SIMULATED PERFORMANCE OF A HYBRID ENERGY SYSTEM FOR A REMOTE AREA

Ph.D. THESIS

by

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A THESIS

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in this thesis entitled **"SIMULATED PERFORMANCE OF A HYBRID ENERGY SYSTEM FOR A REMOTE AREA"** in partial fulfilment of the requirements for the award of the Degree of Doctor of Philosophy and submitted in the Department of Electrical Engineering of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during a period from July, 2013 to December, 2016 under the supervision of Dr. Eugene Fernandez, Associate Professor, Department of Electrical Engineering, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in this thesis has not been submitted by me for the award of any other degree of this or any other Institute.

(SARANGTHEM SANAJAOBA SINGH)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Eugene Fernandez)
Supervisor

Date: ____________

ABSTRACT

In India, as a developing country, the concept of providing sustainable power supply is required in order to provide electricity to remotely located villages which have no access to grid supply due to difficult terrain. Conventionally, remote consumers are supplied by diesel generator based system which operation is constraint by depleting nature of fossil fuel reserves, and negative social and environmental impacts. Recently, the concept of providing electricity to remote inaccessible locations through locally available renewable energy based power systems is being increasingly recognized and gaining interest globally. Among the available renewable energy sources, solar and wind are considered as the major energy sources in satisfying future electricity demand. Such renewable energy sources are environmentally friendly and available free of cost. However, the stochastic behavior inherent to renewable energy sources such as solar and wind pose serious challenges in designing power systems based on renewable energy sources. One excellent solution for nullifying the impacts of intermittency coming out of experience is the hybrid integration of two or more different energy sources so that the energy generated from different sources are complemented each other. But, the combination of different energy sources to form a hybrid system not only increases the complexity of the system , but also complicates the system optimum design process on account of unpredictable renewable energy sources, time changing load demand, system components non-linear characteristics and, the interdependent behavior of the system optimum configuration and optimum control strategy. These complexities introduce more difficulties in designing and analysis of hybrid systems. Hence, a comprehensive study related with different aspects of hybrid energy system is essential before any plan is executed.

The current thesis focuses on the development of a new approach for sizing of a hybrid energy system consisting of solar, wind and battery storage with the objective of minimizing total system cost and supplying the required demand reliably. To carry out the study, a case study area located in a remote hilly region of Uttarakhand, India is considered and required hourly renewable energy inputs data are synthesized using the available monthly average solar radiation and monthly average wind speed. The load profile is generated using the seasonal peak energy requirement.

Designing the techno-economic aspects of a hybrid energy system for remote area applications has showed a remarkable increase recently and consequently determining the system design which is optimal in terms of operation and component size is much crucial in order to have reliable and economical power supply. Owing to the fluctuating nature of

renewable energy sources, correct sizing of hybrid energy system require accurate modeling of its components so that their power output can be estimated exactly. Reported literatures suggest various techniques for modeling of each hybrid energy system component. However, they either adopted deterministic or probabilistic methods. In the current study, photovoltaic component of hybrid energy system is modeled taking into account the hardware availability and unavailability of photovoltaic panels. Various hardware failure events of photovoltaic modules can be represented by a random variable and is assumed to follow a Binomial distribution. In addition, the power output modeling of wind turbine components consider the effect of wind turbine generator force outage rate (FOR). The operating state of wind turbine generator is decided at start of each hour by drawing a uniform random number and finally the sequential up down up cycles of a wind turbine generator are combined with the hourly available wind power to evaluate the actual hourly generated wind power.

The design problem of a hybrid energy system can be taken as an optimization problem which maximize or minimize an objective function by changing the values of decision variables. In this study, a composite objective function is formulated fulfilling both economic and reliability criteria subject to various design and operational constraints. The number of each hybrid system component unit such as number of photovoltaic arrays, wind turbine generator, battery storage unit and converter constitute the design variables which values are updated during each objective function evaluation such that the given optimization objective is achieved. The key issue in solving a hybrid energy system design problem is the selection of a sizing technique in terms of computational simplicity and optimal utilization of the available resources. The optimization method adopted in the current study is based on a new meta-heuristic optimization algorithm called as Cuckoo Search (CS) via Levy flights. The developed methodology is implemented in MATLAB programming environment. Unlike other optimization algorithms, the numbers of parameters to be fine tuned during optimization is very less in case of Cuckoo Search (CS) algorithm. The performance of Cuckoo Search (CS) in solving hybrid energy system design problem is tested by comparing with other well known optimization algorithms like Genetic algorithm (GA) and Particle Swarm Optimization (PSO) taking the optimization of three different system schemes such as photovoltaic-battery, wind-battery and photovoltaic-wind-battery applicable to the considered case study area. Analysis result shows better performance of the proposed methodology based on Cuckoo Search (CS) in terms of computational speed and better quality solutions. Moreover, the optimization results indicate that system scheme comprising of photovoltaic, wind and battery storage provides the most techno-economical viable option for meeting the energy requirement of the study area.

An analysis on economic performance sensitivity of the optimal hybrid photovoltaic-wind-battery is necessary from the planning perspective point of view. A sensitivity analysis is carried out to determine the impact of various influencing parameters on the cost of energy (COE). The parameters considered are wind speed, solar radiation, capital cost of the system component, load demand, wind turbine generator force outage rate (FOR) and physical unavailability of the photovoltaic panels. Each parameter is varied over a range of values around the base value.

The reliability assessment of a renewable energy based hybrid energy system need to be address differently compared to the conventional system of power generation as renewable energy generation units are not considered as fixed capacity generation systems. Several studies have been reported on the analysis of reliability aspects of hybrid energy system which can be broadly grouped into two main categories such as analytical methods and Monte Carlo simulation. Monte Carlo simulation overcomes the limitations of analytical methods by treating the problems as a series of real experiments and simulating the actual stochastic behavior of the system components. Hence, the current work makes use of Monte Carlo simulation for reliability assessment of hybrid energy system through evaluation of loss of load expected (LOLE) reliability index. LOLE is the expected period during which the system load is expected to exceed the available generation capacity. It is expressed as number of hours per year. The reliability analysis is carried out by simulating various contingency conditions such as reduction in solar radiation and wind speed, increase in energy consumption, and increase in failure rate of wind turbine and photovoltaic (PV) panels. The hourly generation from each component of hybrid energy system obtained from the generation models constructed for the purpose is compared with the hourly variation in the load to evaluate the reliability index. Analysis of LOLE evaluation results suggest better reliability performance of photovoltaic-wind-battery system compared to standalone photovoltaic-battery and wind-battery only systems at all the contingency conditions simulated.

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LIST OF ABBREVIATIONS

COE	Cost of energy
CS	Cuckoo Search
EENS	Expected Energy Not Supplied
ENS	Energy Not Supplied
FOR	Force Outage Rate
GA	Genetic Algorithm
HES	Hybrid Energy System
HOMER	Hybrid Optimization Model for Electric Renewables
KW	Kilo Watt
LOLE	Loss of Load Expected
MCS	Monte Carlo Simulation
MTTR	Mean Time to Repair
MTTF	Mean Time to Failure
PD	Probability Distribution
PV	Photovoltaic
PSO	Particle Swarm Optimization
SOC	State of Charge
VPKAS	Vivekananda Parvatiya Krishi Anusandhan Sansthan
WTG	Wind Turbine Generator

LIST OF SYMBOLS

A_k	unit cost of k^{th} component, Rs/kWh
α	power law exponent
C_{Total}	total system cost, Rs
C_{ENS}	cost for energy not supplied, Rs/kWh
C_{pv}	probability distribution for capacity states of PV array
C_1, C_2	acceleration constants
E_{batt}	energy rating of battery storage, kWh
η_{inv}	inverter efficiency
η_{batt}	battery charging/discharging efficiency
$F_{pv}(i)$	probability associated with $P_{pv}(i)$
f_{pv}	PV derating factor
h_{hub}	wind turbine hub height, m
h_{anem}	height of the anemometer, m
I_T	global solar radiation incident on the PV array
$l(t)$	length of t^{th} time unit
$Load^t$	load during t^{th} time unit, kW
m	component life time, years
M_k	maximum number of k^{th} component
n_k	number of k^{th} component
N_{pv}	total number of PV modules
om	percentage operation and maintenance cost
p_m	maximum power available from the PV module
P_a	discovery rate of alien eggs/solutions
P_c	crossover probability
P_m	mutation probability
P_{rated}	rated output power of wind turbine generator

$P^t{}_{pv}$	output power of PV at t^{th} time unit
$P^t{}_{pv-actual}$	actual output power of PV at t^{th} time unit
$P_{pv}(i)$	capacity level of PV array when i out of N_{pv} modules are operating
$P^t{}_{WTG}$	output power of WTG at t^{th} time unit, kW
$P^t{}_{WTG-actual}$	actual output power of WTG at t^{th} time unit, kW
$P^t{}_{batt}$	charged/discharge battery power, kW
$P^t{}_{inv-out}$	inverter output power, kW
Q_{pv}	unavailability of PV
R_k	capacity of k^{th} component
r	random number
r_0	annual interest rate
s	step size
$SOC_{\min}$	minimum value of battery SOC
$SOC_{\max}$	maximum value of battery SOC
σ	self discharge rate of battery
$V(h_{hub})$	wind speed at hub height, m/s
$V(h_{anem})$	wind speed at anemometer height, m/s
$v_{cut\ in}$	cut in speed of wind turbine generator
$v_{cut\ out}$	cut out speed of wind turbine generator
v_{rated}	rated speed of wind turbine generator
W	inertia weight factor
Y_{pv}	PV array capacity, kW

CHAPTER 1

Introduction

1.1Global energy scenario

Global energy consumption with respect to all types of energy sources continue to increase requiring more attention on energy security, harmful emission effects on environment as well as rising oil prices. Fossil fuel based energy sources contribute most of the world energy needs. With various governmental and non-governmental organizations providing incentives for utilization of non-fossil fuel based energy sources and rapid advancement in renewable energy technologies, renewable energy is the fastest growing source of energy at an average rate of 2.6% per year while the use of nuclear energy increase at a rate of 2.3% per year and natural gas at a rate of 1.9% per year as depicted in fig.1.1. Coal records a slowest growing rate of 0.6% per year.

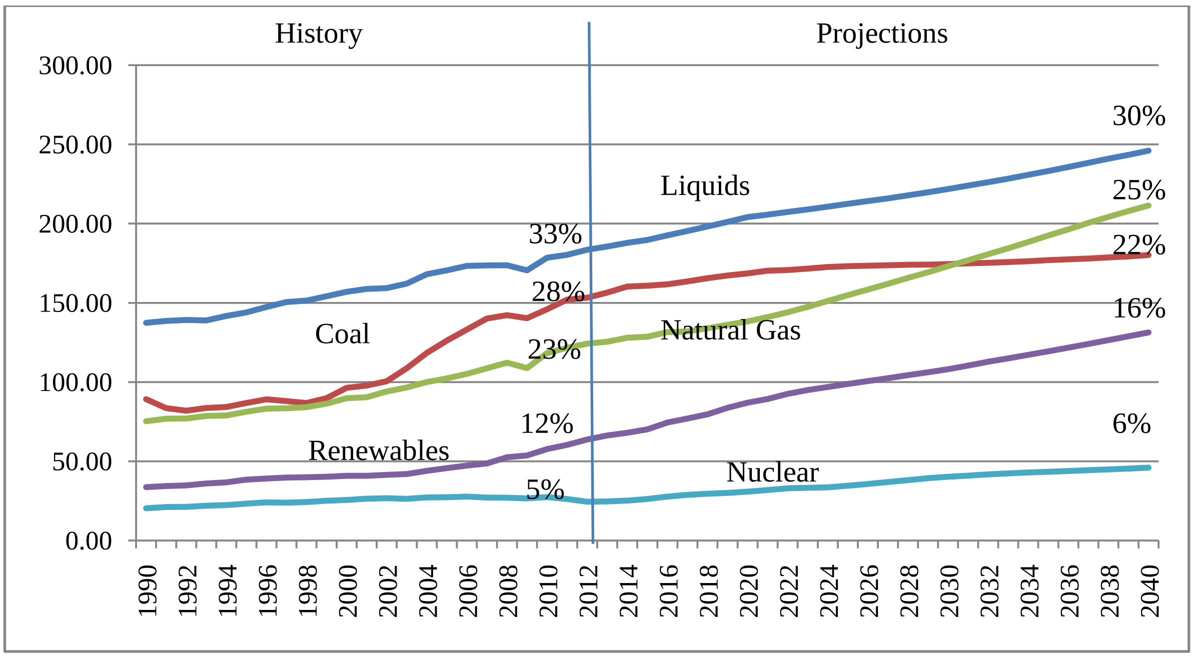

Fig. 1.1: World energy consumption by fuel type in quadrillion Btu, 1990-2040 [1]

The per capita energy consumption of different countries is depicted as in fig.1.2. Iceland has maximum per capita energy consumption of 54799 kWh while India's per capita energy consumption is around 765 kWh and it is ranked 155 based on the world energy consumption.

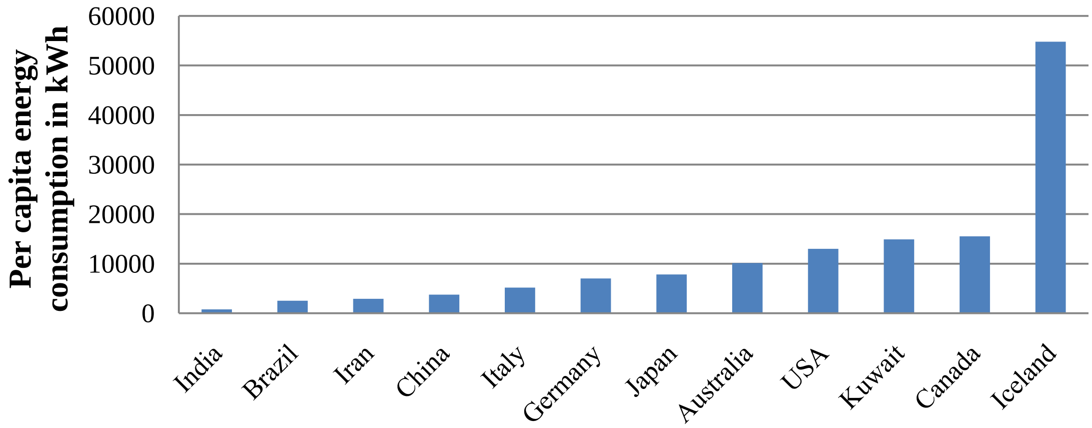

Fig. 1.2: Per capita energy consumption of different countries [2]

1.2 India's energy scenario

The India's energy sector is expanding quickly and its energy utilization has almost doubled since 2000. But, the consumption of energy per capita is still only around one third of the global average. Majority of Indian energy demand is met by fossil fuels and coal remains the backbone of the Indian power sector. Figure 1.3 depicts the percentagewise share of different energy sources in India's installed capacity. Table 1.1 gives the installed capacity of major energy sources in India.

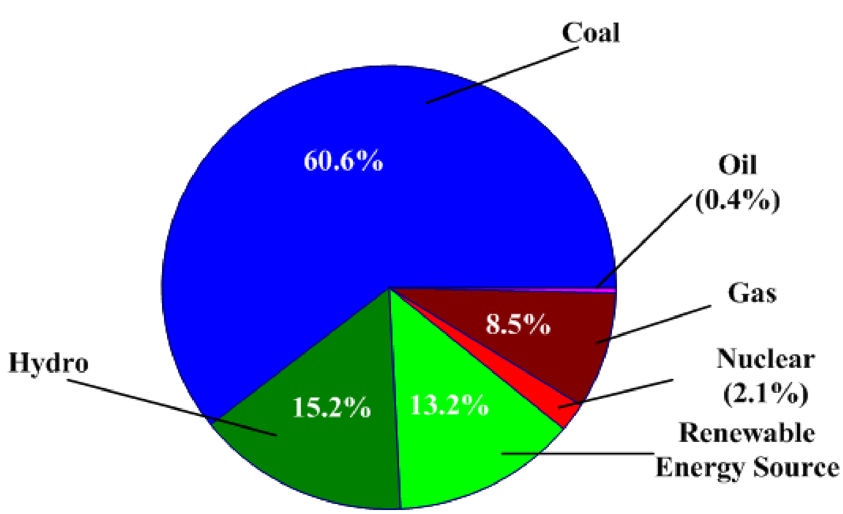

Fig 1.3: Sources of electricity in India by installed capacity [3].

Table 1.1: Installed capacity of energy sources in India [3]

Sl. No.	Energy Source	Installed Capacity (MW)
1	Coal	164635.88
2	Hydro	41267.43
3	Renewable Energy Source	35776.96
4	Nuclear	5780.00
5	Gas	23062.15
6	Oil	1199.75
7	Grand Total	**271722.17**

1.3 Rural electrification in Indian context

As on May, 2015, a total of 19706 villages out of 597464 inhabited villages in the country have no electricity access [4]. Various factors which hinder the extension of grid supply to isolated remote locations are high cost of grid extension, sparsely distributed population, high operation and maintenance costs, maintenance responsibility, dependence on subsidy leading to low recovery [5]. In rural areas, requirement for electricity is mainly in four main sectors which include household sector (lighting, heating, cooking, food processing), agricultural sector (irrigation), community and social services (water pumping, refrigeration for health centre, community lighting), rural industry and commercial services sector.

1.4 Hybrid energy system in remote area

Worldwide environmental concerns coupled with ever increasing energy demand and limited nature of conventional energy sources are opening up new opportunities for utilization of renewable energy sources such as solar, wind power etc. In developing nations, these energy resources can either supplement conventional energy inputs, or else serve as suitable alternatives for energy in very remote and backward geographical pockets. Renewable energy sources are currently one of the most, if not the only suitable option to supply electricity in fragmented areas or at certain distances from the grid. Indeed, renewable energy sources are already contributing to the realization of important economic, environmental and social objectives by the enhancement of energy supply, the reduction of green house gases and other pollutants and by the creation of local employment which leads to the improvement of general social welfare and living conditions.

However, the unpredictable behavior inherent to renewable energy sources such as solar, wind etc. offers a major technical drawback leading to considerable over sizing of the system and large storage requirements for maintaining system reliability when operated on standalone basis. One possible solution that comes out from experience is the utilization of Hybrid Energy Systems (HES) involving two or more different renewable energy inputs. Moreover, the independent operation of. photovoltaic (PV) system or wind energy system gives costlier system design, and hence their integration to form hybrid energy system is usually preferred. Applications of hybrid energy system include providing electricity in remote isolated areas use for lighting, telecommunication stations, other electrical appliances and rural community electrification where the grid extension is not economically feasible or not encouraged by the hilly terrain. Therefore, investments in rural areas in terms of infrastructure development have to be made with cost effective, reliable and efficient mechanism in order to provide access to electricity in a sustainable way.

A hybrid energy system (HES) may consists of alternative energy sources such as renewable as well as conventional sources like diesel generator or grid connection or energy storage elements like battery, fuel cell etc. This method of system integration results in higher system availability, increase overall energy output, lower energy cost and drastically reduce the storage size. But, the combination of different sources of energy to form hybrid system not only complicates the system , but also the optimal design process of system increases in complexity because of the unpredictable nature of renewable energy sources, time dependent load demand, and system components non-linear characteristics. These issues bring in more difficulties in analysis and designing aspects of hybrid systems. Therefore, one of the important challenges in the areas of HES is their design and operation in optimal manner under changing meteorological and load conditions. Correct sizing of hybrid system components and their optimal operation dictates the techno-economic feasibility of such systems. Hence, the vast market penetration by renewable sources based energy technology depends largely on the methodologies adopted for optimal designing of hybrid energy systems. high quality In rural areas, HES offers the best option for delivering community energy services in terms of quality, low cost energy along with providing benefits socially and environmentally.

1.4.1 Advantages of hybrid energy system over single renewable energy system

1. Hybrid energy system increases the system availability as hybrid integration of different energy sources reduce daily and seasonal resource variation.
2. Hybrid energy system results in lower cost of energy (COE) as diversity of resources in hybrid system reduces the battery storage size and quantity of fuel usage.
3. Overall system energy output is enhanced and significantly minimizes the storage requirement.
4. In hybrid energy system, the operations of energy sources are such that a strong energy source complements the operation of weak energy sources.
5. As hybrid system results in reduced fossil fuel requirement, its operation is hardly affected by fuel price fluctuation.
6. Hybrid energy system can be implemented at remote locations and avoids the time lag in grid extension; and its modular design allows connection of grid when it comes.

1.4.2 Application areas of hybrid energy system

1. Electrification of remotely located villages which includes household lighting, public lighting, community lighting.
2. Supplying power for public water supply system for drinking, irrigation, purification, desalination etc.
3. Applications in motive power/ processing which includes drying and food preservation, crop processing etc.
4. In times of blackouts and weak grids, hybrid energy system can provide timely and effective backup solutions.
5. Nowadays, renewable energy based hybrid energy system are increasingly used in supplying power for telecommunication stations located in remote areas, special rooms in hospital meant for emergency lighting.

1.5. Literature review

1.5.1 Introduction

The rapidly increasing energy demand and the concerns on environmental degradation resulted from use of conventional energy sources have opened the options for exploring more alternative sources for energy production. However, the relative cost disadvantage of such alternative energy sources like solar, wind energy conversion systems etc. compared to conventional means of energy production demands for an optimum sizing approach in order to avoid system components over-sizing without sacrificing system reliability level considering the erratic nature of meteorological conditions and power demand. A large number of studies are available in literature addressing the issues related to optimal sizing of renewable energy based hybrid energy system. An attempt is made here to present a brief spectrum of the various types of studies that are reported in technical literature.

1.5.2 Global and Indian applications of hybrid energy system

The reviews on some of the reported studies are presented which highlights the applications of hybrid energy system in global and Indian context.

The complementary characteristics of solar radiation and wind power is analyzed [6] using weather data of a typical weather year in Hong Kong and a simulation model of hybrid photovoltaic–wind systems with a storage battery is developed for calculating loss of power supply probability (LPSP). The optimum combinations of the hybrid system components are obtained for different desired LPSPs. Results of a case study of hybrid solar–wind power supply for a telecommunication system show that hybrid system with 3 days power storage battery is capable of ensuring LPSP of 1%, while hybrid system with 5 days storage capacity is suitable for ensuring a LPSP of 0%. In [7], the feasibility of a hybrid system is investigated that utilizes hydrogen as an energy carrier in Newfoundland, Canada via HOMER. A case study is conducted on a remote house having an energy consumption of 25kWh/d with a 4.73 kW peak power demand using various renewable and non-renewable energy sources and energy storage methods. Wind-diesel-battery was found as the most feasible solution for current costs. However a 15% reduction in fuel cell cost would have made the wind-fuel cell system more attractive. The feasibility of utilizing hybrid wind diesel battery system is carried out [8] to meet the annual electrical energy demand of

620,000 kWh for a typical commercial building in Dhahran, Saudi Arabia while minimizing diesel generator operation. Different combinations of the commercial 10 kW wind energy conversion systems (WECS), along with battery storage unit and diesel back-up are considered for the analysis. The simulation study resulted in a hybrid system consisting of thirty 10 kW WECS and 3 days of battery storage where diesel back-up has to provide only 9% of the load demand while it has to contribute 40% of the load without battery back-up. The feasibility study of utilizing hybrid photovoltaic diesel battery system is performed to meet the annual electrical energy demand of 35 200 kWh for a typical residential building in Dhahran, Saudi Arabia with the object of minimizing diesel generator operation [9]. Different array sizes of PV panels along with battery storage unit and diesel back-up are considered for the study. The simulation study resulted in a hybrid system of 225 m^2 PV together with 12 h of battery storage where diesel back-up has to provide only 9% of the load demand while it has to contribute 58% of the load without battery back-up. The potential of utilizing hybrid wind-diesel power system is explored in [10] to meet residential loads with annual demand of 3512 MWh for Dhahran region of Saudi Arabia. Different combination of 150 kW wind machines along with battery and diesel back up are considered for the study. The analysis has been carried out to evaluate the percentage of load demand supported by diesel generator for different battery capacities with seven 150 kW wind machines such as diesel back up provide 21.6%, 17.5% of the load demand respectively with one and three days of battery storage and 37% of the load needs to be provided in the absence of battery storage. Further different wind machine sizes (150 kW, 250 kW, 600 kW) are considered to identify the optimum wind machine based on energy production and the analysis results shows that a cluster of forty 150kW wind machines yields about 48% more energy as compared to a cluster of ten 600 kW wind machines for a given 6 MW wind farm size. An optimal hybrid renewable energy systems consisting of a heat pump, a biomass boiler, wind turbines, solar heat collector, photovoltaic panels, and a heat storage tank is designed in [11] for a residential building located in a cold Canadian climate. The techno-economic feasibility of hybrid PV-diesel-battery system is analyzed in [12] for meeting the energy demand of a building with annual electrical energy demand of 620,000kWh using NREL's HOMER software. The solar radiation data of Dahran was utilized for the purpose and simulation results in a optimum hybrid system comprising of 80kWp PV system with 175kW diesel system and a battery storage of 3 h of autonomy with corresponding cost of energy (COE) as 0.149 $/kWh. The authors also investigated the unmet load situations, excess electricity, emission decrease, and energy cost for different scenarios in that study. An optimization model is proposed in [13] for sizing a micro hydro-PV-hybrid system to meet the power demand of Batocha region in Cameroon using HOMER software. Analysis of the results which take into account the variations in resource availability and systems cost reveal that for such place where hydro alone cannot satisfy the yearly demands of the population, introduction of PV together with a diesel and batteries can solve rural electrification problems.

