Feasibility and Sensitivity Analysis of Hybrid Energy Systems for Uninterrupted Power Supply

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by

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CERTIFICATE

I hereby certify that the work presented in the dissertation entitled **‘‘Feasibility and Sensitivity Analysis of Hybrid Energy Systems for Uninterrupted Power Supply”** in the fulfillment of the requirement for the award of the Master Of Technology **in “Energy Technology”** and submitted in the **Centre for Energy & Environment** of the National Institute of Technology, Hamirpur, H.P. is an authentic record of my own work carried out during the period from July-2012 to June-2013 under the supervision of **Prof. (Dr.) S. S. Chandel**, Centre for Energy & Environment, National Institute of Technology, Hamirpur (HP).

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

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CEE, NIT Hamirpur **Rahul Rawat**

EXCECUTIVE SUMMARY

Wind and solar are clean energy sources with vast potential to reduce the dependence on conventional energy sources and are being utilized for power generation worldwide. However, solar energy is available only on clear day while wind is very intermittent. The stochastic nature of these energy sources with dependence on environmental conditions raise the reliability issues of solar or wind power systems. A stand-alone solar energy system or a wind energy system may not able to supply reliable power as such, for a reliable power supply; hybrid power generation is the best option. The need for reliable power and maximum utilization of renewable resources at the location of interest has led to the development of reliable hybrid systems in recent years. The hybrid renewable energy systems are those in which two or more energy sources are integrated to operate simultaneously to supply power with at least one renewable energy source. These hybrid energy systems can become appropriate alternative to conventional energy systems and can cater to the requirements of institutions, industries and communities in urban and remote rural regions.

The main objective of the present study is to utilize the available wind and solar resource at a location to meet the energy needs of residential/institutional buildings in Western Himalayan Indian State of Himachal Pradesh.

In the present study, optimum configuration of a solar-diesel-battery hybrid energy system is determined for the uninterrupted power supply system for the National Institute of Technology, Hamirpur [NIT-H] using Hybrid Optimization Model for Electric Renewables software developed by National Renewable Energy Laboratory [NREL]. In order to assess the feasibility of the reliable hybrid renewable energy system, a 6kWp solar-wind hybrid system installed on the roof top of Centre for Energy and Environment, NIT-H is analyzed and optimized at different reliability levels.

Based on the techno-economic analysis, the optimum configurations of a standalone and a grid interactive solar-diesel hybrid system are proposed for the reliable

uninterrupted power supply for NIT-H. The optimum configurations found are, a standalone solar-diesel hybrid system consisting of 300kWp solar PV system and 128kWp diesel generator with battery bank of 1080Ah and a grid interactive solar-diesel hybrid system of 100kWp solar PV system and 128kWp diesel generator with a battery bank of 120Ah with net present cost of $3,804,559 and $1,189,963 respectively. These hybrid energy systems are analyzed on the basis of economics, excess electricity and greenhouse gas emissions. The sensitivity analysis is carried out to determine the effect of diesel costs and solar radiation on the net present cost and CO_2 emissions.

The results indicate that available solar and wind resource can be utilized economically using hybrid energy systems for decentralized applications in the Western Himalayan terrain. The solar-wind hybrid systems will be reliable systems for residential/Institutional buildings both in urban and rural locations in this region. The integration of a diesel generator in a solar-wind-battery hybrid system can result in avoiding over-sizing and enhancing the reliability of the system.

The work presented in the dissociation is organized as follows: In Chapter 1, an introduction to the hybrid energy system and energy scenario of India is given; a literature survey on hybrid energy systems is carried out in Chapter 2; the statement of problem, objectives and summary of solution methodology are given in Chapter 3; The methodology followed in the study is described in Chapter 4; the results of the study are presented and discussed in chapter 5 and conclusion of the study and further research are given in Chapter 6.

Further follow up research areas identified in the study are:

- Detailed resource mapping and analysis of the hilly regions of the country
- Optimization of hybrid systems for maximum renewable resource utilization at a site to maximize the promotion of renewable technologies in urban and rural areas.
- Feasibility study of hybrid energy systems employing small hydro and solar and wind resource for remote locations in Himalayan region.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	Ampere
A_i	Anisotropy index
AC	Alternate Current
c	Weibull Scale Parameter
C_p	Wind Power Coefficient
CEE	Centre for Energy and Environment
CO_2	Carbon dioxide
COE	Cost of Energy
C-WET	Centre for Wind Energy Technology
D_{pv}	Derating Factor
DC	Direct Current
f	Horizon brightening factor
F_0	Fuel Curve Intercept Coefficient
F_1	Marginal Fuel Consumption
$\overline{G_t}$	Hourly averaged global radiation on tilted surface (kW/m^2)
$\overline{G_d}$	Hourly averaged diffuse radiation (kW/m^2)
$\overline{G_b}$	Hourly averaged beam radiation (kW/m^2)
$\overline{G}$	Hourly averaged global horizontal radiation (kW/m^2)
$\overline{G_o}$	Hourly averaged extraterrestrial radiation (kW/m^2)
G_o	Extraterrestrial horizontal radiation (kW/m^2)
G_{on}	Extraterrestrial normal radiation (kW/m^2)
G_{sc}	Solar constant=1.367 kW/m2
GMT	Greenwich Mean Time
HOMER	Hybrid Optimization Model for Electric Renewables
IEEE	Institute of Electrical and Electronics Engineers

iHOGA	Improved Hybrid Optimization using Genetic Algorithm
k	Weibull shape parameter
k_t	Clearness Index
kWh	Kilo Watt hour
$\mathrm{m/s}$	Meter per second
MNRE	Ministry of New and renewable Energy
n	Day of the year (1 to 365)
n_{batt}	Number of batteries in the battery bank
NAPCC	National Action Plan for Climate Change
NIT	National Institute of Technology
NPC	Net Present Cost
NREL	National Renewable Energy Laboratory
O&M	Operation and Maintenance
P_{gen}	Power produced by the generator
$P_{r,gen}$	Rated capacity of generator
P_w	Wind power
PV	Photovoltaic
Q_{annual}	Annual throughput of battery
$Q_{lifetime}$	Lifetime throughput of battery
R_b	Geometric factor
R_{batt}	Lifetime of the battery
$R_{batt,f}$	Float life of the battery
STC	Standard Test Conditions
TRNSYS	Transient System Simulation Program
UPS	Uninterruptible Power Supply
USA	United States of America
v	Wind Velocity
V	Volt
℃	Degree Celsius
$	US Dollar

ρ	Air density
ϕ	Latitude (31.708°)
λ	Longitude (76.52°)
ω_2	Hour angle at next time step
ω_1	Hour angle at a time step
ω	Hour angle (hourly time step)
β	Slope of the PV Module (Degree)
θ_z	Zenith Angle (Degree)
θ	Incidence angle
δ	Solar declination angle (degree)
γ	Azimuth angle ($0°$ for south facing)
μ	Ground Reflectance (0.2)

Chapter 1

INTRODUCTION

1.1 Background

The energy needs are increasing rapidly worldwide whereas in developing and under developed countries, a major part is still to be connected to the power grid, even the grid connected regions have frequent power cuts especially in rural areas. The shortage of electricity is a major hurdle in the social, educational and economic development of the population living in the remote off grid and undersupplied grid connected areas (Akella et al. 2009). The decentralized generation is better solution for remote villages, in which the energy is generated and utilized at the same location. The diesel generator is mostly used as primary energy source to cater the energy demand of remote off grid regions and as backup source for energy shortage in grid connected regions. The diesel generator is not only an expensive source but also leads to pollution and global warming. Additionally, the fossil fuel resources are depleting fast and global warming is increasing alarmingly. As a result, there is worldwide interest among researchers to explore the pollution free and abundantly available alternative energy resources.

The solar and wind energy sources are pollution free alternative to the conventional sources, both in grid connected and off-grid regions and capable of overcoming the worldwide energy crisis. The solar and wind energy resources are available in abundance and are a cost competitive substitute of diesel generators in remote areas where the grid extension is too expensive and diesel price increases considerably due to transportation to remote locations.

1.2 India's Energy Scenario

In Indian perspective, the per capita electric power consumption is currently very low but is increasing rapidly and expected to rise continuously in near future (Fig. 1.1). It was only 616kWh per capita in 2010 as compared to 2,944kWh per capita of China (The World Bank). According to the 17th Electric Power Survey of India carried out in 2007 by Central Electricity Authority, the electric energy demand of country is estimated to be 1915TWh in 2021-22 having growth rate of about 10% per year (Central Electricity Authority, 2007).

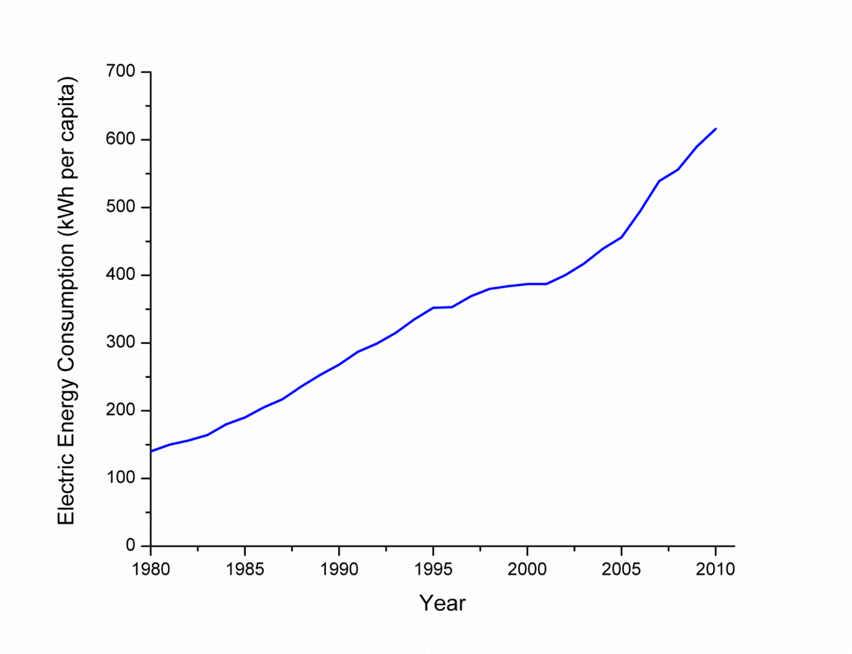


Fig. 1.1 Per capita electric energy consumption of India*(Source: The World Bank)

India has total 223,625.60MW installed power generation capacity, as on 30-04-2013, out of which major part (58.30%) is produced from coal and only 12.31% (27,541.71MW) is generated from renewable energy sources. The installed power generating capacity from different resources in India is given in Table 1.1 (Central Electricity Authority, Ministry of Power, Govt. of India).

Table 1.1 Total installed capacity of power plants in India (as on 30-04-2013)*

Sr. No.	**Resource**	**Installed Capacity (MW)**	**Percentage (%)**
1	Coal	130,370.89	58.30
2	Gas	20,109.85	8.99
3	Oil	1,199.75	0.54
4	Hydro	39,623.40	17.72
5	Nuclear	4,780.00	2.14
6	Renewable	27,541.71	12.31
7	**Total**	**223,625.60**	**100.00**

*Source: Central Electricity Authority, Ministry of Power, Govt. of India

Despite of all generations, the average electric energy shortage of India is about 12.7%. A total number of 100,917 un-electrified villages are electrified till the end of year 2012 under the programme “Rajeev Gandhi Grameen Vidyutikaran Yojana” (RGGYY) which was launched in March 2005 (Ministry of Power, Govt. of India: Annual Report 2011-12). Upto now 400 million people of about 18000 villages in India still are inaccessible to grid supply (Ministry of Power, Govt. of India; Ministry of New and Renewable Energy, Govt. of India).

1.2.1 Renewable Energy in India

India has huge renewable energy potential for producing enough power to overcome the power shortage challenges and to meet increasing electric energy consumption. The Ministry of New and Renewable Energy (MNRE), Govt. of India is working for the deployment, commercialization, research & development and demonstration of renewable energy the development of renewable energy sector.

India has recently completed its 11th five year plan in 2011-12, during which tremendous efforts were under taken to accelerate the renewable energy sector. During 11th five year plan, a total of 14,658 MW has been added to the installed renewable power generation capacity. The growth of total installed renewable power generation by the end of last three five year plan is shown in Table 1.2.

Table 1.2 Growth of renewable power generation capacity*

Resource	**Installed renewable power generation capacity (MW)**			**Capacity addition during 11th plan (MW)**
	End of 9th Plan (March 2002)	**End of 10th Plan (March 2007)**	**End of 11th Plan (March 2012)**	
Solar	2	3	941	938
Wind	1,628	7,092	17,352	10,260
Small Hydro	1,434	1,976	3,395	1,419
Bio-energy	389	1,184	3,225	2,041
Total	**3,453**	**10,255**	**24,913**	**14,658**

*Source: Annual Report 2012-13, MNRE

1.2.1.1 Solar Energy in India

Solar energy is an everlasting renewable source resource which can be utilized for thermal applications as well as for electric power generation. India is receiving enormous amount of solar energy almost in each part of the country, about 4-7kWh/m^2/day (average 7000MJ/m^2 energy in a year) of global horizontal solar radiation. The Rann of Kutch receives maximum irradiation of average 22MJ/m^2/day while north region (Kashmir valley) and north eastern region receives 16.5MJ/m^2/day and 15MJ/m^2/day respectively (India Meteorological Department, Govt. of India).

The Jawaharlal Nehru National Solar Mission under NAPCC was launched during 11th five year plan with a target of deploying 20,000MW of grid-connected solar power generation capacity and 2,000MW of off-grid solar application by 2022 (Ministry of New and Renewable Energy: Annual Report 2012-13). As a result the installed solar power generation capacity has increased from 3 MW in March 2007 to 1,446MW as on January 2013.

1.2.1.1 Wind Energy in India

The wind blows on the earth because of the pressure difference caused by the uneven heating of earth's surface by solar radiation. The power in the wind is converted into electricity by using wind generators commonly known as wind turbines. Worldwide, wind electricity generation has increased by 13 times between 2000 and 2011. The average wind speed of India is considered as 5-6m/s with maximum during monsoon from May to September. The Centre for Wind Energy Technology (C-WET) is carrying out wind resource assessment of India and has installed, a total number of 665 wind monitoring station all over the country till 31-03-2012, out of which the wind power density of 233 locations have been found to be more than 200kW/m^2 (Centre for Wind Energy Technology: Annual Report 2011-12).

Because of policy framework, incentives and private-utility partnership, wind energy leads to India's renewable energy industry and holds fifth rank worldwide in wind power production after USA, Germany, Spain and China with total installed capacity of 18,634.9 MW as on 31-01-2013 (Ministry of New and Renewable Energy: Annual Report 2012-13). The wind power production is mainly concentrated in following states of India i.e. Karnataka, Rajasthan, Gujarat, Kerala, Madhya Pradesh, Maharashtra and Tamil Nadu. In other parts of the country, the wind speeds are found to be low, not enough for large scale power generation based on the existing wind resource assessment done by C-WET. However, detailed regional wind mapping & micro level mapping is required in order to identify the true wind potential.

1.3 Need for Hybrid energy systems

Because of the energy shortage, the diesel generator is being used as primary and backup source of energy in industries, institutions, shopping malls, commercial offices, households and remote villages (Goswami, 2012). This diesel consumption needs to be reduced, as it is increasing the country's import dependence besides leading to greenhouse gas emissions.

In India, both solar and wind resources are available in plenty as discussed, which needs to be utilized effectively. These resources have the potential to replace totally or reduce the dependency on fossil fuels and can be utilized for decentralized generation to electrify remote areas. However, both the resources have the drawback of stochastic nature with dependence on environmental conditions which directly raise the reliability issues of solar/wind power systems. Therefore, a stand-alone solar energy system or a wind energy system may not able to supply reliable power. Solar energy is available only on clear day while wind is very intermittent as such, for a reliable power supply, hybrid power generation is the best option (Khaparde, 2007).

Therefore, hybrid energy systems are needed for maximum utilization of renewable resources for the location of interest with reliable power supply. Hybrid energy systems are those which utilize more than one energy source for power production. Most commonly, solar and/or wind energy, according to their availability at location, are integrated with diesel generator to supply energy continuously (Fig. 1.2). Because of availability of solar radiation all over the country and continuously decreasing solar PV module costs, the solar based hybrid energy systems are emerging out as cost-effective and feasible alternatives to reduce energy poverty without grid extension in remote villages (Anantha 1997; Katti and Khedkar 2005; Karmacharya and De-Vries 2009).This not only improves the reliability but also reduces the energy storage requirement and overcomes the over sizing problem, however, it enhances the degree of complexity of the system. Therefore, the optimal sizing of each component of hybrid system, based upon the resource availability, is necessary to make the system technically as well as economically feasible and efficient.

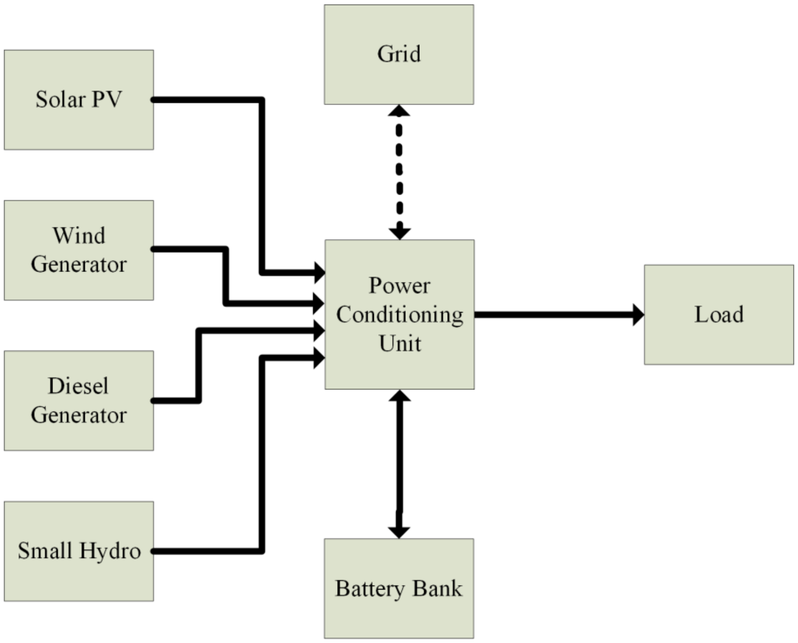


Fig. 1.2 Configuration of hybrid energy system

In the present study, based on the performance analysis of an existing 6kWp solar wind hybrid system, resource availability and net present cost, the feasibility of a hybrid energy system is assessed for uninterrupted power supply of National Institute of Technology, Hamirpur. The simulation and size optimization of hybrid energy systems are carried out using Hybrid Optimization Model for Electric Renewables (HOMER) software for a high solar resource and low wind speed location to identify optimum hybrid energy system configurations.

In Chapter 2, a literature survey is carried out in order to identify research gaps, study of hybrid energy systems, various hybrid configurations, analysis software tools and optimization techniques for optimum sizing of hybrid systems. The statement of problem, objectives and summary of solution methodology are given in Chapter 3. The methodology followed in the study is described in Chapter 4. The results of the study are presented and discussed in chapter 5 and conclusion of the study and further research are given in Chapter 6.

Chapter 2

LITERATURE SURVEY

In this Chapter, literature survey related to hybrid energy systems' research carried out is reviewed. The main focus of the literature survey was on the basics, hybrid systems types, integration schemes, optimization techniques for sizing, software tools and other design aspects of renewable hybrid systems.

The main renewable power generation technologies are solar PV, solar thermal, wind, ocean, tidal, micro-hydro, geothermal, biomass and fuel cells. These technologies are either used alone or in combination with two or more energy systems making a hybrid system. The stand-alone hybrid renewable energy systems are economical with higher reliability than systems with single renewable energy resource (Bernal-Agustin and Dufo-Lopez, 2009). The most common hybrid systems are PV–Wind–Battery and PV–Diesel–Battery. For applications where a reliable power supply is needed, the diesel generators are generally preferred which are inefficient when operated at light loads, resulting short lifetime and high maintenance costs of the diesel generator. An economic and reliable system is made by combining renewable and conventional energy sources (diesel generator) with a battery bank for storage (Wichert 1997; Khatib 2011).

One of the most important issues in the hybrid system is to optimally size the hybrid system components so that sufficient energy is produced to meet the load requirements with minimum investment and operating costs (Erdinc and Uzunoglu, 2012). The optimum sizing of these systems is complicated because of intermittent renewable resources, uncertain load demand, non-linearity in performance of the components, and large number of variables (Zhou et al., 2010). An optimum sizing method with economical objectives is used to ensure the lowest investment and system power reliability by using a PV array, wind turbine and battery storage.

Ngan and Tan (2012) determined the technical and economical feasibility of a photovoltaic /wind turbine/diesel hybrid system in Johor Bahru, a southern city of Malaysia, using HOMER simulation software. They studied and analyzed 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, wind-solar-diesel system with and without storage; and found that the excess electricity produced by the wind turbine and PV is inversely proportional to the number of batteries.

The commercial 10 kW wind turbines (10, 20, 25 and 30 numbers) connected with fixed battery storage and backup diesel genset was simulated and analyzed by Elhadidy and Shaahid (2004). Elhadidy (2002) investigates the feasibility of hybrid wind-solar-diesel systems at Dhahran to meet the energy needs of twenty, 2-bedroom houses and observed that the wind farm with a rated power close to peak load gives the best wind energy utilization factor. A pre-feasibility analysis of wind penetration into an existing diesel plant of a village in north eastern part of Saudi Arabia was performed by Rehman et al. (2007).

Kusakana and Vermaak (2013) investigates the possibility of using hybrid PV-wind system as primary source to supply energy to mobile telephone base transceiver stations in rural regions of Democratic Republic of Congo. Four different possible options including a hybrid PV-wind, a diesel generator, a pure PV and a pure wind energy system are compared to evaluate their technical performance, economics and environmental impact. Erdinc and Uzunoglu (2011) proposed a hybrid renewable energy system consisting of wind turbine, photovoltaic, proton exchange membrane Fuel Cell and battery with a fuzzy logic based intelligent controller for energy management.

Nayar et al. (2000) presents a practical implementation of a grid interactive photovoltaic uninterruptible power supply (UPS) system using battery storage and a back up diesel generator. Paska et al. (2009) proposed a hybrid DC microgrid to reduce the complexity of integration and transmission losses of hybrid systems. Muralikrishna and Lakshminarayana (2011) describes a 10kW wind and solar hybrid system designing. Nafeh (2010) optimizes the number of the PV modules, number of batteries and operation of the diesel generator in order to design a hybrid system having lowest cost. A multi-objective optimization, with objectives of minimizing life cycle cost and CO_2 emission, of standalone solar-diesel-battery hybrid energy system is carried out for remote village of Uttar Pradesh, India and found that the optimum configuration have 86% of PV power penetration (Agarwal et al. 2013). Gokcol and Dursun (2013) investigates the feasibility of renewable energy systems for Pinarhisar Educational Campus in Kirklareli University.

2.1 Renewable hybrid energy system configurations

It is essential to have a standardized procedure for connecting renewable energy sources of different operating characteristics to form a hybrid system (Nehrir et al., 2011). On the basis of integration methods, the hybrid energy systems are generally classified into three categories: DC-based system, AC-based system, and AC-DC integrated system (Farret and Simões, 2006).

