Optimization and Reliability Evaluation of Hybrid Solar-Wind Energy Systems for Remote Areas

Animesh Masih*, H K Verma*

*Electrical Engineering Department, SGSITS Indore (M.P.), India

(animeshmasih.gs@gmail.com, vermaharishgs@gmail.com)

‡ Animesh Masih, Corresponding Author, Electrical Engineering Department, SGSITS, Indore (M.P.), India, Tel: +917869327208, animeshmasih.gs@gmail.com

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Abstract-This paper presents optimization and reliability analysis of renewable energy system for farm house electricity and irrigation load demand located at remote area. Optimum sizing of solar PV, wind turbine and battery energy system has been obtained to fully utilize the capacity of the system. The economic analysis has been carried out for different configuration of hybrid energy system in terms of net present cost (NPC), operating cost (OC), levelized cost of energy (LCOE). This paper proposes a recent evolutionary technique based on meta-heuristic optimization algorithm called grasshopper optimization algorithm (GOA), to be used for selecting optimal energy system configuration. Markov method has been employed for evaluating the reliability indices i.e. system failure rate, repair rate, availability, unavailability, mean up time (MUT), mean down time (MDT), loss of load probability (LOLP) and expected energy not supplied (EENS). Economic analysis, GOA and Markov method-based result shows that hybrid PV-Wind-battery energy system is more reliable and cost effective system as compared to other configuration. The NPC and LCOE of the optimal hybrid PV-wind-battery energy system are $26,450 and 0.502$/kWh respectively. The optimal hybrid PV-wind-battery energy system reliability indices like LOLP (0.0000103), MUT (84.60), EENS (0.63189), failure rate (0.011819) and unavailability (0.09027) are evaluated.

Keywords: availability, grasshopper optimization algorithm, hybrid energy system, loss of load probability, Markov model

1. Introduction

Energy consumption dictates social discrepancy and disparities between one country to other country. Conventional energy sources (coal, natural gas, oil) have been resources of world energy needs since the industrial revolution. However, the fast depleting rate of convention energy resources causes climate change, environment problems and face energy crisis required clean, affordable and eco-friendly energy resources. Renewable energy (RE) resources from the sun (solar intensity, heat, wind), the earth (geothermal, bio-mass) and the sea (tides, ocean thermal) are the major sources that meet such objectives and fulfill the present and future energy demands [1-2]. Solar energy can be converted into electricity by PV cells and this electricity is used for lighting, home, building, irrigation, electric appliances etc. Wind energy (WE) is used for pumping water in remote areas, battery charging and for operating domestic appliances [3]. Ref [4] developed daily global solar radiation model for hybrid renewable energy system and tested on six different environment locations in India. It also used NASA data and predicted ANFIS data for selection of optimal energy system configuration. Any RE system have some objectives and goals to fulfill the demand requirement. The RE system have treated as a reliable and unreliable. The system components failure rate is not forecast, system is to be unreliable so system quality have reduced. For system quality improving, it requires to analysis reliability of the system and its components [5].

In ref [6] presents novel approach for evaluate LOLP, LOLE and ELL reliability indices of a hybrid mini-grid system (HMS) using HOMER software. It is also evaluated net present cost (NPC), levelized electricity tariff, pollutant emissions and sensitivity analysis for HMS. Results shows hybrid energy system is economic and consistent system for HMS [7].

Linear TORSCHE method is used for get to an optimal solution of the hybrid PV-Wind energy system. Step by step analysis is done, i.e. First analysis with PV only, wind only configuration and then compared to hybrid PV-Wind configuration. Economic analysis NPV, CC, payback period and Cost of energy (COE) has been calculated to obtain optimum solution [8]. A new method analytic hierarchy process (AHP) for the selection of most favorable renewable energy integration system. In this study, comparison of AHP method is done by best worst method and stochastic multi-criteria acceptability analysis of favorable renewable energy integration system [9]. Ref. [10] investigated PV system optimum sizing and techno-economic analysis in remote areas. He calculated optimum configuration by using fixed tilt, annual optimum tilt and economic analysis.

A Numerical Heuristic Searching Algorithm (NHSA) is uses for estimation of PV module parameters [11]. Ref. [12] presents GOA for the economical operation of a hybrid (thermal and windmill) energy system. GOA is used for selecting the optimal number of systems, required for load. GOA based results are compared with quantum-inspired PSO method. Meta-heuristic optimization algorithm (GOA) is appropriate for solving partially shaded PV array reconfiguration process. GOA results are compared with total cross tied connection (TCT) and genetic algorithm (GA) configuration. Enhancement PV output power using whale optimization algorithm under normal and shading conditions [13]. Ref. [14] proposed binary version of GOA (NBGOA) for the second strategy based element subset selection. The number of algorithms i.e. binary dragonfly optimization (BDO), binary GOA, binary grey wolf optimization approach (bGWOA) and novel binary PSO was used for results comparisons. GOA was best for fitness function, average classification accuracy.

In this manuscript, consider a case study of a remote village farmhouse. First, to carry out an optimum sizing of RE system by using GOA. Second, to select best energy system configuration for remote area as per requirement by using HOMER software. Finally, we calculate reliability index of all hybrid RE system configurations by using Markov method. The aim of this study to obtain an optimum configuration of a hybrid RE system with more economic and reliable.

2. Methodology

Sizing of the hybrid RE system is done as per the load demand. Since, a huge capital cost is involved in the installation of the RE system, over sizing of the RE system will lead to high price of the electricity generated. On the other hand, under sizing the system reduces the reliability. Hence an optimum sizing has to be arrived at. The following section will discuss the methodology followed for optimum design of the energy system as per the requirement.

Step-I: Obtaining the electric load data and energy demand

Farm house load is divided in two type loads i.e. irrigation load and residential load. Figure 1 shows the average load in the months of April, May and June residential load, consumption is highest due to high temperatures. The utilization of electricity is higher than the other months. Residential load includes tube light, CFL, ceiling fan, TV, refrigerator, mixer, flour mill. These will be used on an average of six hours daily. The farm house residential average peak load is 2.5kW and the energy demand is 10kWh per day shown Table-1. In irrigation, load is higher in the months of October, November, December and January as the crops are sown in this season. Rabi crops require more water, such as wheat, gram, peas, mustard, potatoes, etc. The farm house irrigation average peak load is 3.7kW and the energy demand is 15kWh per day.