A methodology is demonstrated [14]based on the long term data for both wind speed and solar irradiance for calculating the optimum battery bank and PV array size in a hybrid wind/PV system for a given load and level of reliability. The load profile considered is of a typical house in Massachusetts and optimization is done based on the minimization of the system cost where the system cost is assumed to be linearly related to both the numbers of PV modules and batteries. Ref. [15] shows that the sizing and profitability of wind/ PV hybrid system for remote application is greatly influence by the characteristics of the of the solar and wind energy resources. The study is carried out considering the solar and wind energy potential for five meteorological sites in a Mediterranean island. Out of the five sites, two meteorological sites are chosen based on how solar and wind energy support each other using correlation coefficient (CC) for quantifying the simultaneity of the two energy productions. The technical and economic feasibility of hybrid PV/wind turbine/diesel system is investigated [16] in southern city of Malaysia, Johor Bahru using HOMER (hybrid optimization for electric renewable). Seven different system configurations, namely stand-alone diesel system, hybrid PV–diesel system with and without battery storage element, hybrid wind–diesel system with and without battery storage element, PV–wind–diesel system with and without storage element are simulated to minimize the net present costs, cost of energy, excess electricity produced and CO2 emission. Further, the impact of high diesel price is analyzed for the system configuration- PV–diesel system with battery storage element, PV–wind–diesel system with battery storage element and the stand-alone diesel system. Ref. [17] evaluates the economic perspective of renewable energy source with a hydrogen system for a standalone system and grid connected structure for a pilot region- Electrics & Electronics Faculty, Istanbul Technical University. The simulation of the system operation and calculation of the technical and economic parameters are done using, micro power optimization program HOMER (NERL, US). The evaluation shows that grid connected hybrid RE systems have a higher probability of adaptation than the standalone (100% renewable system) configurations. Further the impacts of future increases in the electricity price and decreases in the RE cost on the viability of the system were examined. A reduction of 50% in component cost lead to approximately 35% and 26%

decreases in the standalone system and grid connected structure, respectively. A new algorithm is proposed [18] for sizing hybrid energy system components based on the optimization of the power dispatch simulations and implements the proposed algorithm on a hybrid system comprising diesel generator (DG), photovoltaic (PV) panels, and battery bank applicable to Alaminos, Philippines for minimizing the cost of energy (COE). The proposed sizing search algorithm results in faster convergence to the objective solutions with less sampling populations leading to reduction in computational burden. An optimal sizing method of a PV/ wind hybrid energy conversion system with battery backup is presented [19] using Box–Behnken design and RSM (Response Surface Meta-models) based on an hourly operating cost and a breakeven analysis to decide the economic aspect of grid extension. The case study is conducted on a GSM based station at Izmir Institute of Technology Campus Area, Urla, Izmir, Turkey for satisfying its electricity demand and optimum result obtained by RSM is confirmed using LLP and autonomy analysis.

The unit sizing method and cost analysis of a standalone hybrid wind/photovoltaic/fuel cell (FC) generation system is carried out in [20] for a typical home in the Pacific Northwest and compared its performance with a traditional hybrid energy system with battery storage. The optimal sizing is carried out through a graphical user interface programmed in MATLAB in most cost effective way. Resulted cost figure as well as a break even distance comparison shows a clear economic advantage of the traditional wind/PV/battery system over the wind/PV/ FC/electrolyser system. A numerical optimization routine is utilized [21] for determining the optimal wind generator capacity, number of PV panels and storage capacity while minimizing the total annual cost for a hypothetical site in Montana. The optimization routine constrained the objective function to minimize the difference between the generation and demand for a given period of time and required storage capacity is determined by finding the difference between the positive and negative peaks of the energy curve over time.

The sizing and profitability of wind/ PV hybrid system for remote application is greatly influence by the characteristics of the of the solar and wind energy resources [22].The study is carried out considering the solar and wind energy potential for five meteorological sites in a Mediterranean island. Out of the five sites, two meteorological sites are chosen based on how solar and wind energy support each other using correlation coefficient (CC) for quantifying the simultaneity of the two energy productions. A complete sizing model is developed in [23] which estimate the optimal configuration of a stand-alone hybrid PV/wind system (HPWS) in Corsica Island base on the levelised cost of energy (LCE). For all sites under investigation, the hybrid system is the best option with least LCE and further simulation results show that renewable energy potential greatly affects the LCE with wind generator contribution of more than 40% of the total energy production at high wind potential site and less than 20% of total energy production at low wind potential sites. The techno-economic feasibility of autonomous photovoltaic system is analyzed at three representative islands all over Greece [24]. A numerical code ‘‘PHOTOV-III’’ developed by the author has been used for finding the energy autonomy photovoltaic panel number and battery capacity for each of the representative location along with the optimum PV panel tilt angle that will give the minimum first installation cost. One of the remarkable finding is the photovoltaic system size difference between northern and southern locations of Greece resulting in higher initial cost of more than 70% in the north than in south Greece. Above all this, if state subsidization opportunities are considered small photovoltaic systems are economically attractive investments for high solar radiation areas. The optimal sizing and energy behavior of a stand-alone photovoltaic system capable of satisfying the energy demand of remote consumers located in typical Greek territories is investigated in detail in [25]. A fast and reliable numerical algorithm developed by the author called as PHOTOV-III is utilized for estimating the optimal system configuration with minimum initial cost and for analyzing the detailed energy balance while examining the impact of different reliability level on system energy behavior and initial cost. Results show that battery capacity is significantly affected by the desired system reliability especially up to reliability value of 99% and at the same a linear relationship is observed with the PV panel reduction as the system reliability level decrease from 100% to 95%. According to the energy balanced analysis results obtained, the 2/3 of the energy production from photovoltaic generator is finally utilized for consumption, with system components energy loss of 12–14%. A methodology is developed [26] for techno-economic evaluation of stand-alone hybrid wind–photovoltaic power systems seeking optimal system configuration for a representative remote consumer based on economic performance criteria. The application of the developed model is tested on four representative regions of the Greek territory having diverse wind potential based on minimum initial investment and total cost for a span of 10-year and 20-year. The cost analysis results highlight significant cost advantage of the proposed optimum configuration compare to diesel only, wind only and PV only solutions. Ref. [27] carried out a techno-economical optimization of a PV-wind hybrid system utilized for hydrogen production in a filling station in Huesca (Spain) providing fuel for 100 hydrogen vehicles with option for selling the surplus electrical energy to the grid. Optimization was carried out based on two different types: type a, use for finding the combination of components yielding lower hydrogen selling price so that NPV=0 and type b, meant for finding components combination with a lower hydrogen selling price so as to get an investment recovery within 10 years time. Results obtained from analysis show that for recovery of initial investment of such facilities within a stipulated time of 10 years, hydrogen selling price is mostly influenced by spare electricity price sold to the grid along with solar irradiation, wind conditions and acquisition cost of the components.

A general optimal model of hybrid energy system is discussed in [28] for a typical rural community minimizing the life cycle cost based on a numerical iterative algorithm. Out of the possible configurations of hybrid energy system, the optimal combination is found to be with Micro-hydro-wind systems for the electrification of the rural villages in Western Ghats (Kerala) India, with a unit cost of Rs. 6.5/kW h and 100% renewable energy contribution thereby eliminating the use of conventional diesel generator. A multi-objective optimization model is developed [29] to optimally design a solar–diesel–battery based hybrid energy system with primary objective to minimize life cycle cost (LCC) and secondary objective to minimize CO2 emissions subject to power generation constraints, reliability constraints and state of the charge of the battery. A case study result for an un-electrified remote village in Moradabad district of Uttar Pradesh, India reveals the applicability of the optimization model. Optimization and simulation studies of a hybrid renewable energy system for a police control room at Sagar in central India is carried out in [30]. Optimization results depict the use of hybrid solar-wind system as an alternative option to conventional energy sources prove to be a feasible solution as an stand alone system for the police control room. Size optimization and sensitivity evaluation of a hybrid energy system applicable for a hilly village cluster of Jaunpur block of Tehri Garhwal district in Uttarakhand, India is presented in [31]. A techno-economic analysis of small wind generator system is carried out in [32] for decentralized power supply in India using levelized unit cost of energy as the criteria. The optimal hybrid system configuration is the one having the least net present cost. Diesel generator is used in the study as the alternative back up power supply with battery banks as the energy storage devices. Besides the impact of variation of diesel price and annual real interest rate on the system type is also investigated. In [33] an optimal model for domestic lighting facilities is proposed considering four sources and six devices for Narayangargh block of Midnapore district in India. The developed model provides a rational decision for allocation of investment in domestic lighting sector in rural energy planning. Various energy management strategies such as cycle charging strategy, load following strategy and peak shaving strategy are adopted in [34] for optimal sizing of hybrid energy system. The locally available energy resources in Dhauladevi block of Almora district in Uttarakhand, India is used for the study along with diesel generator for satisfying the energy deficit. A hybrid photovoltaic-biomass-wind-battery system is proposed in [35] for a case study area comprising of three villages in Chennai, India. Simulation is carried out for one year period for satisfying the load demand taking into account the non-linear seasonal variation of load and equipment constraints.

An allocation of different renewable energy sources in optimal manner is determined in [36] for the year 2020-2021 in India for various end uses. An Integrated Renewable Energy Optimization Model (IREOM) is developed in [37] for designing a decentralized optimal renewable energy system based on minimizing the cost of energy with a required level of reliability applicable for a remote hilly area in Uttarakhand, India. The proposed model is used to select different system components, find the optimal system sizes and operational strategy for a study area comprising of a cluster of villages considering the seasonal variations in load profiles and the proposed model is found to be generic in finding the optimal renewable energy system sizes. Decentralized energy planning (DEP) from village to district level at least cost is carried out in [38] for fulfilling the energy demand of Tumkur district in India. Various scenarios were taken into consideration for the year 2005 and the same decentralized energy plan was analyzed for extending up to year 2020. An integrated renewable energy system (IRES) is designed [39] for a remote hypothetical rural village in India. The model makes use of various resources available in the remote area such as wind, solar heat, solar radiation, biomass and falling water. The objective of design is to minimize the initial capital investment while taking loss of load power supply probability (LOLP) as the key system indicator.

1.5.3 Types of HES schemes

1.5.3.1 Photovoltaic (PV) based hybrid system

A hybrid photovoltaic system may consist of PV-battery and PV-diesel generator system. In a hybrid PV-battery system, battery storage increases the overall system availability and flexibility in system operation. A hybrid combination of PV with diesel generator drastically reduces the dependence on fossil fuel (diesel) at the same time the level of emission as compared to the conventional diesel only system. Various approaches such as probabilistic or deterministic have been developed to analyze the hybrid PV system performance and to obtain the optimal PV-diesel mix. A methodology is developed in [40] for optimal sizing and determining the optimum operational strategy of a PV- hybrid system with battery backup and engine generator. Two parameters: the starting (SDM) and the stopping thresholds (SAR) are used to characterize the operational strategy of backup engine generator. The optimal configuration is simulated on the basis of kWh cost minimization and operational strategy study shows that least kWh system cost corresponds to SDM=30% and SAR=70% of the nominal battery capacity. An extensive study is carried out in [41] for photovoltaic operation under partial shaded condition for maximizing its output power. The feasibility of utilizing hybrid photovoltaic diesel battery system is investigated in [42] to meet the annual electrical energy demand of 35 200 kWh for a typical residential building in Dhahran, Saudi Arabia with the object of minimizing diesel generator operation . Different array sizes of PV panels along with battery storage unit and diesel back-up are considered for the study. The simulation study resulted in a hybrid system of 225 m^2 PV together with 12 h of battery storage where diesel back-up has to provide only 9% of the load demand while it has to contribute 58% of the load without battery back-up. The power output modeling of a rooftop photovoltaic system and its practical application is analyzed in [43]. The analysis consider the response of the solar radiation and temperature on the photovoltaic output. The techno-economic feasibility of hybrid PV-diesel-battery system is analyzed in [44] for meeting the energy demand of a building with annual electrical energy demand of 620,000kWh using NREL's HOMER software. The solar radiation data of Dahran was utilized for the purpose and simulation results in a optimum hybrid system comprising of 80kWp PV system with 175kW diesel system and a battery storage of 3 h of autonomy with corresponding cost of energy (COE) as 0.149 $/kWh. A stand alone photovoltaic-battery is designed [45] for supplying residential appliances at Dhaka, Bangladesh. Battery storage is sized to supply the load reliably during periods of low solar radiation. Sizing of PV array is carried out considering the monthly average daily values of solar radiation data for 11 years. An optimal sizing method to find the optimal configuration of PV array and battery storage is presented in [46] for supplying the refrigeration load considering the statistical model for both load demand and solar resource.

1.5.3.2 Wind based hybrid system

An integration of a wind turbine generator with battery storage or wind turbine generator with diesel generator may constitute a wind energy based hybrid system. The effective and economical utilization of hybrid wind energy system is wholly dependent on the wind energy potential of the chosen location [47]. Besides, the prefeasibility studies based on economic and technical criteria need to be carried out over and above the capacity meeting of the demands. In reference [48], the authors examine the feasibility of utilizing hybrid wind diesel battery system to meet the annual electrical energy demand of 620,000 kWh for a typical commercial building in Dhahran, Saudi Arabia while minimizing diesel generator operation. Different combinations of the commercial 10 kW wind energy conversion systems (WECS), along with battery storage unit and diesel back-up are considered for the analysis. The simulation study resulted in a hybrid system thirty 10 kW WECS and 3 days of battery storage where diesel back-up has to provide only 9% of the load demand while it has to contribute 40% of the load without battery back-up. The potential of utilizing hybrid wind-diesel power system is explored in [49] to meet residential loads with annual demand of 3512 MWh for Dhahran region of Saudi Arabia. Different combination of 150 kW wind machines along with battery and diesel back up are considered for the study. The analysis has been carried out to evaluate the percentage of load demand supported by diesel generator for different battery capacities with seven 150 kW wind machines such as diesel back up provide 21.6%, 17.5% of the load demand respectively with one and three days of battery storage and 37% of the load needs to be provided in the absence of battery storage. Further different wind machine sizes (150 kW, 250 kW, 600 kW) are considered to identify the optimum wind machine based on energy production and the analysis results shows that a cluster of forty 150kW wind machines yields about 48% more energy as compared to a cluster of ten 600 kW wind machines for a given 6 MW wind farm size. A simplified methodology is developed [50] for estimating the monthly system performance of a wind energy system with battery back-up solely by making use of monthly-average values of wind speed distribution parameters instead of hourly long term wind data. The accuracy of the proposed methodology in estimating the system performance is validated by comparing with the simulated performance values obtained using hour-by-hour wind speed data.

A new methodology is developed [51] to estimate the yearly performance of hybrid wind energy system for autonomous applications in terms of yearly wind fraction. The wind fraction values are obtained on a yearly basis with each value corresponding to predetermined wind generator capacity and battery size, resulting in a set of curves called as wind fraction (WF) curves. By correlating the distribution dependency characteristics of the WF curves with the wind speed distribution parameters, the author develops a 2-parameter mathematical model of the yearly wind fraction curves. The accurateness of the estimated yearly wind fraction obtained through the developed methodology is confirmed by comparing with the simulated values of wind fraction. In ref. [52], the authors design an optimum configuration of a hybrid wind-diesel stand alone system based on a developed sizing model which analyses a long term energy production cost. The developed model results in optimum size of the hybrid system under investigation on a 10-year or on a 20-year long minimum electricity production cost basis. Finally, the analysis on two selected low and high wind potential regions reveals greater reliability and cost effectiveness of the proposed hybrid system than a diesel-only installation or a wind-only based stand-alone system. Reference [53] provides a detailed mathematical model describing the operational behavior of various components of wind–diesel–battery hybrid system. A new numerical algorithm is developed to estimate exact hybrid system dimensions that guarantees 1year energy autonomy of typical remote consumer and resulted optimum hybrid system configuration is further verified by carrying out sensitivity analysis of the points belonging to the energy autonomous solution curve. A loss of load probability (LOLP) method is adopted in [54] to evaluate the hybrid wind energy systems. An optimal sizing of wind-battery system is carried out in [55] considering resource uncertainty for isolated applications. Chance constraints programming approach is used to model the uncertainty in wind speed. The three different components viz. rotor diameter, generator rating, and battery capacity of a standalone wind battery system is optimally sized in [56] using design space methodology with the object of minimizing cost of energy.

1.5.3.3 Photovoltaic (PV)-wind based hybrid system

Standalone application of photovoltaic only and wind only system fails to produce usable energy throughout the year long. Hybrid integration of photovoltaic and wind into a single system considerably reduces the battery bank size and quantity of diesel requirements. Solar and wind energy potential at a given site are the main deciding factors for checking the feasibility of hybrid photovoltaic-wind system utilization. Enormous feasibility and performance studies are reported in literature for utilization of hybrid photovoltaic-wind energy system.

A PV-solar/wind hybrid energy system is designed in [57] for supplying power to a GSM/CDMA type mobile telephony station. Reference [58] presents a complete sizing model which estimates the optimal configuration of an autonomous stand-alone hybrid PV/wind system (HPWS) in Corsica Island base on the levelised cost of energy (LCE). For all sites under investigation, the hybrid system is the best option with least LCE and further simulation results show that renewable energy potential greatly affects the LCE with wind generator contribution of more than 40% of the total energy production at high wind potential site and less than 20% of total energy production at low wind potential sites. An analysis is performed in [59] on performance-cost relationship and optimization of an autonomous hybrid wind/PV power system considering total system cost and the unit cost of the produced electricity. The optimization is based on energy autonomy of the system and energy to load ratio (ELR) assuming a 24h constant 15W load. The performance of the optimum combination of the hybrid photovoltaic–wind energy system proved to be higher than either of the single systems for the same system cost for every battery storage capacity.

The yearly system performance is analyzed in [60] based on yearly system autonomy of a hybrid photovoltaic-wind energy system by synthetically generating the solar radiation and wind speed data, and a performance comparison is made with that of measured hour by hour data. A methodology based on monthly clearness index value is used to synthesize hourly solar radiation and Weibull wind speed distribution model is utilized to synthesize the daily constant wind speed data. The system autonomy values resulted from synthetically generated solar radiation and wind speed data are found to be very close to those resulted from measured hour by hour data. A novel sizing and techno-economic optimization method applicable to a PV-wind hybrid energy system is introduced in [61] simultaneously taking into account the system autonomy and cost. The author pointed out that sizing such hybrid energy system based on worst month scenarios leads to non optimal solutions resulting in higher system cost and concluded that incorporating an auxiliary energy source rather than employing larger hardware sizes for the worst month results in more optimum systems both technically and economically. A methodology for finding the correct size of a hybrid PV-wind-battery system and optimal management of the system is presented in [62]. The system is assumed to be autonomous and capable of providing power supply for a small remotely located community. A parametric study is carried [63] out on the impact of variation of photovoltaic (PV) array area, number of wind machines, and battery storage capacity on hybrid (wind + solar + diesel) energy system operation while satisfying a specific annual load of 41,500 kWh. Analysis results indicate that diesel backup contribute about 23% of the load demand while deploying two 10 kW wind machines, 30 m^2 photovoltaic with three days of battery storage and in the absence of battery storage, diesel system needs to provide about 48% of the load.

The performance of hybrid systems is evaluated in [64] consisting of different rated power wind farms, photovoltaic (PV) areas, and storage capacities together with a diesel back-up while meeting a specific annual electrical energy demand of 702,358 kWh. The best wind energy utilization is observed with a rated power close to the peak load and increasing the wind farm capacity from 100kW to 200kW results in reduction of diesel energy generation and operating hours by 25% and 18% respectively. It is also observed that there is small reduction in diesel energy generation associated with large increase in PV and owing to high PV system cost, such system is uneconomical. Further incorporating battery storage capacity of 3024kWh reduces diesel energy generation and operating hours by 17% and 30% respectively. An optimum sizing approach is proposed [65] based on component performance degradation for sizing of a hybrid alternative energy system consisting of wind/PV/fuel cell (FC) electrolyser combination for hydrogen energy as main back-up and a battery system. Further different hybrid system combinations including FC back-up fed by gas reformation based hydrogen and only battery banks based back-up are also considered. The optimization is performed by "observe and focus" algorithm utilizing the dynamic models of each hybrid system component. The inclusion of component performance degradation in the sizing procedure results in a significant increase in the component size for all the considered combinations of hybrid system components and hence this new perspective of performance degradation may be considered in future studies. Modeling and simulation of a hybrid energy system is carried out in [66] taking LEC (Levelized Energy Cost), ICC (Initial Capital Cost) and GHG (Green House Gas) emission as objective functions in the optimization. Simplifying the three dimensional Pareto front of LEC, ICC and GHG emission into two separate two dimensional Pareto fronts: ICC-LEC and LEC-GHG emission, study reveals that ICC and GHG emission increase with the increase of power supply reliability. Further, fuel price escalation is having a significant impact on solutions in ICC-LEC Pareto front as well as reduction of renewable energy component prices is having a positive impact on LEC-emission Pareto front and hence gradual integration of renewable energy sources in a number of design stages into HES becomes an attractive solution. A simulation optimization model based on meta-model based algorithm called A-STRONG is developed [67] to find the optimal size of PV, wind and diesel power generator as well as the optimal size of energy storage system. The study also considers the power generation, allocation and transmission within the HRES for finding minimum expected total cost under uncertain environments. A techno-economic feasibility study of an off-grid hybrid renewable energy based power systems is carried out in [68] for satisfying the electrical needs of a rural community in Sri Lanka. A combination of 40 kW wind turbines, 30 kW photovoltaic (PV) systems, a 222kWh battery bank, and a 25 kW diesel generator results in the optimum hybrid system configuration.

1.5.4 Sizing methodology used in HES

1.5.4.1 Classical techniques for hybrid energy system design

Classical techniques for optimization adhere to finding optimum solutions of continuous and differentiable functions. They make use of differential calculus in finding the optimal solutions and are categorized as analytical methods. The conventional optimization techniques available in the literature are linear programming (LP) [69-70], mixed integer linear programming (MILP) [71-73], loss of load probability (LOLP) method [74-75], dynamic programming (DP) [76], multi-objective goal programming [77], , and analytical method [78],[79].

A detailed mathematical model describing the operational behavior of the basic hybrid energy system components is provided in [69] and utilizes integer linear programming method to determine the optimal unit cost and optimal operation under demand and potential constraints. The proposed model is found to be sufficiently accurate and hence can be used in further planning studies. A smart hybrid renewable for a community (SHREC) is proposed [70] considering both thermal and electricity market in a large community level. The developed SHREC system is optimized using linear programming (LP) algorithm in a weekly period. Results show the effectiveness and flexibility of developed methodology for the smart hybrid renewable energy system. A mixed integer linear programming (MILP) is used to design a hybrid wind-photovoltaic system with micro-grids in [71]. A mathematical programming model is used to solve the design problem which minimizes the initial investment cost required to meet the demand.

