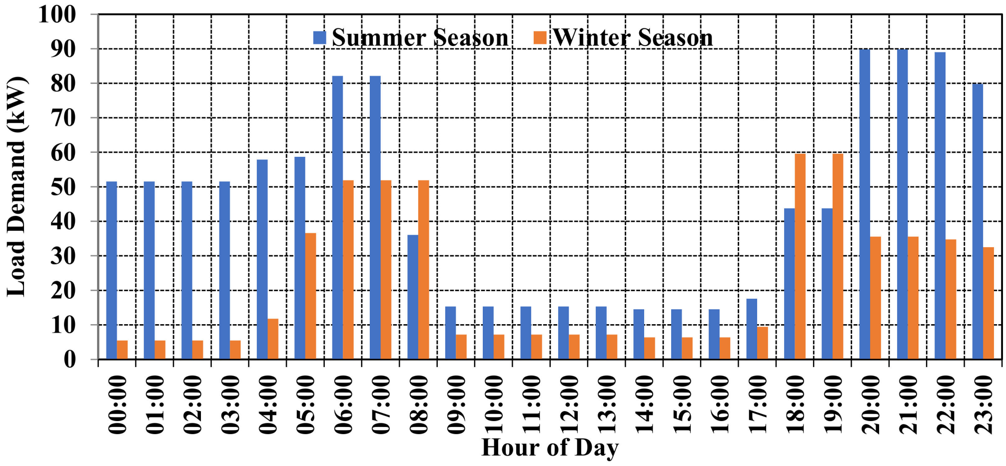

Figure 9. Hourly load demand of the study area.

Table 1. Detail specifications of system components.

(a)	**Diesel Generator**						
Type	**Power Rating DG (kVA)**		**Capital Cost ($)**		**Diesel ($/Ltr)**		
1	20		3450		1.05		
2	30		5133		1.05		
3	50		5818		1.05		
(b)	**Solar Photovoltaic Module**						
Type	**Voc (V)**	**Isc (A)**	**Vmax (V)**	**Imax (A)**	**Pmax (kW)**	**NCOT (°C)**	**Capital Cost ($)**
1	44.5	9.9	39	9.62	0.375	48	273.79
2	45	9.17	36.2	8.84	0.320	48	205.34
(c)	**Battery**						
Type	**Nominal Capacity (Ah)**		**Voltage (V)**		**DOD (%)**		**Capital cost ($)**
1	100		12		80		96
2	150		12		80		130
3	250		12		80		219
(d)	**Charge Controller**						
Type	**n1 (%) PV Battery Charger**		**n2 (%) PV battery Charger**		**Power Rating (kW)**		**Capital Cost ($)**
1	95		70		0.24		68.45
(e)	**Bidirectional Converter**						
Type	**Efficiency of Inv (%)**		**Power rating (kW)**		**Capital cost ($)**		
1	90		5.5		205.34		

7.2. Results and Discussions

The hybrid system model has been developed in MATLAB (R2019b, MathWorks, Natick, MA, USA) covering the specifications of individual components. Further, 18 combinations have been modelled and simulated for a year. The optimum configuration of these combinations is obtained using the BBO algorithm in MATLAB. Further, these combinations have been compared based on cost of energy, carbon emission, fuel consumption, renewable fraction and total operating hours. Descriptions of results are explained as follows.

7.2.1. Cost of Energy

For each combination of battery, solar photovoltaic module and diesel generator, the cost of energy (COE) is evaluated using cycle charging (CCS) and load following strategies (LFS). A comparison between the cost of energy for both the strategies is shown in Figure 10. Cycle charging strategy shows the minimum COE for each combination of components. The 13th combination provides the least COE of 0.225 $/kWh, with COE of 17th combination at 0.229 $/kWh and 7th combination as 0.231 $/kWh.