Table-1: Electrical loads in farmhouse

Load sector	Appliances	Rating (W)	Quantity	Total power (W)	Operating Hours (Hr/day)	Energy (Wh/day)
Domestic						
Residential load	tube light	45	3	135	8	1080
	CFL	15	10	150	9	1350
	ceiling fan	75	4	300	9	2700
	Television	150	1	150	8	1200
	refrigerator	150	1	150	8	1200
	mixer	750	1	750	1	750
	Flour mill	745	1	745	1	745
	Others	120		120	8	960
			Total	2500		9985=10kWh/day
Agricultural						
Irrigation load	Three phase induction motor-pump	3750	1	3730	4	15000= 15kWh/day
			Total	3750		25kWh/day

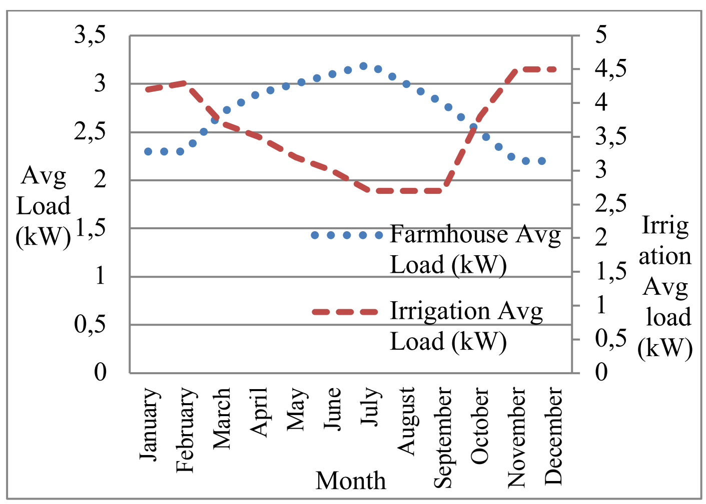

Fig. 1. Monthly average irrigation and farmhouse load profile

Step-II: Pre-sizing of RE system

The input parameters i.e. sun radiation, wind speed data etc. are required for design PV and WE system. In this research work area located at latitude 22.8514° N and longitude 75.5422° E Depalpur village, Indore, Madhya Pradesh, India. The average wind speed and solar radiation intensity are 10.63km/h and 5.63 kWh/m^2/day respectively. Figure 2 shows monthly average wind speed and solar radiation intensity in research work area [26].

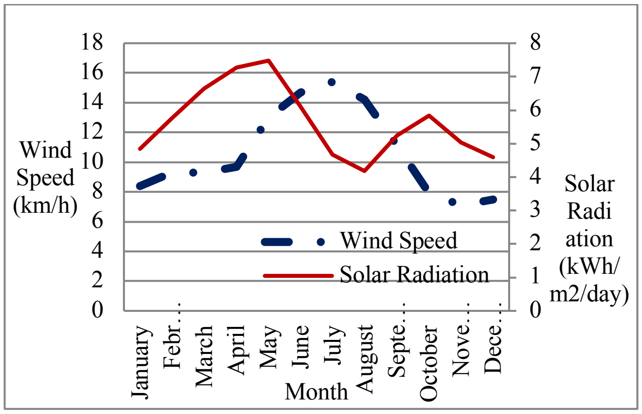

Fig. 2. Monthly average solar radiation and wind speed

3. Modeling of hybrid energy system

Figure 3 shows hybrid PV-wind-battery energy system. PV and WE system are connected in parallel forming a DC link. During favorable wind period, wind turbine generator generates electricity energy. During the day time solar PV generator produces electrical energy. In case of excess of energy, it is stored by battery bank system. The advantage of this system is that PV and wind both are the unreliable source and hence, in absence of the sun and wind the battery bank meets the load demand. Hybrid RE system included PV generator, buck-boost converter, inverter, battery with bidirectional charge converter, wind turbine.

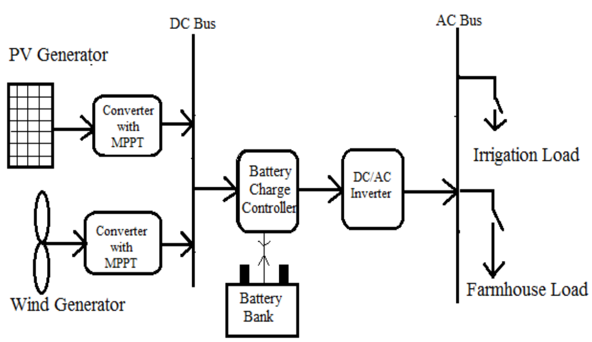

Fig.3. Farmhouse hybrid energy system

3.1 PV generator

PV energy conversion is based on photovoltaic effect. Solar photon energy is converting in DC electrical energy. The amount of this generated electricity depends upon some factors like intensity of solar radiation, size of solar cell and temperature.

PV generator output power is [15-16]

$$P_{pv} = [I_L - I_{rs}\{Exp\left(\frac{eV}{kT}\right) - 1\}] \times V \quad (1)$$

Where, I_L and I_{rs} are light generated current and reverse saturation current respectively; e is electron charge; k and T are Boltzmann's constant (J/K) and temperature(Kelvin) respectively and V is output voltage of cells.

3.2 Buck-Boost control Converter

Buck-boost control converter is a combination of step-up and step-down converter. The buck-boost control converter output voltage control by the duty cycle of the converter.

The output voltage of DC-DC converter is [15-16]

$$V_0 = -V_{in}\left[\frac{D}{1-D}\right] \quad (2)$$

Where, V_{in} and D are input voltage and duty cycle respectively.

The efficiency of buck-boost converter is as

$$\eta_C = \frac{V_o I_o}{V_{pv} I_{PV}} \quad (3)$$

Where, V_o and I_o are converter output voltage and current respectively, V_{pv} and I_{PV} are PV generator voltage and output current respectively.

3.3 Battery bank

Solar and wind energy system is generated power only when sunshine hours and flow of wind a particular speed, so batteries are needed for energy storage. This stored energy is used when renewable energy not available.