An integrated solar and biomass system is proposed [72] for a smart eco-village in tropical countries and a MILP model is applied to design the cost effective system configuration subject to biomass availability and renewable energy resource variations. The techno-economic performance of a hybrid energy system consisting of small/micro hydro based power generation, biogas based power generation, bio-mass (fuel wood) based power generation, photovoltaic array, a battery bank and a fossil fuel generator is evaluated in [73]. In order to determine the optimal operation and optimal configuration while assessing the economic penetration levels of PV array area, a mixed integer linear mathematical model based on combined dispatch strategy is developed. The model introduced a cost constant (cost/unit) such that the resource having lesser unit cost covers the greater share of the total energy demand in order to optimize the cost function. An extensive case study analysis demonstrates the validity of the model and proposed strategy. Using demand side management (DSM), the system components size is further reduced leading to reduction in the capital cost of the system. The complementary characteristics of solar radiation and wind power using weather data of a typical weather year in Hong Kong is discussed in [74] and a simulation model of hybrid photovoltaic–wind systems with a storage battery is developed for calculating loss of power supply probability (LPSP). The optimum combinations of the hybrid system components are obtained for different desired LPSPs. Results of a case study of hybrid solar–wind power supply for a telecommunication system show that hybrid system with 3 days power storage battery is capable of ensuring LPSP of 1%, while hybrid system with 5 days storage capacity is suitable for ensuring a LPSP of 0%. The performance of a stand-alone photovoltaic (PV) system is analyzed [75] in terms of loss-of-load probability (LLP) expressed as function of two variables viz. SLR (solar to load ratio) and BLR (battery to load ratio) considering five different weekly load profiles. The yearly simulated values of LLP for different load profiles are plotted as a function of SLR and BLR to give LLP curves. A considerable change in LLP curves is observed for same SLR and BLR when the system is subjected to different load profiles. Further it is observed that employing increase number of PV modules does not lead to lower values of LLP after a limiting point and in this case battery capacity is required to be increased in order to achieve smaller LLP. Dynamic programming is used in [76] for maximizing the total benefits from a fixed investment for selecting appropriate alternative energy technologies in the agriculture and household activities. A multi-stage decision making process is formulated with the objective of maximizing total achievable benefit. A multi objective goal programming (MOGP) is applied in [77] for obtaining the optimized energy scenario for a case study area in northern part of Rajasthan, India. The model aims at minimizing use of petroleum products, emission and cost at the same time maximizing the reliability, efficiency, employment generation and social acceptance. A small autonomous power system (SAPS) model based on analytical approach is developed in [78]. The model consists of solar and wind sources which aim at minimal production cost of SAPS. A study period of one year was considered and the year is divided into numerous time frames with each time frame considered independently. An analytical model is proposed in [79] for evaluating the performance of photovoltaic array-wind turbine system operating in standalone mode. In the study, hydrogen production is used for long term energy storage. The study further determines the effective photovoltaic output contribution in meeting the load and supplying power to energy storage based on a concept called as solar radiation usability.

1.5.4.2 Software based hybrid energy system design

The performance evaluation of a hybrid renewable energy systems are done most commonly by software based simulations program. Many software programs are currently available that can be downloaded from the websites of several research laboratories and universities. The optimal system configuration can be found with the help of simulation programs based on a performance formulation that can be optimized for a set of decision variables. A detail review on various software packages available for analysis of hybrid energy system is given in [80].

One of the most commonly utilized simulation software for hybrid energy system sizing is HOMER developed by National Renewable Energy Laboratory (NREL), United States. HOMER is simulation software developed by the U.S. National Renewable Energy Laboratory (NREL) [81] to assist in planning and design of renewable energy based micro-grids. It simplifies the task of evaluating design options of varied off-grid and grid connected systems for autonomous, remote and distributed generation applications. It also facilitates the comparison of power generation technologies across a wide range of applications. Through HOMER, a modeler can compare a number of different design options considering the technical and economic features of system components and provide a method to find the lowest cost system design on the basis of energy source data, system components and a given load demand. Simulation, optimization and sensitivity analysis are the main tasks that can be performed in HOMER.

Besides HOMER, several others software are also available for solving hybrid energy system design problem. Some of them are The Hybrid Power System Simulation Model (HYBRID2)[93-94], LINDO [25], [95], the General Algebraic Modeling System (GAMS) [96], Dividing Rectangles (DIRECT) [97], Simulation of Photovoltaic Energy Systems (SimPhoSys) [98], Geo-Spatial Planner for Energy Investment Strategies (GSPEIS) [99], Matlab simulink [100], [101], [102] etc.

HOMER is adopted in [82], to analyze the technical and economic potential of autonomous hybrid wind/PV/diesel power system for a typical remote village in Saudi Arabia. Size optimization of a hybrid energy system combining solar photovoltaic and wind turbine using HOMER is carried out in [83] considering diesel generator as the back-up source and the battery as the storage device. An analysis of a PV-biomass-battery is carried out using HOMER for system expansion process under three different load growth scenarios [84]. Simulation result shows the possibility of the system size expansion with accurate load estimation at the time of expansion. An optimal hybrid renewable energy based micro grid is designed in [85] using HOMER while taking into account various factors such as economics, operational performance and environmental emissions. A comparative analysis on various cases including a diesel-only, a fully renewable-based, a diesel-renewable mixed, and external grid-connected micro-grid configurations reveals that diesel-renewable mix micro grid with lowest net present cost has fairly small carbon foot-print and fully renewable based micro grid has no carbon foot-print although the net present cost is higher which is considered the most environmental friendly micro grid. A techno-economic feasibility analysis is carried out in [86] to utilize a hybrid wind-PV-diesel power system to satisfy the electrical loads of Al Hallaniyat Island. The analysis is done using HOMER.

An analysis on the techno-economic feasibility of adding wind turbine in the existing grid connected diesel power plant is carried out in [87] aiming at reducing the diesel consumption and environmental pollution using HOMER simulation model. The feasibility of the wind-diesel hybrid system is obtained at a wind speed of 5.48m/s or more and a fuel price 0.162$/L or more. Further findings pointed out that maximum annual capacity shortage did not have any impact on the system optimization owing to larger capacity of wind turbine and diesel generators. A hybrid photovoltaic diesel power system is designed using HOMER in [88] by minimizing the cost of the battery storage for a remote area in Australia. The techno-economic feasibility of hybrid PV-diesel-battery system is analyzed in [89] for meeting the energy demand of a building with annual electrical energy demand of 620,000kWh using NREL's HOMER software. The solar radiation data of Dahran was utilized for the purpose and simulation results in a optimum hybrid system comprising of 80kWp PV system with 175kW diesel system and a battery storage of 3 h of autonomy with corresponding cost of energy (COE) as 0.149 $/kWh.. An investigation is presented in [90] into the techno-economic feasibility of an autonomous hybrid wind / photovoltaic (PV)/battery power system for a household in Urumqi, China, using Hybrid Optimization Model for Electric Renewable (HOMER) simulation software taking into account the effect of ambient temperature, the variation of load and PV module tilt angles during simulation. The optimal system configuration found is hybrid wind/PV/battery system consisting of 5 kW of PV arrays (72% solar energy penetration), one wind turbine of 2.5 kW (28% wind energy penetration), 8 unit batteries each of 6.94 kWh and 5 kW sized power converters reducing the total net present cost (NPC) about

9% and 11% compared with PV/battery and wind/battery power systems. Further applications of HOMER simulation software are reported in the literatures [91-92]. A benchmark predictive dispatch strategy is developed in [93] based on assumed perfect knowledge of future load and wind conditions and a comparison of non-predictive dispatch strategies are done using (1) an analysis of cost trade-offs, (2) a simple, quasi-steady-state time-series model, and finally (3) HYBRID2, a more sophisticated stochastic time-series model. Results reveals that the one of two simple diesel dispatch strategies-either load-following or full power for a minimum run time-can, in conjunction with the frugal use of stored energy (the Frugal Discharge Strategy), be virtually as cost- effective as the Ideal Predictive Strategy. A hybrid energy system with renewable energy inputs from wind and solar for a hypothetical Alaskan village is designed using HYBRID2 in [94] utilizing advanced storage technologies such as compressed hydrogen or zinc pellets. An integrated renewable energy system (IRES) consisting of MHP, SPV, WES, and BES is modeled in [95] for meeting the energy needs of 12 un-electrified villages in Jaunpur block of Uttaranchal state of India. The model has been optimized using LINDO software 6.10 version. The results indicate that the proposed model is feasible for the study region only with (electric power delivery factor, maximum equal to 1) EPDF 1.0–0.75 and beyond this the model becomes unfeasible. A cost effective action plan for power generation in remote rural area is formulated in [96] and LINDO software is utilized to carry out the sizing and optimization through minimization of energy production cost.

A simulated studies has been carried out in [97] using the General Algebraic Modeling System (GAMS) for optimal design of a hybrid solar-wind energy plant with the objective of minimizing cost while satisfying a specific load. The decision variables include the number of wind turbines, solar arrays, wind turbine height and rotor diameter. The DIRECT (Dividing RECTangles) algorithm has been used in [98] for sizing optimization of an autonomous hybrid wind/PV/Diesel, wind/Diesel and PV/Diesel energy systems. Minimizing the total cost the algorithm search for the optimal number and type of the units while guaranteeing the availability of energy. A simulation tool called as Simulation of Photovoltaic Energy Systems (SimPhoSys) is utilized in [99] for sizing and performance evaluation of photovoltaic energy system. The simulation model allows modular structure of the system design and simulation of advanced operation control strategies. The concept of geo-spatial data analysis along with optimal modeling of renewable energy planning and investment is implemented in [100] using Geo-Spatial Planner for Energy Investment Strategies (GSPEIS) considering development cost, constraints on resources and new infrastructure requirement. Detailed modeling, simulation and analysis of a standalone wind-hydrogen [101], wind-fuel cell [102] is carried out using Matlab simulink models. A photovoltaic-variable speed diesel generator is modeled in [103] using Matlab simulink for off grid operation and its performance analysis result is validated by comparing the results with those of HOMER software. Results show better performance of the system with variable speed diesel generator compare to conventional constant speed diesel generator.

1.5.4.3 Evolutionary Algorithm based hybrid energy system design

Evolutionary algorithms are computer programs capable of solving complex problems by mimicking the biological process of evolution. Various computational problems have their search space that is proportional to the problem dimensions. These problems cannot be solved using exhaustive search techniques. On the other hand, evolutionary algorithm provides a framework for effectively sampling the large search space within an acceptable time frame. Numerous evolutionary algorithm techniques have been applied by various researchers in context of solving hybrid energy system design problem and performance analysis. EA techniques reviewed from the available literatures are: genetic algorithm (GA) [104-112], particle swarm optimization (PSO) [113-117], simulated annealing (SA) [118], ant colony optimization [119-120], Biogeography Based Optimization (BBO) algorithm [121], Strength Pareto Evolutionary Algorithm (SPEA) [122-123], multi-objective evolutionary algorithm (MOEA) [124], and preference-inspired co-evolutionary algorithm (PICEA) [125].

An optimization program called Hybrid Optimization by Genetic Algorithms (HOGA) is developed in [104], for determining the sizing and operation control of a PV-Diesel system in C++. HOGA calculates the optimal configuration in a very precise manner as it provides various information such as the number of PV panels and the type of PV panels, the number of batteries and the type of battery, the inverter power, the Diesel generator power, the optimal control strategy of the system with its parameters, the Total Net Present Value of the system and the different relative costs such as the fuel cost, and finally, the number of running hours for the Diesel generator per year. The proposed program also optimized the SOC (state of charge) set point although the control strategy adopted is based on the one used by HOMER program. Reference [105] is an upgraded version of the previous work by the same authors [104] where a Genetic algorithm (GA) based optimization program optimize both the configuration and control strategy of a hybrid PV-diesel system with AC loads. This work is mainly focused on the control strategy optimization and proposed strategy optimize the different control parameters of the hybrid system through GA which will result in minimal NPC (net present cost). Several improvements are incorporated in the design tools such as option for different type of energy sources and energy storage; two different mathematical models applicable to battery operation, option for different types of load either AC or DC and estimation of battery lifetime through different methods. Finally the proposed strategy is applied to optimize the control parameters of a PV–diesel–battery–hydrogen system with fixed size of its physical components. Reference [106] considers a complex photovoltaic (PV)–wind–diesel–batteries–hydrogen system to evaluate the performance behavior of a Genetic algorithm (GA) based evolutionary algorithm consisting of two sub algorithms: main algorithm search for the optimal combination of the physical components of the system and secondary algorithm determines the optimal control strategy. Results recommend the following parameters values of GA for any hybrid system design: population size at least equal to 0.003% of all possible solutions, generation at least equal to 15, crossing and mutation (uniform) rate respectively equal to 90% and 1%.An optimal sizing method based on Genetic algorithm (GA) for a hybrid solar-wind system with battery storage is developed in [107] to obtain the optimal system size at a required loss of power supply probability (LOLP) with minimal annualized system cost. The developed model is applied for the hybrid system design for a telecommunication relay station. An optimum hybrid PV, wind and fuel cell system is designed [108] using genetic algorithm (GA), based on economic criteria. A multi-objective genetic algorithm (GA) based sizing methodology is [109] applied for sizing of a hybrid solar-wind-battery system applicable for a remote location in northern coast of Senegal. The influence of load profiles on the cost of optimal system configuration is also carried out in the study. A detail analysis on the techno-economic and designing aspect of a hybrid system consisting of photovoltaic (PV) panels, a battery system and a diesel generator is carried out in [110]. In order to maximize the PV generated energy, the PV tilt angle is optimized using genetic algorithm. Simulation result of the hybrid system considering two different scenario of a standalone PV and a diesel generator indicates the optimal scenario as the one consisting of the PV panels, battery bank and a diesel generator. Sensitivity of COE (cost of energy) to variation of different parameters like discounted rate, diesel price, project life time, PV capital cost was also examined. The interdependency of hybrid operational strategies and system sizing, is highlighted in [111] and develops a general method to jointly determine the sizing and operational control of hybrid-PV systems. The design algorithm to evaluate the costing of the operating strategies and component sizes is based on Genetic algorithm optimization technique which chose an optimum system configuration together with the recommendation for an operational strategy for a given site and requirement. An optimal sizing methodology of a standalone hybrid system is presented in [112] using Genetic algorithm which minimizes the total system cost. The determination of the feasible system configuration is carried out by taking the system design characteristics into account; such as the photovoltaic (PV) modules tilt angle, and the wind turbine installation height. The simulation results verify that hybrid solar-wind systems lower the system costs in comparison with the solar/wind only systems.

Particle swarm optimization algorithm is applied in ref. [113] for optimal sizing of a stand-alone hybrid power system based on minimizing system total cost for a residential area consisting of fuel cells, some wind units, some electrolyzers, a reformer, an anaerobic reactor and some hydrogen tanks. Since fuel cells are used as backup for wind turbines, the proposed hybrid system has high reliability. Moreover, hydrogen tank is fed by both electrolyzer and reformer which further increase the system reliability in satisfying the load demand. A multi-objective hybrid renewable energy system optimization problem is solved using particle swarm optimization (PSO) in [114] with the objective of minimizing total cost of the system, unmet load and fuel emission.
An optimum hybrid wind/photovoltaic/fuel cell generation system is designed in [115] using a novel variation of Particle Swarm Optimization algorithm taking into account the outage probabilities of three major components i.e. wind turbine generators, photovoltaic arrays, and DC/AC converter . A case study result testifies that the components outages can extremely impact the system reliability and economy, and further observed that the inverter reliability is an upper limit for system reliability. A hybrid renewable energy system (PV/WT/battery) optimization model is developed [116] based on particle swarm optimization for a small load area in Kerman, Iran. Different variants of PSO are used to find the optimal values of design variables minimizing the life cycle cost, out of which adaptive inertia weight based PSO proves to be more promising. An optimal sizing of a wind-photovoltaic-fuel cell is done in [117] for meeting the demand of an isolated residential load. The solution is obtained by using particle swarm optimization technique while minimizing the total system cost.

Simulated annealing is used and performs the size optimization of a PV/wind hybrid energy conversion system with battery storage in [118]. Size optimization of hybrid photovoltaic-wind energy system is carried out using ant colony optimization [119] for a continuous domain based integer programming with the objective of minimizing total system design cost. Three separate system configurations such as standalone solar system, standalone wind system and hybrid system are considered for the study. A methodology based on ant colony optimization is adopted in [120] for sizing and performance analysis of a standalone hybrid wind-solar photovoltaic system. In reference [121], Biogeography Based Optimization (BBO) algorithm is successfully applied for evaluating optimal components size and operational strategy of a stand-alone wind/photovoltaic hybrid energy system located in the area of Jaipur Rajasthan (India). Results show the superiority of the proposed algorithm with other conventional optimization methods in terms of fast convergence and less computational time and concluded that the hybrid systems are more suitable than systems with only one source of energy for off grid applications. A multi objective evolutionary algorithm called as Strength Pareto Evolutionary Algorithm (SPEA) is applied for the first time in [122] for designing an isolated hybrid system subject to minimizing total cost and pollutant emissions (only from fuel consumption). The design process involves finding the optimal system configuration and control strategy, and the adopted control strategy is similar to the one used by HOMER program. Using the proposed algorithm, the authors carried out the design of PV–wind–diesel system and the achieved results demonstrate the practical utility of the design method used. In reference [123], the authors present a novel control strategy and optimal design of isolated hybrid systems with twin objectives of minimizing cost and unmet load. A multi-objective evolutionary algorithm (MOEA) called as the strength Pareto evolutionary algorithm is applied to search the optimal system configuration and Genetic algorithm is used to optimize the control strategy. The practical utility of the proposed methodology is ascertained through its application on a PV–wind–diesel system. The authors in ref. [124] apply a multi-objective evolutionary algorithm (MOEA) which search for the optimal combination of components of a complex PV–wind–diesel–hydrogen–battery hybrid system minimizing simultaneously the NPC (Net Present Cost), pollutant emissions (CO_2) and unmet load. The best control for each combination of components is achieved using Genetic algorithm (GA). The results state the practical value this method has for the designer, making it possible to select any of the solutions obtained by the proposed algorithm. Design of multi-objective hybrid renewable energy system is carried out [125] using preference-inspired co-evolutionary algorithm (PICEA) and is applied to a case study system consisting of PV panels, wind turbines, batteries and diesel generators. The algorithm is improved by proposing an enhanced fitness assignment method using goal vectors.

1.5.4.4 Artificial Neural Network based HES design

Artificial neural networks (ANNs) are massively parallel distributed processing system which is purely based on the biological neuron system. Neurons are the structural constituents of neural network which perform computations. ANNs are adaptive by nature and a training mechanism is needed to make ANN acquire knowledge.

The options for utilizing artificial neural network is explored in [126] for controlling the operation of hybrid photovoltaic/diesel system. The optimum diesel generator operation patterns with minimal fuel consumption are first estimated using dynamic programming (DP) under given solar insolation and load demand. The neural network model is trained with the optimum operation patterns resulted from dynamic programming and the same is tested under different solar insolation and load demand. The same authors carried out the similar analysis in ref. [127] considering two different artificial neural network one with four inputs and other with thirteen inputs. Results show the superior performance of the NN with larger number of inputs compared to one with less number of inputs. A new methodology is proposed in [128] for generating LOLP curves used for sizing of standalone PV system based on Multilayer Perceptron (MLP) neural network. Ten widespread Spanish locations having different climates are considered and the training of the MLP is done with real LOLP curves values obtained through simulation but only from first seven locations. Once the MLP is trained, it is capable of generating LOLP curves for any value and location.

An artificial neural network based methodology is presented in [129] for predicting the sizing parameters of photovoltaic system for any locations considering minimum number of input data. The training of the neural network is carried out by making use of 54 identified sizing parameter data for 54 Algerian regions. The validation of the proposed neural network model is performed using unknown data and the maximum prediction error is only 6% which is well with the acceptable limit for use by a design engineer. An adaptive RBF-IIR (Radial Basis Function network and Infinite Impulse Response filter) model is developed in [130] for estimating the sizing coefficient of standalone photovoltaic (SAPV) systems utilizing minimum of input data. The model uses 200 known sizing coefficients for training purpose and validation is done with unknown data set. Estimation results with 98% correlation coefficient show superior performance of the proposed model compare to classical models and other neural network architectures. Though the present model refers to Algerian locations, the methodology can be generalized for different locations in the world. An adaptive artificial neural network (ANN) combining Levenberg–Marquardt algorithm (LM) with infinite impulse response (IIR) filter for modeling and simulation of standalone photovoltaic system (SAPV) is found in [131]. The ANN model is capable of predicting each component output of the system with reasonable accuracy and system output current under different climatic conditions. Different experimental measurements from the data acquisition system of a SAPV system in south of Algeria have been utilized for simulation. Further a new sizing method capable of predicting the future optimal system configuration is presented based on predicted signals by the ANN model. A model for sizing of standalone photovoltaic system is developed in [132] based on adaptive radial basis function (RBF) using infinite impulse response (IIR) filter. The developed model allows the user to estimate the photovoltaic panel number and battery storage capacity using only minimum input data such as altitude, longitude and takes less computation time. The trained adaptive model is able to produce very accurate sizing coefficients with correlation coefficient of 97% between RBF-IIR model and the actual. A methodology based on artificial neural network (ANN) optimized with genetic algorithm (GA) [133] is developed for creating sizing curves applicable to remote areas standalone photovoltaic system in Algeria. The proposed method makes use of only geographical inputs such as Lat, Lon and Alt and the specified loss of load probability (LLP) for creating sizing curves. Further the authors develop three coefficients two new regression model and demonstrate the accurateness of the proposed regressions models compared to the available conventional regression models. An artificial neural network based photovoltaic solar integrated system is modeled in [134] and considered 27 patterns of system performance data with each pattern consisting of 7 inputs and 4 outputs for training and testing the model. The system operating conditions corresponding to maximum system efficiencies are obtained by application of complex constrained optimization method to the ANN model.

1.5.4.5 Hybrid Techniques for hybrid energy system design

Hybrid computational techniques are advance class of optimization techniques which have been successfully applied to various aspects of engineering and economics. They are robust and highly powerful techniques. They are best suited to handle complex and uncertain real world optimization problems. The hybrid techniques may comprise of a hybrid among the classical methods, between classical and artificial intelligence methods, or among artificial intelligence based methods. The hybrid techniques widely used in literature for hybrid energy system design are: DE-fuzzy [135], SA-Tabu search [136], PSO-Monte Carlo simulation [137], hybrid iterative/GA [138], multi-objective design optimization (MODO)/GA [139], adaptive neuro-fuzzy inference system (ANFIS) [140], [141], artificial neural network/GA/MCS [142], PSO/DE [143], PSO-sampling average method [144].

An integrated Power Management System (PMS) and sizing procedure of hybrid energy system consisting of wind turbines, PV panels, fuel cells, electrolysers, hydrogen tanks, batteries, and diesel generators are presented in [135]. The differential evolution algorithm (DEA) accompanied with fuzzy technique is used to simultaneously minimize the overall system cost, unmet load, and fuel emission considering the uncertainties associated with renewable energy sources (RES). Further proposed algorithm is used to calculate the optimum monthly PV tilt angles and optimum tower height for wind turbines to effectively utilize the power output from the RES. The optimal sizing problem of a small autonomous power system (SAPS) is solved in [136] using simulated annealing (SA)-Tabu search (TS) heuristic method. The minimization of cost of energy is used as the objective function and design variables include size of PV, wind turbine, diesel generator, battery, converter, fuel cell along with optimal control strategy parameters. A new methodology based on PSO-Monte Carlo simulation is adopted in [137] for determining the optimal system size of a hybrid photovoltaic-wind-battery system. The objective function is formulated as minimization of cost subject to specific reliability constraint. The optimal system configuration is sized using particle swam optimization and the uncertainties in generated wind and solar power is simulated using Monte Carlo simulation.

A hybrid iterative/genetic algorithm is used in [138] to find the optimal capacities of photovoltaic array and wind turbine for a hybrid PV/wind system that will give minimum cost. The set of possible system configuration is generated using the iterative part of the proposed algorithm and optimal solution is achieved using genetic algorithm. A multi-objective design optimization (MODO) for an autonomous hybrid PV-wind-battery is proposed in [139]. The objective is to find the best compromise between the life cycle cost, embodied energy and loss of load power supply probability. A controlled elitist genetic algorithm is adopted to solve the optimization problem. An optimal hybrid system configuration with lowest cost, lowest excess energy is achieved using Adaptive Neuro-fuzzy inference system (ANFIS) in [140] at a desired loss of load probability (LOLP). Photovoltaic (PV) and wind sources are modeled with ANFIS model using real weather data which can learn, predict and linearize the output. The developed algorithm is compared with other well known simulations tools like HOMER and HOGA (hybrid optimization by genetic algorithm and the results show a performance accuracy of 96%. The operation of a hybrid photovoltaic-diesel-fuel cell ac micro grid is controlled using neuro-fuzzy controller in [141] A probabilistic analysis based on Monte Carlo simulation and a genetic algorithm trained artificial neural network (ANN) [142] is used to analyze the installation of a typical hybrid system. An input-output dataset of 519 samples are generated using probabilistic model which is then used to train the ANNs. Root mean square error (RMSE), mean bias error (MBE), mean absolute error (MAE) and R-squared estimators are used to measure the generalization ability of ANNs using another data group of 200 samples. Analysis shows that the developed model is used to represent the main characteristics of a typical hybrid power system under various uncertain operating conditions. An optimal sizing strategy is proposed in [143] based on PSO/DE for a standalone wind-photovoltaic-hydrogen power system at south east region of Mexico. The optimization satisfies both energy reliability and cost commitment. A dynamic multi-objective particle swarm optimization along with sampling average method is used in [144] for designing a hybrid renewable energy system in the applications of buildings with low to high renewable energy ratio.

1.5.5 Reliability aspects of HES

The reliability assessment of renewable energy based hybrid energy system without or with energy storage need to be addressed differently from conventional power system since they are considered as variable capacity generation systems. The reported techniques in literature for reliability assessment can be broadly grouped under two categories: (i) analytical techniques (ii) Monte Carlo simulation. Analytical techniques model the system with mathematical equations and evaluate the desired reliability indices through direct numerical solution [145]. It fails to simulate the actual behaviors of the system which are stochastic in nature. This is overcome by Monte Carlo simulation by treating the problems as a series of real experiments and simulating the random behavior of system components [146]. Reliability evaluation of renewable energy based power system was started in 1980s. In [147], authors introduced new reliability concepts and terminology applicable to PV technology and applications. These new concepts accounts for the variability of input solar energy as well as unique characteristics of the PV array. Many researchers have made various contributions towards renewable energy sources modeling for reliability assessment [148],

[149]. Simulation based methods are adopted in [148] and [150] whereas analytical techniques are used by researchers in literatures found in [151] and [152].

