A thesis submitted to fulfill the partial requirement for the degree of

MASTER OF SCIENCE IN ELECTRICAL AND ELECTRONIC ENGINEERING

DESIGN STRATEGY FOR AN OFF-GRID SOLAR-WIND HYBRID POWER SYSTEM

By

Ahammad

Student ID: 0409062135 P

Supervised by

Dr. Abdul Hasib Chowdhury

Co-supervised by

Prof. Dr. Shahidul Islam Khan

DEPARTMENT OF ELECTRICAL AND ELECTRONIC ENGINEERING

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

DHAKA, BANGLADESH

December, 2014

Design strategy for an off-grid solar-wind hybrid power system

by

Ahammad

Student ID: 0409062135 P

A thesis submitted to

the Department of Electrical and Electronic Engineering

of

Bangladesh University of Engineering and Technology

in partial fulfillment of the requirement

for the degree of

MASTER OF SCIENCE IN ELECTRICAL AND ELECTRINIC ENGINEERING

The Department of Electrical and Electronic Engineering

BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY

December, 2014

CERTIFICATE OF APPROVAL

The thesis titled “DESIGN STRATEGY FOR AN OFF-GRID SOLAR-WIND HYBRID POWER SYSTEM” submitted by Ahammad, Student No.: 0409062135 P of session April 2009 has been accepted as satisfactory in partial fulfillment of the requirement for the Degree of **Master of Science in Electrical and Electronic Engineering** on December 29, 2014.

BOARD OF EXAMINERS

1.	________________________ Dr. Abdul Hasib Chowdhury Associate Professor Department of Electrical and Electronic Engineering, BUET, Dhaka-1000, Bangladesh	Chairman (Supervisor)
2.	________________________ Dr. Shahidul Islam Khan Professor Department of Electrical and Electronic Engineering, BUET, Dhaka-1000, Bangladesh	Member (Co-Supervisor)
3.	________________________ Dr. Taifur Ahmed Chowdhury Professor and Head Department of Electrical and Electronic Engineering, BUET, Dhaka-1000, Bangladesh	Member (Ex-Officio)
4.	________________________ Dr. Enamul Basher Professor Department of Electrical and Electronic Engineering, BUET, Dhaka-1000, Bangladesh	Member
5.	________________________ Dr. Abdur Rahim Mollah Professor and Head Department of Electrical and Electronic Engineering, Ahsanullah University of Science and Technology, Dhaka-1208, Bangladesh	Member (External)

DECLARATION

It is hereby declared that this thesis titled "**DESIGN STRATEGY FOR AN OFF-GRID SOLAR-WIND HYBRID POWER SYSTEM**" or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Signature of the Author

____
(Ahammad)

ACKNOWLEDGEMENTS

Praise and glory is to the Most Merciful and the Most Compassionate Allah (s.w.t) who has given me the capability, knowledge and skills to complete this work successfully.

I would like to express my gratitude to my supervisor, Dr. Abdul Hasib Chowdhury, Associate Professor, Department of Electrical and Electronic Engineering of Bangladesh University of Engineering and Technology for the guidance and enthusiasm given throughout the progress of this research work.

I would like to take this opportunity to thank my thesis co-supervisor, Dr. Shahidul Islam Khan, Professor, Department of Electrical and Electronic Engineering of Bangladesh University of Engineering and Technology for his comments and suggestions in completing this work.

I am grateful to Dr. Enamul Basher, Professor, Department of Electrical and Electronic Engineering of Bangladesh University of Engineering and Technology for his suggestions and valuable time to complete this work.

I would also like to express my sincere appreciation to my thesis committee member Dr. Abdur Rahim Mollah, Professor and Head, Department of Electrical and Electronic Engineering of Ahsanullah University of Science and Technology for reviewing this thesis in detail and giving important feedback regarding the matter.

I am also grateful to the Head of the Department of Electrical and Electronic Engineering of Bangladesh University of Engineering and Technology Professor Dr. Taifur Ahmed Chowdhury for giving me the opportunity to complete the work and necessary support during the period.

Special thanks to Bangladesh Meteorological Department at Agargaon for providing data of solar irradiation and wind speed which helped me to complete my thesis work.