Battery energy storage capability is [15-17]

$$E_{bat} = \frac{(E_{ag} \times DA)}{(\eta_{In} \times \eta_{bat} \times DD)} \quad (4)$$

Where, E_{ag} is average daily required energy (kWh/day), DA is daily autonomy, DD is depth of discharge of battery, η_{In} is the solar inverter efficiency and η_{bat} is the battery efficiency.

3.4 Charge controller

Battery overcharging and deep discharging drastically reduces the life of battery. Charge controller (CC) protects the battery from such extreme states. CC prevents the battery from further charging once it reaches a fully charged state by automatically disconnecting the modules from the battery bank. It also prevents the drawing of additional energy from a battery when a dangerously low battery level is reached by disconnecting the supply the power to the load.

3.5 Solar Inverter

Solar inverter converts DC power into AC power at desired output voltage and frequency. The DC power input to the solar inverter is obtained from photovoltaic generator. The efficiency of the solar inverter is [17]

$$\eta_{In} = \frac{P_{In\_0}}{V_o I_o} \quad (5)$$

Where, P_{In_0} is the inverter output power.

3.6 Wind energy system

Wind energy a type of kinetic energy associated with movement of large masses of air. In contrast to diurnal availability of direct solar energy, wind energy can be available continuously throughout 24-hrs in a day. Wind energy is harnessed as mechanical energy with the help of wind turbine. Typically, from 5 m/s to about 25 m/s are considered favorable for most wind turbines.
Wind power is proportion to the cube of wind velocity. The general formula for wind power is [17]

$$P_{wind} = \frac{1}{2} C_p \rho A V^3 \quad (6)$$

Where, C_p is wind machine performance coefficient, ρ is air density (kg/m^3), A is the cross-section area of the wind passing through in (m^2), V is the velocity of the wind in (m/s),

4. Optimization analysis of the hybrid RE system

In this research study, two optimization techniques and reliability evolution are used for selecting optimal hybrid energy system configuration for remote areas. First technique, to analysis economic evaluation in terms of NPC, CC, OC LCOE of all possible configurations using HOMER simulation technique. Second technique, to select optimal configuration by using GOA in terms of cost reduction, while reliability evolution is used to calculate reliability indexes of all possible energy configurations using Markov technique.

4.1 Economic evaluation

Economic evaluation is an essential tool for comparing alternative options. Economic optimization is used for system cost calculation, cost analysis, payback time period based on present and future costs for identification of preferred system leading to energy savings. Economic evaluation is calculated by using life cycle cost (C_{LCC}) of the energy system. The complete LCC consists capital cost (C_C), replacement cost (C_{RC}), salvage cost (C_{sc}) operation and maintenance costs (C_{OM}) of the system that can be incurred over its lifetime. Net present cost (C_{np}) consist initial cost (C_{IC}), C_{OM} and C_{RC} in the project life time.

The cost of a system calculated in the preset-day currency is known a NPC. The NPC is as follows [18-19]

$$C_{np} = \frac{C_{TAC}}{C_{crf}(i,N)} \quad (7)$$

$$C_{crf}(i,n) = \frac{i(i+1)^n}{(i+1)^n - 1} \quad (8)$$

Where, C_{TAC} and C_{crf} are the total annualized cost (\$/year) and capital recovery factor respectively, i and n are the annual interest rate (%) and project lifetime in year respectively. Total annualized cost is obtained by

$$C_{TAC} = C_{AC} + C_{OM} \quad (9)$$

The annualized cost is obtained by [20],

$$C_{AC} = \frac{C_{LCC}}{PW} \quad (10)$$

LCC is the sum of all system cost is obtained by [20-21].

$$C_{LCC} = C_{IC} + C_{OM} + C_{RC} \quad (11)$$

The present worth is as follows [19-20]

$$pw = \frac{1}{C_{crf}(i,n)} \quad (12)$$

The levelized cost of energy (LCOE) is as follows [18-21]

$$LCOE = \frac{C_{AC}}{E_s} \quad (13)$$

The operating cost is expressed by this equation [18-20]

$$C_{OC} = C_{LCC} - C_{TAC} \quad (14)$$

Where, C_{AC} is total annualized cost (\$/yr), C_{TAC} is total annualized capital cost (\$/yr) and E_s is total electrical load supplied (kWh/yr).

4.2 Grasshopper optimization algorithm

GOA is a part of swarm intelligence technique (SIT). Social insects like ant, bees, wasps, and grasshopper perform their simple tasks independent of other members of the colony. However, they are able to solve complex problems emerging in their daily lives. GOA utilizes the behavior of non-human living entities for problem solving [12]. The main advantages of this optimization are adaptability, robustness, reliable, simplicity and no central control.

4.2.1 Objective function

The minimization of the RE system total annual cost is the main objective. To get the most favorable design of the hybrid energy system by minimizing the C_{TAC} by using following equation,

$$\text{Minimize } C_{TAC} = C_{AC} + C_{OM} \quad (15)$$

The combined annual cost of the RE system is as follows,

$$C_{AC} = \frac{i(i+1)^n}{(i+1)^n - 1}\left[N_{wind} \times C_{wind} + N_{pv} \times C_{pv} + \left(\frac{n}{ls_{bat}}\right) \times N_{bat} \times C_{bat} + \left(\frac{n}{ls_{inv}}\right) \times C_{inv} + \left(\frac{n}{ls_{con}}\right) \times C_{con}\right] \quad (16)$$

where N_{wind} and C_{wind} are the number of wind turbines and cost of wind turbine per unit respectively, N_{pv} and C_{pv} are the number of PV panels and PV panel cost per unit respectively, ls_{bat} is life span of battery, N_{bat} and C_{bat} are the number of batteries and battery cost per unit, ls_{inv} and ls_{con} are the inverters and converters life span, C_{inv} and C_{con} are the inverter and converter cost per unit respectively.