Loss of power supply probability technique is used in [153] for designing stand-alone photovoltaic systems. In [154], chronological simulation technique is used for estimating the loss of load probability of stand-alone photovoltaic systems based on synthetic radiation sequences. Night time load is assumed constant and the model accounts for the distribution and persistence in daily solar radiation data. A closed-form solution approach is developed in [155] for evaluation of the loss of power supply probability of stand-alone photovoltaic systems with battery storage considering single axis tracking and non-tracking systems. A novel probabilistic model for battery storage is proposed in [156] for reliability assessment of renewable energy based autonomous PV-wind-storage system through analytical techniques. The proposed model generates multiple states of state of charge (SOC) for battery and probability associated with each state. Besides, the model takes into account the variable nature of renewable energy sources and their effect on storage systems. An analytical approach is developed in [157] for well-being assessment of small autonomous wind and solar based power systems. The models used consider generating unit outages, uncertainties associated with solar, wind resources and demand. A modeling and simulation framework based on Goal Tree, Success Tree and Master Logic Diagram (GTST-MLD) is proposed in [158] for the reliability assessment of generic geared wind turbine systems. The developed model is integrated with Monte Carlo simulation method for computing the system reliability. A sizing methodology based on cost versus reliability curves is developed in [159] for an isolated photovoltaic based micro-grids with battery storage.

A reliability evaluation of grid-connected PV (photovoltaic) systems considering intermittent faults is carried out in [160] using DBNs (dynamic Bayesian networks). The developed methodology make use of three-state Markov model for representing state transition relationship of no faults, intermittent faults, and permanent faults for PV components. Reliability assessment of multi-microgrids is discussed in [161] taking into account the optimal operation of small scale energy zones under load-generation uncertainties. The reliability evaluation is done both in interconnected and islanded mode of operation of micro-grid Universal generating function is used in [162] for reliability evaluation of a renewable energy sources based power generation system. Universal generating functions (UGFs) are used to model the wind farms and conventional generators and special operators for these UGFs are defined to evaluate the customer and system reliabilities. A system reliability assessment method based on a discrete convolution process is proposed in [163] for a wind power generation. It is used to compute a two-state probabilistic model in order to define an equivalent capacity model for global wind production. A reliability cost and worth analysis is carried out in [164] for a small autonomous renewable energy sources based power system. A time series simulation model is proposed in [165] for reliability assessment of a stand-alone wind energy conversion systems with battery backup. The reliability analysis is carried out by generating the hourly wind speed and battery state of charge time series using the time series simulation model. Results depict reliability performance of such wind energy system depends on various parameters such as battery size, battery charging rate, WTG rating, WTG force outage rate, load profile along with wind regime. An optimal renewable energy model is analyzed in [166] based on reliability criteria for India in the year 2020-2021 and found that lighting end use will be met by solar PV and biogas system.

Thus the literature reports studies on the following aspects of *HES*:

- Design configurations
- Sizing of systems
- Methodologies of Analysis of Technical performance
- Performance simulations
- Economics and reliability

However, the following gaps have been observed:

- While studies on *HES* design and performance have been reported for different developing countries, case studies for India are few and there are several such areas in Indian states that need to be examined for feasibility of *HES* implementation.
- While modeling of individual HES components, hardware status of photovoltaic panels and wind turbine force outage rate are not normally considered. Attempt should be made to develop a detail mathematical model incorporating such operational criteria.
- Artificial intelligence methods (evolutionary algorithms) are best suited for obtaining global optima. Attempts should be made to apply recently developed such evolutionary algorithm for solving the entire HES design problem.

1.5.6 Organization of thesis

Chapter 1: This chapter introduces the concept of hybrid energy system in general, hybrid energy system in Indian context and also attempts to present a critical literature review of the past works carried out in the area of hybrid energy system.

Chapter 2: This chapter clearly lays down the objectives of the current work and discusses in detail the various aspects of methodology adopted for carrying out the research work. Details of the selected case study area are also given.

Chapter 3: This chapter presents the theoretical background on the modeling of hybrid energy system components and formulation of the hybrid system design problem.

Chapter 4: This chapter highlights the application of a new meta-heuristic algorithm called as Cuckoo Search (CS) algorithm in solving hybrid energy system design problem. A comparative study on the optimization results using Cuckoo Search (CS), Genetic algorithm (GA) and Particle swarm optimization are studied and finally the optimal hybrid energy system scheme is reported.

Chapter 5: This chapter deals with the sensitivity analysis of various input parameters such as solar, wind resources, capital cost of hybrid system components, wind turbine force outage rate and photovoltaic unavailability on the economics of optimal hybrid system taken as cost of energy (COE).

Chapter 6: This chapter investigates the reliability of optimal hybrid system at various contingency conditions. The procedure for calculating loss of load expected (LOLE) reliability index through Monte Carlo simulation (MCS) is presented. Finally, the reliability assessment results are analyzed in details.

Chapter 7: This chapter provides the overall conclusions of the entire research work and scope for future works.

CHAPTER 2

Methodology of the study

2.1 Introduction

The objective of eliminating the un-electrified rural population is currently not feasible through the extension of the grid electricity since the grid extension is neither economical nor encouraged by the topographical conditions. Even though some rural communities have access to existing grid supply, such supplies are not very reliable owing to the problems of load shedding. Further, the hike in fossil fuel prices and the negative impacts of such energy sources on the consumers and on the environment are slowly alienating conventional energy solutions, for example, standalone diesel generator based power systems from the rural development agendas. Therefore, in order to fulfill the electricity demand in rural areas in a sustainable manner, the capital investments have to be approached with cost competitive, reliable and competent tools. Currently renewable energy sources are considered to be one of the most, if not the only suitable options for satisfying the electricity needs of isolated rural areas or at certain critical distances from the public grid. Considering the erratic nature of renewable energy sources, integrating such renewable energy sources to form hybrid system have proved to be one of the best option for delivering power supply to remotely located rural areas economically and reliably.

Evaluation for designing an optimal combination of a hybrid energy system (HES) for fulfilling the demand is carried out on the basis of technical reliability and economics of power supply. Prominent issues involve the determination of the optimum design and operation mode taking into account of regional conditions and load demand characteristics. Finally, it is proposed to investigate the performance of the hybrid energy system (HES) in terms of contingency analysis and scenarios making use of techniques like artificial intelligence methods in accordance with the gaps identified in reported work.

2.2 Objectives

The current work attempts to investigate the feasibility of a hybrid energy system (HES) for a remote and un-electrified village clusters in India. The main objectives of the study are:

a) Modeling of hybrid energy system (HES) components incorporating force outage rate (FOR) of wind turbine generator, physical availability and unavailability of photovoltaic (PV) panels.
b) Development of a hybrid energy system (HES) design problem and solving the formulated problem.
c) Economic performance sensitivity analysis of the optimal hybrid energy system (HES) using cost of energy (COE).
d) Reliability assessment using Monte Carlo simulation (MCS) technique.

To accomplish the above cited objectives, a remote un-electrified village cluster in Almora district of Uttarakhand state, India is chosen. The available energy resources at the village clusters, demand profile are used to synthesized the requited data for carrying out the analysis. Details of the study area are given in the following sections.

2.3 Description of study area and system components

2.3.1. Location

The study area consists of a cluster of seven un-electrified villages located in Almora District of Uttarakhand, India. The geographical location of the study area is identified with latitude of 29^{0}38’’21’N and longitude of 79^{0}29’’56’E having a height of 1576 meters from mean sea level. These seven villages are located close to each other and have a total of 267 households with a total population of 1427. The general information of these seven villages is given in table 2.1.

Table 2.1: General information of the study area

Sl. no.	Name of Village	Area (Ha)	House Hold	Population (No.)
1	Naula	56.77	21	119
2	Paparha	96.20	71	397
3	Lod Bagar	24.06	13	76
4	Kotli Gatoliya	24.38	47	273
5	Obari	16.50	14	83
6	Sangura	56.52	51	303
7	Kharkhet	54.44	32	186

2.3.2. Solar Potential

Solar radiation data for the study area has been taken from Almora district VPKAS Report [167]. The total daily solar insolation for the study area lies between 6.6 kWh/m^2/day and 3.39 kWh/m^2/day and is shown in table 2.2. HOMER simulation program [168] is used to generate synthetic hourly solar radiation from monthly average values available at the given location. The program synthesizes hourly solar radiation data based on Graham algorithm [169] and required only the latitude and monthly averages. Inclination with horizontal surface is taken equal to the latitude (29.75), ground reflectance equal to 20% and azimuth equal to 0. Solar radiation profile spanning over a year is shown in fig.2.1.

Table 2.2: Solar radiation on horizontal surface for year round application

Month	Total Daily Insolation on horizontal Surface (kWh/m2)
January	3.395
February	4.208
March	5.191
April	6.311
May	6.650
June	5.521
July	4.277
August	4.008
September	4.168
October	4.635
November	4.185
December	3.470

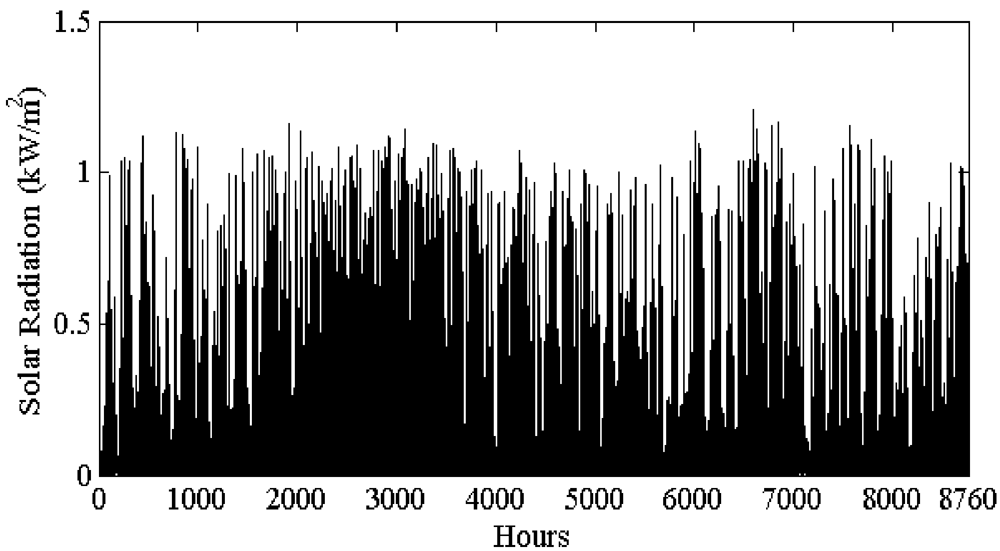

Fig. 2.1: Solar radiation profile of the study area

2.3.3 Wind Potential

The study area has wind speed in the range of 2-15 m/s. Wind speed data measured at Almora are obtained from Almora district VPKAS Report [167] for the period of Jan 2002 to Dec 2002. Table 2.3 provides the mean monthly wind speed for the study area. HOMER simulation program [168] is used to generate synthetic hourly wind speed data and plot of the hourly wind speed is shown in fig.2.2. While using HOMER, the values of parameter used are as in table 2.4.

Table 2.3: Wind speed data

Month	Mean Monthly Wind Speed (m/s)
January	5.57
February	5.69
March	6.33
April	6.58
May	6.47
June	5.32
July	3.78
August	3.22
September	4.81
October	5.54
November	5.93
December	5.96

Table 2.4: Parameters used in synthesizing hourly wind speed

Parameters	Typical value	Value used
Weibull K	1.5-2.5	**2**
Autocorrelation factor	0.80-0.95	**0.85**
Diurnal pattern strength	0.0-0.4	**0.25**
Hour of peak wind speed	14-16	**15**

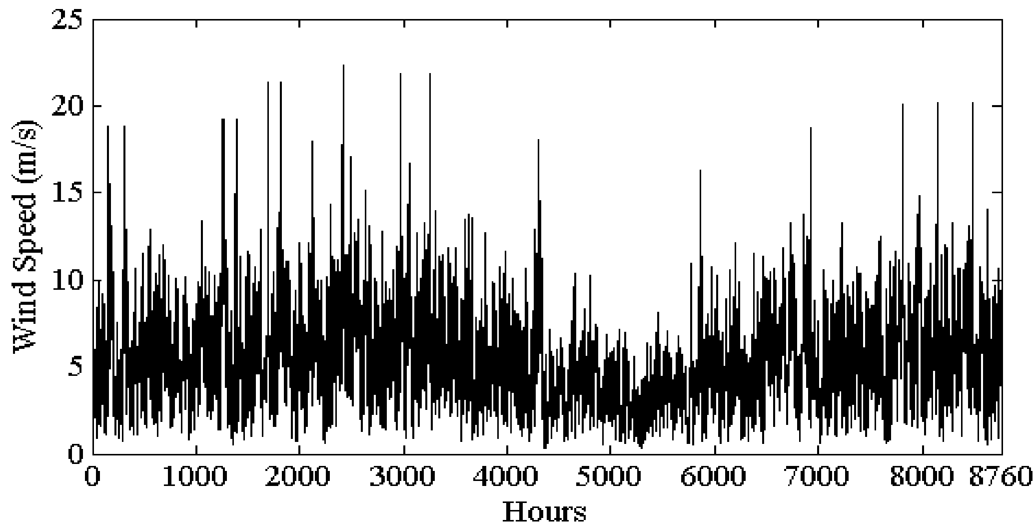

Fig. 2.2: Wind speed profile of the study area

2.3.4. Load Profile

Depending on the energy requirements and energy consumption pattern, a year is divided into four seasons. The name of the season, its duration and peak energy requirement are as given in table 2.5. Seasonal peak energy requirement is used to generate different seasonal load profiles using a typical reference load profile of similar remote area. The generated load profile has been plotted as in fig.2.3.

Table 2.5: Different seasons considered and seasonal peak energy requirement

Season	**Duration (Months)**	**Peak energy requirement (kWh/year)**
I	June to August	63.18
II	December to February	84.18
III	September to November	85.48
IV	March to May	130.13

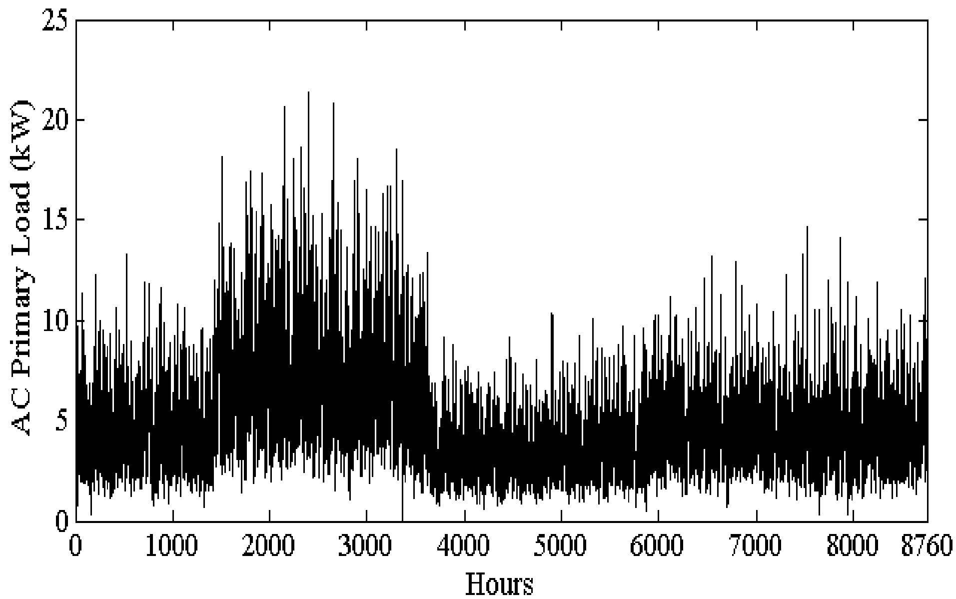

Fig. 2.3: Load profile of the study area

2.3.5. System components

PV modules selected is a 36-cell polycrystalline (PV-MF 100EC4) rated at 100Wp [170]. AMPAIR 3kW, 48V DC type wind turbine is chosen for the study. Batteries rated at 6V, 360 Ah (2.16kWh) are connected in series to form battery string with each string consisting of 8 batteries and capable of producing 17 kWh of electricity. Hence, the system DC bus voltage is fixed at 48V. The technical and economic details of the system components are given in table 2.6.

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Table 2.6: Technical and economic details of the system components.

Description	Data
PV	
Capital Cost	225000 Rs/kW
Lifetime	30 years
Operation and maintenance cost (%)	2%
Wind turbine	
Rated Power	3 kW, 48V DC
Capital Cost	80000 Rs
Lifetime	20 years
Operation and maintenance cost (%)	2%
Cut-in speed	3.5 m/s
Cut-out speed	17 m/s
Batteries	
Nominal voltage (V)	6V
Nominal capacity (Ah)	360 Ah
Nominal energy capacity of each battery	2.16 kWh
Capital Cost	10000 Rs
Lifetime	5 years
Operation and maintenance cost (%)	2%
Converter	
Capital Cost	50000 Rs/kW
Lifetime	10 years
Operation and maintenance cost (%)	2%
Annual interest rate (%)	10%

2.4 Brief outline of proposed methodology

2.4.1 Modeling of HES components

Several hybrid energy system configurations such as hybrid photovoltaic, hybrid wind and hybrid photovoltaic-wind are reported in literature. For the current study area, the candidate units considered for hybrid system component are photovoltaic (PV) panels, wind turbine generator (WTG) and battery storage. Diesel generator as the candidate component of HES is discarded because of storage constraints in the diesel fuel, environmental constraint as well as transportation problem. Various methodologies are adopted by researchers for modeling the individual component of a hybrid energy system. They are modeled either by deterministic or probabilistic methods. The current study model the photovoltaic component of hybrid energy system considering the hardware failure of photovoltaic panels. A probability distribution (PD) represents the various capacity states due to hardware failure of photovoltaic panels and corresponding probabilities. A new methodology based on the concept of random number generation is adopted to calculate the actual hourly available photovoltaic power. Wind turbine power output modeling incorporate force outage rate of the turbine. Actual wind turbine power output is calculated using the sequential up-down-up cycles of the wind turbine generator.

2.4.2. Formulation of HES design problem and finding its solutions

In order to achieve an optimal hybrid energy system scheme fulfilling the electrical needs of the case study area in most economical and reliable way, a hybrid energy system design problem is formulated. The objective function is a composite function which satisfies both economic and reliability criteria subject to various design and operational constraints. The design variables include number of wind turbine generator (WTG), number of PV arrays, number of battery unit and converter. In the current work, an attempt is made to use a new meta-heuristic algorithm called as Cuckoo Search (CS) algorithm in finding solutions to the developed design problem. The robustness and superiority of the Cuckoo Search (CS) algorithm in solving the hybrid system design problem is checked by comparing its performance with other well known optimization algorithms such genetic algorithm (GA) and particle swarm optimization (PSO) in terms of convergence speed and quality solutions.

2.4.3. Economic performance sensitivity analysis

The optimal hybrid energy system obtained for the case study area is subjected to a series of economic performance sensitivity analysis by varying a number of input parameters. The cost of energy (COE) is used as the economic index for sensitivity analysis. The influencing parameters on the cost of energy (COE) considered are wind speed, solar radiation, capital cost of the hybrid system components, load demand, wind turbine force outage rate and physical unavailability of the photovoltaic panels. Each parameter is varied over a range of values around the base case value and sensitivity analysis is carried out.

2.4.4. Reliability assessment of optimal hybrid energy system (HES)

The current work utilizes Monte Carlo simulation (MCS) technique for analyzing the reliability aspects of hybrid energy system. Monte Carlo simulation (MCS) technique estimates the loss of load expected (LOLE) reliability index at various simulated contingency conditions of reduction in renewable energy inputs such as reduction in solar radiation and wind speed, increase in energy consumption, and increase in failure rate of wind turbine and photovoltaic (PV) panels. The total hourly available generation from hybrid system is calculated based on the generation models of each system component which is then compared with the hourly load variation to calculate the reliability index.

CHAPTER 3

Hybrid System Component Modeling and Problem Formulation

3.1Introduction

A hybrid photovoltaic-wind-battery power generating system consists of a photovoltaic array, wind turbine generator, battery storage, converter and other accessory devices. In order to predict the hybrid system performance, the individual component such as photovoltaic panel, wind turbine generator, battery and converter need to be modeled first, and then their integration can be evaluated to satisfy the energy requirement.

3.2 Hybrid energy system components

A hybrid energy system (HES) integrates different energy sources to form a single system such that the weakness of some energy sources is complemented by the strengths of other energy sources. Figure 3.1 shows a hybrid energy system consisting of photovoltaic (PV), wind turbine generator (WTG) and battery storage.

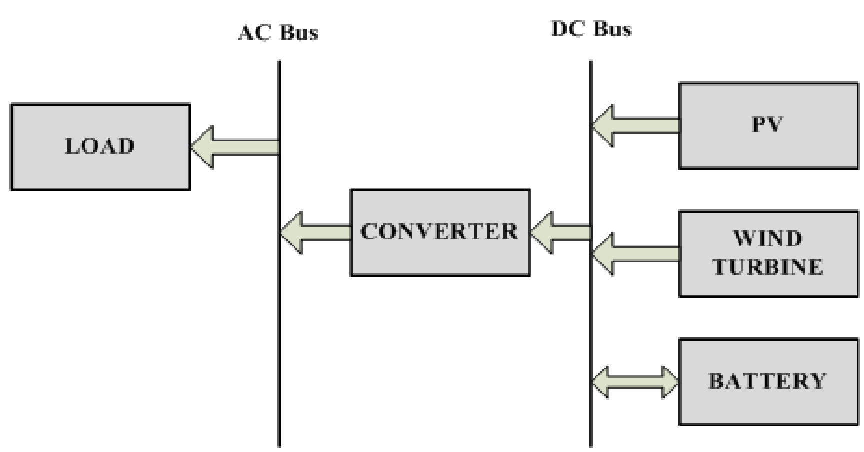


Fig.3.1 Schematic diagram of a PV-WTG-battery hybrid energy system

3.3 Modeling of PV component

3.3.1 Available solar power

The power output from a photovoltaic cell is determined by the quantity of solar radiation at a particular site. The hourly output of the PV array is calculated using the following formula.

$$P^t{}_{pv} = f_{pv} Y_{pv} \left(\frac{I_T}{I_S} \right) \tag{3.1}$$

where

f_{pv} = PV derating factor.

Y_{pv} = PV array capacity.

I_T = global solar radiation incident on the PV array.

I_S = 1 kW/m^2.

The PV derating factor is a scaling factor (typically less than or equal to 100%) applied to the PV array output to account for losses incurred due to higher ambient temperatures, different operating voltages, and soiling of the panels.

3.3.2 Capacity levels due to hardware failure of PV

Photovoltaic modules consist of packaged, connected assembly of PV cells which are often considered as the most reliable elements in PV systems. Nevertheless, the modules can also fail or degrade in their long-term lifecycle. Hardware failure of photovoltaic modules results in different capacity states of PV system. In PV system, failure of some PV strings only decreases the PV output and does not lead to failure of the whole PV system. Several PV modules fail independent of one another and hence the hardware failure events can be represented by a random variable and is assumed to follow a Binomial distribution [171]. Various capacity states due to hardware failure of the PV system and corresponding probabilities can be represented by the following probability distribution:

$$C_{pv} = \{ P_{pv}(i),\ F_{pv}(i);\ i = 0\ to\ N_{pv} \} \tag{3.2}$$

where $P_{pv}(i)$ is the capacity state when i modules are operating out of N_{pv} total modules and is given by $P_{pv}(i) = \frac{i \times p_m}{N_{pv}}$; p_m is the maximum power available from the PV modules.

The probabilities corresponding to different capacity states for a set of identical modules are given by

$$F_{pv}(i) = \binom{N_{pv}}{i}(1-Q_{pv})^i \, Q_{pv}{}^{N_{pv}-i} \tag{3.3}$$

where Q_{pv} = unavailability of PV panels.

The value of Q_{pv} is calculated based on mean time to failure $(MTTF_{pv})$ value of 1920 hours and mean time to repair $(MTTR_{pv})$ value of 80 hours as

$$Q_{pv} = \frac{MTTR_{pv}}{MTTF_{pv} + MTTR_{pv}} \tag{3.4}$$

3.3.3 Actual hourly available power

The following steps describe the procedure for calculation of actual hourly available power from PV taking into account the capacity states due to hardware failure.

