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International Journal of ChemTech Research
CODEN(USA): IJCRGG ISSN : 0974-4290
Vol.5, No.2, pp 771-779, April-June 2013

ICGSEE-2013[14th – 16th March 2013]
International Conference on Global Scenario in Environment and Energy

Development Of A Cost-Optimized Hybrid Off-Grid Power System For A Model Site In North-Eastern India Involving Photovoltaic Arrays, Diesel Generators And Battery Storage

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Abstract: A model site in the north-eastern state of India is selected for economic analysis and optimization of an off-grid hybrid power system with an average electrical energy demand of 35.6 kW. Off-grid hybrid power systems are evaluated in different configurations of solar photovoltaic (PV), diesel generators (DG) and batteries (BAT) for minimization of cost of energy (CoE) and maximized renewable share. The cost analysis of hybrid power system is performed using Hybrid Optimization Model for Electric Renewables (HOMER) optimization software. The CoE is computed by varying PV, DG sizes and BAT cells; and the optimal system configuration is assessed. A comparison of cost analysis with simulated system architectures and literature is also presented in this study.
Keyword: Batteries (BAT); Cost of Energy (CoE); Diesel Generators (DG); HOMER optimization; Off-grid hybrid power systems.

1. Introduction

The access to electricity is closely linked with development and economic well-being of a nation and there is a tremendous increase in the demand for electricity globally. However, according to the International Energy Agency (IEA), about 1.4 billion people in the world do not have access to electricity[1-3]. In India, a considerable fraction of population of many north-eastern states is suffering from economic and developmental impediment due to lack of stable grid power or unavailability of grid power. Huge financial resources have been invested in India to extend the grid electricity in rural areas, but the reality is different[2,4,5]. As compared to other countries, in India about 20-40% of electricity is lost in the grid during transmission and distribution. Also, the extension of grid to remote villages costs around one rupee per unit per kilometer[6]. Alternatively, hybrid power system can be considered an option for the remote rural localities in where the grid cannot be available. Hybrid power systems are composed of conventional and renewable or more than one renewable source for supply of electricity. The renewable sources include wind, solar, geothermal, tidal, hydel, and bioenergy[7,8]. A majority of hybrid systems designed for stand-alone operation comprise of solar photovoltaic and/or wind energy. The suitability of renewable sources depends on the environmental location and climatic condition of the area, accessible resources and the economics of the power system[9]. Hilly northeastern states of India are not suited for off-grid wind energy based power systems, coastal regions are best suited[10,11]. Solar photovoltaic power systems are best suited all over India, due to the tropical climate[6]. But, the accessibility of solar irradiance and high capital cost often require solar photovoltaic power systems to be complimented by additional power sources or storage. Other than renewable, the conventional diesel generator has been considered as an alternative for hybrid power systems for remotely located site. Diesel generator is a suitable compliment for hybrid systems due to low capital cost, easy operation and simple installation. However the operation of diesel generator (DG) is often limiting due to fluctuating fossil fuel prices and environmental burden of greenhouse gas (GHG) emissions. Thus, evaluation of hybrid power systems in terms of cost of energy (CoE) with various alternative energy sources considering the demand of the considered location and available resources is highly relevant for configuring a hybrid power system for remote localities.

Several hybrid system configurations involving solar photovoltaic together with wind turbine, hydrogen fuel cell has been assessed in earlier reports[13-16]. Jennings in his report stated that the hybrid PV-DG system is an attractive configuration for homeowners in remote locations[17]. Gupta et. al.[18] evaluated CoE for hybrid systems based on PV, DG and bio-energy as a specific option for energy source of remotely located hilly communities of India. J. Dekker et. al.[19] suggested that hybrid PV-DG configuration is an excellent example for rural electrification by water pumping and irrigation, water heating, lighting etc. C.W. Ajan et. al.[20] represented a study on the technical aspect and life-cycle cost of hybrid PV-DG system for a remote school. A recent study discussed about the identification of alternative methodological options and analyzes the suitability of various options for off-grid power system[21]. Hence the objectives of the present study is to minimize CoE and maximize the renewable share of a remotely located model site by considering different combinations of various power sources involving solar photovoltaic panel (PV), diesel generator (DG) and battery storage (BAT) for hybrid off-grid power systems using Hybrid Optimization Model for Electric Renewables (HOMER) optimization tool developed by National Renewable Energy Laboratory’s (NREL, Golden, CO, USA).