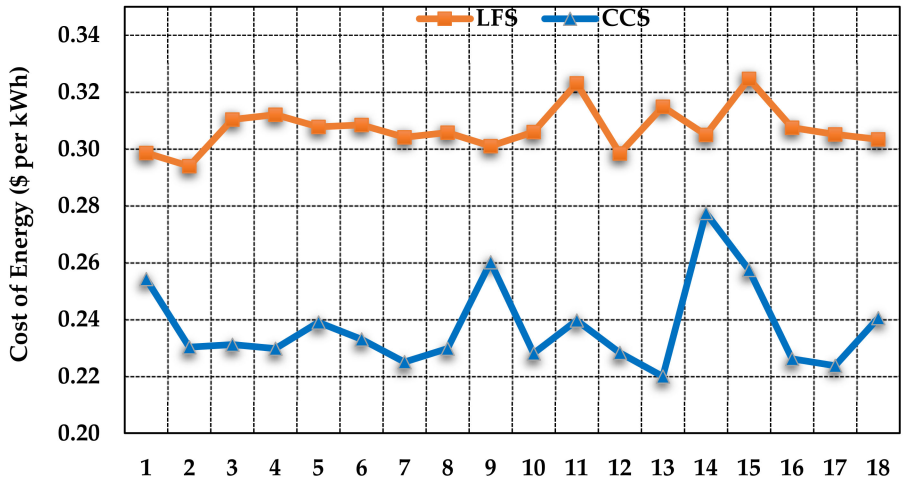

Figure 10. COE for each combination of specifications using BBO with CCS and LFS.

7.2.2. Optimum Size for Each Combination

Each combination has been simulated and optimized using BBO algorithm in MATLAB. Results for each combination are given in Table 2. From the Table 2, it has been found that combination 13 offers minimum cost of energy generation. The net present cost of this combination is calculated as $1,204,972. Combination optimum sizes consist of five numbers of DGs, 519 numbers of PV modules and 307 numbers of batteries.

7.2.3. Carbon Emission

The total CO2 emission is found to be at minimum about 155,184 kg/yr in case of the 13th combination as compared to the 7th and 17th combinations. This is due to the number of operating hours of diesel generator, about 732 for 13th combination as compared to 776 in case of the 7th combination. The carbon emission for each emission has been calculated and given in Table 3.

7.2.4. Renewable Fraction

Renewable fraction is directly dependent on the total output power of diesel generator and the renewable power output. This further depends on the overall fuel consumption by the diesel generator. Hence, higher fuel consumption of DG means minimum renewable fraction, the 13th combination has a maximum renewable fraction of 55% compared to 53% and 52% for the 7th and 17th combinations, respectively. Renewable energy for each combination is given in Table 3.

7.2.5. Total Fuel Consumption

The total fuel consumption of DG is minimal in the case of the 13th combination of 60,418 l, versus 7th and 17th combinations.

Table 2. Optimum size for each combination of hybrid system.

Combination	Device Type			Number of DGs	Number of Batteries	Number of PV Modules	Cost of Energy ($/kWh)	Total Net Present Cost ($)
	DG	SPV	Battery					
1	1	1	1	5	254	466	0.261	1,201,939
2	1	1	2	10	260	490	0.236	1,214,814
3	1	1	3	10	162	489	0.237	1,204,933
4	1	2	1	11	353	495	0.235	1,226,900
5	1	2	2	9	152	524	0.245	1,322,258
6	1	2	3	8	104	495	0.239	1,207,519
7	2	1	1	8	134	493	0.231	1,224,802
8	2	1	2	7	258	488	0.235	1,215,611
9	2	1	3	8	79	493	0.267	1,621,356
10	2	2	1	7	380	495	0.234	1,195,032
11	2	2	2	6	139	495	0.245	1,300,750
12	2	2	3	7	136	483	0.234	1,218,686
13	3	1	1	5	307	519	**0.225**	1,204,972
14	3	1	2	3	65	519	0.284	1,655,641
15	3	1	3	5	78	519	0.264	1,642,181
16	3	2	1	4	386	495	0.232	1,184,115
17	3	2	2	4	261	495	0.229	1,170,417
18	3	2	3	2	104	495	0.246	1,139,395

Note: Bold represents minimum cost of energy generation.

Table 3. Carbon emission, total fuel consumption and renewable fraction for each combination.

Combination	Emissions of CO_2 by DG (kg/yr)	Total Fuel Consumption by DG (Litre)	Renewable Fraction (%)	Energy Index Ratio
1	165,106	64,280	0.38	1
2	154,845	60,285	0.52	1
3	149,587	58,239	0.54	1
4	160,815	62,610	0.51	1
5	195,227	76,007	0.37	1
6	173,399	67,509	0.42	1
7	157,932	61,487	0.53	1
8	154,395	60,110	0.53	1
9	260,302	101,343	0.15	1
10	154,395	60,110	0.52	1
11	195,227	76,007	0.35	1
12	165,258	64,340	0.48	1
13	155,184	60,418	0.55	1
14	270,936	105,483	0.004	1
15	264,576	103,007	0.16	1
16	155,693	60,616	0.52	1
17	155,523	60,550	0.52	1
18	162,562	63,290	0.4	1