1) Generate hourly output power from (3.1) using the hourly variation in solar radiation.
2) Model the PV modules operating states using Binomial distribution given in (3.3).
3) Generate a random number between [0, U]; U= upper limit on the probability of capacity state.
4) Check if random number < probabilities of residing in capacity state *i* chosen randomly from model developed in step 2.
5) If yes, calculate $P^t{}_{pv-actual} = \dfrac{P^t{}_{pv} \times P_{pv}(i)}{P(N_{pv})}$
6) Else $P^t{}_{pv-actual} = P^t{}_{pv}$

3.3.4 Illustration for calculating actual hourly available power

Let us consider a 1 kW PV array formed by series connection of 10 nos. of 100 W PV modules.

1. Generating hourly PV output power from (3.1) using the hourly variation in solar radiation.

2. Modeling of PV modules operating states using Binomial distribution given in (3.3) as in table 3.1.

Table 3.1: Hourly PV output, various capacity states with corresponding probabilities

Hours	Incident Solar Radiation kW/m2	Hourly PV Output (kW)
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0	0
7	0.023	0.02
8	0.08	0.069
9	0.095	0.082
10	0.092	0.079
11	0.117	0.1
12	0.244	0.209
13	0.086	0.073
14	0.075	0.064
15	0.188	0.161
16	0.08	0.068
…	…	…
…	…	…
…	…	…
8760	0	0

i	$F_{pv}(i)$
0	0
1	0
2	0
3	0
4	0
5	0
6	0.00042
7	0.00580
8	0.00519
9	0.27700
10	0.66480

3. Let r be the random number generated against each hour simulated. j is an index to denote randomly chosen i^{th} capacity state against each hour simulated. j value of 9 indicates random number generated at 9^{th} hour (r = 0.280387) is used to compare with probability ($F_{pv}(6)$ =*0.00042)* of residing in capacity state where 6 modules are operating out of total 10 modules to calculate the actual PV output at 9^{th} hour. At 8^{th} hour, r = 0.185146 and $F_{pv}(i)$ = 0.27700 which is the capacity state where 9 modules are operating out of total 10

modules. Here, $r < F_{pv}(9)$ and calculated actual PV output is 0.0621 kW instead of 0.069 kW as given in table 3.2.

Table.3.2 Calculation of actual hourly PV output

Hours	**Incident Solar Radiation kW/m2**	**Hourly PV Output (kW)**	***r***	**Actual hourly PV Output (kW)**
1	0	0	0.541628	0
2	0	0	0.084421	0
3	0	0	0.420392	0
4	0	0	0.175146	0
5	0	0	0.636551	0
6	0	0	0.104781	0
7	0.023	0.02	0.676325	0.02
8	0.08	0.069	0.185146	0.0621
9	0.095	0.082	0.280387	0.082
10	0.092	0.079	0.526659	0.079
11	0.117	0.1	0.435936	0.1
12	0.244	0.209	0.674501	0.209
13	0.086	0.073	0.451223	0.073
14	0.075	0.064	0.494034	0.064
15	0.188	0.161	0.435762	0.161
16	0.08	0.068	0.469379	0.068
…				
…				
…				
8760	0	0	0.298969	0

i	$F_{pv}(i)$	j
0	0	6
1	0	11
2	0	5
3	0	2, 8760
4	0	10
5	0	3, 14
6	0.00042	9
7	0.00580	1, 13
8	0.00519	4, 15
9	0.27700	8, 16
10	0.66480	7, 12

3.4 Modeling of WTG component

For calculating the wind turbine generator (WTG) power output, the measured wind speed at the anemometer height is first adjusted to the corresponding hub height using the power law profile [172].

$$\frac{V(h_{hub})}{V(h_{anem})} = \left(\frac{h_{hub}}{h_{anem}}\right)^{\alpha} \tag{3.5}$$

where h_{hub} is the wind turbine hub height (m) , h_{anem} is the height of the anemometer in meter (m), $V(h_{hub})$ is the wind speed at the hub height of the wind turbine (m/s), $V(h_{anem})$ is the wind speed at anemometer height (m/s), α is the power law exponent.

The power output is calculated by referring the power curve of the wind turbine as:

$$P^{t}_{WTG} = \begin{cases} 0 & 0 \le v \le v_{cut\ in}\ \ and\ v \ge v_{cut\ out} \\ a \times v^{3} + b \times P_{rated} & v_{cut\ in} \le v \le v_{rated} \\ P_{rated} & v_{rated} \le v \le v_{cut\ out} \end{cases} \tag{3.6}$$

The constants a and b are given by the following equations:

$$a = \frac{P_{rated}}{v^{3}_{rated} - v^{3}_{cut\ in}}$$

$$b = \frac{v_{cut\ in}}{v^{3}_{rated} - v^{3}_{cut\ in}}$$

where $v_{cut\ in}$, $v_{cut\ out}$ and v_{rated} are the cut in, cut out and rated speed of WTG respectively in m/s. P_{rated} is the rated output power of WTG unit in kW.

In addition, the effect of WTG force outage rate is incorporated in the WTG power output modeling. A WTG can reside in either of the following two states: fully available and unavailable. At the start of each hour, a uniformly distributed random number (u) on the interval [0, 1] is drawn for each WTG in order to decide its operating state, based on the following procedure:

1. If $u \le FOR$, WTG is unavailable.
2. If $u > FOR$, WTG is fully available.

Finally, the sequential up down up cycles of a WTG are then combined with the hourly available wind power derived from (3.6) to obtain the actual hourly available wind power $(P^t{}_{WTG-actual})$ output.

3.5 Modeling of Storage battery

The kW power flow through the battery is given by

$$P^t{}_{batt} = \sum P^t{}_{pv-actual} + \sum P^t{}_{WTG-actual} - Load^t / \eta_{inv} \tag{3.7}$$

where $Load^t$ is the load during t^{th} time unit, kW, η_{inv} is the inverter efficiency.

A positive value of (3.7) signifies battery charging mode and a negative value indicates the discharging mode of battery. The charging and discharging operation of the battery changes the battery state of charge (SOC) accordingly and can be calculated as

$$SOC^{t+1} = SOC^t\left[1-\frac{\sigma}{24}\right] + \frac{P^t{}_{batt} \times l(t) \times \eta_{batt}}{E_{batt}} \tag{3.8}$$

where η_{batt} is battery charging efficiency in charging operation and discharging efficiency in discharging operation, σ is the self discharge rate of battery, $l(t)$ is the length of t^{th} time unit and E_{batt} is the energy rating of battery storage.

Further, the battery charging and discharging operation is constrained by following equation.

$$P^t{}_{batt,c\max} \le P^t{}_{batt} \le P^t{}_{batt,d\max} \tag{3.9}$$

where $P^t{}_{batt,c\max} = (SOC_{\max} - SOC^t) \times E_{batt}$ is the maximum battery charge power and $P^t{}_{batt,d\max} = (SOC^t - SOC_{\min}) \times E_{batt}$ is the maximum battery discharge power.

3.6 Modeling of Converter

Systems consisting of both AC and DC components require a converter. An inverter converts DC electricity to AC electricity and the efficiency (η_{inv}) at which the conversion takes place is assumed constant and taken as 90% with a life time of 10 years.

$$P^t{}_{inv-out} = (P^t{}_{pv-actual} + P^t{}_{WTG-actual} + P^t{}_{batt}) \times \eta_{inv} \tag{3.10}$$

3.7 Optimization problem formulation

Optimal designing of hybrid energy system is necessary to make the system more cost effective, reliable and to reduce the mismatch between generation and demand. The hybrid energy system design problem is formulated as an optimization problem with the objective of minimizing total system cost (C_{Total}) subject to various design and operational constraints. For the hybrid energy system, the design variables include number of wind turbine generator (WTG), number of PV arrays, number of battery unit and converter.

$$\text{Minimize: } C_{Total} = Min \sum n_k \left\{ R_k A_k \times \frac{r_0(1+r_0)^{m_k}}{(1+r_0)^m - 1} + om \times R_k A_k \right\} + Cost_{\mathrm{Re}liability,k} \quad (3.11)$$

$$k = PV, WTG, Battery, Converter$$

$$Cost_{\mathrm{Re}liability} = C_{ENS} \times EENS$$

$$\text{Subject to: } \sum P^t{}_{pv-actual} + \sum P^t{}_{WTG-actual} + \sum P^t{}_{batt} + ENS^t = \frac{Load^t}{\eta_{inv}}$$

$$0 \le n_k \le M_k \quad (3.12)$$

$$SOC_{\min} \le SOC \le SOC_{\max}$$

where n_k represents the number of k^{th} component, R_k is the capacity of the k^{th} component, A_k is the unit cost (Rs/kWh) of the k^{th} component, r_0 is the annual interest rate, m_k is the life time of the k^{th} component, om is the percentage operation and maintenance cost, C_{ENS} is the cost for energy not supplied (Rs/kWh) and $EENS$ is the expected energy not supplied (kWh/year), $P^t{}_{pv-actual}$, $P^t{}_{WTG-actual}$, $P^t{}_{batt}$, ENS^t, $Load^t$ are the PV power, WTG power, charged/discharged battery power, energy not supplied and system load demand respectively at any period t, M_k is the maximum number of the k^{th} component, $SOC_{\min}$ and $SOC_{\max}$ are the minimum and maximum state of charge value of the storage battery.

In the calculation of $Cost_{\mathrm{Re}liability}$, Monte Carlo simulation technique (MCS) is used to evaluate the value of $EENS$ which is defined as:

$$EENS = \sum_{t=0}^{8760} E_{unserved}(t) \quad (3.13)$$

where $E_{unserved}(t)$ is the amount of energy that will not be served in the t^{th} hour of the year, and the steps for evaluating $EENS$ using MCS is given in Appendix B.

3.8 Conclusions

A detail mathematical modeling of individual components of a hybrid energy system is provided. The models incorporate the force outage rate of wind turbine generator, physical availability and unavailability of photovoltaic panels. These two parameters are an important factor for predicting the reliability performance of hybrid energy system. Moreover, a hybrid system design optimization problem is formulated with the objective of minimizing total system cost. The design variables include number of wind turbine generator (WTG), number of PV arrays, number of battery unit and converter.

CHAPTER 4

Optimization of hybrid energy system (HES)

4.1 Introduction

The rapid depletion of fossil fuel resources coupled with ill effects of conventional fuel consumption like global warming, air pollutions etc. are matters of serious concern nowadays. One way of tackling environmental problems associated with fossil fuel use along with fulfilling future energy demands is the utilization of renewable energy which offers vast economic, social and environmental benefits. In remote areas, where extension of grid supply is not feasible due to hilly terrain, a hybrid integration of renewable energy sources may prove to be key alternative solution for meeting the electrical needs. However, selecting an optimal hybrid system design fulfilling both reliability and economic criteria is a much debated issue.

Recently in the literature a new meta-heuristic algorithm called as Cuckoo Search (CS) has been applied for optimization of objectives in different studies [173],[174], [175]. It has been reported that this technique has shown results superior to other optimization algorithms like genetic algorithm, particle swarm optimization, ant colony optimization etc. [174], [175]. Hence, in the present analysis it was proposed to investigate the suitability of the Cuckoo Search (CS) algorithm for sizing the hybrid energy system (HES) design for the study area.

. The optimization problem for the Cuckoo Search (CS) is formulated provided in section 3.7 for finding the optimal system size that satisfies the demand reliably and has lowest total system cost considering seasonal variation in load profile with measured solar and wind energy resources, cost of the components and cost of operation and maintenance. While modeling system components outages due to hardware failure of photovoltaic panel and wind turbine generator force outage rate are considered taking into account the variable behavior of solar and wind resources. The developed methodology is tested for finding the optimal system size of three different system schemes viz. photovoltaic-battery, wind-battery and photovoltaic-wind-battery applicable to a remote case study area in India. The various system schemes are depicted as in fig.4.1, 4.2, and 4.3.

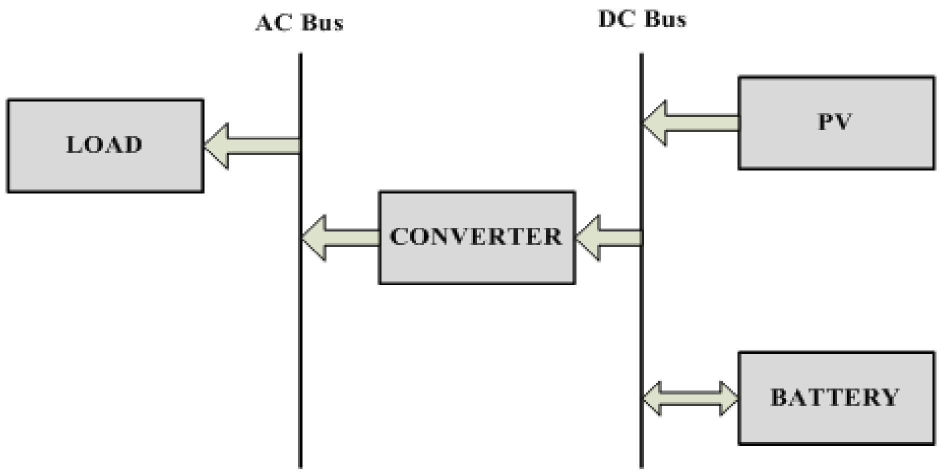


Fig. 4.1 Configuration of a standalone PV-battery system

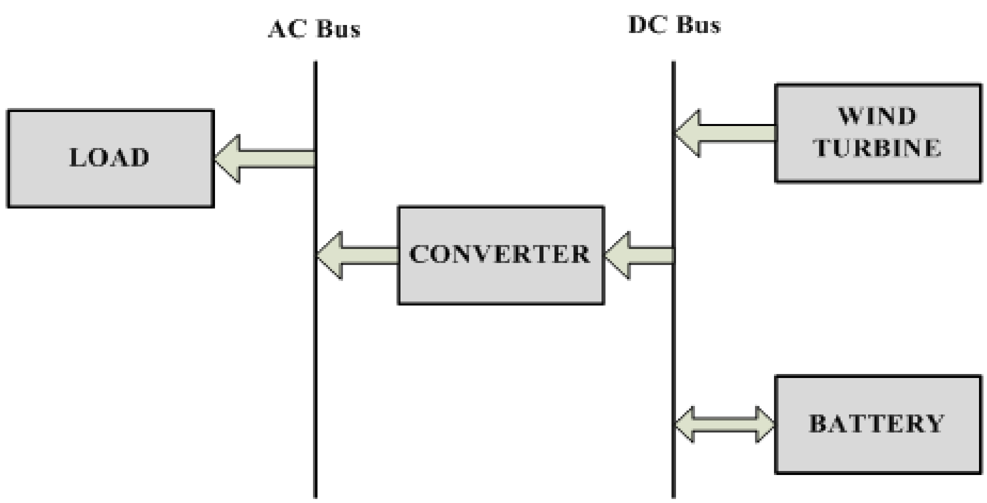


Fig. 4.2 Configuration of a standalone WTG-battery system

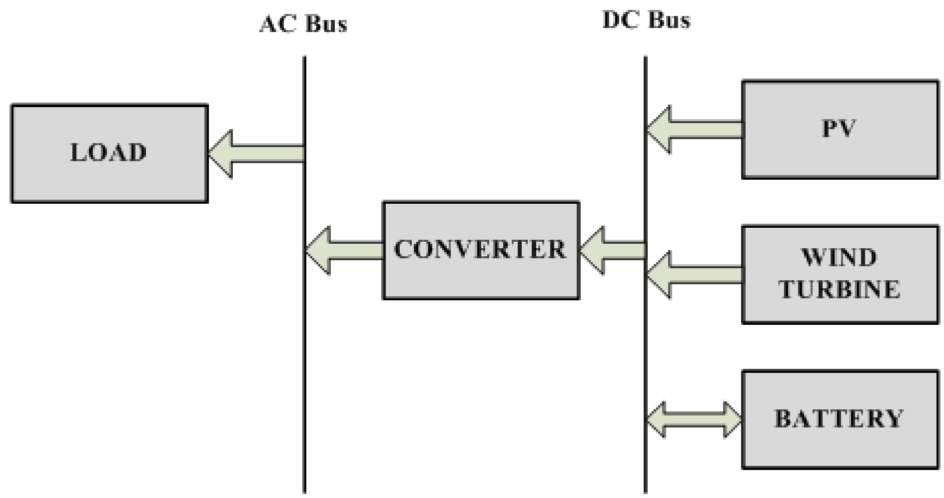


Fig. 4.3 Configuration of a standalone PV-WTG-battery system

4.2 Overview of Cuckoo Search algorithm

Cuckoo Search (CS) is a new meta-heuristic optimization algorithm developed by Yang and Deb [173]. It is developed based on the interesting breeding behavior such as brood parasitism of some species of cuckoos and the characteristics of Levy flights. It is a population based search algorithm and contains a population of nests or eggs. Female cuckoos lay eggs that mimic the eggs of their host nest in color and pattern. As an idealized rule each cuckoo lays one egg at a time and dumps it in a randomly chosen nest.

The best nests with high quality of eggs (solutions) will carry over to the next generations, and the number of available host nests is fixed. On the other hand, some host birds can engage direct conflict with the intruding cuckoos and they discovered the alien eggs with a probability of $P_a \in [0,1]$ .Once the eggs are discovered, they are either thrown away or the nest is abandoned and a completely new nest is built in a new location by host birds The pseudo code of the Cuckoo Search can be summarized as follows:

Begin

Objective function $f(x)$, $x = (x_1,.....,x_d)^T$, d *is the number of variables*

Generate initial population of n *host nests* x_j, $j = 1, 2, , n$

While (t <MaxGeneration) or (stop criterion)

Get a cuckoo randomly by L´evy flights

Evaluate its quality/fitness F_j

Choose a nest among n *(say,* k *) randomly*

If $(F_j > F_k)$,

Replace k *by the new solution;*

End

A fraction (P_a) *of worse nests is abandoned and new ones are built;*

Keep the best solutions

Rank the solutions and find the current best

End while

Post process results and visualization

End

Starting with a randomly distributed initial population of host nest, cuckoo birds undergo repeated search process to lay an egg. The random host nest position for laying egg is decided by performing Levy flights and is given as

$$x_i^{(t+1)} = x_i^t + s \oplus Levy(\lambda) \quad (4.1)$$

where t is the current generation number and $s > 0$ is the step size, which should be related to the scale of the problem of interest. The product $\oplus$ means entry-wise multiplication. Basically, random steps in Levy flight are drawn from a Levy distribution for large steps as

$$Levy \sim u = t^{-\lambda}, \ (-1 < \lambda \leq 3) \quad (4.2)$$

This has an infinite variance with an infinite mean. In the real world, if a cuckoo's egg is very similar to a host's egg, then this cuckoo's egg is less likely to be discovered, thus the fitness should be related to the difference in solutions. Therefore, it is wise to do a random walk in a biased way with some random step sizes.

4.3 Comparison of CS with GA and PSO

The developed methodology based on Cuckoo Search is implemented in MATLAB programming environment and applied to a hybrid system design problem applicable to a remote case study area. To assess the effectiveness of Cuckoo Search in solving hybrid system design problem, the optimization of three different system schemes viz. PV-battery, WTG-battery and PV-WTG-battery has been carried out and its performance is compared with other optimization algorithms like GA and PSO. While performance comparison is made, the stopping criteria and initial population in each of the case using CS, GA and PSO are kept the same. Wind turbine generator force outage rate (FOR) of 0.05 is considered during optimization. Crossover operation in GA occurs at a rate that ranges from 0.6 to 1.0 whereas a small mutation rate less than 0.1 is usually used [176], [177]. Acceleration constants in PSO are selected such that $C_2 > C_1$ which is beneficial for complex nonlinear integral problem [178]. Taking into account the above cited criteria and after a number of hit and trial operation, mutation probability $(P_m) = 0.07$ and crossover probability $(P_c) = 0.83$ are taken for GA and mutation under PSO is carried out with acceleration constants $C_1 = 1.8, C_2 = 2.2$ Inertial weight factor (W) is initially set at 1 and decreases as the algorithm progress till a 0 value is reached at the end of the run. In case of CS, discovery rate of alien eggs/solutions $(P_a) = 0.25$ is chosen for the study as the studies carried out in [173], [174] have concluded that $(P_a) = 0.25$ is sufficient for most optimization problems and this value of (P_a) do not have to fine tune for a specific problem. Values of various control parameters of algorithms used in the study are given as in table 4.1.

Table 4.1: Values of control parameters used in the optimization

Sl.no.	**Optimization technique**	**Population size**	**Control Parameters**
1	GA	20	P_m =0.07, P_c =0.83
2	PSO	20	C_1=1.8, C_1=2.2
3	CS	20	P_a = 0.25

The convergence characteristics of CS, GA and PSO for each of the PV-battery, WTG-battery and PV-WTG-battery system are shown respectively in fig.4.4, fig.4.5 and fig.4.6. Abscissa of the convergence plot is taken as number of C_{Total} evaluation to provide a platform for comparison of the considered optimization algorithms. For the current study, computational time required is almost equal to the number of C_{Total} evaluation since the calculation of C_{Total} takes almost all the computational time. Hence, faster converging algorithm will result in reduce computational burden. The convergence characteristics depict that the objective function converges to final optimum value more or less after 100 numbers of generations. Hence, 150 numbers of generations is taken as a fair stopping criterion.