2. System Description

2.1. Study area and its load profile

A model site is chosen from north-eastern state of India for the feasibility study of hybrid renewable energy system. The model site is a section of an academic institution. The section is having loads of 150 units of 40 W fluorescent lights, 100 units of 85 W fans, and 140 units of 150 W computers. 23.80 N and 91.50 E respectively are the latitude and longitude of the model site. The site has accessibility to one renewable energy source namely, PV. The model site has a peak load of 75kW, average daily load of 35.6kW and the scaled annual average energy demand is 854 kWh/day.

2.2 Solar Photovoltaic (PV)

The rated capacity of each PV module used in the study is 205 W, with area of 3.66 m^2. PV modules are connected in series in order to generate the desired output. Since the PV module converts the sunlight into electricity, it is impossible to harvest PV energy throughout 24 hour period. In general, the monthly solar radiation of the studied model site varies from 2.85 to 6.22 $kWh/m^2/day$, with an annual average of 4.7 $kWh/m^2/day$. The considered lifetime of PV array is 25 years. During any period when excess electricity from PV would be used to charge the battery storage. The excess power (P_{EXCS}) is calculated in HOMER from the difference of the output of the PV array and the load served,

$$P_{EXCS} = P_{PV} - P_{LOAD} \qquad \text{.........................} (1)$$

2.3 Diesel Generator (DG)

The cost of a diesel generator depends on its size. For the present study, the DG capacity is varied from 40 kW to 80 kW. The fuel consumption is modeled by a linear relationship characterized by a slope and an intercept of value 0.25 L/h/kW and 0.08 L/h/kW respectively[22]. The fuel cost is considered 0.8 $ per liter. The lifetime of DG is 150000 operating hours. The generator model is designed in such a way that it can operate in standalone mode to feed the load and also in combination with the battery bank and other renewable sources. The DG output is utilized to meet the load. In case of excess generation, the excess energy would be used to charge the battery storage. The P_{EXCS} of the system is computed as,

$P_{EXCS} = P_{DG} - P_{LOAD}$ .... (2)

The emission factors of DG for carbon monoxide is considered as 6.5 g/L of fuel, unburned hydrocarbon as 0.72 g/L of fuel, particulate matter is 0.49 g/L of fuel, proportion of fuel sulfur converted to PM is 2.2%, nitrogen oxide is 58 g/L of fuel.

2.4 Storage Battery

The battery model Surrette block 40 is chosen as the storage element in this simulation. This model consists of 5 volts of 40 unit battery. Numbers of batteries are varied to meet demand providing storage of excess electricity from PV and/or DG. The considered lifetime of BAT is 3 years. Battery units are charged with P_{EXCS} until the SOC_{BAT} reaches maximum state of charge (SOC_{MAX}). The value of SOC_{MAX} is considered as 1. Similarly the batteries are discharged to meet the load as and when required till maximum state of charge (SOC_{MIN})[23]. SOC_{MIN} is taken as 0.35 for all system architectures that are assessed in this study. Mathematically the constraints of the battery operation can be expressed as:

$SOC_{MIN} \leq SOC_{BAT} \leq SOC_{MAX}$ .... (3)

3. HOMER simulation and cost optimization

Various system architectures of hybrid power system are evaluated by simulating their performance and calculating the cost heads in HOMER software version 2.68. For evaluating various system architectures, HOMER simulates the operation of a system by making energy balance calculations and displays a list of configurations, sorted by net present cost (NPC). In designing the hybrid power system, the input information to be provided to HOMER are: electric loads, power sources, costs and sizes of the components, controls, constraints, types of dispatch strategy etc[24,25]. The summation of the capital, replacement and operation and maintenance (O&M) cost of a component power source is the total cost of that component based on present value. Thus the total cost of component power source (Total Cost $_{comp}$(i)) is given by,

Total Cost $_{comp}$ (i) = (Capital $Cost_i$) + (Repalcement $Cost_i$) + (O&M $Cost_i$) .... (4)

The nominal interest rate is pegged at 10% and the annual inflation rate is considered at 6.95%, thus the annual real interest rate used for HOMER simulation is 2.85%. The project lifetime is assumed to be 25 years. The net present cost of a component (NPC_{comp}) is computed as,

NPC_{comp} = [Total $Cost_{comp}$]/[i*CRF*R] . ... (5)

where, CRF is the capital recovery factor, i is the real interest rate, R is the project lifetime.