The annual O&M cost is as follows,

$$C_{OM} = \left[C_{OM}^{wind} \times \sum_{tm=1}^{24} P_{wind}^{t} + C_{OM}^{pv} \times \sum_{tm=1}^{24} P_{pv}^{t} + C_{OM}^{bat} \times \sum_{tm=1}^{24} P_{bat}^{t}\right] \times 365 \quad (17)$$

Where, C_{OM}^{wind} and P_{wind}^{t} are the O&M cost of wind turbine per kWh and wind power at time tm, C_{OM}^{pv} and P_{pv}^{t} are the O&M cost of PV panels per kWh and PV power generated at time tm. C_{OM}^{bat} and P_{bat}^{t} are the O&M cost of battery bank and battery power at time tm. The O&M cost of inverter and converter are neglected.

4.2.2 Hybrid energy system constraints

Hybrid energy system objective functions are shown in eq (16) and (17). For optimization the needed constrains are as follows

$$N_{wind} = \text{Integer value}, \quad N_{wind}^{min} \leq N_{wind} \leq N_{wind}^{max} \qquad (18)$$

$$N_{pv} = \text{Integer value}, \quad N_{pv}^{min} \leq N_{pv} \leq N_{pv}^{max} \qquad (19)$$

$$N_{bat} = \text{Integer value}, \quad N_{bat}^{min} \leq N_{bat} \leq N_{bat}^{max} \qquad (20)$$

Where, N_{wind}^{min}, N_{pv}^{min} and N_{bat}^{min} are the minimum required units of wind turbines, PV panels and batteries respectively while N_{wind}^{max}, N_{pv}^{max} and N_{bat}^{max} are the maximum required units of wind turbines, PV panels and batteries respectively.

4.2.3 Proposed GOA optimization problem

GOA is best optimization techniques of SIT. It was developed as a probabilistic technique that could be used for solving computational problems, for which good path could be found using graphs. Grasshoppers exhibits two different forces i.e. attraction and repulsion [12-14]. For obtaining best fitness function, the grasshopper's position should be the closest one to the target. The actions of grasshopper can be obtained by using mathematical model. The mathematically representation of GOA is as follows:

$$Z_i^p(t+1) = \alpha\left(\sum_{\substack{j=1 \\ j\neq i}}^{N} \alpha \frac{up_p - lw_p}{2} k(r)\left(\left|X_j^p(t) - X_i^p(t)\right|\right)\frac{x_j(t)-x_i(t)}{f_{ij}}\right) + T_p \quad (21)$$

Where t and N are the iteration and number of grasshoppers in the swarm respectively, , up_p and lw_p are upper and lower bound dimension, f_{ij} is the distance between i^{th} and j^{th} grasshopper, T_p is the p-dimensional position, α is the comfort zone proportional, k is a strength of social forces. Strength of social forces is as follows [12-14]

$$k(r) = s \times \exp\left(\frac{-d}{l_a}\right) - \exp(-d) \qquad (22)$$

Where, s is the strength of attraction, d and l_a are distance and attractive length.

The comfort zone proportional is as follows [12-14]

$$\alpha = \alpha_{maxi} - t\frac{\alpha_{maxi} - \alpha_{mini}}{t_{maxi}} \qquad (23)$$

Where, α_{maxi} and α_{mini} are the maximum and minimum value respectively, t and t_{maxi} are present and maximum iteration respectively.

The main steps of proposed GOA flowchart are shown in Fig.4.

Proposed GOA is described as follows:

Step 1: Initially enter the number of grasshoppers (N) and iterations for optimization.

Step 2: Initialize the all cost (AC, OM).

Step 3: Evaluate the initial fitness function of the population by using objective function equation (15).

Step 4: Arrange the population from good to bad condition.

Step 5: Update the independent variables (wind, PV, battery) by using equation (15).

Step 6: If constraints are satisfied. Than evaluate the fitness of each grasshopper and store the best-fit by using eq.(15)

Step 7: Increase the number of iteration one by one, i.e. i= i+1.

Step 8: Calculate the fitness function and updating the best agent. Otherwise, go to step 5.

Step 9: Display the optimal fitness function and corresponding best agent.

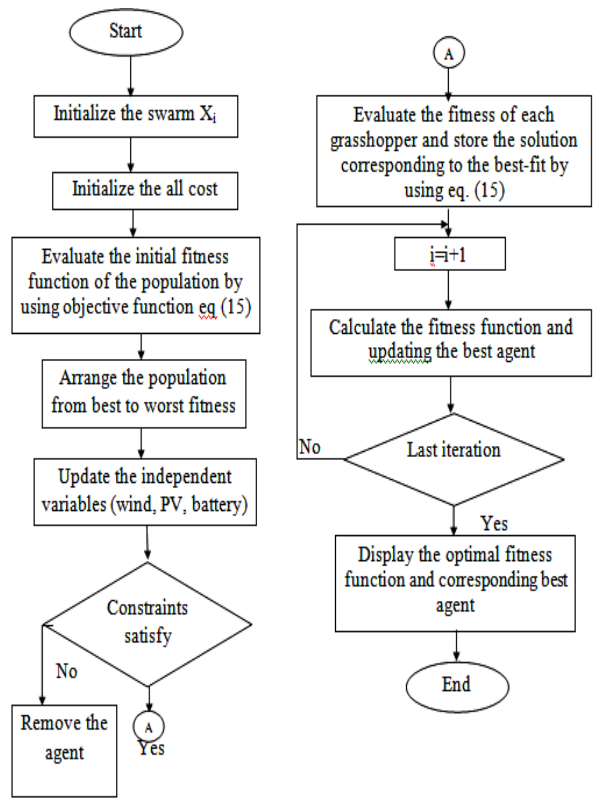

Fig. 4. Flowchart of the proposed GOA

4.3 Reliability optimization models

The word reliability is commonly used in the same sense as probability. When a statement is made to the effect that a particular electrical component is reliable, means that the components will behave in the manner that is expected from it. Further, if that particular electrical component fails unexpectedly, accept it as a chance failure. The pattern of failure can be obtained from life test results, i.e., by testing a fairly large number of models until failure occurs and observing the failure rate characteristics as a function of time. In RE system mainly used electronics components, to failure of electronics components causes some mechanism like fatigue, short circuit, creep, wear, corrosions etc. This study of RE system reliability block diagram is shown in Fig. 5.