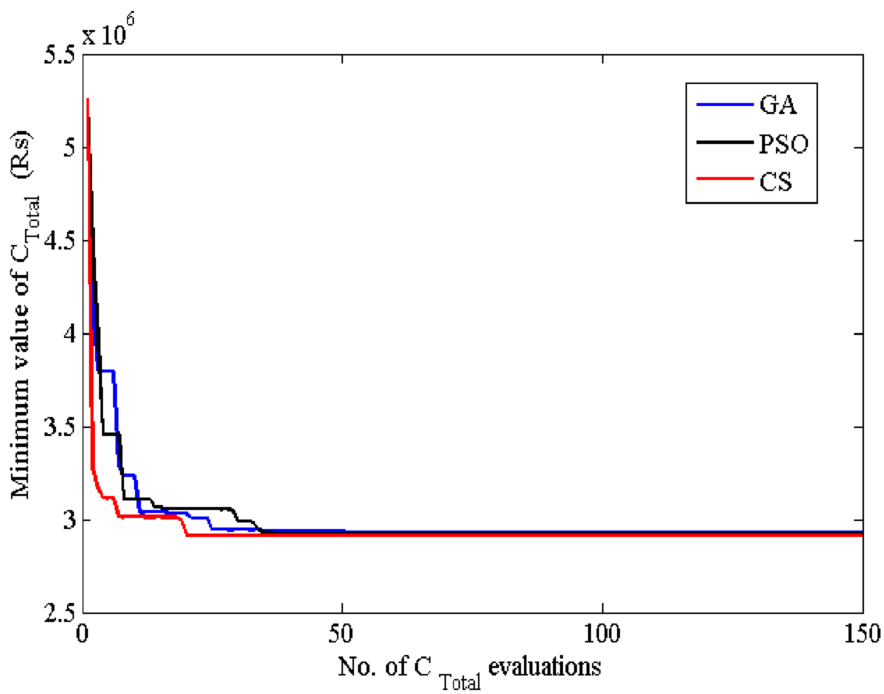


Fig.4.4 Convergence characteristics of the CS, GA and PSO algorithm for PV-battery system

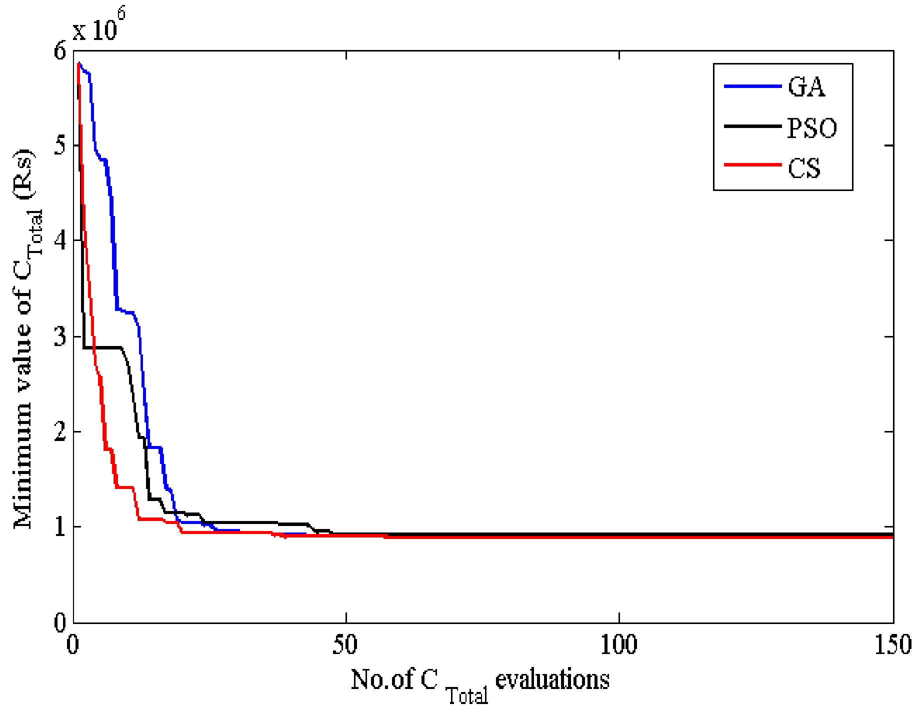


Fig.4.5 Convergence characteristics of the CS, GA and PSO algorithm for WTG-battery system

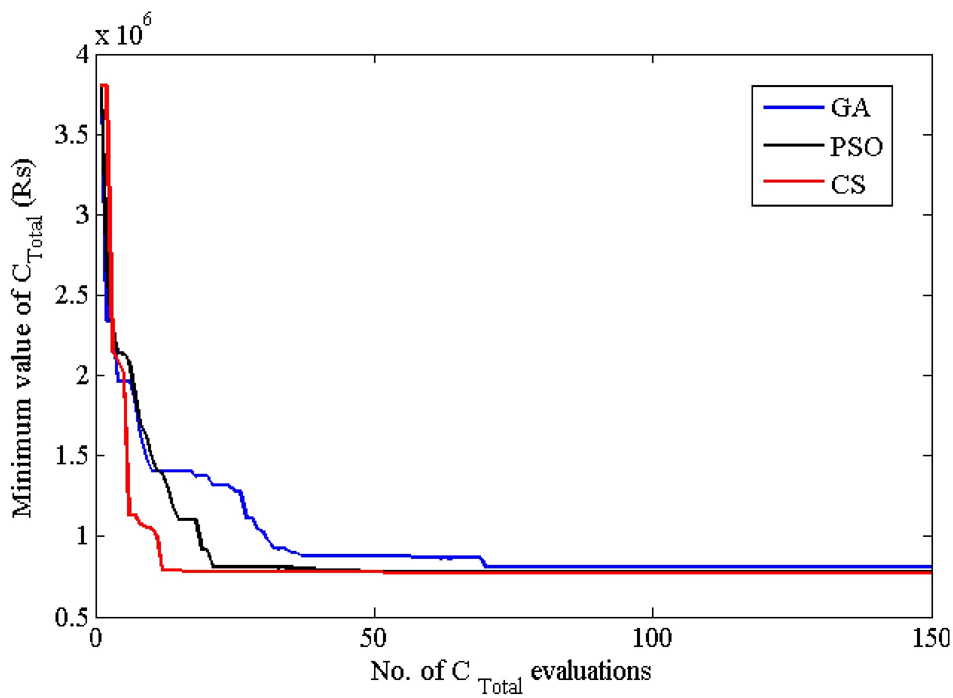


Fig.4.6 Convergence characteristics of the CS, GA and PSO algorithm for PV-WTG-battery system

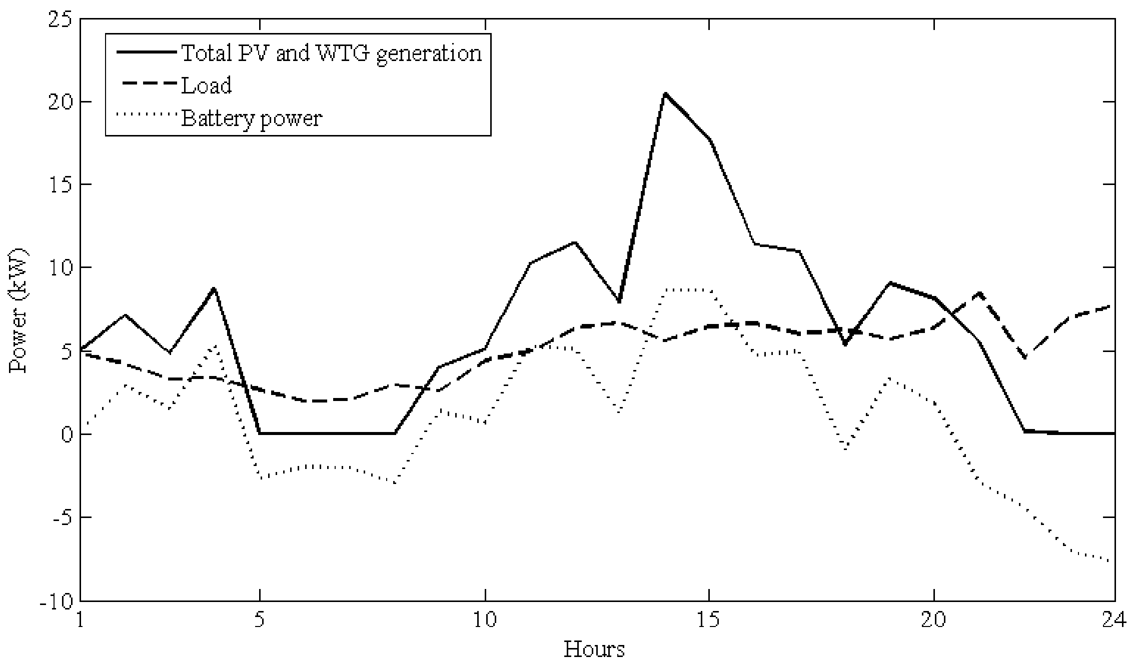
Careful examination of convergence characteristics of CS, GA and PSO reveal that CS is quite faster in optimization which reduces the computation burden and leads to minimal computer resource utilization. The optimal solutions using different optimization algorithms are shown in table 4.2.

Table 4.2: Optimization results using different optimization algorithms

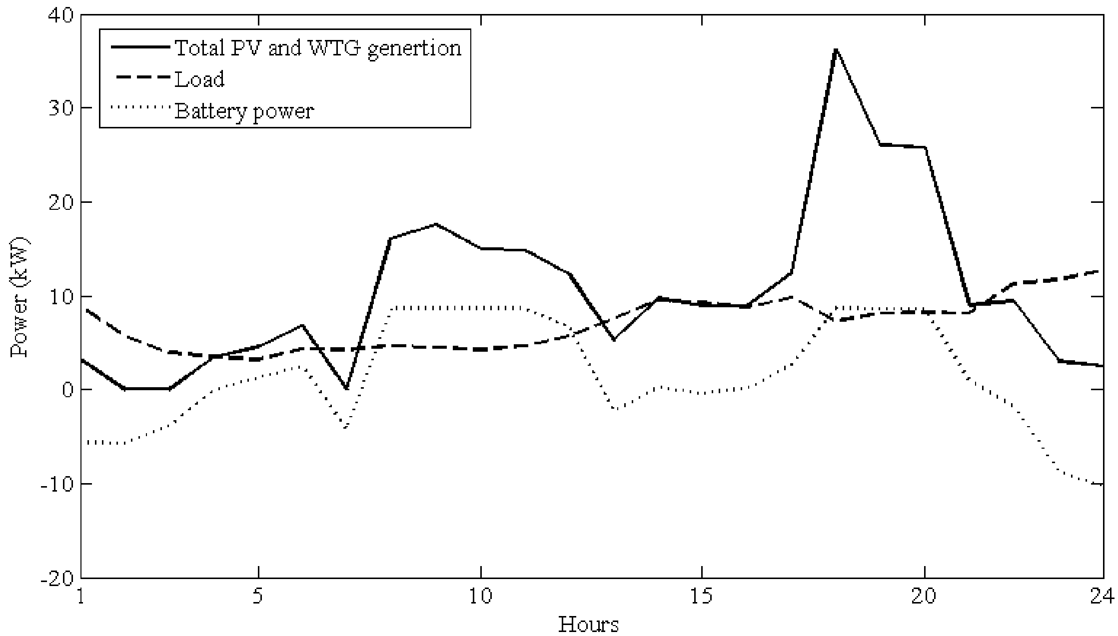
System Scheme	Optimization Algorithm	No. of 1 kW PV	No. of 3kW WTG	No. of battery string each of 17 kWh	Converter (kW)	Computation Time (s)	Optimized Cost (Rs.)	Cost of energy (Rs/kWh)
PV-battery	GA	45	0	64	21	1371	2921661	69.85
	PSO	45	0	63	21	1316	2921016	69.83
	CS	44	0	64	21	1031	2912505	69.62
WTG-battery	GA	0	23	20	21	1208	897451	21.45
	PSO	0	23	21	21	1150	920091	21.99
	CS	0	24	19	21	935	885803	21.18
PV-WTG-battery	GA	8	20	8	20	1807	810460	19.37
	PSO	6	25	6	21	1756	772575	18.46
	CS	3	25	10	20	1442	768950	18.38

It is clear from table 4.2 that CS results in least cost solution as compare to results obtained using GA and PSO in each of the system scheme considered, although GA and PSO are able to find the optimal design parameters. In CS, the generation of new explorative moves in terms of Levy flights helps to sample the search space more effectively, and generated new solutions are diverse enough as the step of the move is larger. Further, too much large move is avoided by elitism so that the exploitation moves are within the neighborhood of the best solutions locally. Compare to either uniform distributions or Gaussian as utilized by most meta-heuristic algorithms to generate new explorative moves, Levy flights are usually more efficient if the search space is large. As the number of parameters to be fine-tuned in CS is less compared to GA and PSO algorithms, it is more potential and generic one to adapt to wider class of optimization problems. Therefore, the developed CS based optimization methodology can effectively be utilized for finding the optimal solution of complex HES design problem.

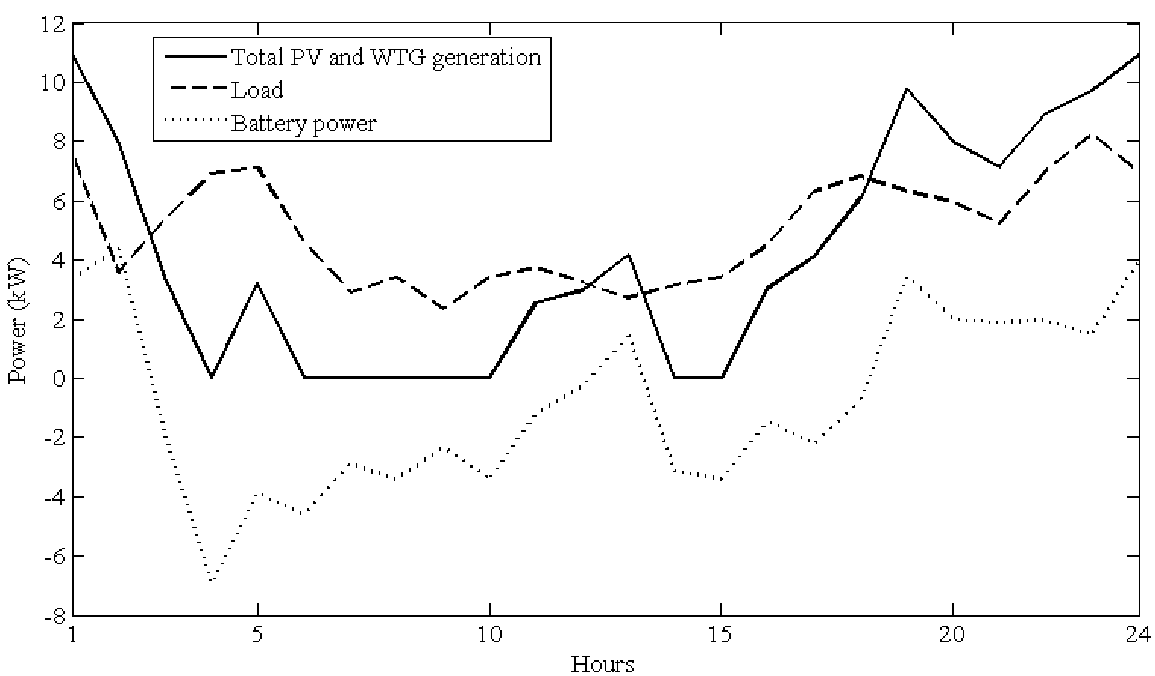
Furthermore, out of the three system scheme optimized by CS taking into account all the inputs of size and cost of components, most reliable and economical system scheme for the study area is that of hybrid PV-WTG-battery system with an optimized system cost of Rs. 7.69 lakhs and cost of energy of 18.38 Rs/kWh. Such PV-WTG-battery system consists of 3kW PV, 25 numbers of 3kW WTG, 20 kW converters along with battery bank comprising of 10 numbers of strings each of 17 kWh capacities in which PV contributes 11%, WTG contributes 36%, battery contributes 29% and converter about 24% of the total annual cost of Rs. 768950. The hybrid integration of PV and WTG in the system drastically reduces the battery storage requirement as compared to the standalone system schemes of PV-battery and WTG-battery. The profiles of the optimal hybrid PV-WTG-battery system power generation and the load demand for any random day in each of the season considered are shown in fig.4.7.(a-d). In each of these days, the battery power is in a variable state of discharging or charging which depends upon the rate of battery charging throughout the day due to fluctuating magnitude of PV and WTG generation and corresponding load demand.



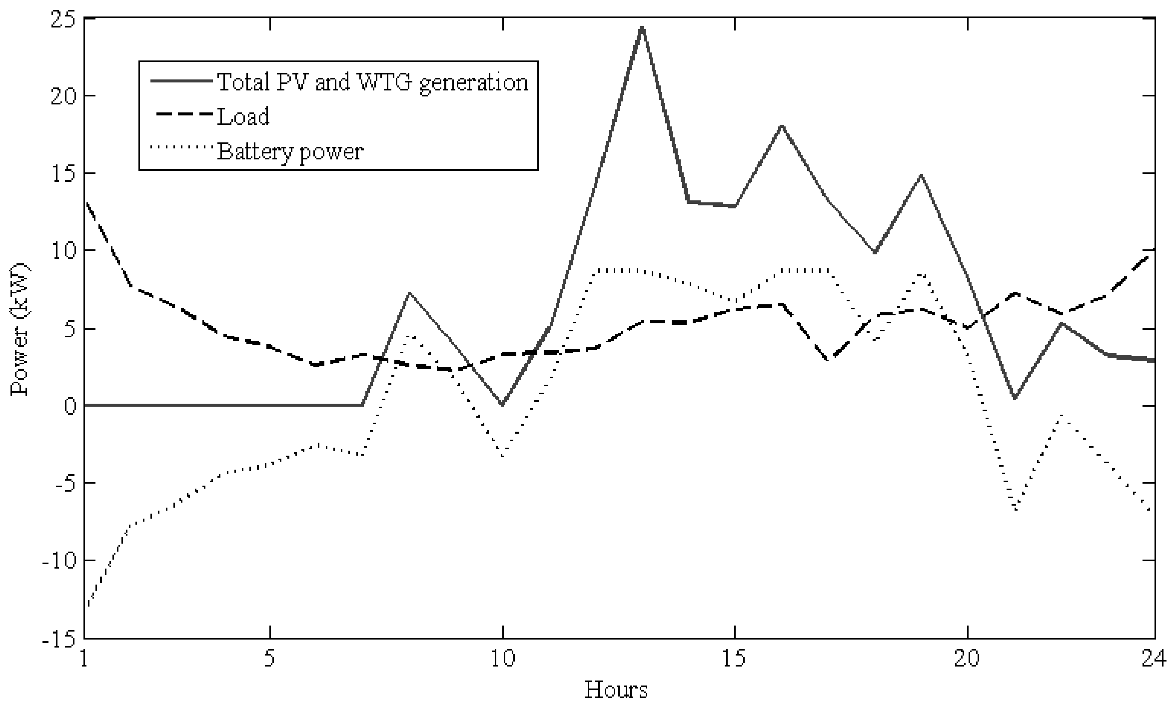
(a) Season I



(b) Season II



(c) Season III



(d) Season IV

Fig.4.7: Profiles of the optimal hybrid PV-WTG-battery system power generation and load profile

4.4 Conclusions

In this chapter, a maiden attempt has been made to apply a new meta-heuristic algorithm called as Cuckoo Search algorithm for solving HES design problem. The developed methodology is tested in the HES design problem of a remote case study area in India and results have been compared with those obtained from GA and PSO. Results reveal that CS in combination with Levy flights outperforms GA and PSO in terms of better quality solutions and faster convergence in each of the system scheme considered. A hybrid system comprising of 3 kW PV, 25 numbers of 3kW wind turbine with 10 numbers of battery string each of 17 kWh capacity along with 20 kW converter results in the most reliable and economical solution for the considered case study area. The developed model takes into account the outages due to hardware failure of photovoltaic modules, force outage rate of wind turbine unit as well as the intermittent characteristics of the solar and wind resources.

CHAPTER 5

Economic Performance Sensitivity Analysis

5.1 Introduction

A sensitivity analysis is carried out to access the degree of sensitivity of each input variable such as wind speed, solar radiation, capital cost, load demand, wind turbine generator force outage rate and photovoltaic unavailability on the economics of the optimal system taken as cost of energy (COE) in the present case. This will help the energy planner to give preference in the design of hybrid energy system (HES) to those input variables that exercise greater control on the output. Input parameters viz. wind speed, solar radiation and capital cost are varied over a range of values up to $\pm 30\%$ around the base case value. An increase in 10%, 20% and 30% of annual peak load is considered while wind turbine generator FOR values of 0.05, 0.075, 0.1, 0.125, 0.15 and photovoltaic unavailability (Q_{pv}) values 0.04, 0.06, 0.08, 0.1, 0.12 are considered for the analysis. The performance variables used for evaluation are the annual average wind speed, annual average solar radiation, annual peak load, capital cost of PV panels, wind turbine generator, storage battery and converter; wind turbine generator FOR and photovoltaic unavailability (Q_{pv}). The cost of energy (COE) is calculated based on the following formula.

Cost of Energy (COE)

$$COE = \frac{\left\{ R_k A_k \times \frac{r_0 (1+r_0)^{m_k}}{(1+r_0)^m - 1} + om \times R_k A_k \right\} + Cost_{\mathrm{Re}liability,k}}{Annual\ Energy\ served\ (kWh / yr)} \tag{5.1}$$

where R_k is the capacity of the k^{th} component, A_k is the unit cost (Rs/kWh) of the k^{th} component, r_0 is the annual interest rate, m_k is the life time of the component k^{th}, om is the percentage operation and maintenance cost, calculation of $Cost_{reliabilty}$ is given in section 3.7.

5.1.1 Annual Average Wind speed

The power output of wind turbine is a cubic function of wind speed, small deviation in the average wind speed will result in large changes in power generation and, hence the COE. The hybrid PV-Wind-battery system is optimized at variation in annual average wind speed over a range of values upto $\pm 30\%$ using CS algorithm. The optimization results are given as in Table 5.1. Fig. 5.1 depicts the sensitivity analysis of annual average wind speed on COE. The study reveals that COE decreases as the annual average wind speed increases showing an inverse relationship. The cost of energy varies from 31 % to -38.76 %, when the annual average wind speed is increased from 3.80 m/s to 7.06 m/s over a variation of $\pm 30\%$. The COE is very sensitive to changes in annual average wind speed.

Table 5.1: Optimization results with variation in annual average wind speed of up to $\pm 30\%$

Annual Average Wind speed	No. of 1 kW PV	No. of 3kW WTG	No. of Battery string each of 17 kWh	Converter (kW)	Optimized Cost (Rs.)	Cost of Energy (Rs./kWh)
(+) 10%	1	25	4	20	576410	13.78
(+) 20%	1	21	3	20	516720	12.35
(+) 30%	1	17	3	20	470849	11.25
(-) 10%	7	25	8	20	837433	20.02
(-) 20%	7	25	12	20	927630	22.17
(-) 30%	13	25	8	20	1007170	24.07

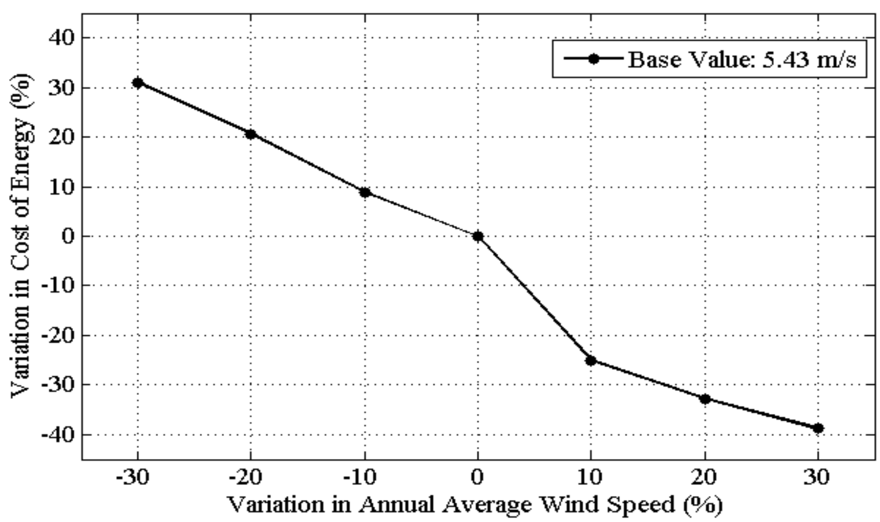


Fig.5.1: Sensitivity analysis of COE with variation in annual average wind speed.

5.1.2 Annual Average Solar radiation

The hybrid PV-Wind-battery system is optimized taking annual average solar radiation variation of $\pm 10\%$, $\pm 20\%$ and $\pm 30\%$ around a base value using CS algorithm to study the impact of variation on COE for the hybrid system. The optimal solutions for the considered variation in annual average solar radiation are given in table 5.2. Sensitivity analysis of annual average solar radiation on COE is depicted in fig.5.2. The COE varies from 6.59 % to -6.85 %, when the annual average solar radiation is increased from 3.27 kWh/m^2 to 6.07 kWh/m^2 over a variation of $\pm 30\%$. The COE is relatively less sensitive to changes in annual average solar radiation compared with the annual average wind speed. However, an inverse relationship is observed.

Table 5.2: Optimization results with variation in annual average solar radiation of up to $\pm 30\%$

Annual Average Solar radiation	**No. of 1 kW PV**	**No. of 3kW WTG**	**No. of Battery string each of 17 kWh**	**Converter (kW)**	**Optimized Cost (Rs.)**	**Cost of Energy (Rs./kWh)**
(+) 10%	5	25	6	20	739342	17.68
(+) 20%	6	25	4	20	731900	17.50
(+) 30%	5	25	5	20	716157	17.12
(-) 10%	4	25	9	20	776707	18.57
(-) 20%	1	26	13	20	791162	18.91
(-) 30%	2	26	13	20	819512	19.59

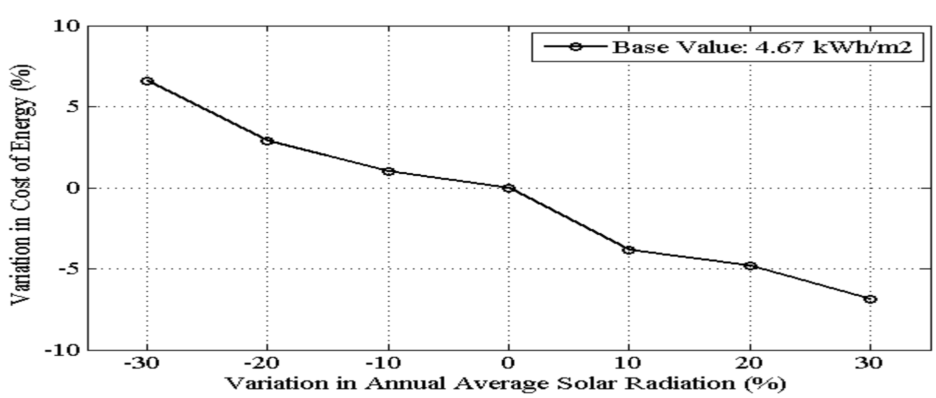


Fig.5.2: Sensitivity analysis of COE with variation in annual average solar radiation

5.1.3 Capital cost

The capital cost depends on site, size and technology of the system components. Fig. 5.3 shows the sensitivity study of COE with variation in capital cost of photovoltaic panels, wind turbine generator (WTG), storage battery and converter for the optimal hybrid energy system. A positive relationship is observed. The sensitivity results show that COE increases as the capital of each system component viz. photovoltaic panels, WTG, storage battery and converter increases. A 30% increase in capital cost of photovoltaic panels, WTG, storage battery and converter increase the COE respectively by 3.34%, 10.74%, 8.85% and 7.15%.On the other hand, a 30% decrease in capital cost of photovoltaic panels, WTG, storage battery and converter decrease the COE by 3.30%, 10.71%, 8.82% and 7.11% respectively. All the variations observed show a linear relationship. Hence, the capital cost of WTG has the greatest impact on the COE followed by capital cost of storage battery and converter while capital cost of photovoltaic panels has least impact on the COE.