The NPC of a hybrid power system, consisting of 'n' components, with 'N_i' number of i^{th} component integrated together, can be defined by the following equation[26,27,28],

NPC = $^{n}\sum$ (N_i* Total cost $_{comp}$ (i)) .... (6)

HOMER was used to compute the cost of energy (CoE) from the NPC of the hybrid system. CoE is the average cost per kilowatt hour ($/kWh) of useful electrical energy produced by the system.

4. System Architecture

The two different power sources PV and DG with BAT storage is assessed in three different system architectures for minimization of CoE and maximization of renewable share. The evaluated system architectures are: (1) DG with BAT, (2) PV with BAT and (3) PV with DG and BAT. Converter (CONV) is added in all the architectures as a system element to stabilize the flow of energy between the AC and DC components. The capital cost assumed for PV unit is $4200 per kW; for BAT is $3000 per unit, for DG is $500 per kW and for CONV is $750 per kW respectively.

4.1. Architecture-I: DG-BAT system

DG is the primary power source for the system configuration of architecture-I. The system configuration of this architecture is presented in Fig. 1A. BAT compliment the DG as energy storage in order to meet the demand. The replacement cost is 80% of the capital cost and the O&M cost is considered 0.5 $/hr. The DG sizes in architecture-I is varied from 40 to 70 kW for simulation. For the system configuration and load profile of the studied area, simulation was not possible with DG sizes below 40 kW. Increasing DG size above 70 kW was unbalanced for the system load. The total cost of a component (Total $Cost_{comp}$(i)) is the summation of capital, replacement and O&M cost (Equation 4). The O&M cost of BAT is $560/yr and the replacement cost is 85% of the capital cost. The number of BAT units is varied from 100 to 1000 units. For minimum considered DG size, BAT cell below 100 units is not possible. The number of BAT units above 2000 units is redundant for the system load. The O&M cost of CONV is considered $650/yr and replacement cost as 67% of the capital cost. For simulation of the system, CONV size is kept invariant at 80 kW in accord with the system load. For architecture-I, the O&M cost of the component holds the major contribution towards Total $Cost_{comp}$(i) and the O&M cost of DG is 98% of the total DG cost. The relation between O&M Cost of DG (OMC_{DG}) with the DG sizes (DG_{Size}) can represent by the Eq. (7),

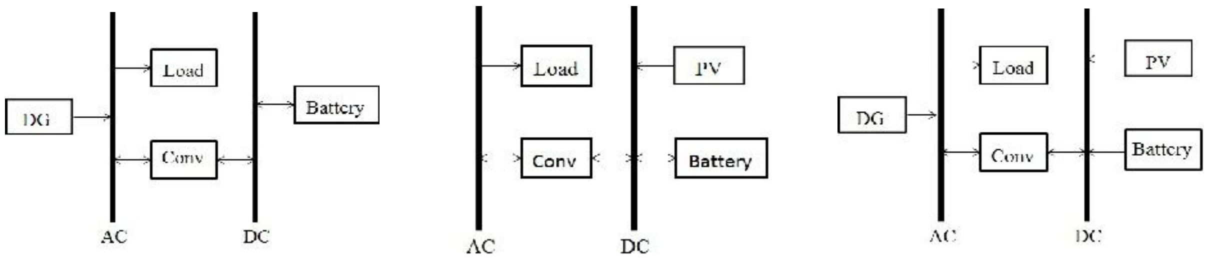
$$OMC_{DG} = 125000*(DG_{Size}) + 25000 \quad \text{.........................} \quad (7)$$

Eq. (8) represents the relation between the total cost (Total $Cost_{DG-BAT}$) of the power system in architecture I with DG sizes (DG_{Size}), BAT cells (BAT_{Cell}), and CONV sizes ($CONV_{Size}$).

$$\text{Total } Cost_{DG-BAT} = 125000*(DG_{Size}) + 54500 * (BAT_{Cell}) + 15000*(Conv_{Size}) + 92500 \quad \text{......................} \quad (8)$$

4.2. Architecture-II: PV-BAT system

The configuration of the system architecture-II is presented in Fig. 1B. The basic power source for this architecture is considered as PV. In order to meet the demand from stored energy, PV is complimented with BAT. In the simulation of PV-BAT system no annual shortage was considered. This architecture has 100% renewable energy fraction, as the total demand is meet from the energy produced by the PV array.