Finally, I would like to thank my loving wife. She particularly helped during this thesis by providing ideas, when I needed an urgent computational facility at home. Also, my deepest gratitude to my caring and supportive family; always encouraged me to excel my professional life. Their support can‟t express in word

ABSTRACT

A solar-wind hybrid power system consists of many components including PV panels, wind turbine, battery, power electronic control and interfacing, etc. Sizing of different components is the main challenge. In this work an off-grid solar-wind hybrid power system is considered for the design. Component sizes are determined in steps based on demand, optimum utilization of components, reliability requirement and cost. Corresponding control strategy is proposed. MATLAB code is developed for the purpose.

Internationally available comprehensive data set is used as the design input. The data set includes wind data, solar irradiation data and weather data. Cost of different component is collected from different manufacturer.

The dependency of the design strategy of solar-wind hybrid power system on the available natural resources such as the wind speed and the solar irradiation has not been studied yet. Depending on the available natural resources such as the wind speed and the solar radiation the load sharing strategy, sizing of the wind-PV generation and the sizing of battery are the main focus of this thesis.

Result from the proposed design output is compared with different types of Solar-Wind Hybrid Power Systems (SWHPSs). Then a Unit Electricity Cost (UEC) analysis for a period of 20 years has been computed for each of the SWHPSs. A comparative study has been made reflecting both the performance and UEC of those SWHPSs so that a solution could be made for the electricity shortage problem. A comparative study with the existing strategies has also been done including their environmental impact in the duration of 20 years.

TABLE OF CONTENTS

Chapter 1 : INTRODUCTION

Chapter 2 : SOLAR AND WIND POWER

Chapter 3 : DESIGN STRATEGIES OF THE EXISTING OFF-GRID HYBRID SOLAR-WIND POWER SYSTEMS

Chapter 4 : PROPOSED DESIGN STRATEGY FOR OFF-GRID HYBRID SOLAR-WIND POWER SYSTEM

Chapter 5 : COST CALCULATION

Chapter 6 : OPTIMIZATION OF UNIT ELECTRICITY COST FOR BANGLADESH USING PROPOSED STRATEGY

Chapter 7 : CONCLUSION

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 INTRODUCTION

Being a modern part of civilization, government of every county has its urge to develop its economy as well as serve its citizen with the utilities as a part of its duties. Recent statistics shows that the power sector has been lagging behind due to its dependence in gas and hydro power stations to generate major portions of power. Although at present the power sector has shown a quick growth due to installation of quick rental power plants, still it is not the ultimate solution for a country‟s overall power generation. That is why renewable energy comes into the discussion.

There are many rural areas and newly expanded urban areas, where grid supply has not reached yet but an opportunity of using renewable energy has always been available. Moreover, the dependence of economy on depleting fossil fuel has reached at its highest peak, which concerns the government. That‟s why interest has grown in rebuilding the power generation sector with suitable energy economy. Having said that, it is to be informed that solar-wind hybrid energy is the fastest growing energy sources at an increasing rate of 25-30% annually over the last decade in the whole world [1, 2].

Bangladesh has centralized in its capital and other urban regions which make it difficult to provide support utilities like electricity in every city. For example, Dhaka is the capital city where 43% electricity is used in household. Industrial and commercial demands are fulfilled by the rest of the electricity supply. Recent measurements are quick initiatives for managing the crisis; still it is not a secured future for our power sector. A proper prophesized plan is needed which will not only emphasize upon the importance of using renewable energy, but also show its attention over the application and implementation of the energy in every power related sector.

A quick glance at the electrification world map will show that rural or urban areas are in great need of affordable and reliable electricity to achieve development. Likewise, an overview through the most important literature on rural or urban electrification will prove that renewable energy (RE) are one of the most suitable and environmentally friendly solutions to provide electricity in rural areas.

Autonomous decentralized (off grid) rural or urban electrification based on the generation of renewable energy power on site through the installation of suitable power system in households, and the setup of electricity distribution mini-grid, fed by RE or mixed, have been proven capable of delivering high quality and reliable electricity for lighting, communication, water supply and motive power, among others.