2.1.1 DC-based system

In a DC-based system configuration, the different sources are connected to a DC bus through appropriate power electronic interfacing circuits as shown in Fig 2.1. This system is simple to design and no synchronization is needed between the different energy sources.

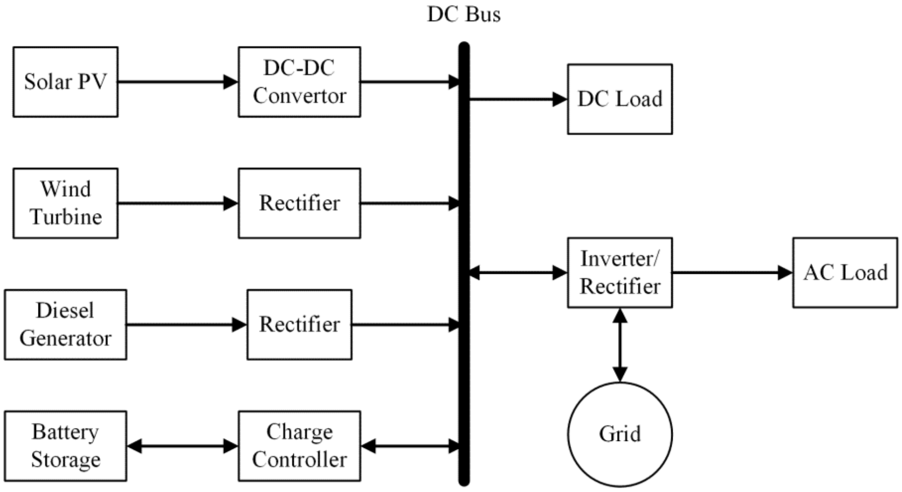


Fig 2.1 Configuration of DC-based hybrid energy system

2.1.2 AC-based system

In an AC-based system, the different energy sources are integrated such that AC sources are connected to AC bus either directly or through power electronic circuit and DC sources is connected to the AC bus through converter (Fig 2.2).

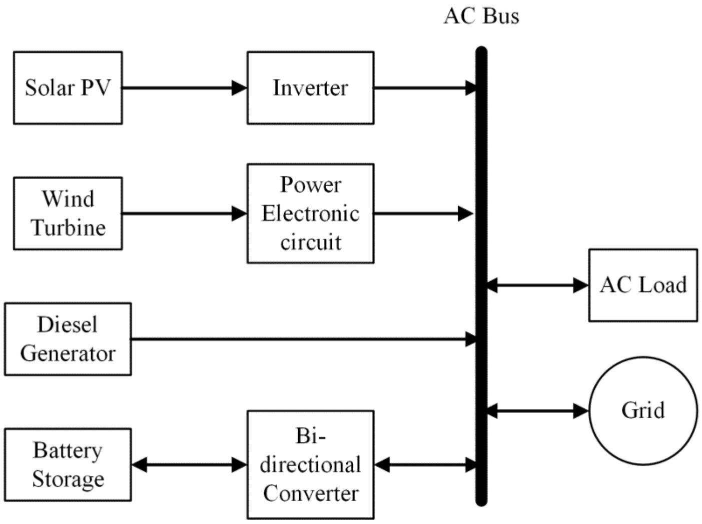


Fig 2.2 Configuration of AC-based hybrid energy system

2.1.3 AC-DC integrated system

In this system, the DC sources are coupled to the DC bus and/or AC sources are connected to AC bus (Fig. 2.3). The AC-DC integrated systems have higher energy efficiency and reduced cost because some energy sources can be integrated directly without extra interfacing circuits.

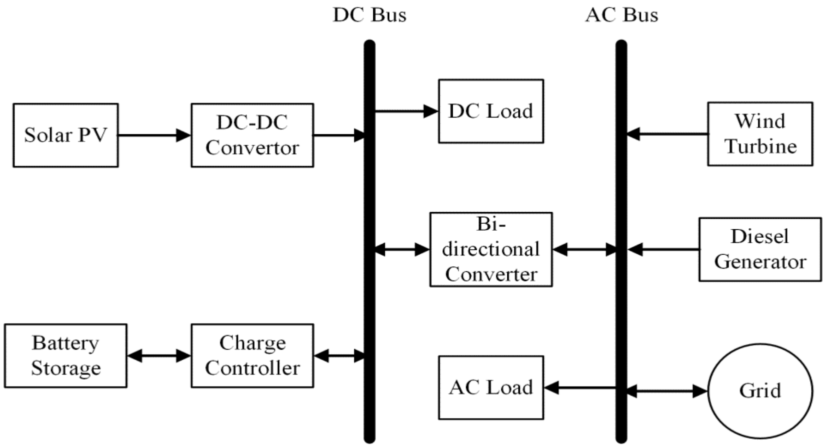


Fig 2.3 Configuration of AC-DC integrated hybrid energy system

2.2 Optimization techniques

The number of simulations and time required for calculation increases with the increase in number of optimization variables. Therefore, the selection of a quick and accurate optimization technique is very important (Erdinc and Uzunoglu, 2012). A number of optimization techniques for hybrid renewable energy system are reported in the literature, such as graphical methods, probabilistic approach, iterative technique and artificial intelligence methods (Luna-Rubio et al. 2012)(Jebaraj and Iniyan, 2006).

2.2.1 Graphical methods

In a graphical method given by Borowy and Salameh (1996), the optimum numbers of PV modules and batteries are calculated for minimum cost of the system, assuming wind turbine as constant. The optimization is achieved by the graphical representation of relationship between the number of PV modules and batteries based upon the total cost (Ai et al. 2003). The minimum cost of the system is located at the point of tangency of the curve.

Another graphical optimization methodology is developed by Markvart (1996) to optimize the size of wind turbine and PV array. The size of wind turbine and PV array is defined as the variable on Cartesian plane and linear programming theory is used to calculate optimum configuration.

2.2.2 Probabilistic approach

The probabilistic approach uses the convolution of probability density function of resources, in place of long term time series data, to calculate total power production of the hybrid system (Karaki et al. 1999). The probabilistic model estimates the long-term average performance of a hybrid power system for size optimization based on the convolution of wind and solar output power (Tina et al. 2006).

2.2.3 Iterative Approach

A numerical iterative algorithm, based on the resources and load demand, is used for hybrid power generation unit sizing to meet load demand and minimize cost. The optimum size is obtained either by linearly changing the values of the variables or employing linear programming techniques which results in suboptimal solutions and increased computational effort requirements. Kellogg et al. (1998) developed such an approach to determine the optimum unit size needed for a stand-alone wind, PV, and hybrid wind-PV system to minimize the total annual cost. Yang et al. (2007) proposed an iterative algorithm which includes levelized cost of energy and loss of load probability for hybrid system optimization. For iterative optimization method, minimization of the system cost was implemented.

2.2.4 Artificial Intelligence Techniques

The artificial intelligence techniques are used to solve non-linear problems efficiently. The genetic algorithm, fuzzy logic, particle swarm optimization and artificial neural network are some widely used techniques for solving optimization problems (Kalogirou, 2004). The genetic algorithm is more accurate with less simulation time, in comparison to the conventional techniques, to find global optimum combination of hybrid energy system incorporating the problems of uncertain renewable energy supplies, load demand (Koutroulis et al. 2006; Yang et al. 2008). Hong and Lian (2012) minimize the total investment and fuel cost of stand-alone wind-PV-diesel generator hybrid system for a given reliability level and limited CO_2 emission using genetic algorithm. An advanced variation of genetic algorithm was proposed by Mostofi and Shayeghi (2012) to solve the optimization problem of hydro/PV/wind/ fuel cell hybrid system and compared the results with HOMER software results which show that genetic algorithm is more accurate than HOMER software. Sometimes combination of two or more optimization techniques are used to improve the optimization process.

2.3 Optimization Software Tools

Simulation software tools are the most common tools for evaluating performance of the hybrid solar–wind systems (Zhou et al. 2010). The simulation program finds optimum configuration by comparing the electrical performance and cost of different system configurations. Several software tools are available for optimization of the hybrid systems. Connolly et al. (2010) listed 67 software tools available for analysis of hybrid energy systems and studied 37 of them and identified the suitable tools for different objectives. Some of the most widely used software tools for hybrid energy systems are summarized as follows:

2.3.1 HOMER

The National Renewable Energy Laboratory's (NREL) Hybrid Optimization Model for Electric Renewables (HOMER), uses hourly load and environmental data inputs to perform hourly simulations for techno-economic analysis of hybrid energy systems (Lopez and Espiritu 2011; Shiroudi et al. 2012; Dursun et al. 2013; HOMER Energy LLC). Peter Lilienthal created HOMER as a linear program back in 1993 and Tom Lambert developed it for windows application in 1997. It facilitates the optimization and sensitivity analysis of simulated renewable energy systems to minimize the Net Present Cost (NPC) for a given set of constraints (Farret and Simões 2006; Al-Karaghouli and Kazmerski 2010; Weis and Ilinca 2008). Sensitivity analysis is a measure that checks the sensitivity of a model when changing the value of the parameters of the model and also changing the structure of the model. Islam et al. (2012) performed sensitivity analysis to study the effects of variation in solar radiation, wind speed and diesel price so that appropriate recommendations can be made in developing a hybrid renewable energy system. HOMER has been widely used by researchers to perform optimization, sensitivity analysis and greenhouse gas emission reduction analysis of hybrid energy systems (Nandi and Ghosh 2010; Li et al. 2013; Ashourian et al. 2013; Silva et al. 2013). The limitationof the program is that it does not enable the user to intuitively select the appropriate components for a system, as algorithms and calculations are not visible or accessible.

2.3.2 HYBRID2

It is developed by Renewable Energy Research Laboratory of the University of Massachusetts (Centre for Energy Efficiency and Renewable Energy, University of Massachussets Amherst). This hybrid system simulation software is very precise which can run simulation for time intervals from 10 min to 1 hr. NREL recommends the HYBRID2 to improve the design of optimum system configuration obtained from HOMER (Green and Manwell 1995).

2.3.3 iHOGA

Improved Hybrid Optimization using Genetic Algorithm (iHOGA) is a simulation and optimization software developed in C++ by Electric Engineering Department of the University of Zaragoza, Spain. The mono-objective and multi-objective optimization is achieved for stand-alone and grid-connected hybrid renewable energy systems (Dufo-Lopez, 2005). The software optimizes the system size alongwith control strategies and slope angle of PV panels (Dr. Rodolfo Dufo-Lopez).

2.3.4 RETScreen

It is developed by Natural Resources Canada to evaluate the energy production, costs, emission reduction and financial viability for various types of renewable and non-renewable energy systems (Thevenard et al. 2000; National Resources Canada). It performs economical comparison between conventional system and proposed system.

2.3.5 TRNSYS

TRNSYS is a transient system simulation program developed by the Solar Energy Laboratory, University of Wisconsin-Madison, USA. It has a modular structure in which components of the system and their connecting modes are specified by the user (Beckman et al. 1994; University of Wisconsin-Madison). Its modular nature makes it flexible and facilitates the user to add mathematical models which are not included in library. It can simulate almost all thermal and renewable power generation systems.

2.4 Research highlights/gaps -Summary

Several researchers have studied different problems associated with optimization and integration of hybrid renewable energy systems. The major findings and research gaps identified are summarized in Table 2.1.

Table 2.1 Summary of hybrid renewable energy system research highlights /gaps

Sr.No.	References	Highlights	Remarks/Research gaps
1.	Alam and Gao (2007)	• The design of hybrid Wind/PV/Fuel cell Power system with battery bank is discussed. • A 20kW Wind turbine, 80kW PV array with 10 kW fuel cell is used in the simulation • Excess power is directed to the batteries first and then to electrolyzer.	• The system has 254kWh/Year unmet load and 368 kWh/Year capacity shortage. • Therefore the system needs to be improved for better reliable performance. • The levelized cost of energy is estimated to be 1.045 $/kWh which is uneconomical.
2.	Reddy and Raturi (2010)	• Optimization and sensitivity analysis of a PV/Wind/Diesel hybrid System is performed alongwith economic analysis. • Diesel generator and wind speed are taken as sensitivity variables.	• Satellite data is used for the study while measured ground data at site will give more accurate results.

3.	Ajao et al. (2011)	• Economic analysis of solar-wind hybrid system is done for Nigeria in order to determine the pay-back period using HOMER. • Hybrid system is found to be expensive because of high capital and installation cost.	• Reduction of greenhouse gas emission is not taken in account. • The system would be cost-effective if the system is designed for remote areas.
4.	Supriya and Siddarthan (2011)	• Quadratic programming techniques are used for optimum sizing to minimize the cost. • Grid supply, Grid connected PV system, Grid connected wind power system and grid connected hybrid system are compared.	• Dump load is used for excess electricity. • The excess power can be utilized efficiently by using energy storage device.
5.	Hirose and Matsuo (2012)	• A standalone solar-wind-diesel hybrid power generation system is proposed with active-reactive power control.	• Effective use of the excess power is effectively used. • The dispatch strategy is not optimized in this system. • Under dump control there is a loss of power.

6.	Kaldellis and Zafirakis (2012)	• The appropriate size of a hybrid system is estimated to meet the energy demand of typical remote consumers with the minimum installation cost. • Case studies of the Greek territory with different quality of wind and solar potential are currently investigated.	• Minimum initial cost is considered as objective function. • The inflation rate and interest rate are not included in the objective function which needs to be included for accurate assessment.
7.	Abdolrahimi and Karegar (2012)	• The optimization and sensitivity analysis of solar-wind-diesel hybrid system is carried out for Kish Island in Iran. • The reliability of the entire system is found to be increased by using the diesel generator as back-up source.	• Reliability of the system is not assessed.
8.	Mcgowan and Manwell (1999)	• Summary of recent progress on Wind/PV/Diesel Hybrid system in the USA with emphasis on	• Progress is needed in the important areas of system and component reliability, accurate documentation and

		the analytical and experimental work carried out at the University of Massachusetts is presented.	monitoring of system performance, and the cost effective improvement of system components.
9.	Zaman and Islam (2012)	• Feasibility of PV-wind-diesel hybrid system is studied for distributed generation in remote locations.	• The sensitivity analysis is not carried out.
10.	Lal and Raturi (2012)	• A wind/solar photovoltaic/diesel generator-based hybrid system is studied in terms of optimal configuration, net present cost and the cost of energy.	• The capacity shortage of the system is 10% for feasible hybrid system based on fully renewable energy resources. • The system reliability of the system can be improved by increasing storage capacity.

Based on the literature survey, it has been found that the size of each component of hybrid energy system needs to be optimized in order to make it technically and economically feasible. Based on the investigation of current status of hybrid energy system research, the research problem is formulated and methodology of the study is determined, which are given in next Chapter.

Chapter 3

PROBLEM FORMULATION

3.1 Statement of Problem

Increasing energy consumption and dependency on fossil fuels the world wide leads to energy shortage and global warming. The diesel generators are generally used in both on-grid and off-grid applications for reliable power supply. This is an expensive option and also causes pollution to the environment. There is a vast resource of renewable energy sources in the country which is not being utilized effectively. With the fast depletion of fossil fuels and continuous increase in diesel prices, there is a need to develop reliable diesel-renewable hybrid systems by utilizing the renewable sources available at the location of interest. Such hybrid systems can be a promising alternative to meet the energy needs in the universities, institutions, hospitals, Industry and remote villages. However, the design of a cost-effective and reliable hybrid energy system is complex due to integration of renewable energy sources with the diesel generator. The design of these systems require the accurate renewable energy resource analysis of the site as without which the hybrid system could be oversized which increases the cost of the system.

Therefore, in order to study the economic and technical feasibility of hybrid energy system, the renewable energy source analysis, feasibility analysis of various system configurations and the energy needs, is necessary.

3.2 Objectives

The main aim of the study is to utilize the available renewable resources in a complex hilly terrain to reduce the dependency on the conventional energy sources for meeting rapidly increasing energy needs. The objectives of the study are as follows:

1. To assess the feasibility of hybrid energy systems in a complex hilly terrain.
2. To simulate and optimize the hybrid energy system components
3. To carry out the techno-economic and feasibility analysis of a reliable hybrid energy system for uninterrupted power supply for National Institute of Technology, Hamirpur.

3.2 Methodology Followed: Summary

In order to fulfill the objectives of the study, following methodology is followed:

1) Assessment of solar and wind resource of Hamirpur, Himachal Pradesh, India.
2) Hourly load estimation and system specification data collection and Analysis
3) Simulation and optimization of hybrid systems using Hybrid Optimization Model for Electric Renewables
4) Techno-economic analysis, optimization and feasibility analysis of the Solar -Diesel –battery storage hybrid energy system for uninterrupted power supply

Chapter 4

METHODOLOGY

In this Chapter the methodology followed in the study is described. This includes solar and wind resource analysis of the site followed by modeling, simulation and optimization of components of hybrid energy systems using Hybrid Optimization Model for Electric Renewables [HOMER] software.

4.1 Data Collection and Analysis

The sources of energy used by the system to generate power are termed as resources. These resources may be renewable like solar, wind, hydro, and biomass as well as any non renewable fuels. The solar and wind resources are intermittent and depend on the location and environmental conditions. Therefore, resource assessment is an essential part of renewable energy system designing process. In this section, the data analysis of solar and wind resource of the location and its modeling using HOMER is described.

Solar radiation, wind speed and ambient temperature time series data is measured by the weather monitoring station located at Centre for Energy and Environment (CEE), National Institute of Technology, Hamirpur (NIT-H), [latitude :31°41' N and longitude :76°31'E in GMT + 5:30 time zone having altitude: 892.7m above sea level (Fig. 4.1)].

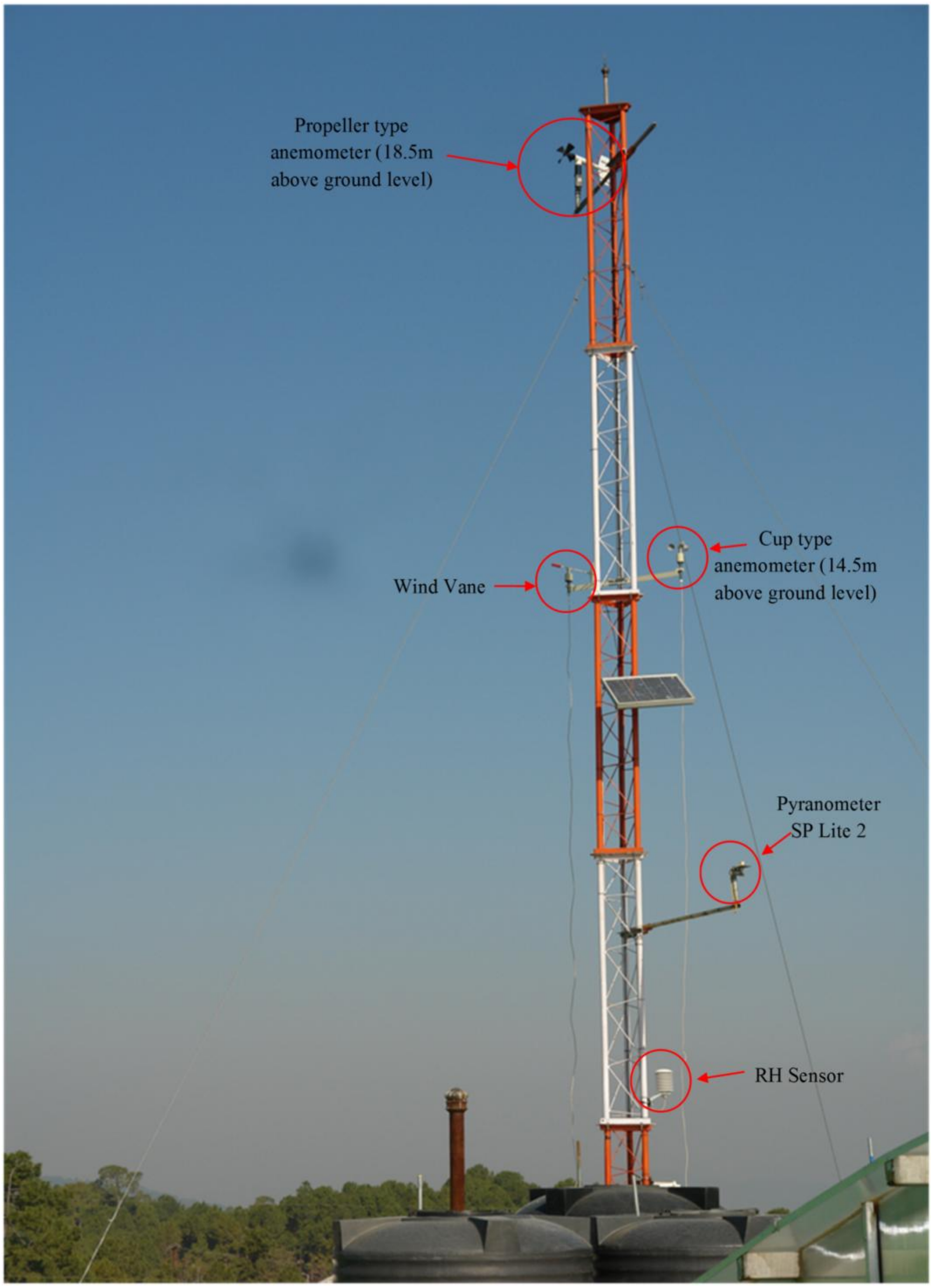


Fig. 4.1 Weather Monitoring Station located at CEE, NIT Hamirpur

The wind velocity is measured at 18.5m and 14.5m above ground level by two different types of anemometers namely Young's propeller type and a cup type anemometer respectively. The global solar radiation is measured using a Kipp & Zonen - Model: SP Lite2 pyranometer - which uses a photodiode detector, which generates voltage that is proportional to the incoming radiation. The ambient temperature is measured by model 108 temperature probe manufactured by Campbell Scientific, Inc which uses thermistor as sensor. Additionally, the weather monitoring station measures pressure, relative humidity, rainfall and soil temperature. The per minute data is stored in a Campbell CR1000 datalogger and downloaded using PC400 software. The time series data of one minute time step is collected for 2012 and analyzed to assess the resource potential at the site. The monthly average solar radiation, wind speed and temperature at CEE, NIT Hamirpur for 2012, are given in Table 4.1.