(A) **(B)** **(C)**

Figure 1. The schematic of the various system architectures, **(A)** Architecture **-** I (DG-BAT system), **(B)** Architecture **-** II (PV-BAT system), **(C)** Architecture **-** III (PV-DG-BAT).

The replacement cost of PV is considered as 75% of the capital cost and the O&M cost is $1000/yr. PV sizes are varied from 180 kW to 240 kW for simulation. For the system configuration, load profile and from the consideration of PV efficiency simulation was infeasible with PV sizes below 180 kW. The PV sizes more than 240 kW was superfluous for the system load. BAT are varied from 1000 to 3000 units. Higher number of BAT are considered in system architecture II compared to architecture-I in order to provide enough storage to meet the load through the period of no solar insolence. CONV maintained at 80 kW for all variations. The O&M cost of system components is less than 5% of the total cost and the capital cost of the components contribute the largest share to the Total $Cost_{comp}$(i). Eq. (9) represents the relation of the capital cost of PV (CC_{PV}) with the PV sizes (PV_{Size}),

$$CC_{PV} = 84000*(PV_{Size}) + 252000 \quad \text{.........................} \quad (9)$$

Also the Eq. (10) represents the relation of total cost of PV-BAT system (Total $Cost_{PV-BAT}$) with the PV sizes (PV_{Size}), Battery cells (BAT_{Cell}) and Converter sizes ($CONV_{Size}$),

Total $Cost_{PV-BAT}$ = 84000*(PV_{Size}) + 15000*($Conv_{Size}$) + 54500 * (BAT_{Cell}) + 319500 ....(10)

4.3. Architecture-III: PV-DG-BAT system

In system architecture-III two primary power sources, PV and DG are considered along with BAT for power storage. Fig. 1C represents the schematic of the architecture of the system. In the system architecture-III, PV and BAT contributes to the renewable share. For the operation system in architecture-III the PV sizes are varied from 40 kW to 200 kW, DG sizes from 40 to 80 kW, BAT units from 100 units to 2000 units and CONV is fixed at 80 kW. Thus the total cost of PV-DG-BAT system (Total $Cost_{PV-DG-BAT}$) in terms of PV sizes (PV_{Size}), DG sizes (DG_{Size}), BAT cells (BAT_{Cell}) and CONV sizes ($CONV_{Size}$) are represented by the Eq. (11),

Total $Cost_{PV-DG-BAT}$ = 84000*(PV_{Size}) + 125000*(DG_{Size}) + 54500 * (BAT_{Cell}) + 15000 * ($CONV_{Size}$) + 344500 .... (11)

5. Results of Architectures

5.1. Architecture-I:

The simulated CoE for the system architecture-I varying DG sizes (40 – 70 kW) and BAT units (100 – 2000 units) are presented in a contour plot (Figure 2). The lower CoE is observed with lower BAT cells (100-200 units) and lower (40-50 kW) DG sizes. Primarily CoE increases significantly with the increasing of DG sizes. CoE remains stable between DG sizes 45- 55 kW with 1000-1200 BAT units. The maximum CoE is observed for higher (60-70 kW) DG sizes and higher (1500-2000 units) BAT cells. The result of HOMER simulation to minimize the CoE is presented in Table 1. The minimum CoE of 0.318 $/kWh was computed for the system architecture-I with DG size of 45 kW, BAT cell of 120 units and CONV size of 80 kW. The fuel consumption rate for the DG was considered to be 110,682 L/yr at mean efficiency of 30.4% and specific fuel consumption value was maintained invariant at 0.3 L/kWh.

Table 1. The result of HOMER simulation to minimize the CoE of DG-BAT (Architecture-I)

DG (kW)	BAT (no. of cells)	CONV (kW)	CoE ($/kWh)
40	400	80	Not feasible [#]
40	600	80	Not feasible [#]
45	600	80	0.329
45	400	80	0.324
45	200	80	0.320
45	120	80	0.318
50	200	80	0.326
50	400	80	0.331
50	120	80	0.325

Note: [#] = HOMER simulation did not result CoE due to inappropriateness of component sizes.

The operation of DG is linked with emissions of gaseous pollutants due to consumption of fossil fuel, of which 97% is CO_2. Hence, CO_2 emission was simulated to quantify the environmental impact of the system. The relation between DG operating hours and CO_2 emission is presented in Eq. (12). The CO_2 emission of 45 kW DG in system architecture-I was simulated to be 291.5 MT/yr.