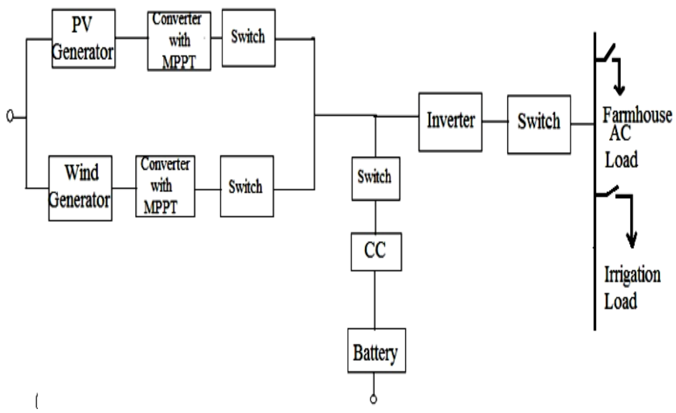

Fig. 5. Reliability block diagram of hybrid energy system

Reliability model of hybrid energy system normally comprises of many components i.e. PV generator, wind generator, converter, controller, battery bank, switches and load. In this system components are connected in series and parallel, system is complex. Reliability assessment of hybrid RE system is presented in terms of reliability indices. Reliability indices like failure & repair, availability & unavailability, MUT & MDT, LOLP and EENS are evaluated by using Markov method.

4.3.1 Markov Method

A technique that has much appeal and works well when failure hazards and repair hazard are constant requires the use of Markov models. A Markov model consists of nodes and branches. The nodes represent the states that the system can be in, and the branches carry with them the respective transitional probabilities. In Markov model two states are associated, UP and DOWN. Where UP means system is operable state and DOWN means, system components are failed. Consider and as failure and repair rate of a single component respectively. System Markov model is as shown in Fig. 6.

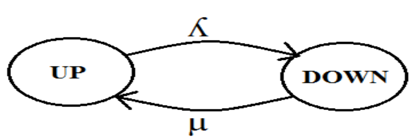

Fig. 6. Two state Markov model

Th availability of a system is the probability that is operating satisfactorily at any point in time when used stated conditions.

Markov model availability (A) and unavailability (U) are as follows[22]

$$A = \frac{\mu}{\lambda+\mu} \quad (24)$$

$$U = \frac{\lambda}{(\lambda+\mu)} \quad (25)$$

Since $\mu \gg \lambda$, the unavailability is as follows

$$U = (\lambda \cdot r) \quad (26)$$

Where,

$$r = \frac{1}{\mu} \quad (27)$$

$$r = \frac{8760}{\mu} \text{hrs}$$

Fig. 7 shows reliability diagram of different components.

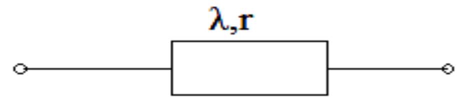

Fig.7. System components reliability diagram

For a complex energy system, a single equivalents module is shows relation between system unavailability, failure rate and average interruption duration as follows

$$U_{sys} = \lambda_{sys} \cdot r_{sys} \text{ hrs/year} \quad (28)$$

A) Series system reliability model

Series system reliability model of two elements is shown in Fig. 8.

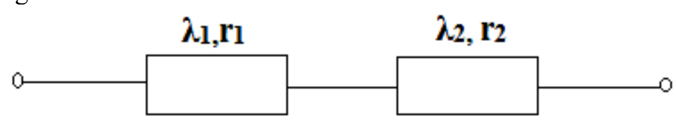

Fig.8. Series components system

Repair rate is the probability that a system will be restored to operational effectiveness within a given period.

System repair rate,

$$\lambda_s = \lambda_1 + \lambda_2 \quad (29)$$

System average interruption durations,

$$r_s = \frac{\lambda_1 \cdot r_1 + \lambda_2 \cdot r_2}{\lambda_1 + \lambda_2} \quad (30)$$

For number of components (NC) connected in series, the system unavailability, failure rate and average interruption durations are given as follows [22]

$$U_{Sr} = \sum_{i=1}^{NC} \lambda_i \cdot r_i \quad (31)$$

$$\lambda_{Sr} = \sum_{i=1}^{NC} \lambda_i \quad (32)$$

Now,

$$r_{Sr} = \frac{\sum \lambda_i \cdot r_i}{\sum \lambda_i} \quad (33)$$

Equation (33) shows that the series system failure rate is the summation of the individual element failure rates.

B) Parallel system reliability model

If the two components is connected in parallel shown in Fig. 9.

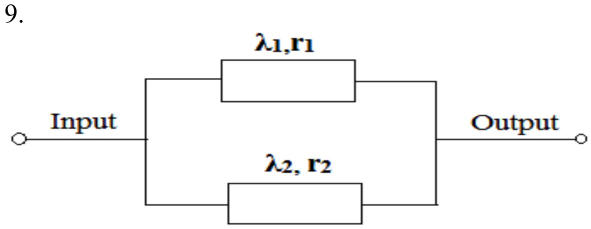

Fig.9. Parallel components system

The system is unavailable when both the components are not operable (available). Hence unavailability of parallel system is given as follows [22-23].

$$U_p = \frac{\lambda_1\lambda_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \quad (34)$$

Approximate relations are obtained for indices as follows under the assumptions $\lambda_1 \ll \mu_1, \lambda_2 \ll \mu_2$

$$U_p = (\lambda_1 r_1)(\lambda_2 r_2) \quad (35)$$

$$r_p = \frac{r_1 r_2}{(r_1+r_2)} \quad (36)$$

$$\lambda_p = \lambda_1\lambda_2(r_1 + r_2) \quad (37)$$

For number of components in parallel [22-23]

$$U_{Para} = \sum_{i=1,j=2}^{NC}(\lambda_i \cdot r_i)(\lambda_j \cdot r_j) \quad (38)$$

$$r_{Para} = \frac{\sum_{i=1,j=2}^{NC}(r_i . r_j)}{\sum_{i=1,j=2}^{NC}(r_i + r_j)} \quad (39)$$

Now,

$$\lambda_{Para} = \sum_{i=1,j=2}^{NC}(\lambda_i . \lambda_j)(r_i + r_j) \quad (40)$$

C) Series-parallel system reliability model

Figure 10 shows components in series and in parallel also. Figure 11 shows the equivalent system components.