Table 4.1 Monthly average solar, wind and temperature data -2012

Month	**Solar Radiation ($kWh/m^2/day$)**	**Wind Speed (m/s)**	**Temperature (℃)**
January	2.609	2.034	20.1
February	3.216	2.243	22.2
March	4.925	2.308	18.6
April	5.479	2.412	22.7
May	6.351	2.475	28.4
June	5.886	2.532	30.8
July	4.364	1.727	35.7
August	3.782	1.825	34.9
September	4.249	1.782	34.6
October	4.375	1.901	32.5
November	3.433	1.816	28.8
December	3.026	1.911	24.1
Annual Average	**4.312**	**2.08**	**27.8**

4.1.1 Solar Resource Assessment

The extraterrestrial radiation is the intensity of solar radiation received on unit area outside the earth’s atmosphere. The extraterrestrial solar radiation varies with time because of continuously changing distance between sun and earth over the year. The daily variation of extraterrestrial solar radiation on horizontal surface is calculated by multiplying cosine of zenith angle with extraterrestrial normal radiation (Eq. 4.1). The extraterrestrial normal radiation is defined as the amount of solar radiation incident on a surface perpendicular to the rays coming from sun.

$$G_o = G_{on} \times \cos\theta_z \tag{4.1}$$

where

$$G_{on} = G_{sc} \times \left(1 + 0.033\cos\frac{360\times n}{365}\right) \tag{4.2}$$

$$\cos\theta_z = \cos\phi.\cos\delta.\cos\omega + \sin\phi.\sin\delta \tag{4.3}$$

Eq. 4.1 is integrated over hourly time step to calculate hourly extraterrestrial solar radiation on horizontal surface given by Eq. 4.4. The hourly extraterrestrial radiation calculated for the location is shown in Fig. 4.2.

$$\overline{G_o} = \frac{12}{\pi} \times G_{on} \times \{\cos\phi.\cos\delta.(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180}\sin\phi.\sin\delta\} \tag{4.4}$$

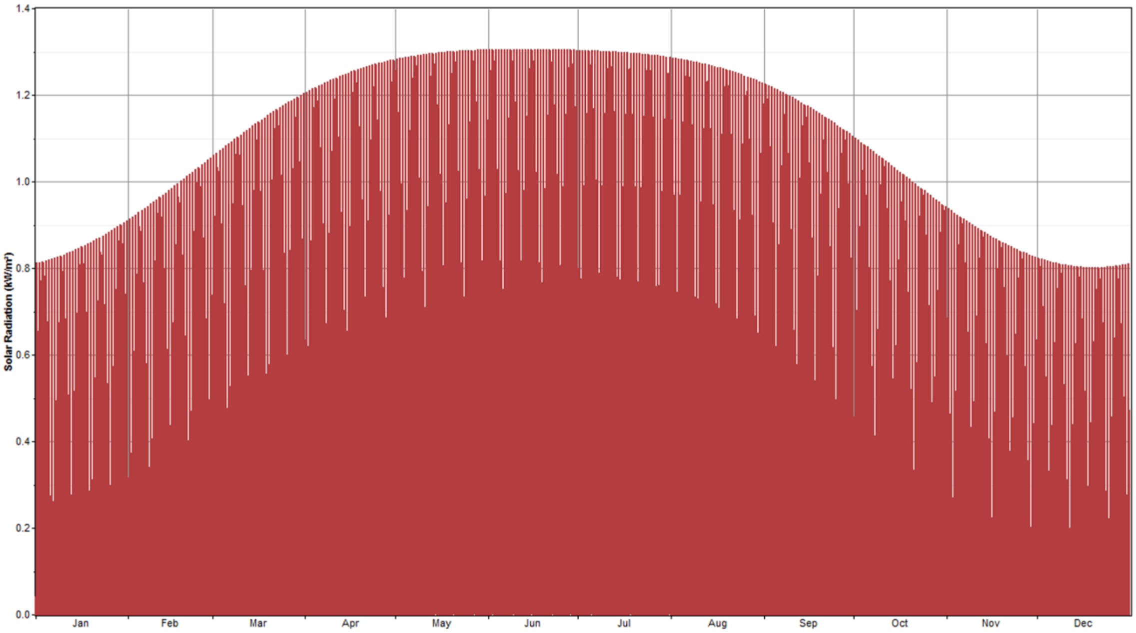


Fig. 4.2 Extraterrestrial hourly radiation at CEE, NIT Hamirpur

The time series data of one minute time step of horizontal solar radiation received on the earth's surface, measured at location, is averaged hourly to obtain hourly solar radiation (Fig. 4.3).

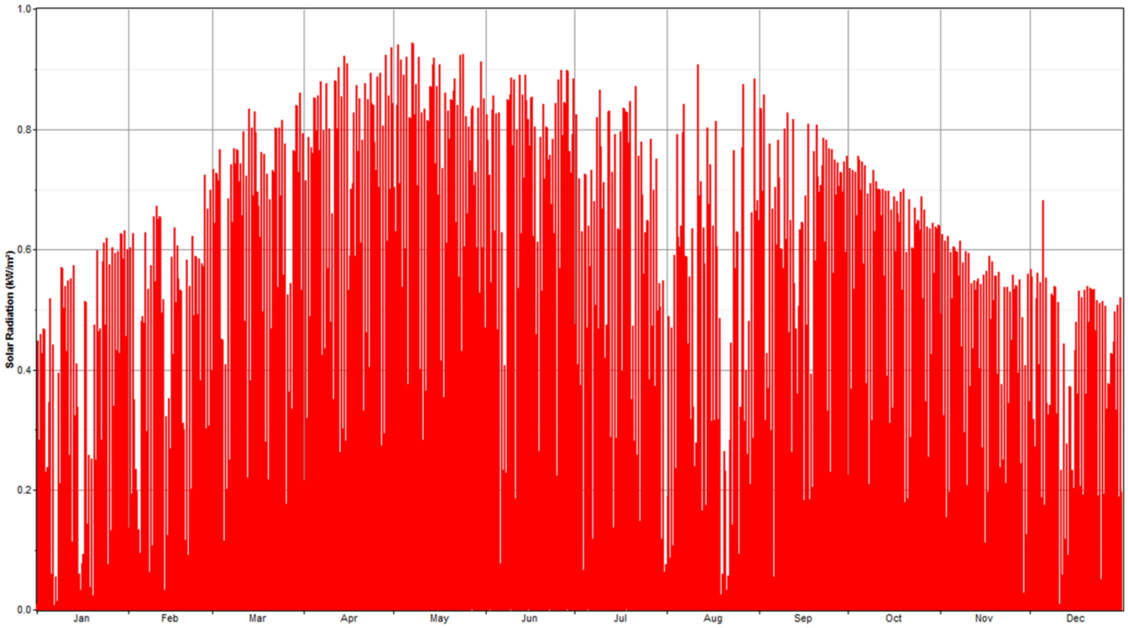


Fig. 4.3 Hourly averaged global solar irradiance at the horizontal surface measured at location

The clearness index is the ratio of solar radiation striking on the horizontal surface of the earth to the extraterrestrial solar radiation (Eq. 4.5). The monthly average irradiation varies from 2.609kWh/m^2 to 6.317kWh/m^2 and the annual average irradiation is found to be 4.312kWh/m^2/day at the site with average clearness index (k_t) of 0.501. The monthly average global horizontal solar radiation and clearness index is shown in Fig. 4.4. The daily profile of solar radiation of each month throughout the year is shown in Fig. 4.5.

$$k_t = \frac{\overline{G}}{\overline{G}_o} \tag{4.5}$$

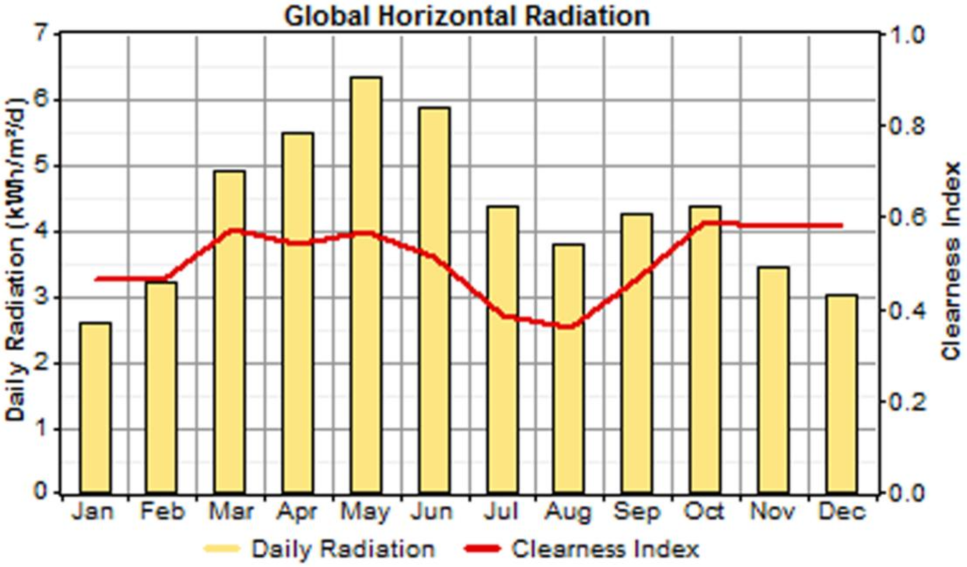


Fig. 4.4 Monthly global solar radiation and clearness index at CEE, NIT Hamirpur

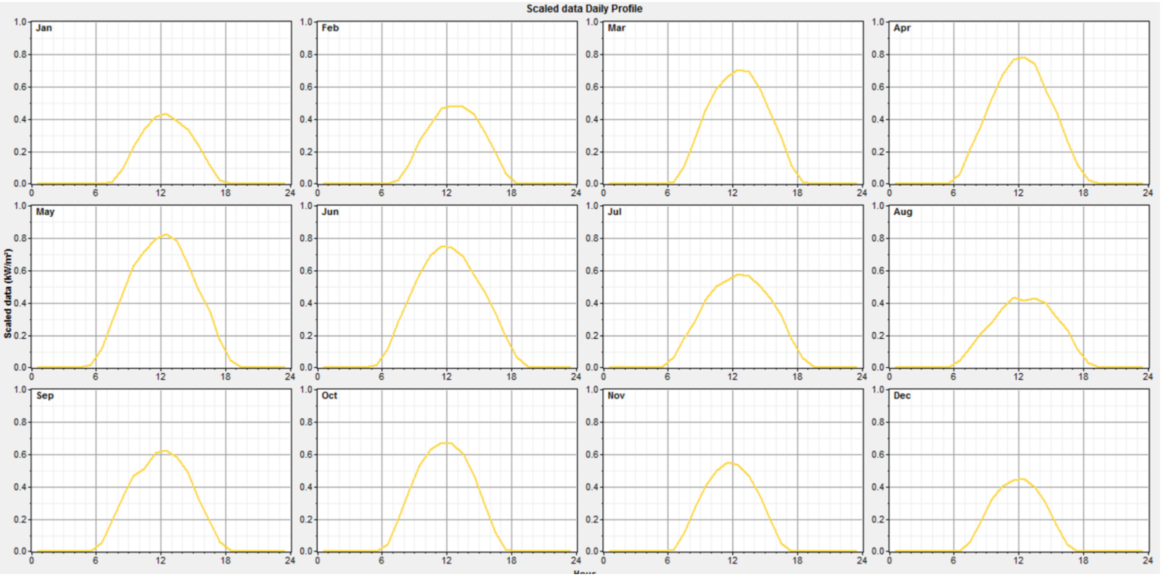


Fig. 4.5 Daily profile of solar irradiance

4.1.2 Wind Resource Assessment

The wind speed data measured at 18.5m height above ground is used to assess the wind resource of the location. The monthly average wind velocity at the site is found to vary from 1.727 m/s to 2.532 m/s with annual average wind velocity of 2.079 m/s. The hourly average wind resource of the site shows that there are various periods during the year when wind speeds are above 3 m/s (Fig. 4.6).

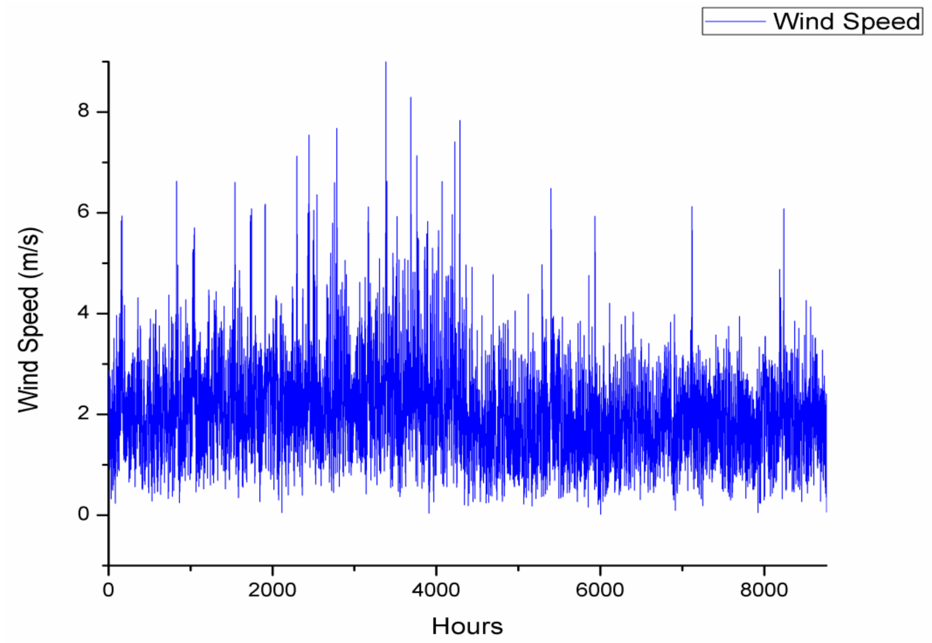


Fig. 4.6 Hourly average wind speed at CEE, NIT Hamirpur

The duration curve of wind velocity is shown in Fig. 4.7 which depicts that the wind speed is more than 3 m/s for about 1247 hours and from 4-10 m/s range for 304 hours in a year. The objective of studying wind resource is to understand the contribution of different wind speeds even of short duration during the year so as to utilize the available wind resource.

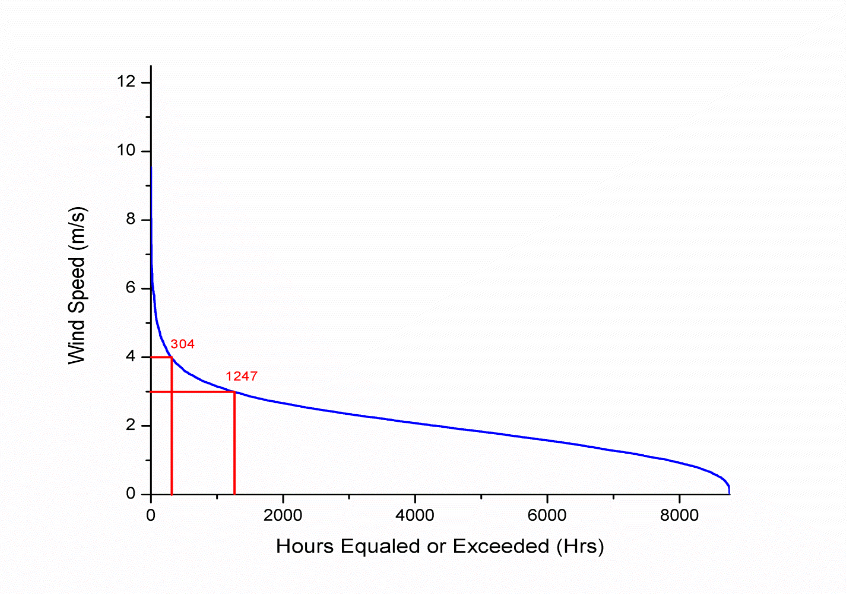


Fig. 4.7 Duration curve of wind speed at the site

The Weibull probability density function is a special case of gamma distribution which used to obtain wind speed probability distribution (Stevens and Smulders, 1979). This function is characterized by its probability density function (Eq. 4.6) and cumulative distribution function (Eq. 4.7).

$$f_w(v) = \begin{cases} \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} ; v > 0 \\ 0 ; v \le 0 \end{cases} \tag{4.6}$$

$$F_w(v) = 1 - e^{-\left(\frac{v}{c}\right)^k} \tag{4.7}$$

The Weibull shape (k) and scale parameters (c) are calculated using HOMER and found to be k= 2.29 and c= 2.35 m/s (Fig. 4.8). The Weibull shape parameter describes the stability of wind speed while scale parameter indicates wind speed magnitudes. Autocorrelation factor (typically 0.80 and 0.95) is the measure of hourly wind speed dependency on wind speeds in previous hours. The autocorrelation factor for this location is calculated as 0.692 which indicates wind velocity is highly variable with time at this location.

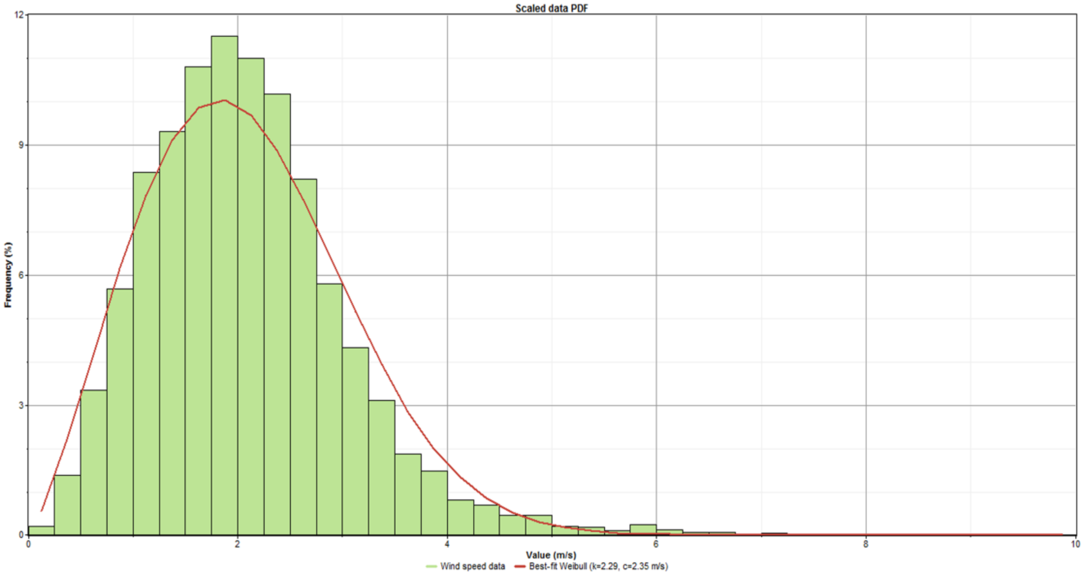


Fig. 4.8 Probability distribution function of wind velocity for the location

4.1.3 Temperature Data

The ambient temperature of the site is an influencing parameter to the PV power generation. The efficiency of PV cell decreases with increasing cell temperature because of negative temperature coefficient of power and the PV cell temperature exceed the ambient temperature by 30℃ or more during the sunshine hours. The hourly averaged ambient temperature, as shown in Fig. 4.9, is calculated from time series data of one minute time step measured at the site and is used to calculate PV cell temperature.

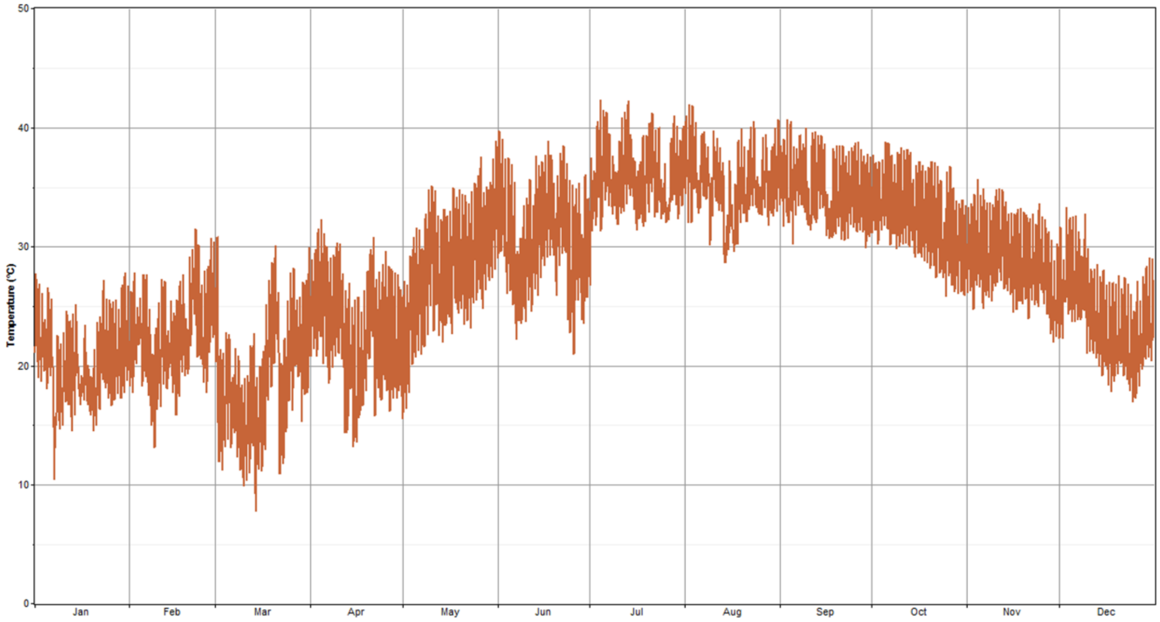


Fig. 4.9 Hourly average ambient temperature of the site (℃)

4.2 Modeling of Hybrid Energy Systems Components

The Hybrid Optimization Model for Electric Renewables (HOMER) is developed by NREL, USA to design and optimize the hybrid systems for wide range of applications. The HOMER 2.68 beta version is used in this study. It simulates the technical and economic behavior of hybrid energy systems to compare different power generation options. It also assists in understanding and quantifying the effects of uncertainty in the inputs. It can model both grid-connected and off-grid power systems comprising of PV modules, wind turbines, small hydro, biomass power, reciprocating engine generators, micro-turbines, fuel cells, batteries, and hydrogen storage for serving electric and thermal loads.

HOMER is used to carry out simulation, optimization, and sensitivity analysis. In the simulation process, it models the hourly performance of a power generation system configuration for techno-economic analysis of the system. In the optimization process, it simulates many different system configurations to determine optimum configuration that satisfies the technical constraints at the lowest net present cost. In the sensitivity analysis process, this software performs multiple optimizations for range of assumptions of single input to assess the effects of uncertainty in the variables such as the average solar radiation, average wind speed or the future fuel price.