DG CO_2 Emission = 0.002*(DG operating hours) + 304.4 .... (12)

5.2. Architecture-II:

The CoE of the system architecture-II was computed by varying the PV (180 – 250 kW) sizes and BAT (1000 – 3200 units) units. The contour plot of CoE of the system architecture-II is shown in Figure 4 and constructed by varying the PV sizes and BAT cells. The contour plot (Figure 4) distinctly shows the maximum and minimum of the CoE simulated for varying component sizes. High CoE was simulated for high PV sizes (above 220 kW) both at low BAT numbers (1000-1200 units) and high BAT numbers (above 2000 units). The CoE remains stable between the PV sizes of 190 kW to 205 kW and BAT cells 1000 to 1700 units. The highest value of CoE is 0.248 $/kWh (at 220 kW of PV and 2500 units of BAT cells).

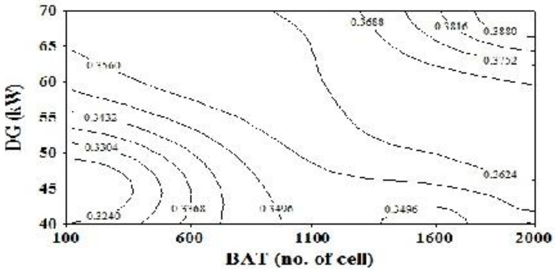


Figure 2

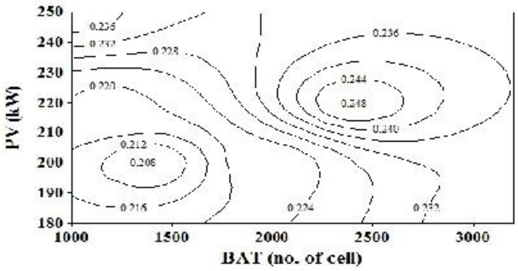


Figure 3

Figure 2. The contour plot of CoE ($/kWh) with variation in BAT capacity (no. of cells) for various DG sizes in architecture-I (DG-BAT system) (CONV size = 80kW).

Figure 3. The contour plot of CoE ($/kWh) with variation in BAT capacity (no. of cells) for various PV sizes in architecture-II (PV-BAT system) (CONV size = 80kW).

Table 2. The result of HOMER simulation to minimize the CoE of PV-BAT (Architecture-II)

PV (kW)	BAT (no. of cells)	CONV (kW)	CoE ($/kWh)
190	2400	80	0.224
200	1600	80	0.213
200	2000	80	0.222
200	1400	80	0.208
220	1200	80	0.219
170	2800	80	0.233
180	2400	80	Not feasible [#]
210	1000	80	Not feasible [#]

Note: [#] = HOMER simulation did not result CoE due to inappropriateness of component sizes.

The simulation result for minimization of CoE is presented in Table 2. The minimum CoE of the system architecture-II was calculated 0.208 $/kWh with PV size of 200 kW, BAT cells of 1400 units and CONV size of 80 kW.

5.3. Architecture-III:

Architecture-I (DG-BAT system) showed the incremental relationship of CoE with the increase in DG sizes and less BAT units for storage. The PV-BAT system (architecture-II), higher PV sizes are linked with higher CoE, but the system required high BAT storage units. However, the CoE of architecture I is lower than architecture II due to lower O&M cost. Accordingly, architecture-III (PV-DG-BAT system) is assessed varying PV, DG sizes and BAT units simultaneously to minimize the CoE and determine optimum renewable share.

The simulation demonstrates that addition of PV in DG-BAT system considerably reduces the DG share (by 27%) and the renewable share is increased by 27.2% (Figure 4A and 5B). On addition of PV in DG-BAT system, the CO_2 emission is also reduced by 24%. Increase in PV size consistently increases the renewable share with decrease in the DG share and cut down in CO_2 emission. Excess electricity is available for storage beyond 120 kW of PV size.