7.2.6. Total Operating Hours of DG and Battery Bank

The diesel generator needs to be operated 732 h and battery bank of 4772 h over a year in case of the 13th combination. The generators are operated for the minimum amount of time in this case while using cycle charging dispatch strategy. Operating hours for each combination are given in Table 4. Additionally, it has been found that replacement of battery bank is found to be minimal in case of CCS compared to LFS. The battery bank is to be replaced in every 3 years with CCS while battery banks are replaced after 2 years with LFS.

Table 4. Total operating hours of DG and battery bank.

Combination	Energy Index Ratio	Total Operating Hours (hr/yr)	
		DGs	Batteries
1	1	1947	3680
2	1	913	4683
3	1	882	4714
4	1	862	4734
5	1	1279	4286
6	1	1278	4318
7	1	776	4789
8	1	867	4729
9	1	1279	4286
10	1	867	4729
11	1	1279	4317
12	1	928	4699
13	1	732	4772
14	1	2130	3374
15	1	1248	4256
16	1	918	4678
17	1	917	4679
18	1	1917	3679

7.2.7. Convergence of BBO Algorithm

Convergence plot using BBO algorithm is shown in Figure 11. The results attained using BBO for the 7th, 13th and 17th combinations, by considering COE as the minimization objective function. For the 13th combination the COE is 0.225 $/kWh compared to 0.229 $/kWh and 0.231 for the 17th and the 7th combinations, respectively.

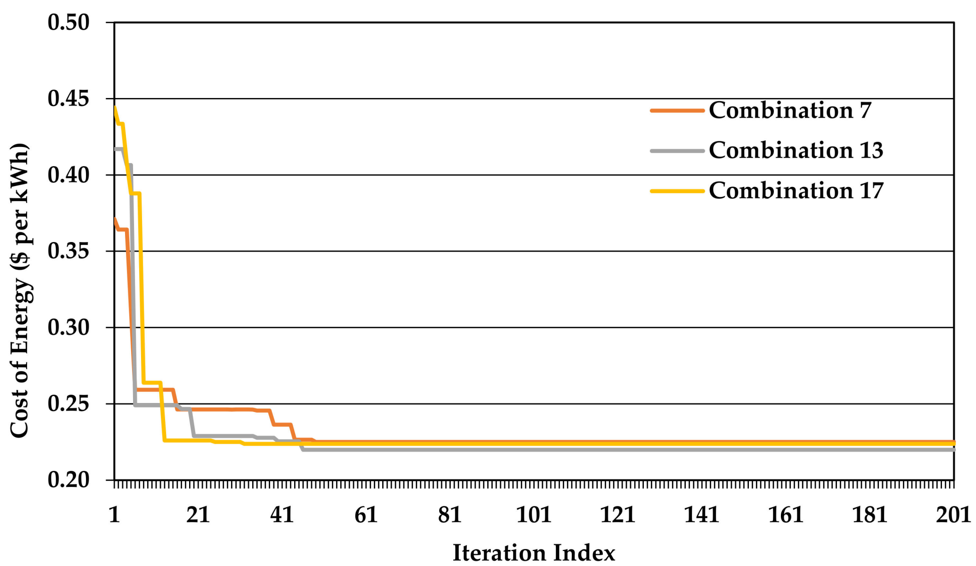

Figure 11. COE convergence plot with BBO for the 7th, 13th and 17th combinations.

8. Conclusions

In the paper, performance investigation of Solar Photovoltaic/DG/Battery-based hybrid system has been performed for the energy access of three hostels and one STP of an institute. In total, 18 combinations of system components sizes available on the market have been considered during the analysis. Cost of energy generation of hybrid system has been optimized using BBO algorithm.

After simulation, it has been found that the cycle charging strategy offers a lower cost compared to the load following strategy. All considered combinations have been compared based on COE, renewable fraction, carbon emission and operating hours of DG's. The optimum configuration offers minimum COE of 0.225 $/kWh, a renewable fraction of 55% and carbon emission of 155,184 kg/yr. Further, government subsidy on the PV module can also further reduce the system cost. In future works, the addition of utility grid and waste utilization, collected from the campus to energy are proposed to make a more sustainable hybrid system.

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