4.2.1 Modeling of solar PV system

Photovoltaic power is highly influenced by solar radiation and PV cell temperature. The power produced by PV module is directly proportional to the global solar radiation incident on its surface and inversely proportional to the surface temperature of the PV array named as PV cell temperature. Thus, solar radiation on tilted plane of PV array and PV cell temperature are two important parameters. Generally the solar radiation is measured at horizontal surface; therefore the global solar radiation on tilted surface is calculated by using the relations as given in Duffie and Beckman (2006). The global solar radiation incident on tilted surface ($\overline{G_t}$) is calculated by

$$\overline{G_t} = \left[(\overline{G_b} + \overline{G_d}.A_i) \times R_b \right] + \left[\overline{G_d} \times (1 - A_i) \times \left(\frac{1 + \cos\beta}{2} \right) \times \left\{ 1 + f \sin^3 \left(\beta/2 \right) \right\} \right] + \left[\overline{G} \times \mu \times \left(\frac{1 + \cos\beta}{2} \right) \right] \qquad (4.8)$$

where $\overline{G_b}$ and $\overline{G_d}$ are the beam and diffuse radiation, the two components of global solar radiation. The diffuse solar radiation is defined as the scattered solar radiation which is coming from all directions of the sky and is calculated by a correlation given by Erbs et al. (1982) as function of clearness index (Eq. 4.9). The clearness index is calculated by Eq. 4.5. The beam radiation is defined as the direct solar radiation which travels from sun to earth without scattering and is calculated by subtracting diffuse solar radiation from global solar radiation.

$$\frac{\overline{G_d}}{\overline{G}} = \left\{ \begin{array}{cl} 1.0 - 0.09k_t & \text{for} \quad k_t \le 0.22 \\ 0.9511 - 0.1604k_t + 4.388k_t^{\,2} - 16.638k_t^{\,3} + 12.336k_t^{\,4} & \text{for} \;\; 0.22 < k_t \le 0.80 \\ 0.165 & \text{for} \quad k_t > 0.80 \end{array} \right\} \quad (4.9)$$

R_b is the relation of beam radiation on the tilted surface with the beam radiation on horizontal surface, named as the geometric factor, and is determined by the ratio of cosine of incidence angle to that of zenith angle

$$R_b = \frac{\cos\theta}{\cos\theta_z} \tag{4.10}$$

A_i is the anisotropy index which is the measure of the environmental transmittance of beam radiation and calculated by

$$A_i = \frac{\overline{G_b}}{\overline{G_o}} \tag{4.11}$$

And f is the factor used to account the fact that more diffuse radiation comes from the horizon in comparison from rest of the sky and is calculated by

$$f = \sqrt{\frac{\overline{G_b}}{\overline{G}}} \tag{4.12}$$

The PV cell temperature (T_c) is calculated from global solar radiation incident on tilted surface and ambient temperature of the location by using.

$$T_c = \frac{T_a + (T_{cn} - T_{an})\left(\frac{G_t}{G_{tn}}\right)\left\{1 - \frac{\eta_{mp}(1 - \alpha_p T_{stc})}{\tau\alpha}\right\}}{1 + (T_{cn} - T_{an})\left(\frac{G_t}{G_{tn}}\right)\left\{\frac{\eta_{mp}\alpha_p}{\tau\alpha}\right\}} \tag{4.13}$$

The output power from PV array is modeled in HOMER by assuming that it linearly depends on the solar radiation incident on it is given by

$$P_{pv} = P_r D_{pv}\left(\frac{\overline{G}_t}{\overline{G}_{stc}}\right)\left\{1 + \alpha_p (T_c - T_{stc})\right\} \tag{4.14}$$

where P_r is the rated capacity of the PV array, the amount of power produced under standard test conditions (STC) defined by 1000W/m^2 irradiance, 25℃ PV cell temperature and 1.5 air mass.

4.2.2 Modeling of wind turbine

Wind turbine converts the kinetic energy of the wind into electric energy. HOMER model the power output of wind turbine by its power curve, a graph between power output and wind speed. It is assumed that the power curve is applied at standard air density (ρ) of 1.225kg/m^3. To calculate power output from wind turbine at hub height, firstly hourly average wind speed at anemometer height is determined; secondly the wind speed is extrapolated from anemometer height to hub height by using either power law or logarithmic law; thirdly the power output is calculated for standard air density; finally it multiplies the power output with air density ratio.

4.2.3 Modeling of diesel generator

An electric dynamo connected with engine which consumes fuel to produce electricity and release heat and gases as a by-product. HOMER models a variety of generators, such as internal combustion engine generators, fuel cells, Stirling engines, thermo-photovoltaic generators, and thermoelectric generators. An IC engine generator which consumes diesel as fuel is used in the study and named as diesel generator. The fuel consumption of the diesel generator is calculated by

$$F = F_0 P_{r,gen} + F_1 P_{gen} \tag{4.15}$$

Where F_0, named as fuel curve intercept coefficient, is the no-load fuel consumption of generator to produce unit of rated power (0.08 L/hr/kW rated) and F_1 is the marginal fuel consumption of the generator (0.25 L/hr/kW output). $P_{r,gen}$ is rated capacity of generator and P_{gen} is power produced by the generator.

The burning of fuel results in emission of pollutants and HOMER calculates six of them namely carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbons (UHC), particulate matters (PM), sulfur dioxide (SO_2) and nitrogen oxides (NO_x).

4.2.3 Modeling of battery storage

The battery bank is a collection of one or more individual batteries connected in series to make strings of bus voltage and the strings are connected in parallel combination to increase the capacity. HOMER models the kinetic battery model to store certain amount of energy at fixed round-trip energy efficiency, with limited charging or discharging rate, depth of discharge and lifetime throughput (Manwell and McGowan, 1993). It is assumed that the properties of the batteries are not affected by time and environmental conditions. The life of the battery bank can be estimated by monitoring the amount of energy cycling through it, without having to consider the depth of the various charge–discharge cycles.

$$R_{batt} = \min\left(\frac{n_{batt} Q_{lifetime}}{Q_{annual}}, R_{batt,f} \right) \tag{4.16}$$

where R_{batt} is lifetime of the battery, n_{batt} is the number of batteries in the battery bank, $Q_{lifetime}$ the lifetime throughput of a single battery, Q_{annual} is the annual throughput and $R_{batt,f}$ is the float life of the battery.

4.2.4 Modeling of grid

An electrical grid is an interconnected network for delivering electricity to consumers which consists of power plants, high-voltage transmission lines and distribution lines. The grid is modeled by HOMER as a source of power from which the hybrid system can purchase ac electricity and to which the excess electricity can be sold. The software also includes the net metering under which the consumer has to pays bill for net grid purchases if purchases exceed sales, whereas the utility pays the consumer for the net grid sales, if sales exceed purchases. The capacity of the grid is described by maximum power sale and maximum grid demand. It calculates the emission of pollutants resulting from grid power purchases using emission coefficient depending upon the source of power generation. If the majority of the electricity is produced from coal, the emission coefficient will be relatively high because burning coal results in large emissions of pollutants. Natural gas generation results in somewhat lower emissions and nuclear and hydro generation result in zero emission. The fixed cost of grid is zero, and the marginal cost is equal to sum of the grid power price and emission penalties.

4.2.5 Control strategy Modeling

The operations of system and dispatch strategies are defined in control inputs. The operation of entire system is simulated for 60 minutes time step. The length of simulation time step can be changed (decreases or increases) but with the decrease of length of time step the calculations increases which results in increased processing overhead whereas increasing time step decrease the accuracy of results.

HOMER determines whether the renewable power sources are capable of supplying the electric load to make decision on the operation of generator. If the generator is in operation then the dispatch strategy of it ,is also decided. The two dispatch strategies can be modeled in HOMER to determine whether the generator should charge the battery bank. The two dispatch strategies are load following and cycle charging (Barley and Winn, 1996). In load following, the generator will run to serve only load while in cycle following, the generator will run at its full capacity to serve load as well as to charge battery bank. The dispatch strategy is determined on the basis of cost minimization of the system. Other settings that affect the type of systems and their operation are following:

- Allow systems with multiple generators (*Allowed in present study*)
- Allow multiple generators to operate simultaneously (*Allowed in present study*)
- Allow systems with generator capacity less than peak load (*Allowed in present study*)
- Allow systems with two types of wind turbines (*Not Applicable*)
- Allow excess electricity to serve thermal load (*Not Applicable*)
- Limit the system from producing too much excess thermal power (*Not Applicable*)

4.3 Simulation of Hybrid Energy Systems

4.3.1 Simulation of Solar PV-Wind Hybrid System

A 6kWp solar - wind hybrid system consisting of 1kWp solar PV, 5kW wind turbine, 4kW converter and 150Ah battery bank, is installed on the rooftop of CEE, NIT Hamirpur building (Fig. 4.10).

Fig. 4.10 Solar-wind-battery hybrid system installed at CEE, NIT Hamirpur

1 kWp south facing PV array consisting of 10 polycrystalline silicon PV panels of 100 W_p each, are mounted at 30°. The efficiency of PV array at STC is 13%. D_{pv} is the derating factor which includes the effect of temperature, intensity, module mis-match, dust, losses in wires etc on the PV power in external operating conditions. The derating factor is taken as 80% in this study which means 20% of the power produced is lost due to above mentioned factors. The slope angle is the angle between plane of the PV surface

and horizontal. It is important to optimize the tilt angle for maximum solar radiation capture for the location. The various methods for the determination of optimum tilt angles for a site of interest are described by Yadav and Chandel (2013). The annual optimum tilt angle of PV array for the site is found to be 27.1° which is used for the optimizing the hybrid system (Yadav and Chandel, 2013). However, the techno-economic analysis of 6kWp solar-wind hybrid system is inclined at 30° is done using HOMER. The azimuth angle is taken as 0° and ground reflectance is 20%. The temperature coefficient of power is -0.5%/℃. The PV system specifications are given in Table 4.2.

Table 4.2 PV system specifications

Description	**Specification**
Manufacturer	Sun Energy Systems
Model	SES-M-12125
PV module material	Polycrystalline
Peak power (Pm)	100 Wp
Voltage at peak power (Vm)	17 V
Current at peak power (Im)	5.9 A
Open circuit voltage (Voc)	21 V
Short circuit current (Isc)	6.4 A
Efficiency	13%
Capital cost of PV system	$ 5057
Replacement cost of PV system	$ 5057
Operation and maintenance cost	$ 0
Estimated lifetime	25 years

A 5kWp horizontal axis micro-wind turbine SNT-50 model of Supernova Technologies Ltd., Anand, Gujrat, India with hub height 28.5m is used to generate and utilize wind resource for power generation. The 5kWp turbine is using direct-drive synchronous permanent magnet 3-phase ac electric generator. The use of direct drive generator reduces installation complexities and wear & tear which in turn reduces installation and maintenance cost as compared to generator with gear box. A tale is used to orient the wind turbine towards the direction of wind. The power curve of SNT- 50 as supplied by the manufacturer is shown in Fig. 4.11.

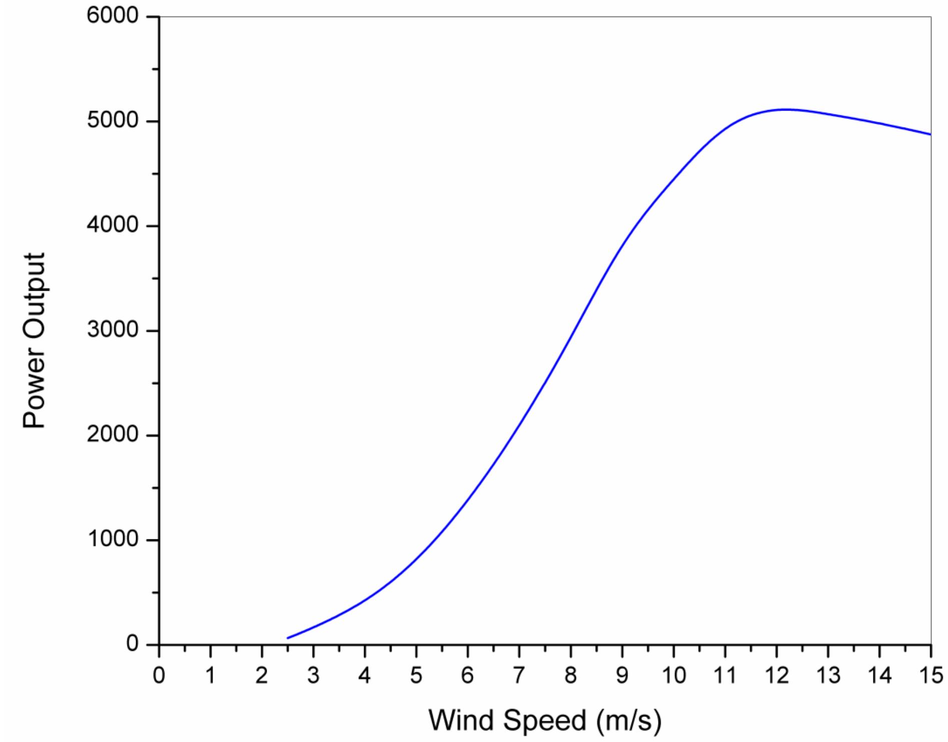


Fig. 4.11 Power curve of 5kW$_p$ wind turbine SNT-50

The power curve of wind turbine shows the electric power output of wind turbine for a given wind speed. The cut-in speed at which the turbine starts to generate power is 2.5 m/s for SNT-50 wind turbine which shows that it requires a very less starting torque and can generate power efficiently at lower wind speeds also. The power law with exponent 0.14 is used in this study to vertically extrapolate the wind speed. The available power of the wind of velocity *v* through an area *A* is given as

$$P_w = \frac{1}{2}\rho A v^3 \tag{4.17}$$

The aerodynamic performance of a wind rotor is defined by the power coefficient as $C_p = P_{rotor}/P_w$. Therefore, power extracted by the wind rotor is given as

$$P_{rotor} = \frac{1}{2}C_p \rho A v^3 \tag{4.18}$$

The specifications of the wind turbine are given in Table 4.3.

Table 4.3 Wind turbine specifications

Description	**Specifications**
Manufacturer	Supernova Technologies Ltd.
Model	SNT-50
Rotor diameter	6.09 m
Rated power	5 kWp
Cut-in wind speed	2.5 m/s
Equivalent rated wind speed	11 m/s
Blade material	Fibre-reinforced plastic (FRP)
Generator type	Permanent magnet 3 phase alternator
Tower	Tripod structure
Capital cost	$ 15016
Replacement cost	$ 7038
Operation and maintenance cost	$ 70/ year
Estimated lifetime	25 Years

Due to intermittent nature of both solar and wind energy, energy storage is needed to supply electric power continuously. A battery bank of 150 Ah rated capacity with 20% maximum allowed depth of discharge is used for energy storage in this system. The 120 V battery bank consists of ten 12 volt Exide inva-tubular IT-500 lead-acid batteries, connected in series. The technical and economic specifications of battery bank are given in Table 4.4.

Table 4.4 Specifications of Battery Storage

Description		**Specifications**
Manufacturer		Exide Industrial
Model		Invatubular IT-500
Capacity at 27℃		150 Ah
Dimension (+/-3mm)	Length	500mm
	Width	187mm

	Height	430mm
Weight (kg+/-5%)	Dry	33.80 kg
	Filled	60.05 kg
Volume of electrolyte		23.80 Litres
Capital cost per string (10 Batteries)		$ 2566
Replacement cost per string (10 Batteries)		$ 2000
Operation and maintenance cost		$ 30/year

The electricity produced by the hybrid system is used to cater the load of faculty rooms and office of CEE, NIT Hamirpur (Table 4.5). The remaining power after serving the load is stored in the battery bank. The hourly load profile of CEE being catered by the hybrid system for the entire year is shown in Fig. 4.12.

Table 4.5 Load catered by solar-wind-battery hybrid system

Hour of Day	**Jan-May & Aug-Dec**		**June-July**	
	Weekdays Load (kW)	**Weekends Load (kW)**	**Weekdays Load (kW)**	**Weekends Load (kW)**
00:00 - 01:00	0	0	0	0
01:00 - 02:00	0	0	0	0
02:00 - 03:00	0	0	0	0
03:00 - 04:00	0	0	0	0
04:00 - 05:00	0	0	0	0
05:00 - 06:00	0	0	0	0
06:00 - 07:00	0	0	0	0
07:00 - 08:00	0	0	0	0
08:00 - 09:00	0	0	0	0
09:00 - 10:00	0.5	0	0	0
10:00 - 11:00	0.8	0	0	0
11:00 - 12:00	0.8	0	0.2	0
12:00 - 13:00	0.8	0	0.2	0
13:00 - 14:00	0.8	0	0.2	0

14:00 - 15:00	0.8	0	0.2	0
15:00 - 16:00	0.8	0	0.2	0
16:00 - 17:00	0.8	0	0.2	0
17:00 - 18:00	0	0	0.2	0
18:00 - 19:00	0	0	0	0
19:00 - 20:00	0	0	0	0
20:00 - 21:00	0	0	0	0
21:00 - 22:00	0	0	0	0
22:00 - 23:00	0	0	0	0
23:00 - 00:00	0	0	0	0

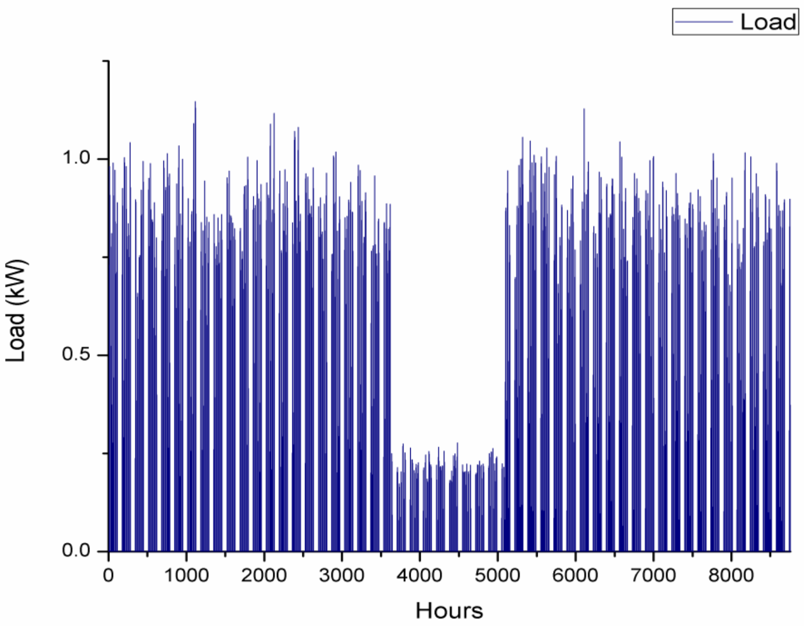


Fig. 4.12 Annual hourly load profile of CEE (2012)

The load demand is less during summers, as only office remains open in the month of June-July due to vacations. The average daily load demand, average energy demand, peak load demand and load factor of the building are 0.156kW, 3.75kWh/d, 1.15kW and 0.136 respectively. The daily and hourly random variability of load is taken as 10%.

The solar-wind-battery hybrid system is integrated as DC-Coupled system in which AC power from wind energy is converted into DC and then connected to DC bus along with DC power from solar photovoltaic (Fig. 4.13).

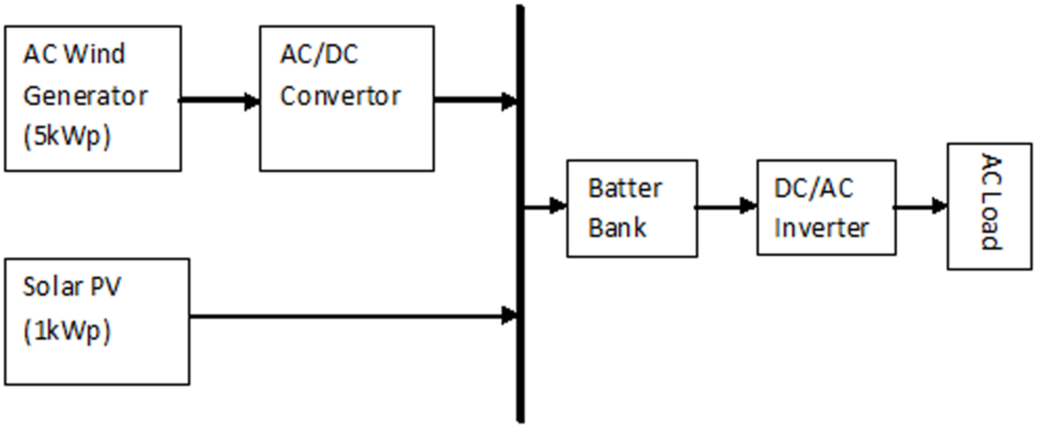


Fig. 4.13 Schematic Diagram of 6 kWp Wind-Solar hybrid system

The economics of system is given in US dollar ($1=Rs. 53 as on 05-02-2013). The projected lifetime of the system is estimated as 25 years. The fixed capital cost of the system, which includes cost of control room, is $1358.5. The configuration of the simulated system in HOMER is shown in Fig. 4.14.

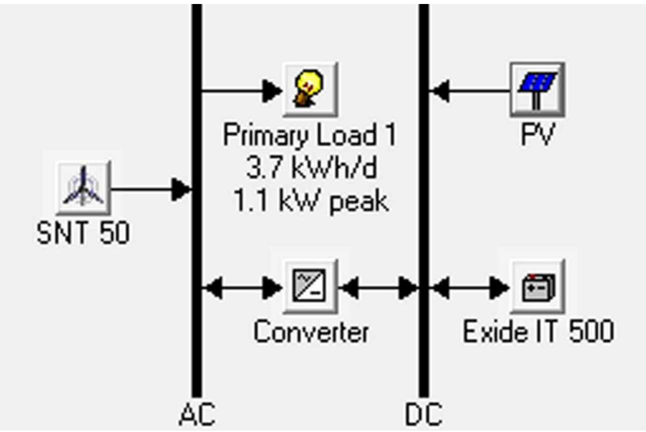


Fig. 4.14 6kWp solar-wind hybrid system configuration (HOMER)

4.3.2 Simulation of Solar-Diesel Hybrid System

A central uninterrupted power supply (UPS) system with diesel generators backup is installed at NIT Hamirpur so as to supply power during grid failure. The system is serving to critical load of computer centre, computer labs of all departments, faculty rooms and academic offices of the institute. The system uses grid as power source to charge the battery bank and two automatic operated diesel generators (128kW and 256 kW) as backup power source (Fig. 4.15).

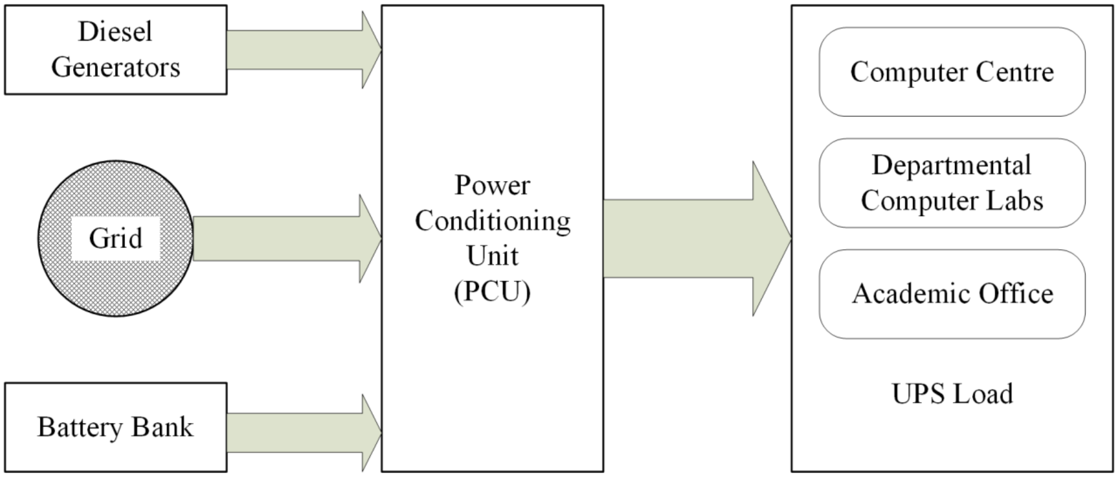


Fig. 4.15 Schematic Diagram of UPS system installed at NIT Hamirpur

The existing system is run by electrical power maintenance division of NIT Hamirpur. The system has two backup diesel generators of Sudhir Gensets and Mahindra & Mahindra Ltd., India, with rated capacity 128kW (160 kVA) and 256 kW (320 kVA) respectively. The grid supply is generally uninterrupted at NIT Hamirpur and the breakdowns are rare and that too for very short duration. The cost of grid purchase is \$0.085 (Rs. 4.5) per kWh. The battery bank is sufficient to cater to load during the short period when the grid supply is off. Because of continuous grid supply at the location the two diesel generators are utilized for negligible periods in a year as per the record of fuel consumed by diesel generator in 2011 at NIT Hamirpur (Table 4.6).