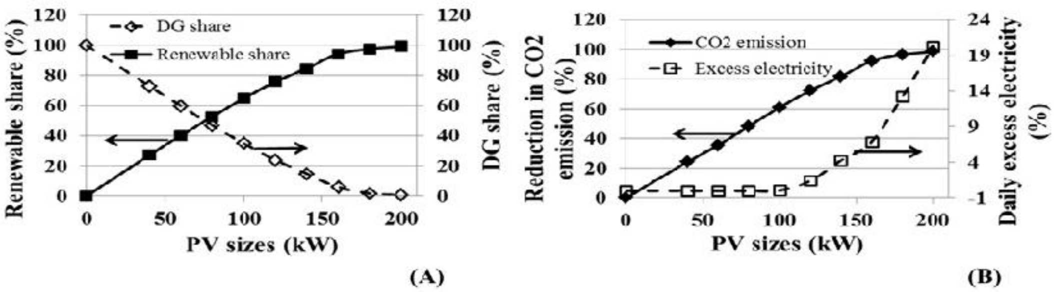


Figure 4(A), (B): The effect of PV sizes on renewable share, DG share, reduction in DG CO_2 emission and excess electricity in architecture-III (PV-DG-BAT system) (CONV size = 80kW).

Table 3. HOMER simulation results for varying PV, DG and BAT in Architecture-III

PV (kW)	DG (kW)	BAT (no. of cells)	CONV (kWh)	Excess electricity (%)	DG share (%)	Renewable (%)	CoE ($/kWh)	CO_2 emission (kg/yr)
160	55	800	80	6.86	6	94	0.191	24,548
160	55	1000	80	6.29	5	95	0.193	22,067
160	50	1000	80	6.29	5	95	0.192	21,317
160	60	1000	80	6.29	5	95	0.194	22,766
165	45	1000	80	7.75	4	96	0.190	16,476
165	45	800	80	8.27	5	95	0.188	18,738
150	60	1000	80	4.24	8	92	0.198	34,655
150	45	1000	80	4.24	8	92	0.194	31,288
155	50	1200	80	4.81	6	94	0.196	24,868
160	45	1200	80	6.08	5	95	0.194	19,232

The Table 3 represents the results of HOMER simulation for varying PV sizes, BAT cells, and DG sizes. The lowest CoE of 0.188 $/kWh is calculated for system architecture-III with the PV size of 165 kW, DG size of 45 kW, BAT cells of 800 units and CONV size of 80 kW. The CO_2 emission of the simulated DG in system architecture-III was 94% lower than that calculated in system architecture-I. For the system architecture-III, the capital cost is 78% and O&M cost is only 14% of the total cost of the system. PV and DG contributed respectively 67% and 12% of the total cost of the system and another 12% of the total cost is added by the BAT. Remaining 9% of the total cost is due to CONV. The fuel cost for the DG contributes 67% of the O&M cost and 14% of the total system cost.

6. Comparison among system architectures: Past and Present

The similar system architectures from literature are compared with present study in terms of CoE and renewable fraction (Table 4). The CoE for DG-BAT system from literature[27] give 0.710 $/kWh, whereas the CoE simulated from the present study by HOMER optimization of component sizes for DG-BAT system is 0.318 $/kWh. The CoE results from literature for PV-DG-BAT varied from 0.489-0.796 $/kWh[25,27,29] but renewable share was significantly lower (43%), while the present study is the CoE of 0.188 $/kWh is simulated with 95% of renewable share. The present study also demonstrated that optimal component sizing through detailed simulation is an effective route for minimizing CoE in various system architectures.

Table 4. The comparative summary of similar system architectures from literature

System type	PV (kW)	DG (kW)	BAT (number)	CONV (kW)	CoE ($/kWh)	Renewable fraction (%)	Referen ce No.
DG+BAT	-	2400	700	700	0.710	0	[27]
PV+BAT	25000	-	32750	3200	1.200	100	[27]
PV+DG+BA	60	50,50	12	60	0.796	22	[25]
PV+DG+BA	2000	2400	1300	2500	0.632	27	[27]
PV+DG+BA	6	10	10	5	0.489	43	[29]

7. Conclusion

The present study discussed about the electricity requirement of a model site in the north-eastern state of India using different available off-grid hybrid power sources. This study presents the comparative economic analysis of three different architectures associating PV, DG and BAT. The architectures evaluated are DG-BAT, PV-BAT, and PV-DG-BAT. Comparative economic study is done by HOMER software. Hybrid PV-DG-BAT system is found as most economic system with minimum CoE of 0.188 $/kWh from the simulated results of three different system architectures. The use of hybrid PV-DG-BAT system comes with advantages of improved reliability and reduced emissions. The CoE simulated in this study is significantly lower than similar system architectures of the reported in the literature.

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