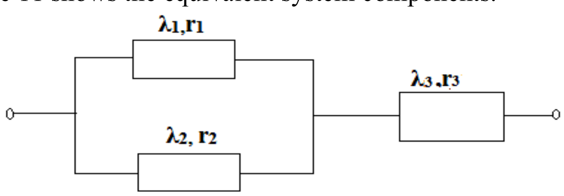

Fig. 10 Series-parallel configuration

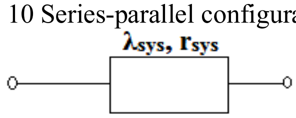

Fig. 11 Equivalent representation of series-parallel configuration

Series-parallel equivalent system components unavailability, failure rate and average interruption durations are as follows [23]

$$\lambda_{sys} = (\lambda_1\lambda_2)(r_1 + r_2)\lambda_3 \quad (41)$$

$$U_{sys} = \left(\lambda_{para} r_{para} + \lambda_3 r_3\right) \quad (42)$$

$$r_{sys} = \frac{\lambda_{para} r_{para} + \lambda_3 r_3}{\lambda_1\lambda_2\lambda_3(r_1+r_2)} \quad (43)$$

Mean down time takes into account the down time due to preventive and corrective maintenance. Mean up time is the reciprocal of the failure rate.

MUT and MD are calculated as [22-23]

$$MUT = \frac{1}{\lambda_{sys}} \quad (44)$$

$$MDT = \frac{1}{\mu_{sys}} \quad (45)$$

LOLP is an estimated value of time the load on a RE system is greater than its generating capacity. Loss of load probability is,

$$LOLP = \frac{U_{sys}}{8760} \quad (46)$$

EENS is an integrated source planning of RE system like maintenance, cost, and expansion of plant. Expected energy not supplied index is as follows [22-23].

$$EENS = L_{avg} U_{sys} \text{ kWh/yrs} \quad (47)$$

5. Results and discussion

In this section to find out optimal energy system, it should fulfill the daily load demand of the farmhouse. In this research work solar and wind are used as an energy resources. Battery is use as backup, whereas the solar and wind turbine generated energy is not sufficient or not available. The bidirectional converter is to maintain the flow of electricity between the AC as well as DC components, whereas battery charger is maintained energy storage systems in low and overcharging state. In this model an energy source are connected in parallel with battery bank, make the hybrid energy system more reliable and gives the energy as per requirement. In this section two methods are employed for the selection of optimal energy system for remote areas farmhouse. In first section, economic analysis using HOMER simulation model is explained while second section, explains the more reliable system selection using reliability indices.

5.1 Economic optimization results

Figure 12 shows hybrid PV-Wind-battery energy system produced by HOMER simulation software. HOMER simulates all feasible system in terms of NPC, IC, OC, AC, and COE. Simulation results are selecting the optimal configuration among the number of simulation results.

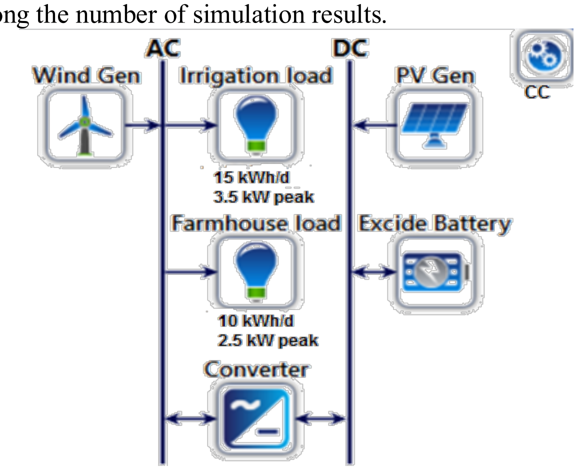

Fig.12. HOMER simulation model of hybrid PV-Wind-battery energy system

The best configuration i.e. PV-battery, Wind-battery and PV-Wind-battery energy system are selected in terms of economic analysis. The remaining configuration i.e. PV only, wind only and PV-Wind only not give the feasible solution as per the load demand. These configurations are provided shortage of electricity, so these configurations are not considered in this section.

Table-2 shows optimal different hybrid RE system configurations in terms of different costs.

Table-2. Economic analysis of different configurations

Description	PV-battery	Wind-battery	PV-Wind-battery
CC	$16,356	$17,136	$22,152
OC	$852.55	$902.55	$3,554
NPC	$17,164	$19,713	$26,450
Annualized Costs	$686.56	$708.51	$1937.98
Capacity Shortage (%)	9	13	0
LCOE, $/kWh	0.405	0.514	0.502

Table-2 shows CC and OC of hybrid PV-battery energy system are $16,356 and $852.55 respectively. NPC and AC are $17,164 and $686.56 respectively. NPC, CC, AC and OC cost are less than as compared to other configuration. In this system electricity shortage is 9% per year. PV-battery energy system LCOE cost is minimum as compared to other configuration.

Fig. 13 shows graphical representation comparison of NPC, AC, LCOE and capacity shortage of different configurations.

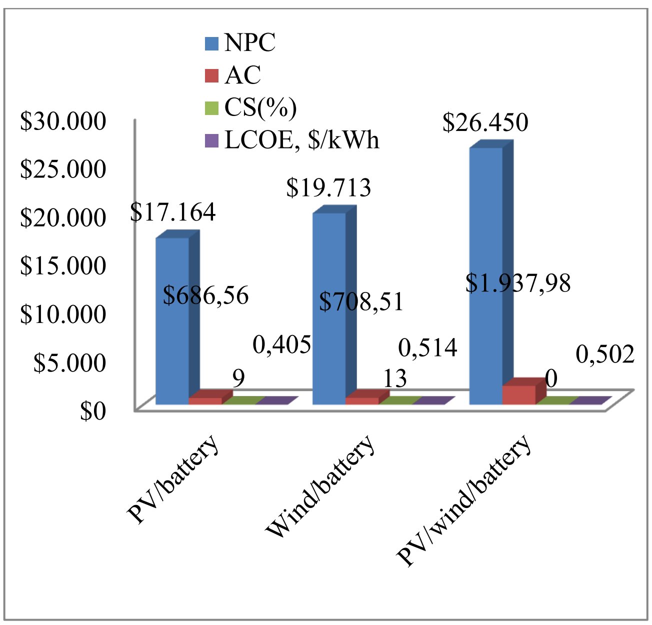

Fig.13 Comparison of NPC, AC, LCOE and capacity shortage of different configurations

CC and OC of Wind-battery energy system configuration are $17,136and $902.55 respectively. NPC and AC are $19,713 and $708.51 respectively. NPC, CC, AC and OC cost are higher than the PV-battery energy system configuration. In this system electricity shortage is 13% per year. The optimal configuration consists of 5 kW PV array (ALP-250W, 29.5 Voc), 5 kW wind turbine, 34 excide (12 V, 100Ah) battery units and 2.5 kW system converter. The detail technical specification of RE system components has been tabulated in Table-3.