Table 4.6 Fuel consumption by diesel generator at NIT Hamirpur during year 2011

Month	**Fuel consumption (Ltrs.)**	**Rate of diesel (Rs.)**	**Total cost (Rs.)**
January	23	38.62	888.26
February	33	38.62	1274.46
March	35	38.62	1351.7
April	164	38.62	6333.68
May	201	38.62	7762.62
June	205	38.62	7917.1
July	29	38.62	1119.98
August	103	38.62	3977.86
September	39	38.62	1506.18
October	161	38.62	6217.82
November	30	38.62	1158.6
December	24	38.62	926.88
Total	**1047**	**38.62**	**40435.14**

The diesel generator manufactured by Mahindra & Mahindra Ltd. of rated capacity of 256kW is used to simulate the solar diesel hybrid system. In case of standalone system, the diesel generator operates in optimized mode during sunshine hours (8:00 AM to 6:00 PM) while operates in 'forced on' mode for night hours (6:00 PM to 8:00 AM) for all weekdays. In case of grid interactive system, the diesel generator run in optimized mode during entire day for all weekdays. The 99.5% of carbon in the fuel is emitted in the form of carbon dioxide. The technical and economic specifications diesel generator is given in Table 4.7. The emission factors which are used to calculate annual amount of emission caused by diesel generator are given in Table 4.8.

Table 4.7 Specifications of diesel generator

Description	**Specifications**
Manufacturer	Mahindra Powerol
Model	64205GC
Rated power	320 kVA (256 kW)
Output Voltage	415 V
Frequency	50Hz
Power factor	0.8
No. of phases	3 Phases
Fuel consumption @75% load	51.1 Ltr/hr
Fuel consumption @100% load	66.6 Ltr/hr
Capital cost	$31,926
Replacement cost	$31,926
Operation & maintenance cost ($/hour)	$0.20/hr
Diesel price	$0.93/Ltr.

Table 4.8 Emission factors of diesel generator

Emission factor	**Amount (g/Litre of fuel)**
Carbon monoxide	6.5
Unburned hydrocarbons	0.72
Particulate matters	0.49
Nitrogen oxides	58

In the present system simulation, the hybrid system is connected to the grid in such a manner that it can only purchase electricity therefore the value of maximum power sale is set to be zero. The system is designed for Himachal Pradesh, India where enough hydro power resource is available and maximum of the electricity supplying in grid is generated by hydro power generation plants. Therefore, neither the emission coefficients nor the emission penalties are taken in account for the present study.

The convertor is device which acts as AC/DC inverter and DC/AC rectifier to transform the form of power supply. The convertor of 144 kW rated capacity manufactured by Riello PCI India Pvt. Ltd., a joint venture of RPS S.p.A, Italy and PCI Ltd, India, is installed in UPS system. The technical and economic specifications of converter are given in Table 4.9.

Table 4.9 Specifications of convertor used in UPS system

Description	**Specifications**
Manufacturer	Riello PCI India Pvt. Ltd.
Model	MPT-160
Rated capacity	144kW
Efficiency	94%
Input voltage	400 V ± 20%
Frequency	45 Hz to 65 Hz
Capital cost	$29,245
Replacement cost	$29,245
Operation & Maintenance cost	$0

The absorbent glass mat sealed (AGM) deep-cycle lead-acid batteries manufactured by Rocket Batteries Ltd. are used in the battery bank of UPS system. AGM battery is a type of valve-regulated lead–acid (VRLA) battery which do not require maintenance i.e. addition of water. The electrolyte of these batteries is absorbed in a fiber-glass mat separator. These batteries have a pressure relief valve. The valve activates during charging at high voltage to release hydrogen. The battery having nominal voltage of 12V and nominal capacity of 120Ah each is installed in the system. The 34 number of batteries are connected in series to make a string of 408V. The technical and economical specifications of battery bank are as follows in Table 4.10.

Table 4.10 Specifications of battery bank installed in UPS system

Description	**Specifications**
Manufacturer	Rocket batteries
Model	ESC 120-12FR
Nominal capacity	120 Ah
Nominal voltage of each battery	12 V

Nominal voltage of battery bank (String)		408V
Dimension (+/- 3mm)	Length	410mm
	Width	176mm
	Height	227mm
Capital cost per string (34 batteries)		$6,390
Replacement cost per string (34 batteries)		$6,390
Operation & maintenance cost		0

The annual average energy demand of a day is 1855kWh/day with annual average load of 77.3 kW and peak load of 158 kW. The computer server and other network & communication devices in the computer centre are operational for 24 hours. This constitutes a fixed load of 61 kW for UPS. The 9:00 to 17:00 hours of weekdays are working hours with peak load. The most of the supplied load is operational during these hours. The UPS load starts decreasing after 17:00 and during evening hours of 17:00 to 20:00, it fell down to 100kW because the academic office is closed but still the computer centre, departmental computer lab and faculty rooms are engaged with students and faculties. During night hours 20:00 to 24:00, the internet service is provided in the hostels increases the load of computer centre but at the same time the load of faculty rooms and departmental computer lab cut down to make net average load of 83kW. The day time load is dropped down to 83 kW in weekends and the summer vacations during the months of May, June and July. The hourly load of NIT Hamirpur being supplied by UPS is shown in Fig. 4.16 and given in Table 4.11.

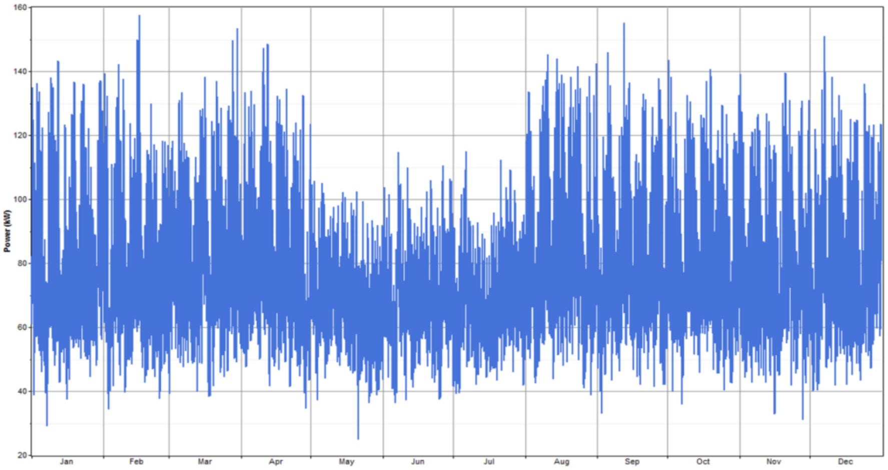


Fig. 4.16 Hourly UPS load of NIT Hamirpur

Table 4.11 Hourly load catered by UPS at NIT Hamirpur

Time of the day	Jan-April and Aug-Dec		May, June and July	
	Weekdays	Weekends	Weekdays	Weekends
Hour	Load (kW)	Load (kW)	Load (kW)	Load (kW)
00:00 - 01:00	61	61	61	61
01:00 - 02:00	61	61	61	61
02:00 - 03:00	61	61	61	61
03:00 - 04:00	61	61	61	61
04:00 - 05:00	61	61	61	61
05:00 - 06:00	61	61	61	61
06:00 - 07:00	61	61	61	61
07:00 - 08:00	61	61	61	61
08:00 - 09:00	61	61	61	61
09:00 - 10:00	110	83	83	83
10:00 - 11:00	110	83	83	83
11:00 - 12:00	110	83	83	83
12:00 - 13:00	110	83	83	83
13:00 - 14:00	110	83	83	83
14:00 - 15:00	110	83	83	83
15:00 - 16:00	110	83	83	83
16:00 - 17:00	110	83	83	83
17:00 - 18:00	100	61	61	61
18:00 - 19:00	100	61	61	61
19:00 - 20:00	100	61	61	61
20:00 - 21:00	83	61	61	61
21:00 - 22:00	83	61	61	61
22:00 - 23:00	83	61	61	61
23:00 - 00:00	83	61	61	61

The specifications given in Table 4.2 are used for PV system. The present cost of PV system is $2264 per kW (Rs. 1,20,000/kW) as on 20.05.13 (NPD Solar Buzz). The real interest rate of India is 2.01% as last reported in 2011 (Trade Economics) which is used to calculate net present cost. The simulated system configurations are shown in Fig. 4.17(a&b).

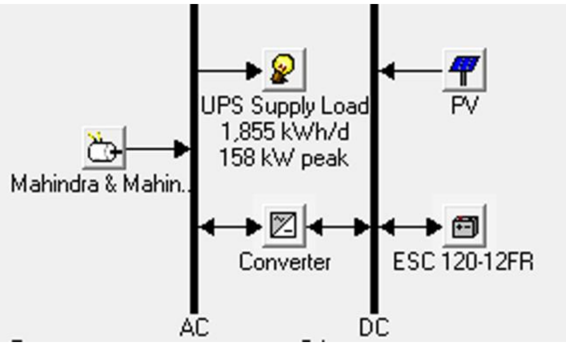


Fig. 4.17a Configuration of standalone solar-diesel generator hybrid system

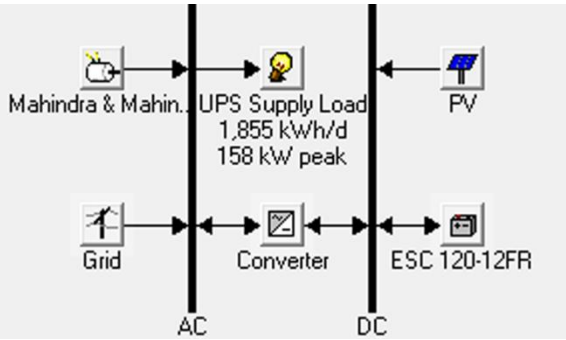


Fig. 4.17b Configuration of grid interactive solar-diesel generator hybrid system

4.4 Optimization of Hybrid Energy Systems

The HOMER optimizes the system configurations for single objective i.e. to minimize the net present cost, with flexibility in determining constraints. Constraints are the necessary conditions for feasible systems. The unfeasible system configurations are discarded by the software and feasible configurations are arranged in the ascending order of net present cost. The main constraints are maximum annual capacity shortage, minimum renewable energy fraction and operating reserve. The value of minimum renewable fraction and operating reserve is zero for the present study. The objective function is the modeling of aim of the optimization with constraints and search space. The objective function of two case studies i.e. solar wind hybrid system and solar diesel hybrid system are as follows:

4.4.1 Objective function of solar-wind hybrid system

The objective of the optimization of solar wind hybrid system is to minimize the net present cost (NPC) of the system with 0%, 5%, 10% and 20% capacity shortage and state of charge of battery bank should not be less than 80%. The formulated objective function with constraints is given by

$$\min \sum NPC \tag{4.19}$$

Constraints: 80%≤SOC≤100%

Capacity Shortage = 0%, 5%, 10% and 20%

The search space for optimization of hybrid system that includes the sizes and quantities of the system components is shown in Table 4.12.

Table 4.12 Search space for the optimization of solar-wind hybrid system

System	**Combinations**
Wind turbine	0, 1, 2, 3, 4, 5 (quantity in numbers)
PV array	0.5, 1, 2, 3, 4, 5 (size in kWp)
Battery bank	0, 1, 2, 3, 4, 5 (number of strings)
Converter	0.5, 1, 2, 3, 4, 5 (size in kWp)

While expecting reliability from renewable power resources, the cost of the system and excess electricity production are the governing factors in the optimization of stand-alone hybrid system. Therefore, the relationship between capacity shortage, cost and excess electricity production for the optimum system configuration is studied. The influence of capacity shortage on total net present cost and excess electricity production is shown by the sensitivity analysis (Fig. 4.18). The slope of net present cost and excess electricity is steep up to 5% and 10% capacity shortage respectively as shown in Fig 4.18. Therefore, the maximum capacity shortage to be selected in this study is up to 10%.

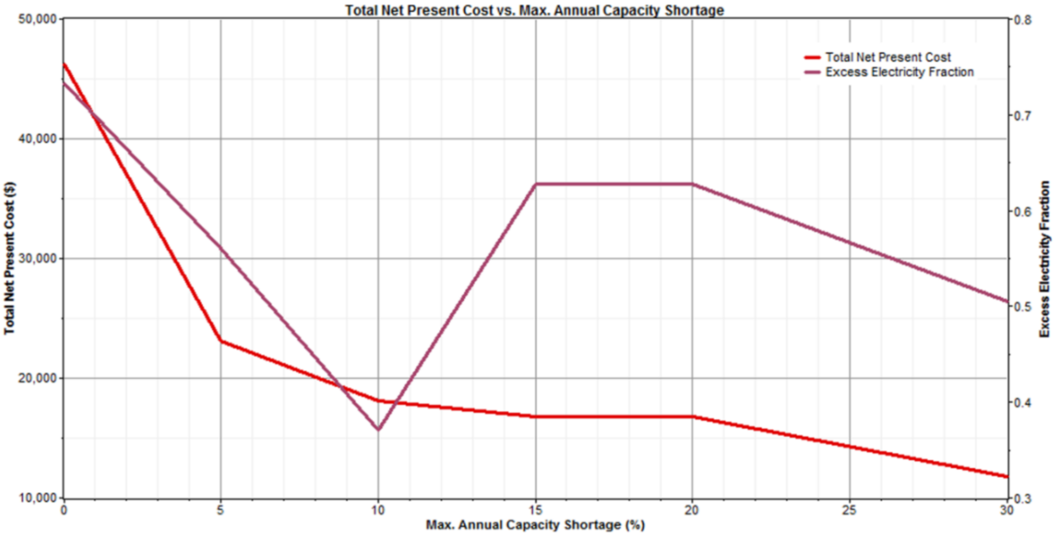


Fig. 4.18 Sensitivity analysis of maximum annual capacity shortage

4.4.2 Objective function of solar-diesel generator hybrid system

The objective of the optimization of grid interactive and standalone solar-diesel generator hybrid system is to minimize the NPC of the system for uninterruptible power supply i.e. with 0% capacity shortage, and state of charge of battery bank should be limited to minimum 40%. The objective function is formulated on the software with constraints as given by Eq. 4.20.

$$\min \sum NPC \tag{4.20}$$

Constraints: 40%≤SOC≤100%
Capacity Shortage = 0%
Minimum renewable fraction = 0%

The size and quantity of components considered for optimization of solar-diesel generator hybrid system is given in Table 4.13.

Table 4.13 Search space for the optimization of solar-diesel generator hybrid system

Sr. No.	**PV Array (kW)**	**DG (kW)**	**Grid (kW)**	**ESC 120-12FR (Strings)**	**Converter (kW)**
1	0	0	100	0	0
2	100	128	200	1	100
3	150	256		2	144
4	200			3	175
5	250			4	200
6	300			5	250
7	350			6	300
8	400			7	
9	450			8	
10	500			9	
11	550			10	

The optimization and sensitivity analysis of these hybrid energy systems are carried out. The results obtained using the methodology discussed are presented in the next chapter.

Chapter 5

RESULTS AND DISCUSSION

In this Chapter the techno-economic analysis and optimization results of solar wind hybrid system and solar- diesel hybrid system for uninterrupted power supply are presented and discussed

5.1 Solar-Wind-Battery storage hybrid system

In this section, the techno-economic analysis and optimization results of solar wind hybrid system are presented and discussed.

5.1.1 Techno-economic analysis of the 6kWp Solar -Wind hybrid System

Using the solar and wind resource of the location, the total electricity production during the year by the 6kWp hybrid system is obtained as 1996kWh/yr in which 61% is of PV array (1214kWh/yr) and 39% energy (782kWh/yr) is estimated to be generated by wind turbine. The monthly average electricity production by wind turbine and PV array is shown in Fig. 5.1. The capacity shortage, NPC and levelized cost of energy (COE) of the system are 306kWh/yr (22.3%), $30,734 and $1.156/kWh respectively.

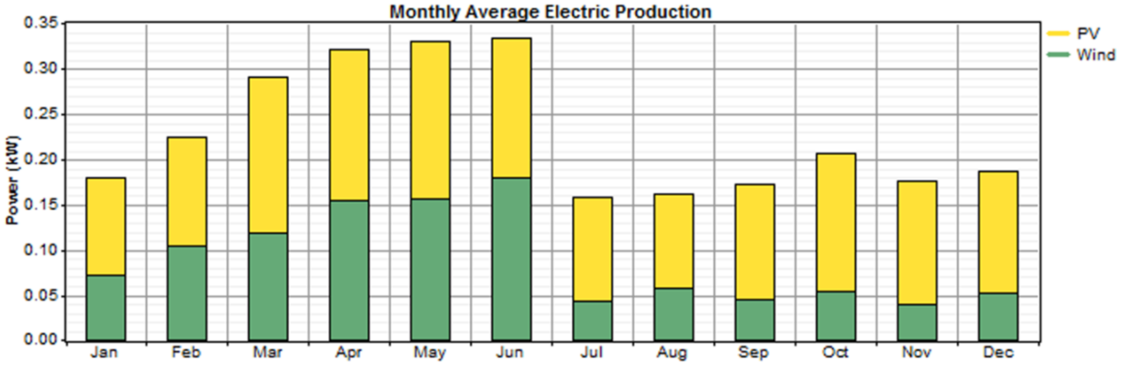
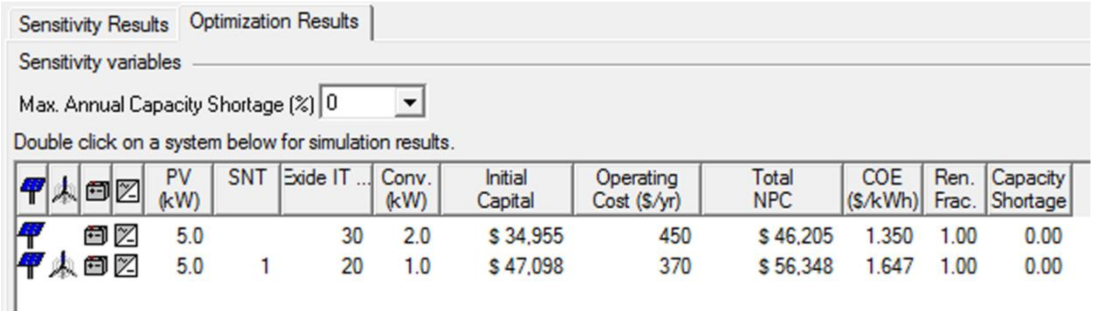


Fig. 5.1 Monthly average electricity production by solar -wind hybrid system

5.1.2 Various optimum combinations of solar- wind hybrid systems

The optimization results of the hybrid system as per load demand, available resources and economics for 0%, 5%, 10% and 20% capacity shortage are shown in Fig. 5.2(a, b, c & d). The results are calculated in 2376 simulations and are aligned in ascending order of net present cost.



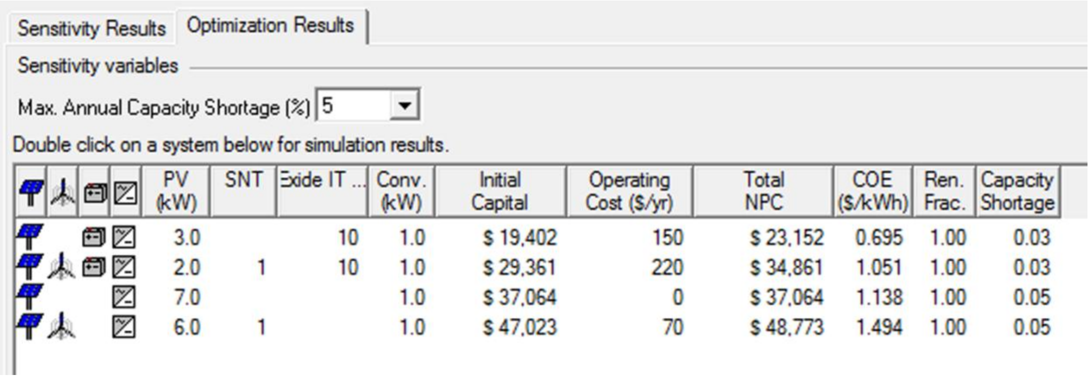
Sensitivity variables

Max. Annual Capacity Shortage (%) 0

Double click on a system below for simulation results.

				PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
●		●	●	5.0		30	2.0	$ 34,955	450	$ 46,205	1.350	1.00	0.00
●	●	●	●	5.0	1	20	1.0	$ 47,098	370	$ 56,348	1.647	1.00	0.00

Fig. 5.2a Optimization results for 0% capacity shortage hybrid systems



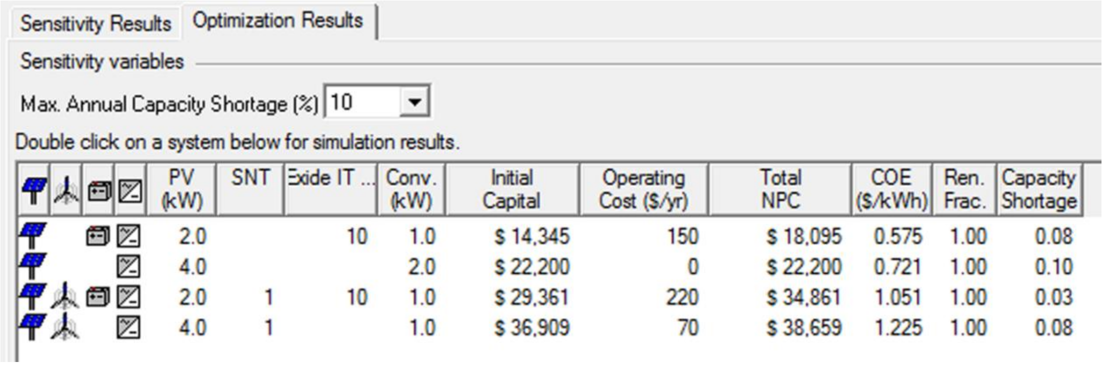
Sensitivity variables

Max. Annual Capacity Shortage (%) 5

Double click on a system below for simulation results.

				PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
●		●	●	3.0		10	1.0	$ 19,402	150	$ 23,152	0.695	1.00	0.03
●	●	●	●	2.0	1	10	1.0	$ 29,361	220	$ 34,861	1.051	1.00	0.03
●			●	7.0			1.0	$ 37,064	0	$ 37,064	1.138	1.00	0.05
●	●		●	6.0	1		1.0	$ 47,023	70	$ 48,773	1.494	1.00	0.05

Fig. 5.2b Optimization results for 5% capacity shortage hybrid systems



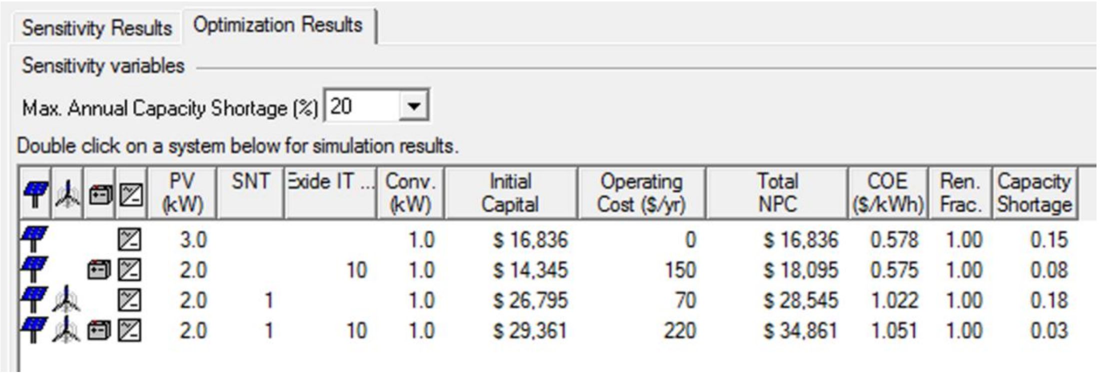
Sensitivity variables

Max. Annual Capacity Shortage (%) 10

Double click on a system below for simulation results.

				PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
●		●	●	2.0		10	1.0	$ 14,345	150	$ 18,095	0.575	1.00	0.08
●			●	4.0			2.0	$ 22,200	0	$ 22,200	0.721	1.00	0.10
●	●	●	●	2.0	1	10	1.0	$ 29,361	220	$ 34,861	1.051	1.00	0.03
●	●		●	4.0	1		1.0	$ 36,909	70	$ 38,659	1.225	1.00	0.08

Fig. 5.2c Optimization results for 10% capacity shortage hybrid systems.



Max. Annual Capacity Shortage (%) 20

Double click on a system below for simulation results.

PV (kW)	SNT	Exide IT ...	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage
3.0			1.0	$ 16,836	0	$ 16,836	0.578	1.00	0.15
2.0		10	1.0	$ 14,345	150	$ 18,095	0.575	1.00	0.08
2.0	1		1.0	$ 26,795	70	$ 28,545	1.022	1.00	0.18
2.0	1	10	1.0	$ 29,361	220	$ 34,861	1.051	1.00	0.03

Fig. 5.2d Optimization results for 20% capacity shortage hybrid systems.

5.1.2.1 Optimum combinations with 0% capacity shortage

The best result for 0% capacity shortage is found to be a 5kWp PV array, 2kW converter, 3 parallel strings of battery bank (30 batteries) with net present cost (NPC) as $46,205 and cost of energy (COE) as $1.350/kWh. The total annual electric production of this system is obtained as 6,064kWh/yr out of which 73.3% (4,444kWh/yr) electricity, is in excess. The hourly electricity production of the best combination and excess electricity, are shown in Fig. 5.3.

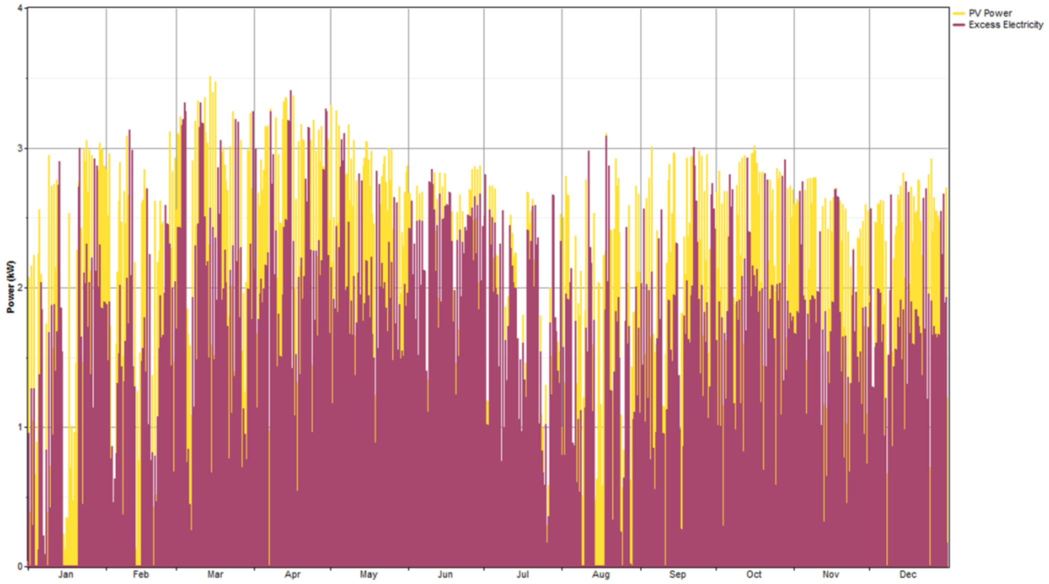


Fig. 5.3 Hourly PV power and excess electricity production by 5kWp solar PV system with 0% capacity shortage

The second best result in the same category is found to be 5kW$_p$ solar array, a wind turbine of 5kW$_p$ with 2 parallel strings battery bank and 1kW converter having \$56,348 NPC and COE to be \$1.647/kWh. This system is estimated to produce total 6,846kWh/yr electricity with 76.9% (5,261kWh/yr) excess electricity. The hourly production from solar array and wind turbine is shown in Fig. 5.4.

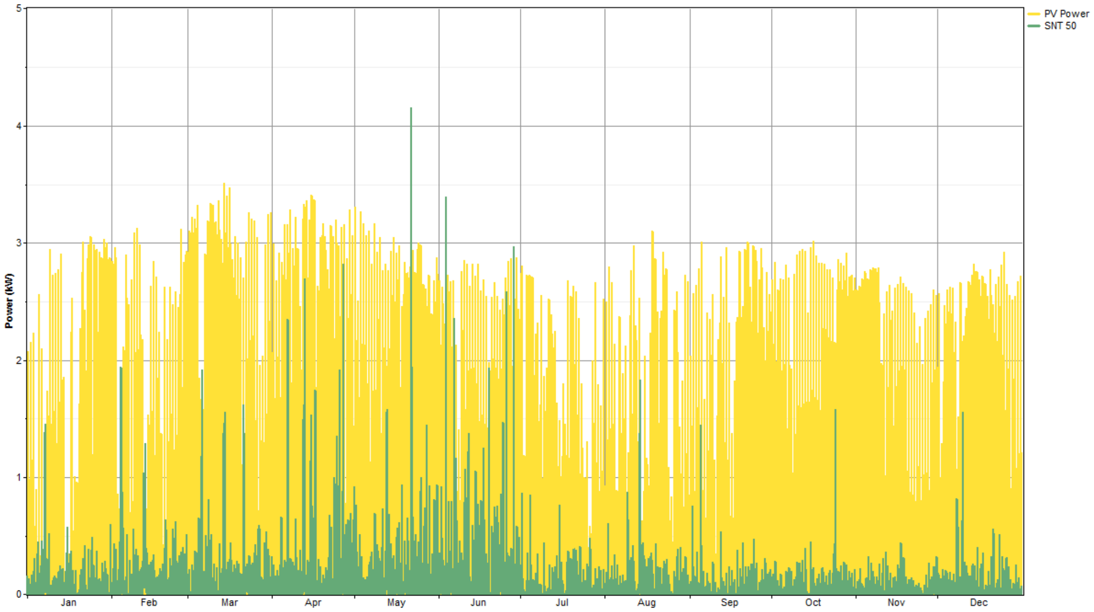
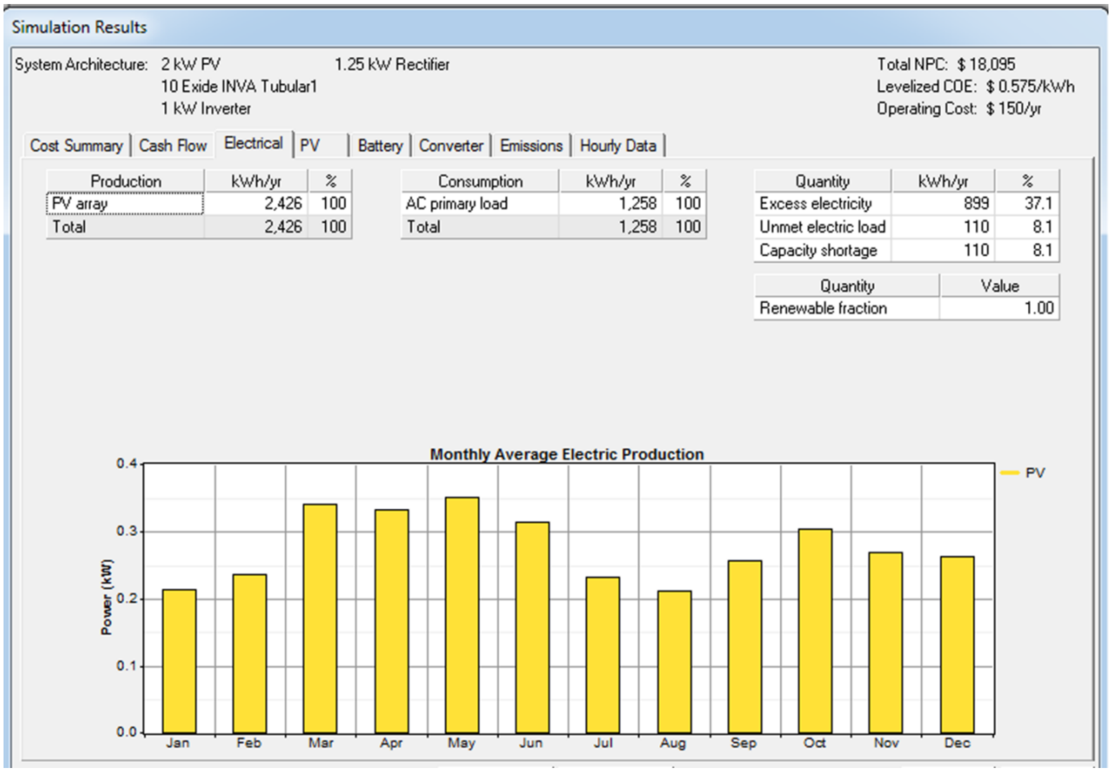


Fig. 5.4 Hourly power production by 5kWp PV and 5kWp wind system with 0% capacity shortage

The results show that the COE of both the systems, are high because of zero capacity shortage in entire year. The cost of energy can be reduced by either adding a diesel generator to the solar wind hybrid system or allowing nominal capacity shortage. The excess electricity production is very high for a 100% reliable system i.e. 0% capacity shortage, which can be utilized by serving deferrable load. A deferrable load is the load which can be deferred over time and can be served during the time of excess electricity production, for example water pumping load. The use of waste electricity in deferrable load doesn’t affect the reliability of the system; moreover, the cost of energy will also reduce. Thus, it is advantageous to use deferrable load in reliable renewable energy systems.

5.1.2.2 Optimum combination with 5-10% capacity shortage

The best result for 5% maximum allowable capacity shortage, is obtained as 3kW PV array with total number of 10 batteries (1 string) having NPC $23,152 and cost of energy $0.695/kWh with 56.1% (2041 kWh/yr) excess electricity production and 3% (35.5 kWh/yr) capacity shortage. For a maximum allowable capacity shortage of 10%, the best optimum combination comprises of 2kWp PV array with 1 string of battery bank (total 10 nos. of batteries) with only 37.1% (899 kWh/yr) excess electricity and 8% (110 kWh/yr) capacity shortage. The NPC and COE of the system are $18,095 and $0.575/kWh. The monthly electrical power production results of this system, is shown in Fig. 5.5. The excess power production by both the systems with 3% and 8% capacity shortage is shown in Fig. 5.6.



System Architecture: 2 kW PV
10 Exide INVA Tubular1
1 kW Inverter
1.25 kW Rectifier

Total NPC: $ 18,095
Levelized COE: $ 0.575/kWh
Operating Cost: $ 150/yr

Production	kWh/yr	%
PV array	2,426	100
Total	2,426	100

Consumption	kWh/yr	%
AC primary load	1,258	100
Total	1,258	100

Quantity	kWh/yr	%
Excess electricity	899	37.1
Unmet electric load	110	8.1
Capacity shortage	110	8.1

Quantity	Value
Renewable fraction	1.00

Fig. 5.5 Monthly Average Electricity production 2kWp PV system

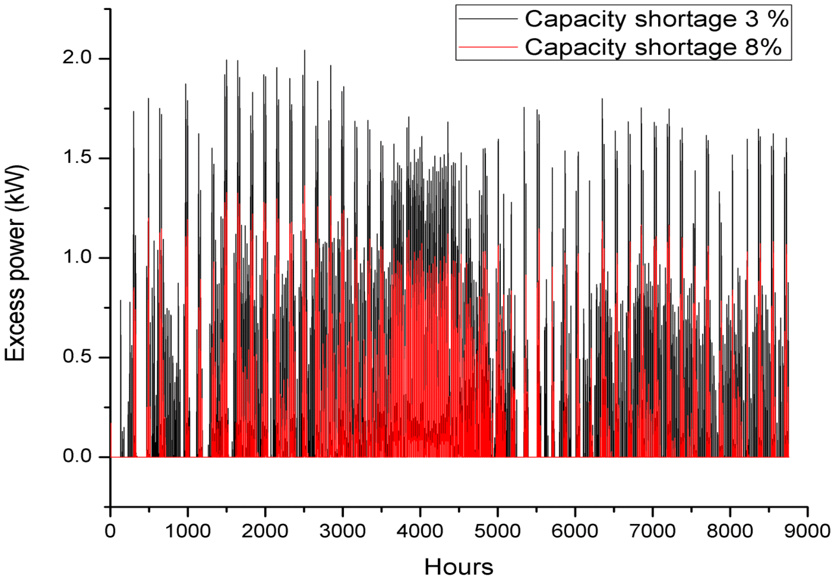
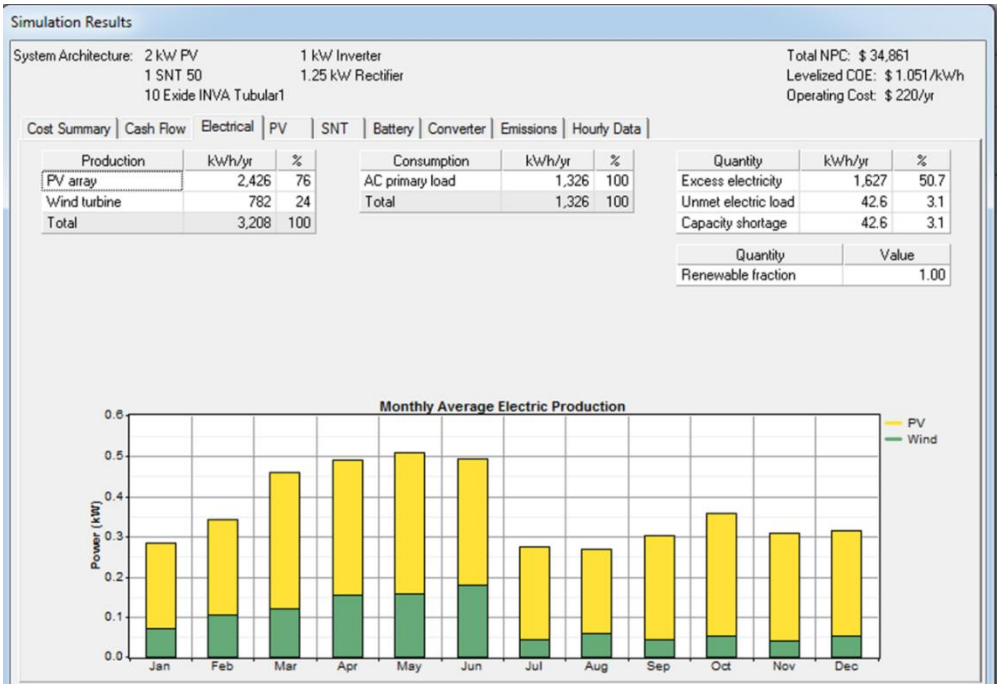


Fig. 5.6 Excess power production for 3% and 8% capacity shortage

In order to utilize both solar and wind resource of the site, the optimized combination for this location, is found to be a 5 kWp wind turbine and 2 kWp PV system with 1 string of 10 batteries. The COE of the system will be 1.051/kWh with 50.7% (1627 kWh/yr) excess electricity production with 3% capacity shortage as shown in Fig. 5.7.



System Architecture: 2 kW PV
1 SNT 50
10 Exide INVA Tubular1
1 kW Inverter
1.25 kW Rectifier

Total NPC: $ 34,861
Levelized COE: $ 1.051/kWh
Operating Cost: $ 220/yr

Production	kWh/yr	%
PV array	2,426	76
Wind turbine	782	24
Total	3,208	100

Consumption	kWh/yr	%
AC primary load	1,326	100
Total	1,326	100

Quantity	kWh/yr	%
Excess electricity	1,627	50.7
Unmet electric load	42.6	3.1
Capacity shortage	42.6	3.1

Quantity	Value
Renewable fraction	1.00

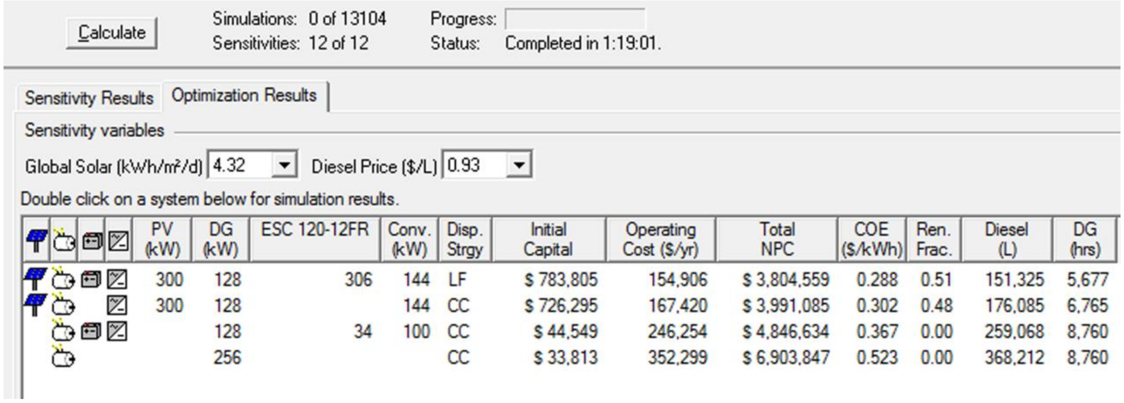
Fig. 5.7 Monthly average electricity production by 2kWp solar PV array and a 5 kW wind turbine hybrid system

5.2 Analysis of Solar-diesel generator hybrid system

In this section, the optimization and sensitivity analysis results of a standalone and grid interactive solar-diesel generator hybrid system, are presented and discussed.

5.2.1 Optimization results of standalone solar-diesel hybrid system

The optimization and sensitivity results of standalone solar PV-diesel generator hybrid system for uninterrupted power supply are calculated in 1 hour 19 minutes and 1 second by running total 157248 simulations (13104 simulations × 12 sensitivities). The optimum sizes of components for four different combinations having minimum NPC are selected. The optimization results are categorized according to the configuration as shown in Fig. 5.8. The four optimum combinations of standalone system are standalone diesel generator system without battery storage, standalone diesel generator with battery storage, standalone solar PV-diesel generator hybrid system without battery storage and standalone solar PV-diesel generator hybrid system with battery storage. A solar PV (300kWp)-diesel generator (128kW rated capacity)-battery storage (306 nos. of batteries) hybrid system is the overall optimum configuration of standalone solar-diesel hybrid system.



Simulations: 0 of 13104
Sensitivities: 12 of 12
Progress:
Status: Completed in 1:19:01.

Sensitivity variables

Global Solar (kWh/m²/d) 4.32
Diesel Price ($/L) 0.93

Double click on a system below for simulation results.

PV (kW)	DG (kW)	ESC 120-12FR	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
300	128	306	144	LF	$ 783,805	154,906	$ 3,804,559	0.288	0.51	151,325	5,677
300	128		144	CC	$ 726,295	167,420	$ 3,991,085	0.302	0.48	176,085	6,765
	128	34	100	CC	$ 44,549	246,254	$ 4,846,634	0.367	0.00	259,068	8,760
	256			CC	$ 33,813	352,299	$ 6,903,847	0.523	0.00	368,212	8,760

Fig. 5.8 Optimization result of standalone solar-diesel hybrid system

5.2.1.1 Standalone diesel generator system without battery storage

The standalone diesel generator of 256kW rated capacity running continuously for 8760 hours (entire year) is sufficient to serve load. The NPC of the system is $ 6,903,847 in which the major fraction is of fuel cost ($ 6,677,716). The diesel generator will consume 368,212 litres of diesel per year to produce monthly average power shown in Fig. 5.9.

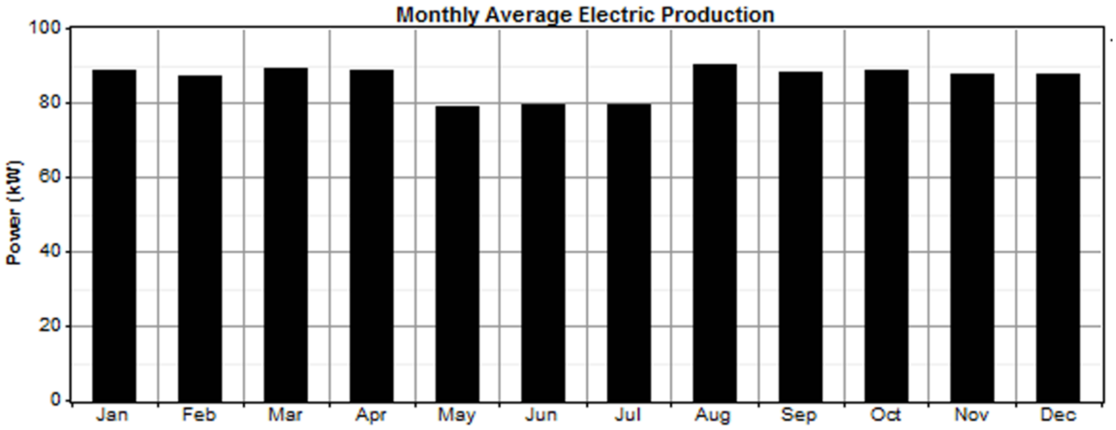


Fig. 5.9 Monthly average power production of Standalone diesel generator system without battery storage

A 10.3% fraction of the total electricity production (78,053kWhr) is surplus per year which is wasted. The levelized cost of energy of the system is $0.523/kWh. This system is composed of only one energy source, hence its installation and operation is very simple. But the 24×7 operation of diesel generator for entire year releases a large amount of emission, a total of 9,95,765 kg pollutants per year and increases O&M cost. The quantity of pollutants emitted per year by the system is given in Table 5.1.

Table 5.1 Emissions by standalone diesel generator system without battery storage

Pollutant	**Emissions (kg/yr)**
Carbon dioxide	9,69,624
Carbon monoxide	2,393
Unburned hydrocarbons	265
Particulate matter	180
Sulfur dioxide	1,947
Nitrogen oxides	21,356
Total emission	**9,95,765**

5.2.1.2 Standalone diesel generator with battery storage

The size of diesel generator and excess energy production decreases with increase in system's reliability by including battery storage in the hybrid energy system. In this category, a diesel generator of 128kW rated capacity with a string of 34 series connected batteries is the optimum configuration having $4,846,633 NPC and $0.367/kWh levelized COE. The summary of net present cost of the system is given in Table 5.2.