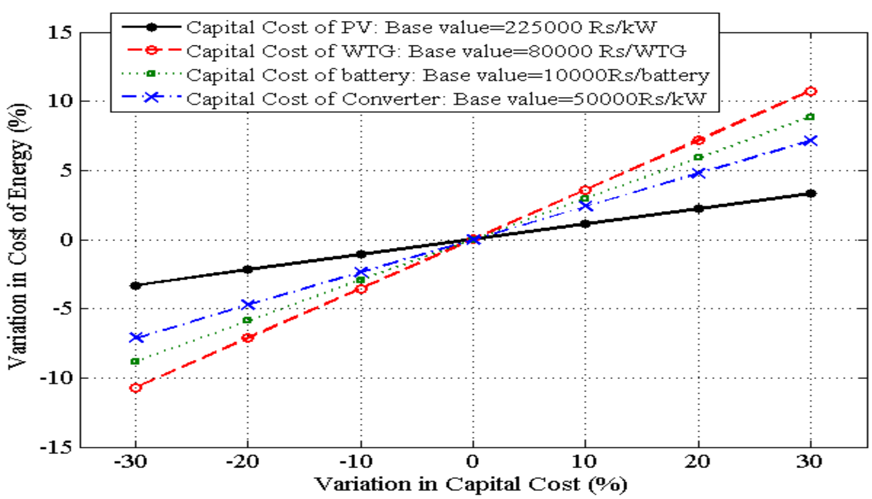


Fig. 5.3: Sensitivity analysis of COE with variation in capital cost.

5.1.4 Annual peak load

An increase in load demand is simulated by taking 10%, 20% and 30% increase in nominal annual peak demand of 21.40 kW. The hybrid PV-WTG-battery system is optimized at these changed conditions of load demand. The optimization results obtained is shown as in table 5.4. When the annual peak load is changed from 10% to 30%, the cost of energy (COE) increases from 16.7% to 52.7% and variation shows a linear relationship as in fig.5.4.

Table 5.4: Optimization results with variation in annual peak load

Peak Load	No. of 1 kW PV	No. of 3kW WTG	No. of Battery string each of 17 kWh	Converter (kW)	Optimized Cost (Rs.)	Cost of Energy (Rs./kWh)
(+) 10%	9	25	8	20	897308	21.45
(+) 20%	9	25	14	20	1030290	24.63
(+) 30%	14	25	14	20	1174719	28.08

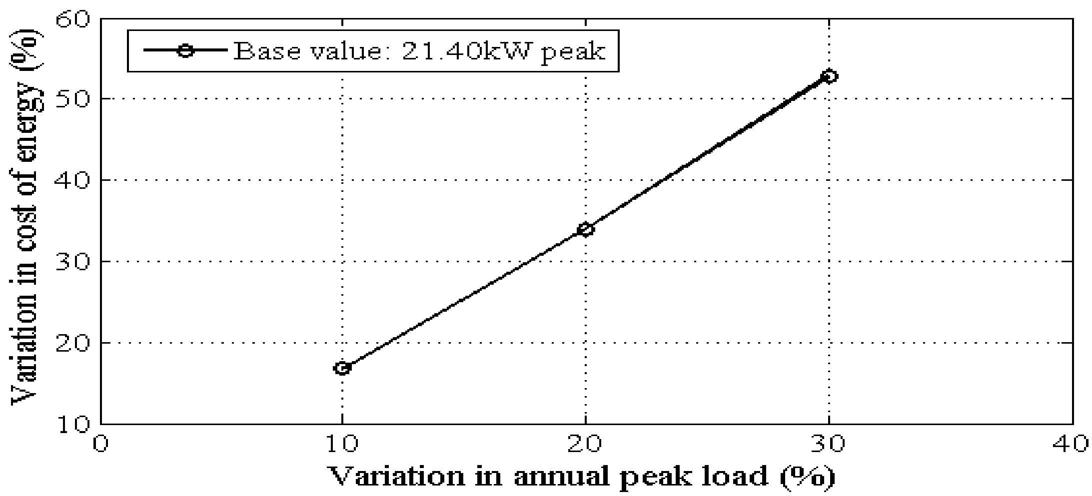


Fig. 5.4: Sensitivity analysis of COE with variation in annual peak load

5.1.5 Wind turbine force outage rate (FOR)

To study the impact of WTG force outage rate on the cost of energy of the hybrid PV-WTG-battery system, wind turbine FOR value is varied from 0.05 to 0.15 with a fixed step size of 0.025 and variation in cost of energy (COE) is observed by optimizing the hybrid PV-WTG-battery system at these values of FOR. The optimization results are shown in table 5.5 and plot of the sensitivity of cost of energy with variation in wind turbine FOR is given in fig.5.5. Sensitivity results show that cost of energy increase with increase in value of wind turbine force outage rate (FOR). The cost of energy increase by 4% from the value of 18.38 Rs/kWh at FOR = 0.075 and it increases up to 14.69% at FOR = 0.15.

Table 5.5: Optimization results with variation in wind turbine force outage rate (FOR)

Wind Turbine FOR	No. of 1 kW PV	No. of 3kW WTG	No. of Battery string each of 17 kWh	Converter (kW)	Optimized Cost (Rs.)	Cost of Energy (Rs./kWh)
0.05	3	25	10	20	768950	18.38
0.075	4	25	10	20	797300	19.06
0.1	4	27	10	20	819284	19.58
0.125	4	26	11	20	853572	20.41
0.15	5	26	12	20	881922	21.08

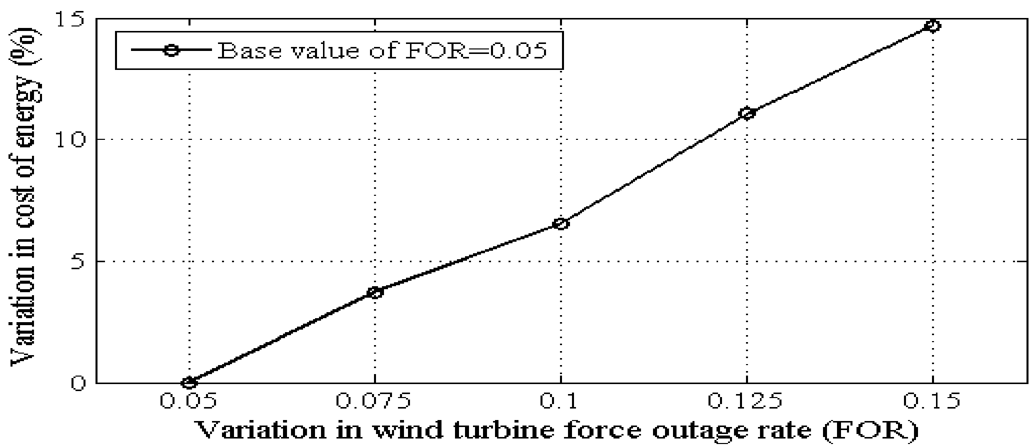


Fig 5.5: Sensitivity analysis of COE with variation in wind turbine force outage rate

5.1.6 Photovoltaic unavailability

The sensitivity analysis is carried out at different values of photovoltaic unavailability Q_{pv} for hybrid PV-WTG-battery system. A range of Q_{pv} values are taken from 0.04 to 0.12 and variation in cost of energy is observed by optimizing the system at these values of Q_{pv}. The optimization results and sensitivity results plot at different values of Q_{pv} are given respectively in table 5.6 and fig. 5.6. Cost of energy increase with increase in the value of Q_{pv}. However, the increase in cost of energy is only 0.7% for Q_{pv} values from 0.04 to 0.8, but cost of energy increases rapidly from $Q_{pv} = 0.8$ onwards and reaches 7% at $Q_{pv} = 0.12$.

Table 5.6: Optimization results with variation in photovoltaic unavailability

Photovoltaic unavailability (Q_{pv})	No. of 1 kW PV	No. of 3kW WTG	No. of Battery string each of 17 kWh	Converter (kW)	Optimized Cost (Rs.)	Cost of Energy (Rs./kWh)
0.04	3	25	10	20	768950	18.38
0.06	7	25	5	20	771297	18.43
0.08	4	25	9	20	774660	18.51
0.1	4	25	10	20	797300	19.06
0.12	5	25	10	20	825650	19.73

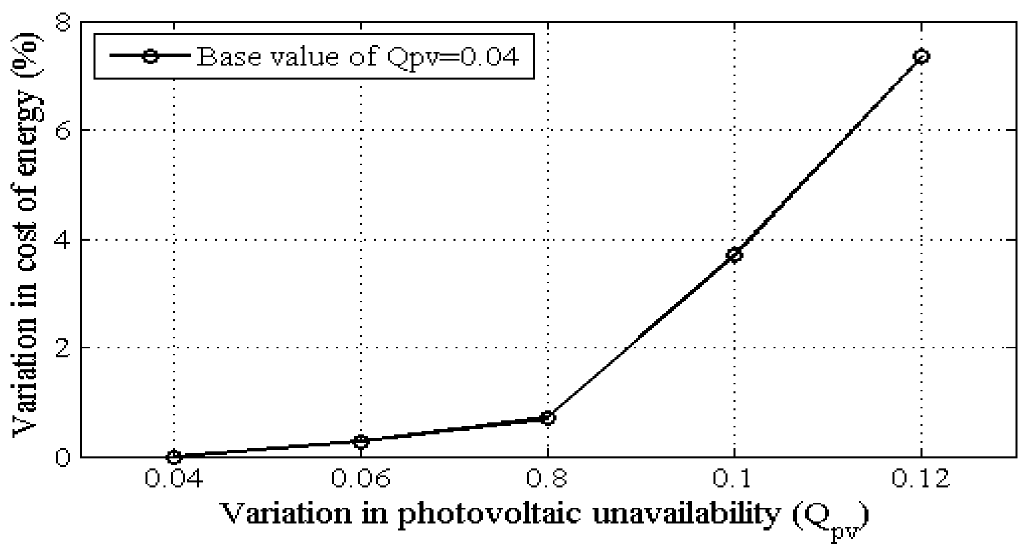


Fig 5.6: Sensitivity analysis of COE with variation in photovoltaic unavailability

5.2 Conclusions

Sensitivity results show that variation in annual average wind speed from 3.08 m/s to 7.06 m/s varies the COE from 31% to -38.76%. However, the variation in annual average solar radiation has relatively less significant impact on the COE. The COE changes from 6.59% to -6.85% when the annual average solar radiation is changed from 3.27 kWh/m^2 to 6.07 kWh/m^2. Variation in capital cost of photovoltaic panels, WTG, storage battery and converter for the optimal hybrid energy system show a positive relationship with the COE. The COE is highly sensitive to the variation in capital cost of wind turbine generator followed by capital cost of battery and converter while cost of photovoltaic panels has least impact. A 30% increase in annual peak load increases the COE by 52.7%. An increase in the value of wind turbine generator force outage rate (FOR) from 0.05 to 0.15, increase the COE by 14.69% while the variation in photovoltaic unavailability (Q_{pv}) from 0.04 to 0.12 increases the COE by 7%.

CHAPTER 6

Reliability Assessment using Monte Carlo Simulation

6.1 Introduction

The utilization of hybrid solar photovoltaic-wind-battery system has significantly reduce the dependence on fossil fuels, need for fuel storage as well as emission of various green house gases. Taking into consideration the various benefits offered by the hybrid renewable based generating units, the use of such system is encouraged all over the word. Nowadays, renewable energy based hybrid generating systems are widely used to satisfy the electrical requirement of remote locations and the islands where the extension of electrical grid utility is impossible due to difficult accessibility and high terrain [179], [180].

Despite the adoption of hybrid energy system, the outage of system components will provide a chance of loss of load in the system and hence the system reliability has to be considered while assessing the hybrid system performance. However, the reliability assessment of renewable energy based hybrid system cannot be covered under well developed reliability evaluation methods applied to conventional generating units because renewable energy sources do not have fixed capacity outputs. Hence, the reliability assessment of a renewable energy based generating systems need to be addressed differently.

In view of this, the current chapter attempts at assessing the reliability of a techno-economical hybrid renewable energy system suitable for a remote location. The reliability assessment through calculation of loss of load expected (LOLE) reliability index is made at various contingency conditions such as reduction in renewable energy inputs, increase in energy consumption and failure of WTG and PV components. The power generation models for each system component considering the outage rate of WTG and hardware status of PV are used to obtain the total available generation for each hour which is then combined with hourly load variation to evaluate the reliability index.

6.2 Reliability Assessment method

System reliability analysis is mainly carried out using two main approaches which are the analytical techniques and computed aided simulation methods. Analytical methods use mathematical models to represent the system and evaluate the reliability indices using direct solutions while simulation methods estimate the reliability indices by simulating the actual system process. A Monte Carlo simulation which is a well known simulation technique is capable of giving a reliable estimate of the system performance and adequacy and hence adopted for the current study.

6.2.1 Monte Carlo Simulation (MCS)

MCS is a computational algorithm which simulates the random behavior of various physical and mathematical systems using random numbers. They are stochastic method that is non-deterministic and hence distinguished from other simulation techniques [181], [182]. Basic characteristics of MCS are: MCS uses several inputs at the same time and create the probability distribution of one or more outputs; the inputs of the model can be represented using different types of probability distributions. When the distribution is unknown the one that represents the best fit can be chosen; MCS can be categorized as stochastic technique because of the use of random numbers. The random numbers have to be independent; no correlation should exist between them; the output of MCS is generated as a range instead of a fixed value and shows how likely the output is to occur in the range. In this study, MCS is applied to a hybrid renewable energy system for evaluating LOLE index at various contingency conditions. Sufficient numbers of iterations are required to arrive at statistically viable result and to obtain the real value of a parameter. The steps involved in evaluation of LOLE using Monte Carlo simulations are given as follows:

1. Read hourly generation and load state (X_i); i =1 to 8760, initialise sample size (N), $C = 0$, $E = 0$.
2. Randomly select X_j sample with size N, where $X_j \in X_i$; $j = 1$
3. Classify X_j as $X_{failure}$ and $X_{success}$. $X_{failure}$ is identified when system load level is greater than total generation while $X_{success}$ is identified when system load is equal to or less than total generation.
4. If $X_j = X_{failure}$ then, $C = C + 1$.

5. Repeat steps 3 to 4 till $j = N$.
6. Calculate $LOLE = \frac{C}{N} \times 8760$
7. Repeat steps 2 to 6 until acceptable values of $LOLE$ or stopping criteria is reached.

6.2.2 Assumptions made for MCS

1. Total duration of time series taken as 1 year is discretized with each time unit equal to 1 hour.
2. Same year has been sampled many times equal to the total number of iterations.
3. Load demand and generated power remain constant during each hour simulated.
4. Each state representing load demand and generation is unique and will occur only once in total duration of time series for small discretization.
5. Each state representing load demand, generation is sampled by randomly choosing an integer uniformly distributed in [1, 8760].

6.2.3 Loss of load expected (LOLE)

Loss of load expected is the average number of hours for which the system load is expected to exceed the available generation capacity. It is expressed in hours per year.

$$LOLE = \sum_{t=1}^{8760} t_{outage}(t) \quad (6.1)$$

where $t_{outage}(t)$ is equal to 1 when the load in t^{th} hour is greater than the sum of the generating capacity and battery storage level and 0 otherwise.

6.3 Evaluation Model

The hourly solar radiation and wind speed data are generated in the first step. Depending on the above generated renewable energy inputs, the output power from respective renewable energy source is calculated based on a mathematical model. Finally, the hourly load data is compared with the total hourly generation and the battery power to calculate the required reliability index. The reliability evaluation model is shown as in fig.6.1. The mathematical modeling adopted is as described in sections 3.3, 3.4, 3.5 and 3.6.

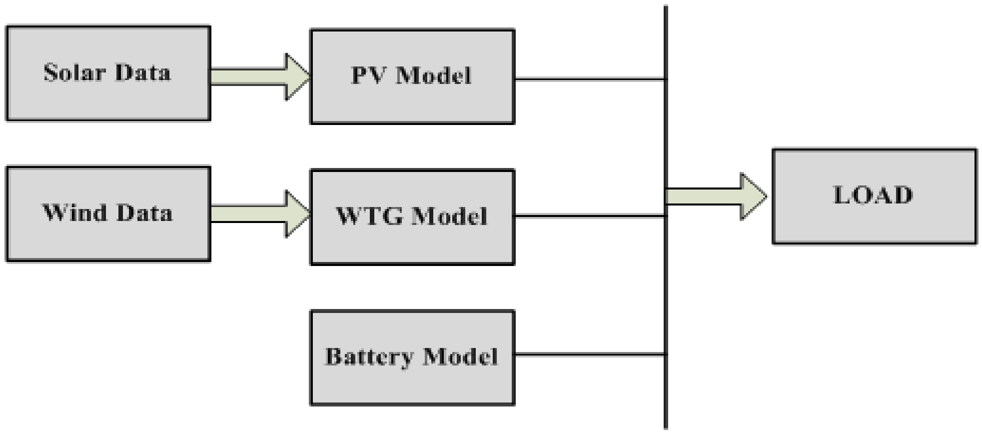


Fig. 6.1 Evaluation model for system reliability

6.4 Results and discussions

The optimal system configuration obtained in the previous section 4.3 for the case study area located in remote Almora district of Uttarakhand for three different system schemes are again reproduced in table 6.1. The solar radiation data, wind speed data and load demand profile of the study area are given as in fig.6.2, fig.6.3, and fig.6.4. System optimization were carried out at WTG FOR=0.05 and PV unavailability $Q_{pv} = 0.04$. Each of the optimal system is subjected to reliability analysis at various changed condition of renewable energy inputs, WTG force outage rate (FOR), PV unavailability (Q_{pv}) and increase case of load demand.

Table 6.1: Optimal system configuration

System Scheme	**No. of 1 kW PV**	**No. of 3kW WTG**	**No. of Battery string each of 17 kWh**	**Converter (kW)**	**Optimized Cost (Rs.)**
PV-battery	44	0	64	21	2912505
WTG-battery	0	24	19	21	885803
PV-WTG -battery	3	25	10	20	768950

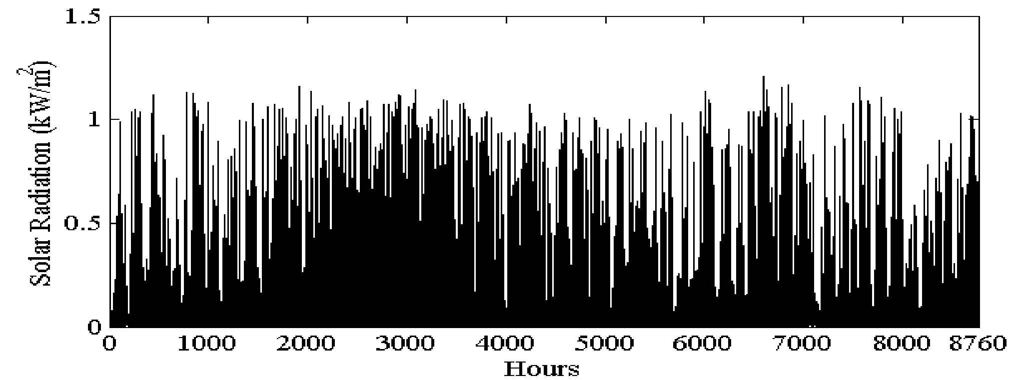


Fig. 6.2: Study area solar radiation profile

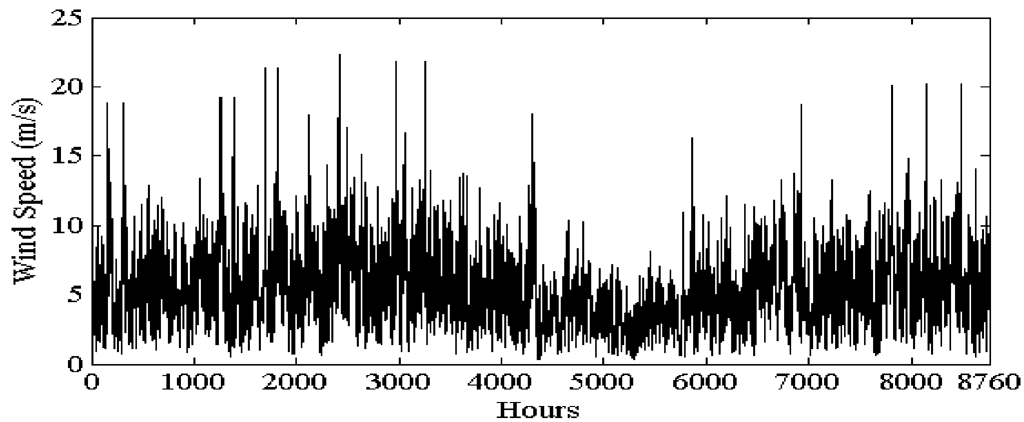


Fig. 6.3: Study area wind speed profile

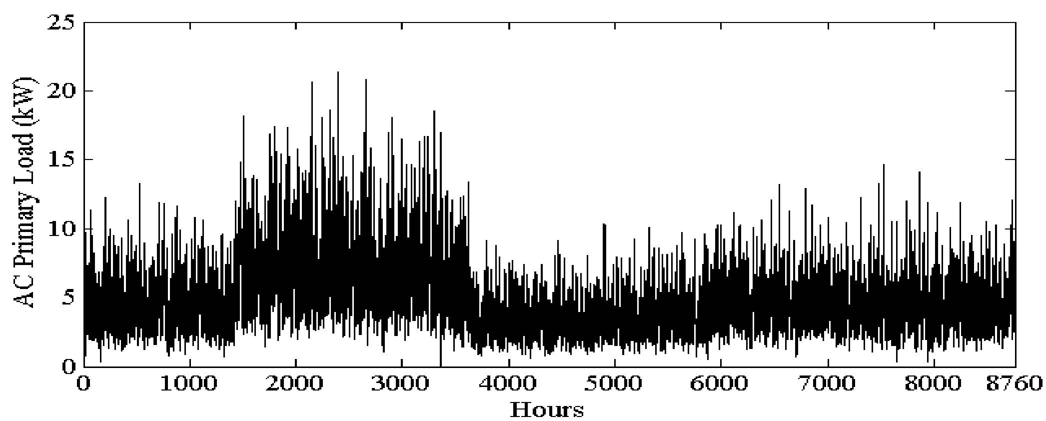


Fig. 6.4: Load profile of the study area

A variation in renewable energy inputs is simulated by 10%, 20% and 30% decrease in annual average solar radiation and annual average wind speed. An increase case of load demand is considered at 10%, 20%, 30% increase in annual peak load. Wind turbine generator FOR values of 0.05, 0.075, 0.1, 0.125, 0.15 and PV unavailability (Q_{pv}) values 0.04, 0.06, 0.08, 0.1, 0.12 are considered to account for the increase failure rate of system components. Various values of changed inputs used for obtaining hourly wind, solar , load demand data as well as the changed values of FOR and (Q_{pv}) are given in table 6. 2.The overall procedure for evaluation of LOLE through Monte Carlo simulation is implemented using Matlab programming environment.

Table 6.2: Various changed parameters used for simulation

	Annual Average Wind Speed (m/s)	Annual Average Solar radiation (kWh/m2)	Annual Peak Load (kW)	Wind Turbine FOR	Photovoltaic Unavailability (Q_{pv})
Base value	5.43	4.67	21.40	0.05	0.04
Changed condition	4.887	4.203	23.54	0.075	0.06
	4.344	3.736	25.68	0.1	0.08
	3.801	3.269	27.82	0.125	0.1
				0.15	0.12

6.4.1 Effect of annual peak load

The level of load demand is an important aspect in reliability analysis of a hybrid energy system. The annual peak load has great impact on the system reliability performance. Table 6.3 gives the calculated value of LOLE in hours per year at 10%, 20% and 30% increase in annual peak load for each of the optimal PV-battery, WTG-battery and PV-WTG-battery system. Careful examination of table 6.3 shows that LOLE is lowest for PV-WTG-battery at all the cases of increase in annual peak load. At 10%, 20% and 30% increase in peak load, PV-battery system has 2.95%, 11.96%, 12.24% higher LOLE values while WTG-battery has 21.57%, 66.05%, 83.46% higher LOLE values compared to PV-WTG-battery system. Further, it is seen that the system reliability deteriorates with peak load for each of the system. Fig.6.5 depicts the convergence characteristics of MCS with 500 simulations for optimal PV-WTG-battery system for 10% increase in peak load.