Table-3: Technical specification of RE system components

Components	Parameters	Value
ALP 250W PV module (polycrystalline)	Nominal power	250W
	Open-circuit-voltage (Voc)	37.25V
	Short circuit current (Isc)	8.95 A
	Current at maximum power point (Impp)	8.35 A
	Voltage in maximum power point (Vmpp)	29.95 V
	No of Cells in Series	60
	module efficiency	15.6%
	Temperature Range	(-40°C) to (85°C)
Whisper 200 Wind turbine	Rotor diameter	2.72 M
	Blades	3
	cut-in/cut-off wind speed	3.1 m/s
	Rated power	1000 watts peak
	Voltage	120volts/240volts DC
	Material of blades	Polypropylene/Carbon Reinforced
	Rated wind speed	11.6 m/s to 13 m/s
	Swept area	5.8 meter square
	Rotational speed	1200 rpm
Exide Solar battery 6LMS100	Battery Capacity	100AH
	Voltage	12V
	Battery Type	Tubular Battery
NXT+ 2.5 kVA Luminous Inverter	VA Rating	2.5kVA
	Maximum Power Voltage Vmp (V)	65V-130V
	Max. supported panel power (Wp)	2000 Wp
	Input Voltage Range	80V-165V
	Charge Controller	MPPT

Hybrid PV-Wind-battery energy system CC and OC are $20,152 and $2,554 respectively. This configuration NPC and AC cost are higher than the other configuration. The annual electricity shortage is nil, this system is meet annual energy demand in the given site. Figure 14 shows that the capital cost of the hybrid energy system includes, 45% battery with charging system, 30% wind energy system 20% PV energy system and 5% converters. Operating cost of the battery bank is higher than the other component cost. The battery NPC is dominated to wind and PV energy system cost.

Figure 15 shows PV and wind generator monthly average electricity production. PV generator electricity production is high as compared to WE system in the month of Dec to May due to lower wind speed. WE system electricity production is high as compared to PV generator system in the month of June to August due to higher wind speed. The both renewable energy systems on combination can fulfill the load demand. PV energy system contributes to 57% and wind energy system contributes 43% of the average total electricity production.

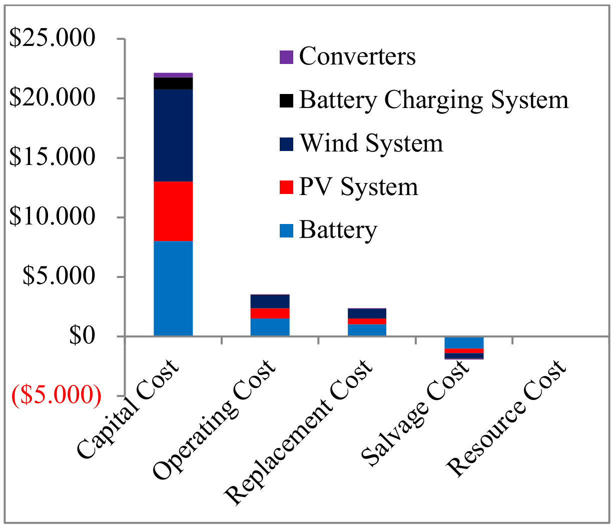

Fig. 14. Annualized cash flow summary by hybrid system component PV-wind-battery-converter

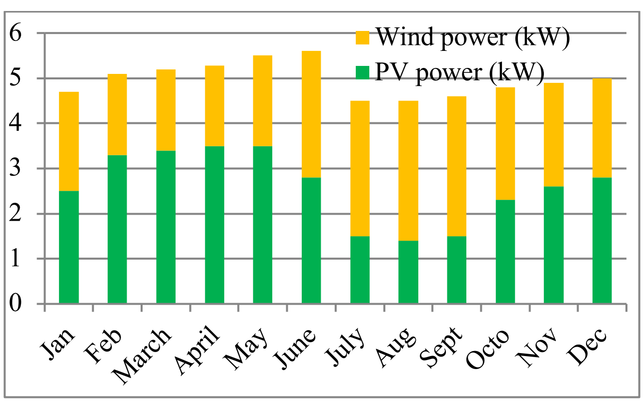

Fig.15. Monthly average electric production of PV and wind generator

Figure 16 shows annual SOC of battery. In number of day's battery bank is 90% charge, only few days battery is charged up to 60% due to unavailability of resources. In evening battery bank discharges due to insufficient renewable energy while in afternoon, battery bank is fully charged. Figure 16 clearly indicates that battery bank can deliver the required energy to the load.

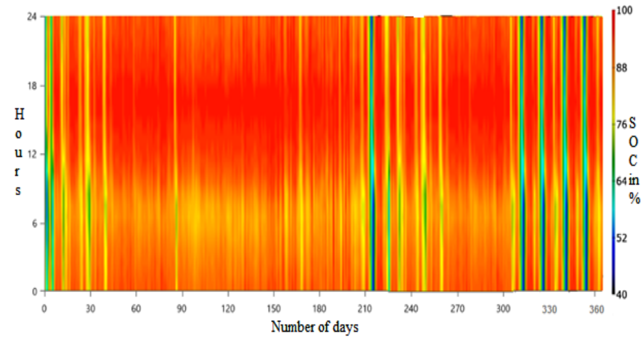

Fig.16 Annual SOC of battery

Above results shows PV-battery and PV-Wind are not suitable to fulfill daily load demand. Hybrid PV-Wind-battery energy system can fulfill daily load requirement without any shortage of energy.