Table 5.2 Cost summary (NPC) of standalone diesel generator with battery storage

Component	**Capital ($)**	**Replacement ($)**	**O&M ($)**	**Fuel ($)**	**Salvage ($)**	**Total ($)**
Diesel Generator	15,963	85,871	17,082	4,698,340	-6,794	4,810,462
Battery storage	6,390	9,529	0	0	-1,943	13,976
Converter	20,309	0	0	0	0	20,309
Other (Control room)	1,887	0	0	0	0	1,887
System	**44,549**	**95,400**	**17,082**	**4,698,340**	**-8,737**	**4,846,633**

The generator is running entire year to produce 677,464kWh electricity. The excess electricity production is reduced to 63.1kWh/yr. The generator will consume 259,068 litres of diesel which is 109,144 litres less than the 256kW diesel generator. The total emission released by the generator is 700,606 kg/yr. The amount of pollutants emitted by the generator is given in Table 5.3. The operation of battery bank is shown by its state of charge as shown in Fig. 5.10.

Table 5.3 Emissions by 128kW diesel generator

Pollutant	**Emissions (kg/yr)**
Carbon dioxide	682,212
Carbon monoxide	1,684
Unburned hydrocarbons	187
Particulate matter	127
Sulfur dioxide	1,370
Nitrogen oxides	15,026
Total	**700,606**

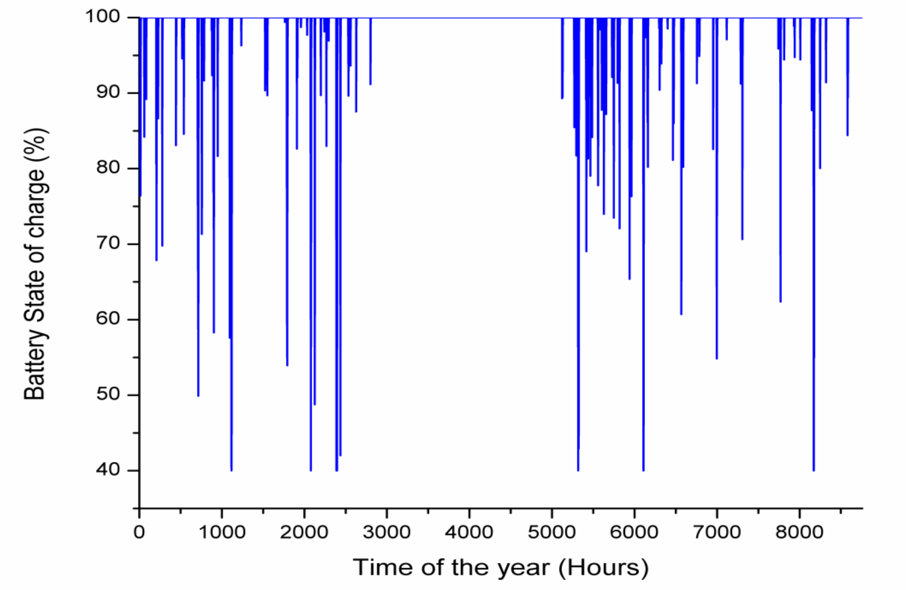


Fig. 5.10 State of charge of battery bank of standalone diesel generator with battery storage

5.2.1.3 Standalone solar PV-diesel generator hybrid system without battery storage

A 300kWp solar PV and 128kW diesel generator is the optimum combination in the category of standalone solar PV-diesel generator hybrid system without battery storage. The NPC and levelized COE of the system are $3,991,085 and $0.302/kWh respectively. The total power produced by the system is 815,075kWh/yr in which the contributions of solar PV and diesel generator are 387,836kWh/yr (48%) and 427,239kWh (52%). The monthly average of power produced by the system is shown in Fig. 5.11.

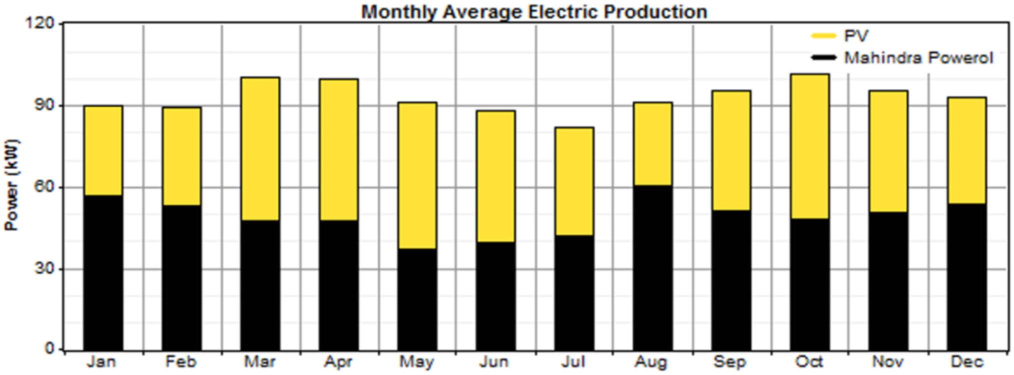


Fig. 5.11 Monthly average power production of standalone solar PV-diesel generator hybrid system without battery storage

A huge amount of surplus electricity is produced by the system due to the absence of energy storage device. The total excess electricity production of the system is 122,077kWh/yr and hourly excess electricity is shown in Fig. 5.12. The diesel generator operates for 6765hr/yr with 397starts/yr and consumes 176,085 litres of diesel per year. The total emission caused by the generator is lowered to 476,191.3kg/yr and amount of pollutants are given in Table 5.4.

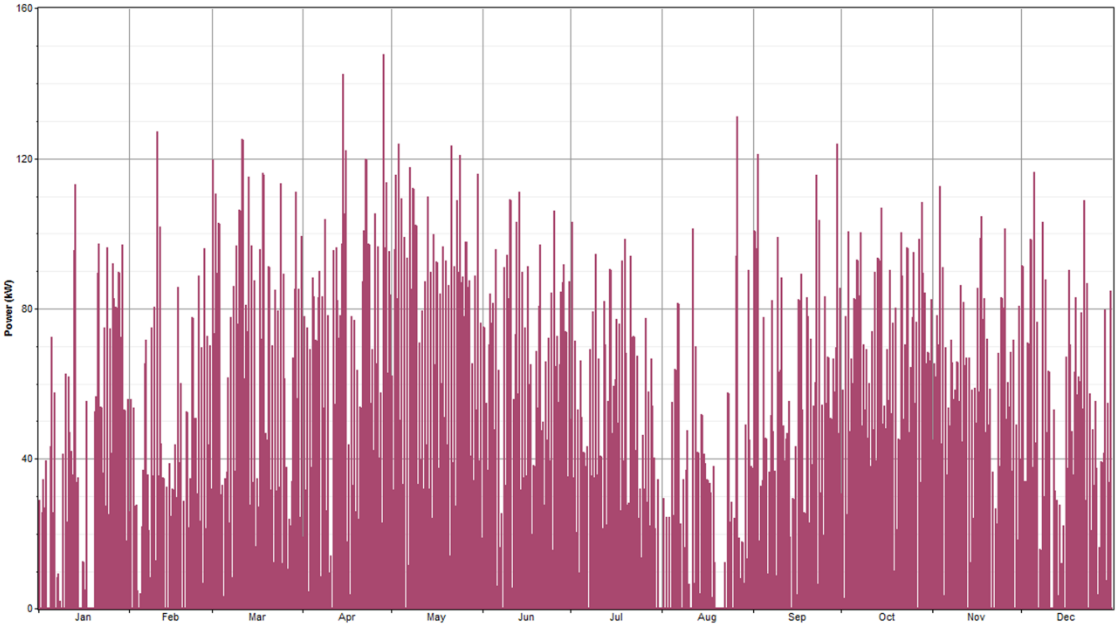


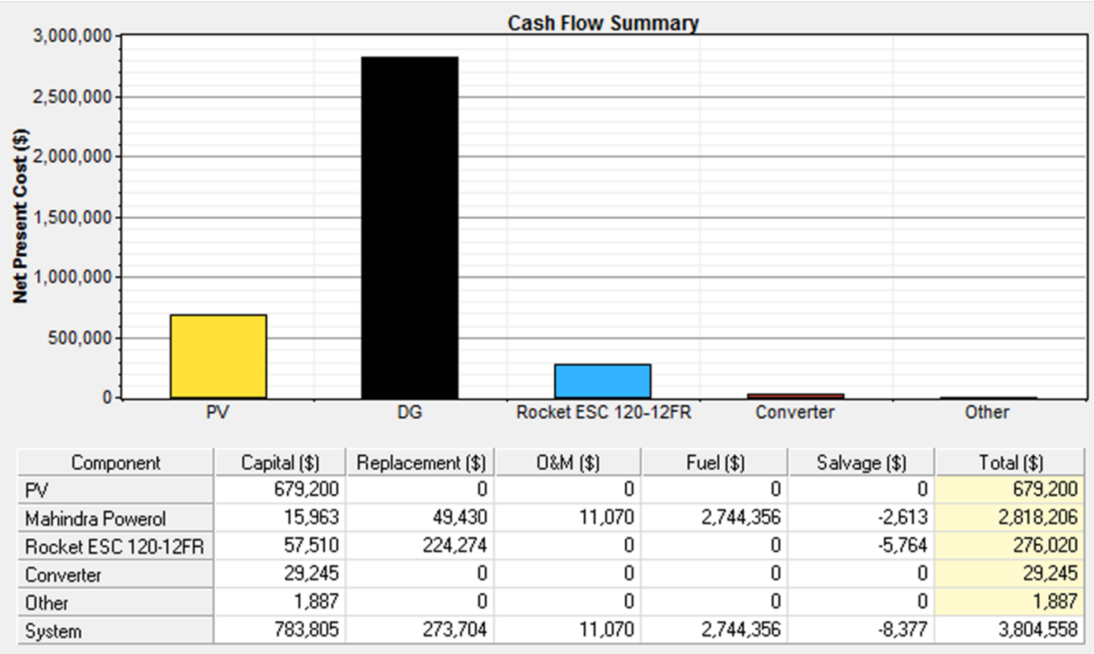
Fig. 5.12 Hourly average excess electricity produced by the standalone solar PV-diesel generator hybrid system without battery storage

Table 5.4 Emissions by standalone solar PV-diesel generator hybrid system without battery storage

Pollutant	**Emissions (kg/yr)**
Carbon dioxide	463,689
Carbon monoxide	1,145
Unburned hydrocarbons	127
Particulate matter	86.3
Sulfur dioxide	931
Nitrogen oxides	10,213
Total	**476,191.3**

5.2.1.4 Standalone solar PV-diesel generator hybrid system with battery storage

The best optimized combination of standalone solar-diesel hybrid system for UPS is comprised of solar PV (300kWp rated capacity), diesel generator (128kW rated capacity) and nine parallel strings of 34 series connected batteries. The NPC and COE of this system configuration are \$3,804,559 and \$0.288/kWh respectively, lowest among all categories. The cash flow summary of components is shown in Fig. 5.13.



Component	Capital ($)	Replacement ($)	O&M ($)	Fuel ($)	Salvage ($)	Total ($)
PV	679,200	0	0	0	0	679,200
Mahindra Powerol	15,963	49,430	11,070	2,744,356	-2,613	2,818,206
Rocket ESC 120-12FR	57,510	224,274	0	0	-5,764	276,020
Converter	29,245	0	0	0	0	29,245
Other	1,887	0	0	0	0	1,887
System	783,805	273,704	11,070	2,744,356	-8,377	3,804,558

Fig. 5.13 Cash flow summary of standalone solar PV-diesel generator hybrid system with battery storage

The monthly average power production of the system is shown in Fig. 5.14. The solar PV and diesel generator contributes 387,836kWh/yr (51%) and 372,769kWh/yr (49%) respectively to the total production of 760,604kWh electricity per year. The system produces 53,191kWh (6.99% of total production) surplus electricity per year which system cannot use.

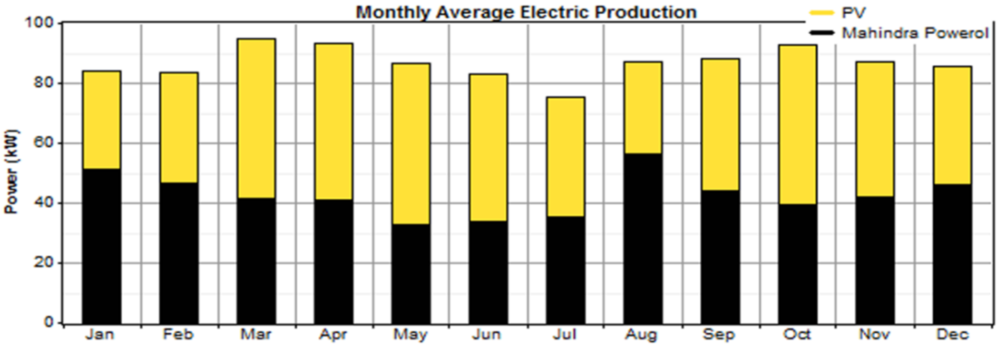


Fig. 5.14 Monthly average power production of standalone solar PV-diesel generator hybrid system with battery storage

The 128kW diesel generator operates in load following dispatch strategy under which the generator produces power to serve only load and not to charge battery bank. The surplus power produced by solar PV after serving load is used to charge battery bank. The state of charge of battery bank during entire year is shown in Fig. 5.15.

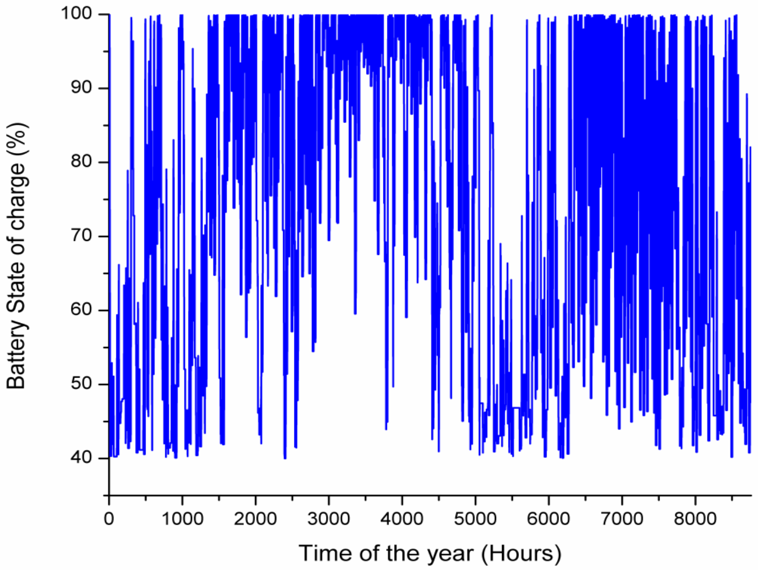


Fig. 5.15 State of charge of battery bank of standalone solar PV-diesel generator hybrid system with battery storage

The diesel generator starts 404 times per year to meet load demand. The total hour of operation is 5,677hr/yr and total fuel consumption is 151,325Ltr/yr. The fuel consumed by this system is 41.6% (107,743Ltr/yr) less than the fuel consumed by standalone diesel generator system with battery storage.

The total emission caused by this system is 409,232.1kg/yr. The emission is also reduced by 41.6% (291,373.9kg/yr) as compared to the standalone diesel generator system with battery storage. The amount of pollutants emitted by this system is given in Table 5.5.

Table 5.5 Emissions by standalone solar PV-diesel generator hybrid system with battery storage

Pollutant	**Emissions (kg/yr)**
Carbon dioxide	398,488
Carbon monoxide	984
Unburned hydrocarbons	109
Particulate matter	74.1
Sulfur dioxide	800
Nitrogen oxides	8,777
Total emission	**409,232.1**

5.2.2 Sensitivity analysis of standalone solar-diesel hybrid system

The continuously increasing diesel price and intermittent solar radiation nominate them as sensitivity input variables to assess the effects of their uncertainty on the various parameters of the hybrid system, known as sensitivity analysis. The sensitivity inputs for diesel price are \$0.93, \$1 and \$1.1 per litre and for solar radiation are 4, 4.32, 4.5 and 5kWh/m^2/day. The change in CO_2 emission and total NPC with one of the sensitivity variable while other remains fixed, is evaluated in this section.

The variation of CO_2 emission and total NPC with the solar radiation varying from 4 to 5kWh/m^2/day for fixed diesel price equals to \$0.93, \$1 and \$1.1 per litre is shown in Fig. 5.16, 5.17 and 5.18 respectively. The total NPC decreases continuously at a constant rate with the increasing solar radiation for all the three values of diesel price. The slope of CO_2 emissions is negative upto 4.5kWh/m^2/day solar radiation and then it becomes positive till 5kWh/m^2/day for diesel price equals to \$0.93 and \$1 per litre. Whereas, for fixed diesel price equals to \$1.1/Ltr, firstly the CO_2 emissions increases upto solar radiation 4.32kWh/m^2/day and then decreases. The increase in CO_2 emissions implies the increasing operating hours of diesel generator and vice versa.

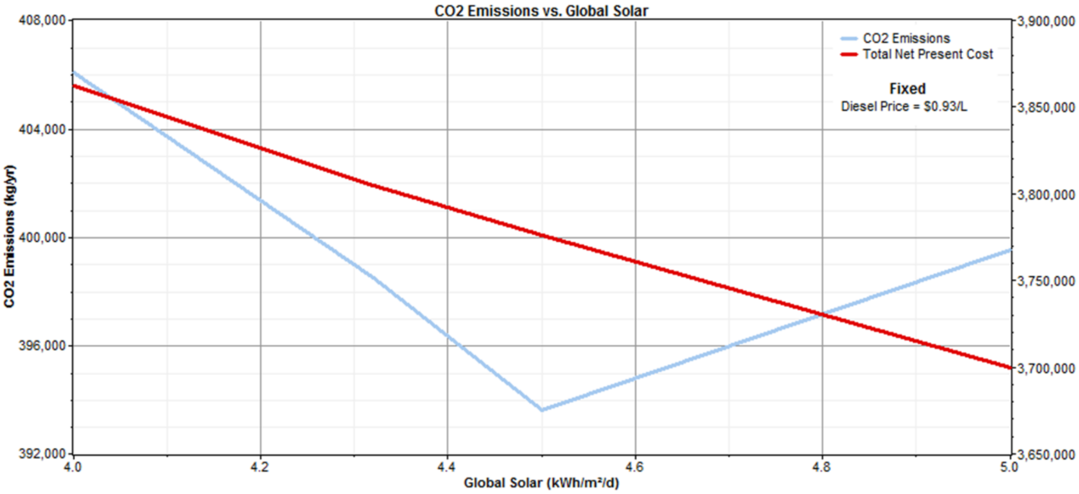


Fig. 5.16 Line graph between CO_2 emissions, total NPC and Global solar radiation at fixed diesel price = \$0.93/Ltr

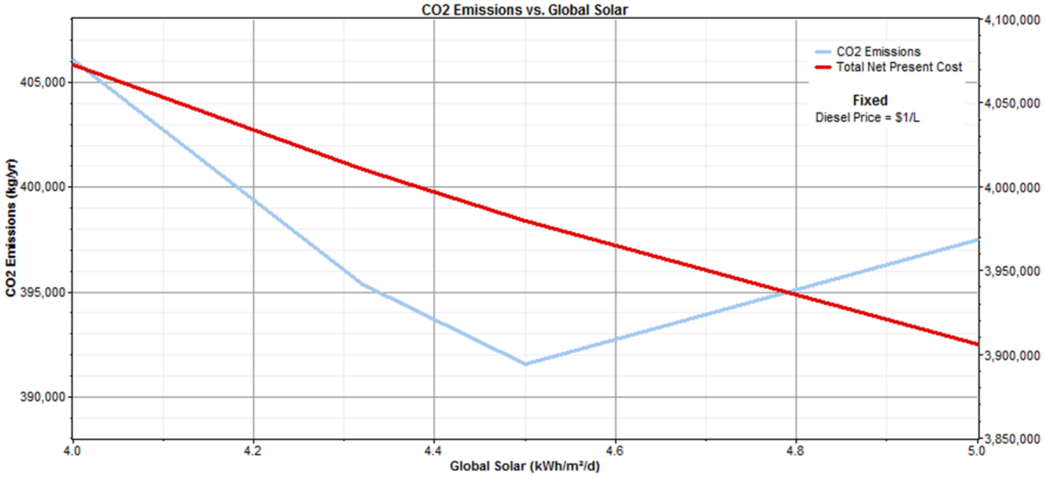


Fig. 5.17 Line graph between CO_2 emissions, total NPC and Global solar radiation at fixed diesel price = \$1.0/Ltr

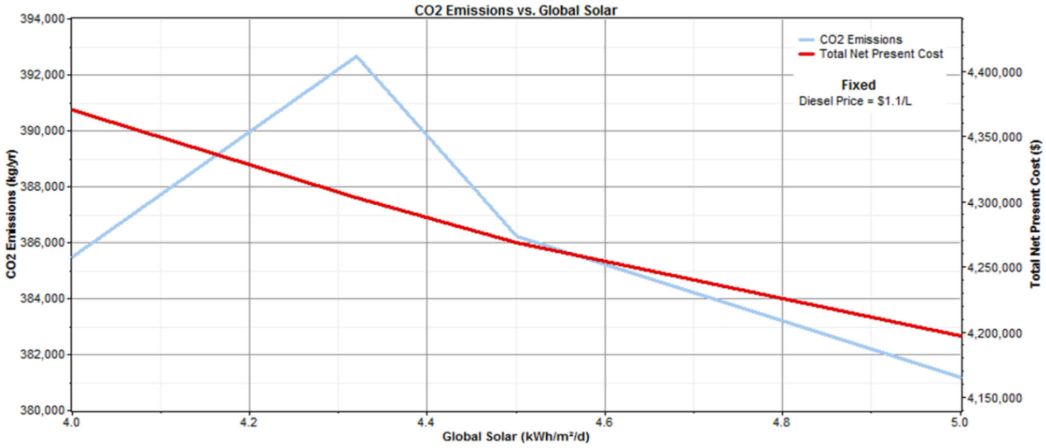


Fig. 5.18 Line graph between CO_2 emissions, total NPC and Global solar radiation at fixed diesel price = $1.1/Ltr

The effect of diesel price, varying from $0.93/Ltr to $1.1, on CO_2 emission and total NPC for four fixed values of annual average solar radiation (4 kWh/m^2/day, 4.32kWh/m^2/day, 4.5 kWh/m^2/day and 5kWh/m^2/day) is shown in Fig. 5.19-Fig. 5.22.