Table 6.3: LOLE results with variation in annual average peak load

	LOLE (hr/year)		
Peak load	**(+) 10%**	**(+) 20%**	**(+) 30%**
PV-battery	328.28	600.23	893.3
WTG-battery	387.64	890.22	1460.1
PV-WTG-battery	318.86	536.11	795.86

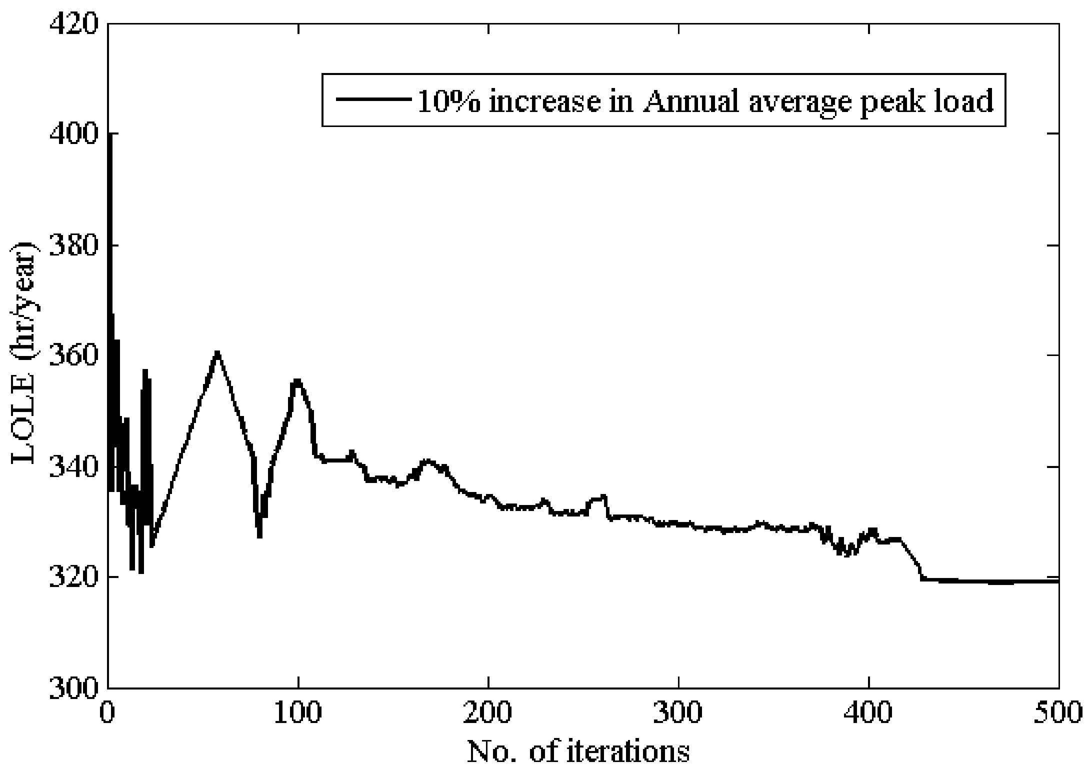


Fig.6.5: Convergence characteristics of MCS for PV-WTG-battery at 10% increase in annual average peak load

6.4.2 Effect of annual average solar radiation

The power output from PV panels is directly related to the solar radiation at a specific location. Two system schemes having PV component viz. PV-battery, PV-wind-battery are considered to investigate the impact of solar radiation on system reliability performance. A 10%, 20% and 30% decrease in annual average solar radiation is taken to calculate LOLE reliability index for both the system. LOLE calculated results are shown as in table 6.4 and convergence characteristic of MCS for PV-WTG-battery at 10% decrease in annual average solar radiation is shown in fig. 6.6. Table 6.4, clearly shows that PV-WTG-battery has lower values of LOLE at all the changed conditions of annual average solar radiation than those of PV-battery system. The percentage reduction in LOLE values are 89.80%, 84.61% and 85.16% respectively at 10%, 20% and 30% reduction in annual average solar radiation.

Table 6.4: LOLE results with variation in annual average solar radiation

LOLE (hr/year)			
Annual Average Solar radiation	**(-) 10%**	**(-) 20%**	**(-) 30%**
PV-battery	146.71	287.99	439.96
PV-WTG-battery	14.96	44.32	65.27

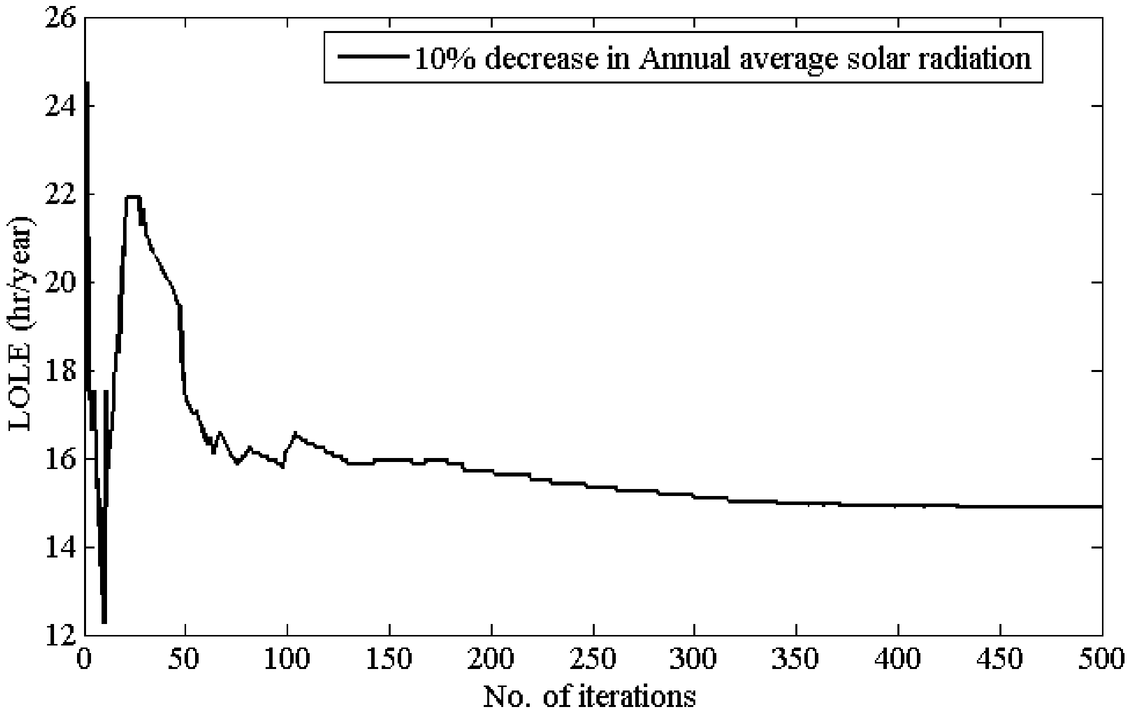


Fig.6.6: Convergence characteristics of MCS for PV-WTG-battery at 10% decrease in annual average solar radiation

6.4.3 Effect of annual average wind speed

The power output from WTG is strongly influence by annual average wind speed. The power output is a cubic function of wind speed and hence a small fluctuation in the wind speed will result in large deviation in power output from WTG. A reduced condition in wind speed is simulated at 10%, 20% and 30% reduction in annual average wind speed and LOLE reliability index is calculated at each of the changed condition for both WTG-battery and PV-WTG-battery system. LOLE results with variation in annual average wind speed are given in table 6.5. The convergence plot of MCS at 10% reduction in annual average wind speed for PV-WTG-battery system is given in fig. 6.7. Analysis of table 6.5 reveals that integration of PV and WTG in a single system reduces the system risk of loss of load hours by 4.61%, 12.94%, and 17.05% respectively at 10%, 20%, and 30% decrease in annual average wind speed. However, both the system suffers from increase risk of loss of load hours with increase reduction of wind speed.

Table 6.5: LOLE results with variation in annual average wind speed

LOLE (hr/year)			
Annual Average Wind speed	**(-) 10%**	**(-) 20%**	**(-) 30%**
WTG-battery	234.9	691.54	1360
PV-WTG-battery	224.08	602.05	1128

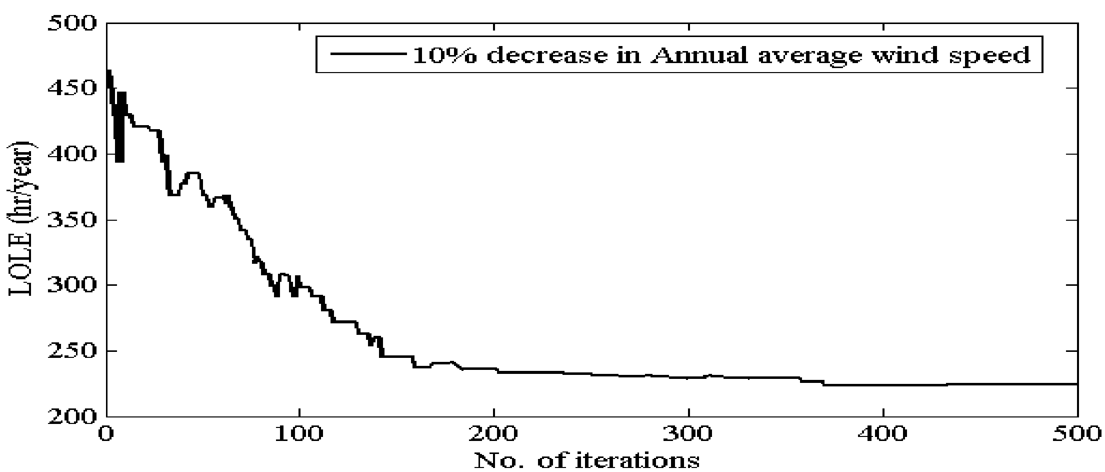


Fig.6.7: Convergence characteristics of MCS for PV-WTG-battery at 10% decrease in annual average wind speed

6.4.4 Effect of WTG force outage rate

In general, the force outage rate of generating component has significant impact on system reliability. In the current study, the WTG failure and repair characteristics are simulated using sequential up down up cycles of WTG which are then mapped with the available wind power to get the final wind power output. To illustrate the effect of WTG force outage rate on the system reliability systems consisting of WTG unit viz. WTG-battery and PV-WTG-battery are considered and , the FOR value is varied from 0.05 to 0.15 with a fixed step size of 0.025. Table 6.6 shows the variation of system LOLE for the range of considered WTG force outage rate while convergence plot of MCS is depicted in fig. 6.8. The LOLE value of 0 at FOR=0.05 is due to the fact that the optimal system configuration of WTG-battery and PV-WTG-battery were obtained for zero loss of load taking force outage rate value of 0.05 during optimization. An increasing trend in LOLE values is observed for both the system with increase in WTG force outage rate. However, the optimal PV-WTG-battery system is less impacted by the change in WTG force outage rate as compared to the WTG-battery system.

Table 6.6: LOLE results with variation in WTG force outage rate (FOR)

	LOLE (hr/year)				
Wind Turbine FOR	FOR=0.05	FOR=0.075	FOR=0.1	FOR=0.125	FOR=0.15
WTG-battery	0	79.3	185	336.9	449.8
PV-WTG-battery	0	64.5	170.5	288.3	413.7

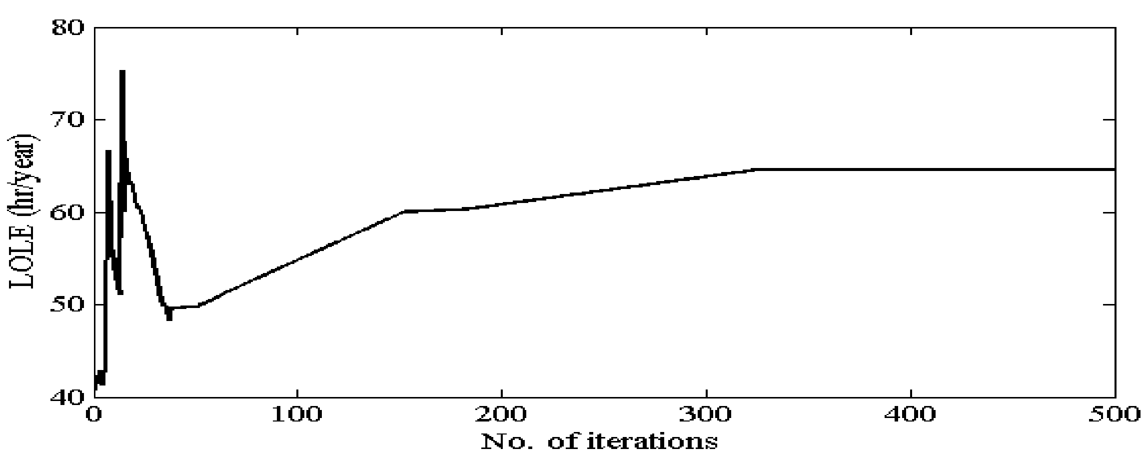


Fig.6.8: Convergence characteristics of MCS for PV-WTG-battery at WTG FOR = 0.075

6.4.5 *Effect of Photovoltaic unavailability*

The variation of LOLE values with increase level of photovoltaic unavailability (Q_{pv}) is depicted in table 6.7 for PV-battery and PV-WTG-battery system. These optimal systems were obtained at $Q_{pv} = 0.04$ for zero loss of load hours. To study how the system reliability is impacted by the variation in photovoltaic unavailability (Q_{pv}), a range of Q_{pv} values are taken from 0.04 to 0.12 and LOLE values are evaluated at each Q_{pv} value. System reliability deteriorates with increase in the value of Q_{pv} for both type of optimal system. However, PV-wind-battery system suffers from lower loss of load hours compared to PV-battery only system. A convergence plot of MCS for PV-wind-battery system is also depicted in fig. 6.9.

Table 6.7: LOLE results with variation in PV unavailability

	LOLE (hr/year)				
PV unavailability (Q_{pv})	$Q_{pv} = 0.04$	$Q_{pv} = 0.06$	$Q_{pv} = 0.08$	$Q_{pv} = 0.1$	$Q_{pv} = 0.12$
PV-battery	0	29.11	29.74	32.55	34.48
PV-WTG-battery	0	18.11	19.73	23.54	29.44

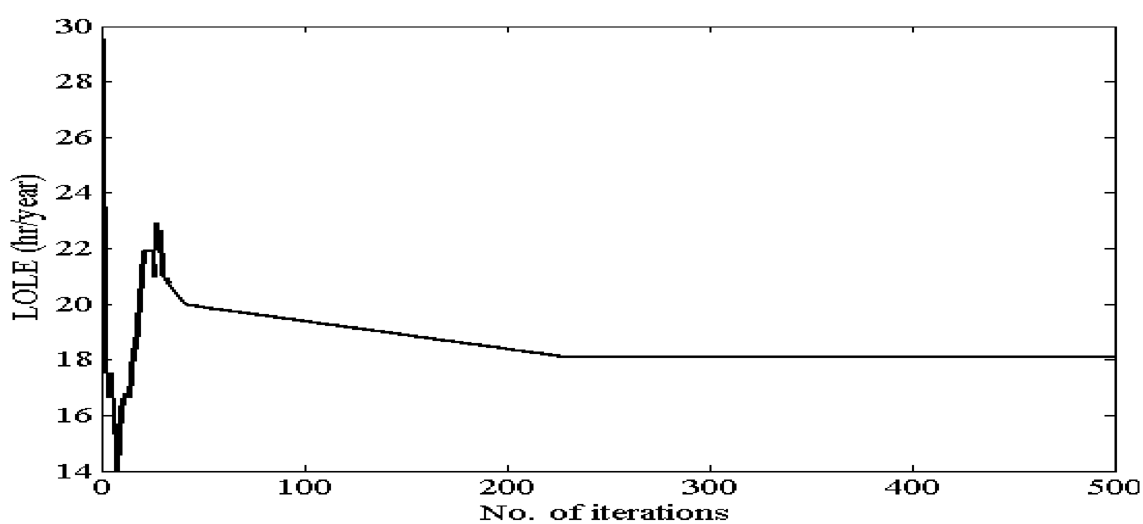


Fig. 6.9: Convergence characteristics of MCS for PV-WTG-battery at $Q_{pv} = 0.06$

6.5 Conclusions

In this chapter, the optimal hybrid energy system obtained for the study area is subjected to reliability performance evaluation at various cases of contingency and results have been compared with those of standalone photovoltaic-battery, and WTG-battery system. Contingency conditions simulated for the study are reduced levels of renewable energy resources inputs, increase in demand, increase in outage rate of WTG unit, and increase in unavailability level of photovoltaic panels. The reliability assessment has been made through evaluation of LOLE index using Monte Carlo simulation.

Analysis of LOLE evaluation results suggest better reliability performance of PV-WTG-battery system compared to standalone PV-battery and WTG-battery only systems at all the contingency conditions simulated. Hence, the optimal hybrid PV-WTG-battery system comprising of 3kW PV, 20 numbers of 3kW wind turbine with 10 numbers of battery string each of 17kWh capacity along with 20 kW converter is the most economical and reliable system not only at the nominal conditions of load demand, renewable energy resources inputs, wind turbine FOR =0.05 and photovoltaic unavailability $Q_{pv} = 0.04$ but also at the changed condition of all these parameters.

CHAPTER 7

Conclusions and scope for future work

7.1 Introduction

The declining fossil fuel reserves, increase environmental concerns from fossil fuel utilization and topographical difficulties in grid extension have led to the development and utilization of renewable energy based hybrid energy system in isolated locations worldwide. Therefore, the aim of the thesis is to develop an evaluation methodology for assessing the design aspects and performance of hybrid energy system. Available wind speed, solar radiation data and load profile of a case study area located in Almora district of Uttarakhand, India are used to create a working database for the study.

7.2 Discussions of results and conclusions

The main contributions of the presented work in the area of hybrid energy system can be summarized as follows:

A detail mathematical power output modeling of main hybrid energy system component such as photovoltaic panels, wind turbine generator, converter and battery storage are presented. While modeling the photovoltaic panels, the hardware availability and unavailability status of photovoltaic panels are considered. Various capacity states resulted from hardware failure of photovoltaic panels and corresponding probabilities of residing in a particular state are represented by a probability distribution (PD). The actual hourly available photovoltaic power is calculated based on the concept of random number generation. The power output models of wind turbine generator also takes into account the force outage rate (FOR) of wind turbine. Actual wind turbine power output is calculated using the sequential up-down-up cycles of the wind turbine generator.

A hybrid energy system design problem is formulated as an optimization problem. The objective of the design problem is to minimize total system cost fulfilling the electrical needs of the case study area in most economical and reliable way subject to various design and operational constraints. An attempt is being made to use a new meta-heuristic algorithm called as Cuckoo Search (CS) via levy flight for solving the hybrid energy system design problem. The performance of the proposed Cuckoo Search (CS) algorithm in solving hybrid energy system design problem is compared with other well known optimization algorithms such as genetic algorithm (GA) and particle swarm optimization (PSO).Three different systems schemes viz. PV-battery, WTG-battery and PV-WTG-battery are considered for optimization. Optimization results depict the superior performance of Cuckoo Search algorithm over GA and PSO in terms of optimization speed and quality solutions in each of the system scheme considered. Cuckoo Search algorithm took computation of 1031s, 935s and 1442 s for optimization of PV-battery, WTG-battery, PV-WTG-battery system respectively .While GA took 1371s, 1208s and 1807s and PSO took 1316s, 1150s and 1756s for each of the PV-battery, WTG-battery, PV-WTG-battery system respectively. Furthermore, hybrid PV-WTG-battery system consisting of 3kW PV, 25 numbers of 3kW WTG, 20 kW converters along with battery bank comprising of 10 numbers of strings each of 17 kWh capacities is the most reliable and economical system scheme compared to PV-battery and WTG-battery system with an optimized system cost of Rs. 7.69 lakhs and cost of energy (COE) of 18.38 Rs/kWh.

The developed optimal hybrid energy system model is used to carry out a sensitivity analysis taking cost of energy (COE) as the economic indicator. The analysis is carried out to study the impact of various influencing parameters such as wind speed, solar radiation, capital cost, load demand, wind turbine force outage rate (FOR) and photovoltaic unavailability (Q_{pv}) on the cost of energy. A variation in annual average wind speed from 3.08 m/s to 7.06 m/s varies the cost of energy (COE) from 31% to -38.76%. However, a relatively less significant change on the cost of energy (COE) is observed when the system is simulated with variation in annual average solar radiation. The cost of energy (COE) changes from 6.59% to -6.85% when the annual average solar radiation is changed from 3.27 kWh/m^2 to 6.07 kWh/m^2. A positive relationship is observed between the variation in capital cost of photovoltaic panels, WTG, storage battery, converter for the optimal hybrid energy system with the cost of energy (COE). The cost of energy (COE) is most sensitive to the variation in capital cost of wind turbine generator followed by capital cost of battery and converter while cost of photovoltaic panels has least impact. A 30% increase in annual peak load increases the cost of energy (COE) by 52.7%. An increase in the value of wind turbine generator force outage rate (FOR) from 0.05 to 0.15, increase the cost of energy (COE) by 14.69% while the variation in photovoltaic unavailability (Q_{pv}) from 0.04 to 0.12 increases the cost of energy (COE) by 7%.

A reliability performance evaluation for the optimal hybrid energy system obtained for the study is carried out at various contingency conditions and results have been compared with those of standalone photovoltaic-battery, and WTG-battery system. The analysis considered reduced levels of renewable energy resources inputs, increase in demand, increase in outage rate of WTG unit, and increase in unavailability level of photovoltaic panels as various contingency conditions for simulation. The reliability assessment has been made through evaluation of LOLE index using Monte Carlo simulation LOLE evaluation results suggest that the optimal hybrid PV-WTG-battery system comprising of 3kW PV, 20 numbers of 3kW wind turbine with 10 numbers of battery string each of 17kWh capacity along with 20 kW converter performs better in terms of reliability compared to standalone PV-battery and WTG-battery only systems at all the contingency conditions simulated.

7.3 Suggestions for future work

1. The developed approach in the present study for the optimal sizing of hybrid energy system does not consider the reliability aspects of energy storage devices (battery storage).Hence, the developed approach can be extended further by incorporating the reliability aspects of energy storage devices.
2. New alternative soft computing tools like Artificial Neural Networks (ANNs), Fuzzy logic based methods and newly developed evolutionary algorithms can be applied for solving hybrid energy system design problem as well as for resource assessment.
3. The current study does not considered diesel generator as a candidate unit for the hybrid energy system components. The analysis method using Cuckoo Search (CS) can also be extended to incorporate the diesel generator as a candidate unit for optimization as well as for optimization of diesel generator operational variables.
4. The developed cost function in the current study can be expanded further to take into account the various financial incentives provided by the governments for promoting renewable energy based power generation systems.
5. Similar analysis can also be extended to hybrid energy system incorporating different varieties of energy storage components like fuel cell, ultra capacitors etc.

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LIST OF PUBLICATIONS

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1. S Sanajaoba, E. Fernandez, "Maiden Application of Cuckoo Search Algorithm for Optimal Sizing of a Remote Hybrid Renewable Energy System," ***Renewable Energy Journal,*** vol. 96, pp.1-10, 2016.
2. S Sanajaoba, E. Fernandez, "Modeling, Size Optimization and Sensitivity Analysis of a Remote Hybrid Renewable Energy System," ***Energy Journal*** (under consideration)
3. S Sanajaoba, E. Fernandez, "Reliability assessment of a remote hybrid energy system using Monte Carlo simulation," ***International Journal of Renewable Energy Technology*** (under consideration)

Conference Papers:

4. S Sanajaoba, E. Fernandez, "Impact of Wind Turbine Generator FOR on the Reliability and Economics of a Remote WTG System," ***In: IEEE first ICPEICES 2016. July 4-6***
5. S Sanajaoba, E. Fernandez, "Reliable PV/Wind Renewable Energy Mix for a Remote Area," ***In: 2015 Annual IEEE India Conference (INDICON), Dec.17-19.***
6. S Sanajaoba, E. Fernandez, "Reliability Evaluation of a Solar Photovoltaic System with and without Battery Storage," ***In: 2015 Annual IEEE India Conference (INDICON), Dec.17-19.***
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9. S Sanajaoba, E. Fernandez, "Economic Comparison of Electrical and Chemical Energy Storage system in a stand-alone Renewable Energy Based Power Generation Scheme," ***National Conference on Advances and Research in Technology***, Yamuna Institute of Engineering and ***Technology, Haryana-2014. March 8-9.***

APPENDIX A

Numerical values of the const used in the study

Sl. no.	Constant	Values
1	σ	0.2%/day
2	$\eta_{batt}(charging)$	75%
3	$\eta_{batt}(discharging)$	100%
4	$SOC_{\max}$	100%
5	$SOC_{\min}$	40%
6	C_{ENS}	336 Rs./kWh [183]
7	α	1/7
8	h_{hub}	25m
9	h_{anem}	10m
10	P_a	0.25

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APPENDIX B

Monte Carlo Simulation steps to evaluate the value of EENS

1. Read hourly generation and load state (X_i); $i = 1$ to 8760, initialise sample size (N), $C = 0$, $E = 0$.

2. Randomly select X_j sample with size N, where $X_j \in X_i$; $j = 1$

3. Classify X_j as $X_{failure}$ and $X_{success}$. $X_{failure}$ is identified when system load level is greater than total generation while $X_{success}$ is identified when system load is equal to or less than total generation.

4. If $X_j = X_{failure}$ then, $C = C + 1$, $E = E + \Delta P$, $\Delta P =$ unbalanced power.

5. Repeat steps 3 to 4 till $j = N$.

6. Calculate $EENS = \frac{8760}{N} \times E$

7. Repeat steps 2 to 6 until acceptable values of $EENS$ or stopping criteria is reached.