5.2 GOA optimization results

The following parameters are taken into consideration, t = 100, $\alpha_{mini} = 0.22$ and $\alpha_{maxi} = 0.99$, n = 50 for GOA.Table-4 shows cost, LCOE, shortage of energy and the number of the energy system unit required using proposed GOA algorithm. To calculate cost index i.e. mean, standard deviation, best and worst values using cost function. Table-4 also shows the optimum size of PV, wind and battery is 7, 2 and 22 respectively. Annually energy shortage is high in PV only and WE system only as compared to other hybrid configuration. PV-Wind-battery is the only one system that shows the energy shortage is zero. LCOE is also better than the PV only and PV-battery system. In this research study PV, wind generator and batteries are calculated as per load demand. Repeating the iterations for more than100 times, the proposed GOA algorithm gives the better results for selecting energy system in remote areas.

Table-4: Different configuration analysis using GOA

Configuration	Cost in $				LCOE, $/kWh	Energy Shortage (%)	Optimum design		
	Mean	SD	Best	Worst			N_{pv}	N_w	N_b
PV only	560	35.245	2170	2267	0.68	48	20	0	0
PV-battery	680	17.453	1813	1925	0.405	8.5	16	0	32
Wind only	770	28.151	1712	1790	0.62	46	0	5	0
Wind-battery	702	26.728	1705	1799	0.535	13	0	5	26

PV-Wind	767	17.456	1867	1978	0.523	7.8	10	4	0
PV-Wind-battery	1707	14.483	1695	1780	0.487	0	7	2	22

Figure17 results clearly indicated that the hybrid energy generated system is only system that achieves daily load demand. The remaining system configuration does not fulfill the daily load demand.

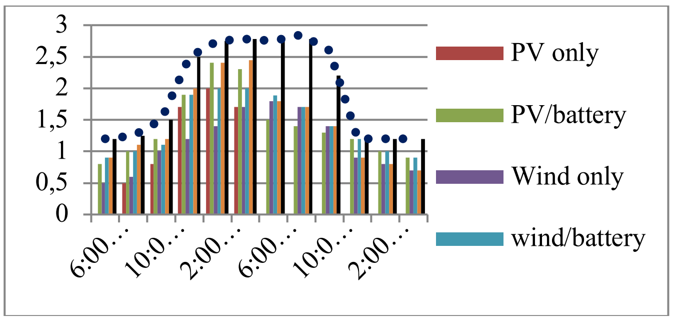

Fig.17 Daily generated energy system configuration

5.3 Reliability optimization results

Hybrid PV-Wind-battery energy system reliability indices have been evaluated using available failure and repair time of the system components as shown in Table-5.

Table-5: failure and repair time of hybrid PV-Wind-battery energy system [22-23]

S. No.	Components	Failure rate (λ_{sys}) /yrs	Repair time (r) in hrs
1	PV module	0.055	32
2	Buck-Boost converter	0.0317	52
3	Inverter	0.097	52
4	Switch	0.081	28
5	Charge controller	0.029	52
6	Battery	0.011	11
7	Wind generator	0.5	67
8	Wind generator converter	.04	50
9	Changeover switch	0.01	5

Hybrid PV-Wind-battery energy system reliability indices are calculated by using Markov model, and tabulated in Table-6. Table-6 shows different configuration of hybrid PV-Wind-battery energy system reliability indices. PV only and WE system only, failure and repair rate, MUT, system unavailability, LOLP and EENS are lower than the other configuration. Reliability indices of PV-Wind-battery energy system are better than the other energy system configuration. This result shows that the more reliable system is hybrid PV-Wind-battery energy system in remote location. Reliability indices LOLP, MUT, EENS, failure rate are lowest in hybrid PV-Wind-battery energy system. Hybrid PV-Wind-battery energy system is optimal system that fulfill electricity demand without shortage of electricity.

Table-6: Different energy system configuration reliability indices

Indices	PV only	PV-battery	Wind only	Wind-battery	PV-Wind	PV-Wind-battery
λ_{sys} /yrs	0.312	0.218	0.418	0.28	0.08	0.011819
U_{sys}hrs/yrs	11.12	10.166	21.01	9.517	0.09957	0.09027
r_{sys}in hrs	38.24	34.21	60.79	35.12	8.129	7.965
MUT	3.2051	4.5871	2.3923	3.571	12.5	84.60
LOLP	0.001269	0.0011605	0.002398	0.001086	0.0000113	0.0000103
EENS in kWh/yrs	77.84	71.162	147.07	66.619	0.6969	0.63189

6. Conclusion

Economic and reliability assessment of a RE energy system and its configurations have been presented for farm house electricity and irrigation load.

The three different optimization techniques used for selecting best configuration

- All feasible systems are simulated in terms of NPC, IC, OC, AC, and COE by using Homer.
- Table-2 shows hybrid PV-battery energy system cost i.e. CC ($16,356) and OC ($852.55), NPC ($17,164) and AC ($686.56) are less as compared to other configuration. This system is not feasible due to shortage of electricity supply (9% annually).
- Wind-battery energy system CC ($17,136), OC ($902.55), NPC ($19,713), LCOE (0.514). The shortage of electricity is 13%, so this system also not feasible.
- Hybrid PV-Wind-battery energy system is more feasible system due to fulfill of the energy demand without shortage of electricity.
- The LCOE, $/kWh of hybrid PV-Wind-battery energy system is less than wind-battery energy system.
- From economic point of view the best cost-effective configuration is PV-wind-battery and worst configuration is PV only system.

- Accordingly GOA results, PV only and wind only system energy shortage is maximum as compared to hybrid energy system configuration.
- The proposed GOA results show the optimum size of the system i.e. PV (7), wind (2) and battery (22) for the given capacity.
- Table-4 shows hybrid PV-Wind-battery energy system is more economic and less energy shortage among the configuration.
- Failure and repair time is less in hybrid PV-Wind-battery energy system.
- PV-Wind-battery energy system LOLP (0.0000103), MUT (84.60), EENS (0.63189) and unavailability (0.09027) are less than the other configuration.

It is concluded that the optimal system is PV-Wind-battery energy system in terms of economic and reliability at remote areas.

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