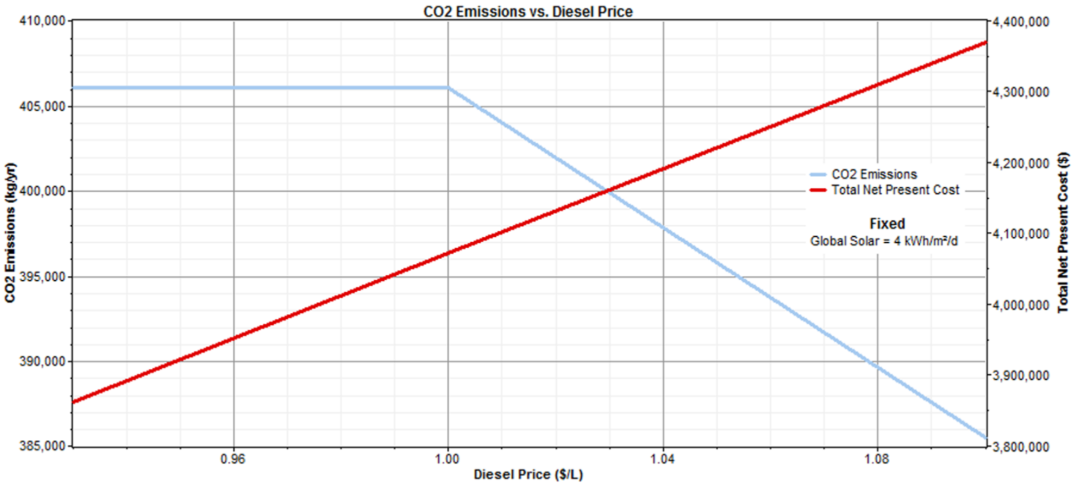


Fig. 5.19 Line graph between CO_2 emissions, total NPC and diesel price at fixed solar radiation = 4kWh/m^2/day

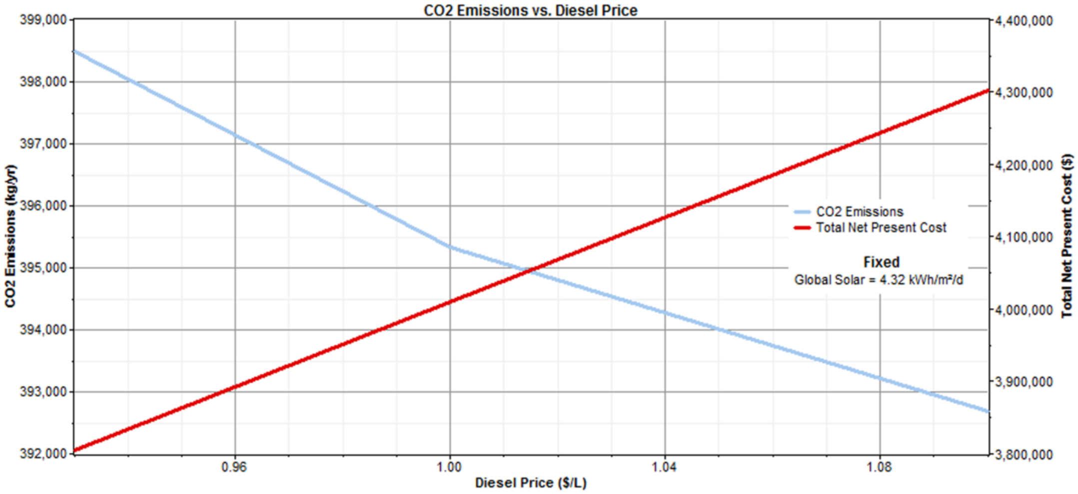


Fig. 5.20 Line graph between CO_2 emissions, total NPC and diesel price at fixed solar radiation = 4.32kWh/m^2/day

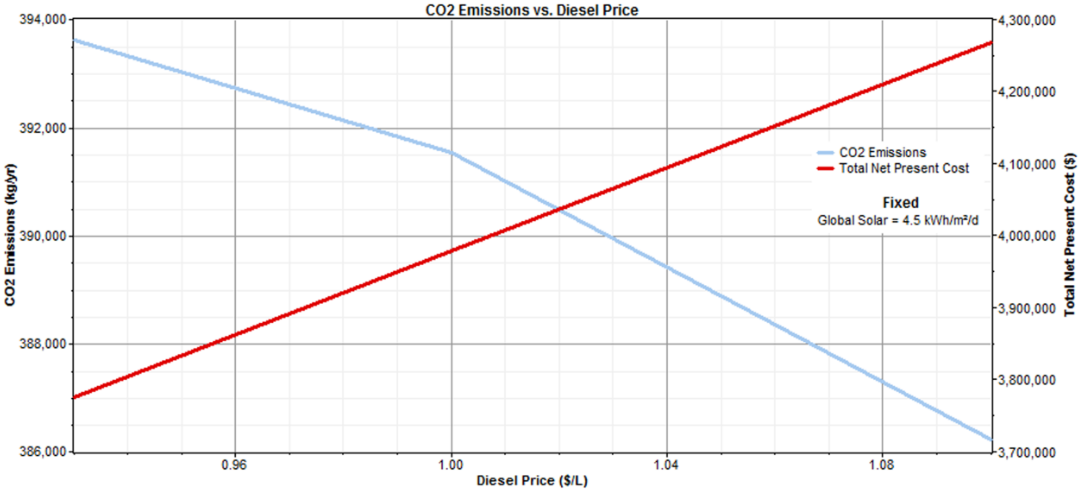


Fig. 5.21 Line graph between CO_2 emissions, total NPC and diesel price at fixed solar radiation = 4.5kWh/m^2/day

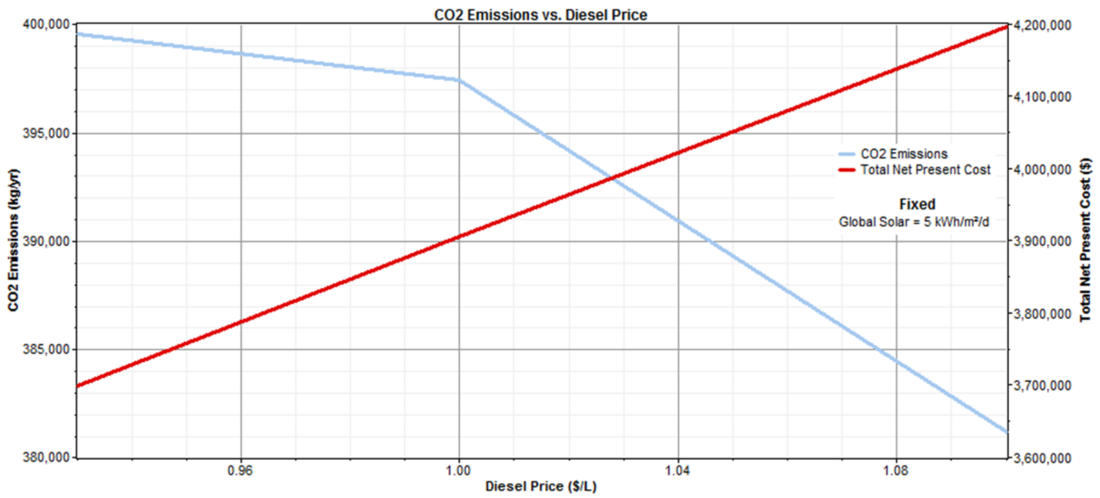


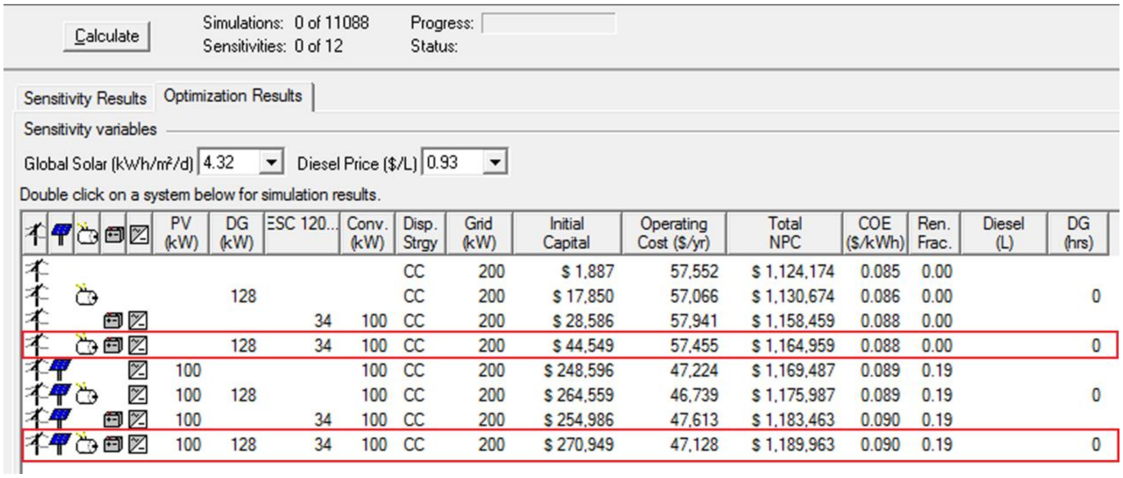
Fig. 5.22 Line graph between CO_2 emissions, total NPC and diesel price at fixed solar radiation = 5kWh/m^2/day

The total NPC increases constantly with diesel price for all four cases while slope of CO_2 emission is dissimilar for each case. The CO_2 emission indirectly depends on the diesel price. In order to minimize the net present cost, the operating hour of diesel generator decreases with the increase in diesel price, this in turn decreases the CO2 emission. The CO_2 emission of the system, for fixed global solar radiation 4kWh/m^2/day, remains constant with the rise in the diesel price from $0.93/Ltr to $1/Ltr and then starts decreasing rapidly when diesel price further rises from $1/Ltr to $1.1/Ltr (Fig. 19). The CO_2 emission dropped to 385,499kg/yr from 406,065kg/yr with the increasing diesel price over $1/Ltr. The slope of decreasing of CO_2 emission is nearly constant with increasing diesel price for solar radiation 4.32kWh/m^2/day, however comparatively, the slope of more for diesel price upto $1/Ltr. than for higher price. For solar radiation 4.5kWh/m^2/day, the slope of CO_2 emission is opposite to that for solar radiation 4.32kWh/m^2/day and 5kWh/m^2/day i.e. the rate of decreasing CO_2 emission is less upto diesel price $1/Ltr. than for higher price.

5.2.3 Optimization results of grid interactive solar-diesel hybrid system

HOMER assumes that the grid is continuous and reliable source of power supply but in reality the availability of grid power also fluctuates. Therefore, a backup power source is generally used to cater load of UPS. The selection of backup power source depends on the frequency and duration of unavailability of grid power. If frequency of fluctuation is high, the battery storage is more appropriate for backup because the frequent starting and stopping of generator, negatively affects its performance. A diesel generator is the appropriate backup source of power, in case of the duration of unavailability of grid power is long. Practically, sometimes the on-off of the grid power is frequent and sometimes it is off for longer durations, in such case both battery bank and diesel generator are used as primary and secondary backup source respectively. The secondary source will be in operation only if the primary source is exhausted. Therefore, in this study the UPS system is considered with battery bank and diesel generator as backup source.

The optimization and sensitivity results of grid interactive solar-diesel hybrid system are calculated for uninterrupted power supply by performing 133,056 simulations (11088 simulations × 12 sensitivities). The calculations take 2 hours 9 minutes and 7 seconds to complete. The categorized optimization results arranged in increasing order of NPC is shown in Fig. 5.23. The optimum configurations identified for grid-interactive solar-diesel hybrid system are grid with battery storage and diesel generator as backup and grid interactive-solar PV system with battery storage and diesel generator as backup.



Global Solar (kWh/m²/d) 4.32

Diesel Price ($/L) 0.93

Double click on a system below for simulation results.

					PV (kW)	DG (kW)	ESC 120...	Conv. (kW)	Disp. Strgy	Grid (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	DG (hrs)
✓									CC	200	$ 1,887	57,552	$ 1,124,174	0.085	0.00		
✓		✓				128			CC	200	$ 17,850	57,066	$ 1,130,674	0.086	0.00		0
✓			✓	✓			34	100	CC	200	$ 28,586	57,941	$ 1,158,459	0.088	0.00		
✓		✓	✓	✓		128	34	100	CC	200	$ 44,549	57,455	$ 1,164,959	0.088	0.00		0
✓	✓			✓	100			100	CC	200	$ 248,596	47,224	$ 1,169,487	0.089	0.19		
✓	✓	✓		✓	100	128		100	CC	200	$ 264,559	46,739	$ 1,175,987	0.089	0.19		0
✓	✓		✓	✓	100		34	100	CC	200	$ 254,986	47,613	$ 1,183,463	0.090	0.19		
✓	✓	✓	✓	✓	100	128	34	100	CC	200	$ 270,949	47,128	$ 1,189,963	0.090	0.19		0

Fig. 5.23 Optimization results of grid interactive solar-diesel hybrid system

5.2.3.1 Grid with battery storage and diesel generator as backup

In this configuration, a 128kW diesel generator and a string of 34 batteries are used as backup with grid supply to serve UPS load. The capital cost of grid is zero as the location is already connected to grid. The NPC of the system is $1,164,959 which includes the cost of electricity purchase at the rate of \$0.085/kWh, capital cost of diesel generator and battery bank. The monthly energy purchased from the grid and monthly charge is given in Table 5.6. The emission is zero as the majority of grid power is produced by hydro power plants and diesel generator is never in operation because of continuous grid supply. The load demand is entirely fulfilled by grid supply.

Table 5.6 Monthly grid purchase of grid with battery and diesel generator system

Month	**Energy Purchased (kWh)**	**Energy Sold (kWh)**	**Energy Charge ($)**
Jan	59,824	0	5,085
Feb	52,712	0	4,481
Mar	60,826	0	5,170
Apr	58,038	0	4,933
May	49,464	0	4,204
Jun	49,401	0	4,199
Jul	50,248	0	4,271
Aug	62,307	0	5,296
Sep	57,865	0	4,919
Oct	60,179	0	5,115
Nov	57,111	0	4,854
Dec	59,103	0	5,024
Annual	**677,077**	**0**	**57,552**

5.2.3.2 Grid interactive-solar PV system with battery storage and diesel generator as backup

In order to utilize available solar resource, the solar PV system of 100kWp rated capacity is found to be optimum PV penetration to introduce in the existing UPS system. This system consists of grid supply, 100kWp solar PV system with one string of 34 batteries and 128kW diesel generator. This hybrid system is the most reliable system among all systems explained above because it has three sources of power and an energy storage device. However, the diesel generator and battery bank are considered standby in the simulation. The NPC and levelized COE of the system is found to be $1,189,963 and $0.09/kWh respectively. The system is estimated to produce total 684,853kWh electricity per year having 19% (129,279kWh/yr) renewable fraction produced by solar photovoltaic system and remaining 81% (555,575kWh/yr) is purchased from the grid. The monthly average power production of the system is shown in Fig. 5.24. The monthly electricity purchased from grid is given in Table 5.7.

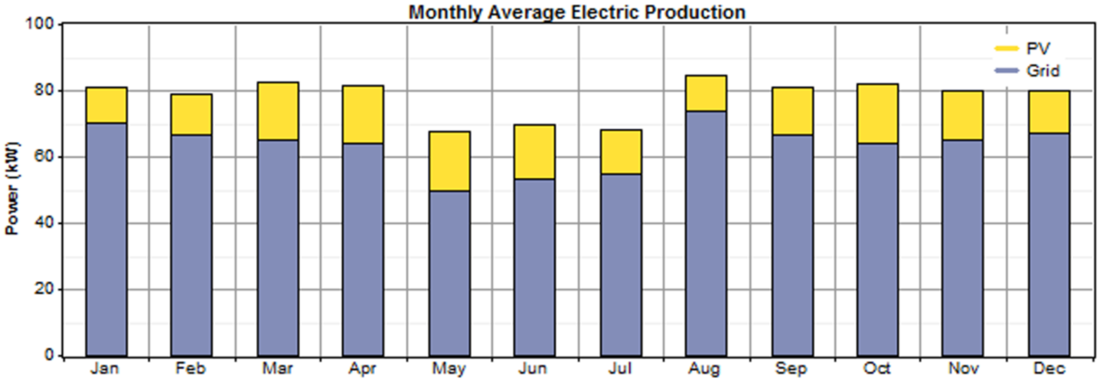


Fig. 5.24 Monthly average power production of grid interactive-solar PV system with battery storage and diesel generator as backup

Table 5.7 Monthly grid purchase of grid interactive-solar PV system with battery storage and diesel generator as backup

Month	**Energy Purchased (kWh)**	**Energy Sold (kWh)**	**Energy Charge ($)**
Jan	52,121	0	4,430
Feb	44,963	0	3,822
Mar	48,480	0	4,121
Apr	46,258	0	3,932
May	36,891	0	3,136
Jun	38,356	0	3,260
Jul	40,896	0	3,476
Aug	55,121	0	4,685
Sep	47,897	0	4,071
Oct	47,719	0	4,056
Nov	46,925	0	3,989
Dec	49,948	0	4,246
Annual	**555,575**	**0**	**47,224**

5.3 Results- Summary

- The optimum solar-wind hybrid system configuration for the location with 0% capacity shortage is found to be a 5kWp PV array, 2kW converter, 3 parallel strings of battery bank (30 batteries) with NPC as $46,205 and COE as $1.350/kWh. The excess electric production of this system is obtained 4,444kWh/yr.
- The solar-wind hybrid system comprises of 2kWp PV array with 1 string of battery bank (150 Ah capacity) is found to be the optimum combination having lowest NPC ($18,095) with 8% (110kWh/yr) capacity shortage and 899kWh/yr excess electricity production.
- In order to utilize both solar and wind resource of the site, the optimum solar-wind hybrid system combination for this location, is found to be a 5kWp wind turbine and 2kWp PV system with 1 string of 10 batteries. The NPC and COE of the system is found to be $34,861 and $1.051/kWh. This system is estimated to produce 1627 kWh/yr excess electricity with 3% capacity shortage.
- The optimum combination of standalone solar-diesel hybrid system for uninterrupted power supply is found to be solar PV (300kWp rated capacity), diesel generator (128kW rated capacity) and nine parallel strings of 34 series connected batteries. The diesel consumed by this system is 107,743Ltr/yr less than the diesel consumed by standalone diesel generator system with battery storage. The total emission caused by this system is estimated to be 409,232.1kg/yr. The NPC and COE of this system configuration are $3,804,559 and $0.288/kWh respectively.
- In order to utilize available solar resource, the solar PV system of 100kWp rated capacity, producing 19% (129,279kWh/yr) of total electricity, is found to be optimum PV penetration to introduce in the existing UPS system. The NPC and levelized COE of the system are found to be $1,189,963 and $0.09/kWh respectively.

Chapter 6

CONCLUSION

6.1 Main Conclusions

In the present study, the feasibility of hybrid energy system in a low wind and high solar resource region in Western Himalayan region is assessed using HOMER software. A 6kWp solar-wind-battery hybrid system installed on the roof top of CEE, NIT Hamirpur building, is analyzed and optimized at different reliability levels. Based on the results of this study, a standalone and grid connected solar- diesel-battery storage hybrid system is proposed as an alternative to the existing diesel and battery based system which is used by NIT-H as an uninterrupted power supply and backup during power failure. The optimization and sensitivity analysis of solar-diesel hybrid system is carried out for NIT Hamirpur's uninterrupted power supply system which indicates that hybrid energy systems will be reliable for urban and rural locations of the country.

The main conclusions are as follows:

1. There is vast scope of solar and wind resource utilization using hybrid systems in rural and urban areas including hilly regions of the country.
2. The hybrid systems using renewable energy sources are reliable power supply systems for standalone applications for residential, institutional buildings and remote locations.

3. The analysis of 5kWp wind and 1 kWp solar hybrid system shows that the system is effectively utilizing both high solar and low wind source available at the location and is able to meet the energy requirements of the day time use of CEE office building.

4. The optimum system for this location, utilizing both solar and wind resources, is found to be a 2kWp solar PV array, 5kWp wind turbine and a string of 10 batteries with total NPC as $34,861 and COE as $1.051/kWh respectively, while NPC and COE of the existing hybrid system is $30,734 and $1.156/kWh respectively. In comparison with the existing system, the cost of optimum wind solar hybrid system is slightly higher but the capacity shortage drops to 3.1% from 22.3% therefore 1kWp Solar PV system can be added to the existing system.

5. A 2kWp solar photovoltaic system using only solar resource is found to be more cost effective than the 6kWp wind- solar hybrid system for this site but utilization of wind resource is of great importance in remote off grid rural locations in the complex Himalayan terrain where sufficient wind resource is available during different periods of year which needs to be utilized.

6. For stand-alone uninterrupted power supply system, solar PV (300kWp)-diesel (128kWp)-battery (9 strings) hybrid system, is found to be optimum and most reliable hybrid configuration with 51% solar PV power penetration. The NPC and levelized COE of the system are found to be $3,804,559 and $0.288/kWh respectively. The greenhouse gas emission is found to be reduced by 41.6% (291,373.9kg/yr) by including solar PV generation and battery storage with standalone diesel generator.

7. The 100% reliable standalone systems are found to be producing enough excess electricity (i.e. 122,077kWh/yr for solar-diesel hybrid system without battery storage and 53,191kWh for solar-diesel hybrid system with battery storage), therefore the addition of deferrable load will be more suitable.

8. The levelized COE of the standalone hybrid energy systems with different combinations of PV array and diesel generator varied from $ 0.523 to $ 0.288. This can be further reduced by optimizing excess electricity production and introducing the capacity shortage, as 0% capacity shortage is suitable only for critical loads like operation theatre in hospitals and computer servers.

9. A grid interactive solar PV- diesel-battery hybrid is proposed in order to upgrade the existing UPS system. The optimum size of solar PV, diesel generator and battery bank are found to be 100kWp, 128kWp and 1 string of 34 batteries respectively. The solar PV penetration of the system is found to be 19% (129,279kWh/yr).The NPC and levelized COE of the system is found to be $1,189,963 and $0.09/kWh respectively.

10. HOMER is most widely used software for quick analysis of hybrid systems, however, some limitations of HOMER are observed during the study as follows :

    - The Homer does not consider depth of discharge (DOD) of battery bank which plays an important role in the optimization of hybrid system, as both life and size of battery bank decreases with the increase in DOD. Therefore, the DOD should either be optimized or be included in sensitivity inputs of the Homer.
    - HOMER doesn't provide flexibility in selecting optimization technique relevant to particular study. Including, this feature in HOMER will enhance the robustness of the tool and facilitates the comparative study of results using different techniques.
    - HOMER allows only single objective function for minimizing the NPC as such the multi-objective problems cannot be formulated.
    - The properties of batteries are affected by time and environment over a period of operation while HOMER assumes that the properties of the batteries are not affected by time and environmental conditions.

6.2 Further Research areas

Based on the study the follow up research areas identified, are as follows:

- There is vast scope of solar and wind resource utilization using hybrid systems which requires detailed and reliable resource mapping and analysis of the hilly regions of the country

- The focus needs to be on the optimization of hybrid systems for maximum renewable resource utilization at a site rather than considering minimizing cost so as to maximize the promotion of renewable technologies in urban and rural areas.
- The feasibility study of hybrid energy systems employing small hydro and solar and wind resource for remote locations in Himalayan regions needs to be carried out.
- Other software packages like iHOGA, PVsyst, Hybrid2 can also be used to design the hybrid energy systems and results can be compared for better analysis.

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