1.2 LITURATURE REVIEW

Micro-grids are modern, small-scale versions of the centralized electricity system. They achieve specific local goals, such as reliability, carbon emission reduction, diversification of energy sources, and cost reduction, established by the community being served. Villages and towns that are far from the utility grid can have their electricity needs met by autonomous micro-grids which can integrate wind, solar, diesel, and other energy sources to create a robust and reliable local grid [3].

Modeling and control strategy for a sustainable micro-grid primarily powered by wind and solar energy is based on the following principles: a) high power supply reliability; b) full utilization of the complementary characteristics of wind and solar; c) small fluctuation of power injected into the micro-grid; d) optimization of the battery's charge and discharge state [4]; and e) minimization of total cost of system [5, 6].

An energy source is considered reliable on this site if it can be used to generate a consistent electrical output and is available to meet predicted peaks in demand. Every energy source has strengths and weaknesses, such as its inherent limitations on reliability of supply, which could contribute to the likelihood of an energy gap, when supply falls short of demand, and might cause interruptions to the electricity supply [7, 8].

A stand-alone hybrid power system consists of solar power, wind power, diesel engine and an intelligent power controller. MATLAB/SIMULINK was used to build the dynamic model and simulate the system. To achieve a fast and stable response for the real power control, the intelligent controller consists of a radial basis function network (RBFN) and an improved Elman neural network (ENN) for maximum power point tracking (MPPT). The pitch angle of wind turbine was controlled by the ENN, and the solar system used RBFN, where the output signal was used to control the dc/dc boost converters to achieve the MPPT [9].

A supervisory model predictive control method is developed for the optimal management and operation of hybrid standalone wind-solar energy generation systems. The supervisory control system is designed via model predictive control which computes the power references for the wind and solar subsystems at each sampling time while minimizing a suitable cost function. The power references are sent to two local controllers which drive the two subsystems to the requested power references. The formulation of the model predictive control optimization problem discusses how to incorporate practical considerations, for example, how to extend the life time of the equipment by reducing the peak values of inrush or surge currents. Several simulation case studies were presented that demonstrate the applicability and effectiveness of the proposed supervisory predictive control architecture [10].

The full utilization of solar and wind resources are very important for the design of the solar-wind hybrid power system. Various strategies have been developed in this regard [11, 12].

A standalone wind/solar/battery hybrid power system, making full use of the nature complementarily between wind and solar energy, has an extensive application prospect among various newly developed energy technologies. The capacity of the hybrid power system needs to be optimized in order to make a tradeoff between power reliability and cost. Each part of the wind/solar/battery hybrid power system was analyzed in detail and an objective function combining total owning cost and loss of power supply probability was built. To solve the problems with non-linearity, complexity and huge computation, an improved particle swarm optimization (PSO) algorithm was developed, which integrated the taboo list to broaden the search range and introduces `restart' and `disturbance' operation to enhance the global searching capability. It was found that the proposed algorithm was more stable and provides better results in solving the optimal allocation of the capacity of the standalone wind/solar/battery hybrid power system compared with the standard PSO algorithm [13].

Voltage fluctuations can be described as repetitive or random variations of the voltage envelop due to sudden changes in the real and reactive power drawn by load. the characteristics of voltage fluctuations depends on the load type and size and the power system capacity[14]. Voltage fluctuations are caused when loads draw currents having significant sudden or periodic variations. The fluctuating current that is drawn from the supply causes additional voltage drop in power system leading to fluctuations in the supply voltage [15].

A unique standalone hybrid power generation system, applying advanced power control techniques, fed by four power sources: wind power, solar power, storage battery, and diesel engine generator, and which is not connected to a commercial power system. Different power sources can be interconnected anywhere on the same power line, leading to flexible system expansion. It is anticipated that this hybrid power generation system, into which natural energy is incorporated, will contribute to global environmental protection on isolated islands and in rural locations without any dependence on commercial power systems. Considerable effort was put into the development of active-reactive power and dump power controls. The results revealed that amplitudes and phases of ac output voltage were well regulated in the proposed hybrid system [16].

The battery energy storage station (BESS) is the current and typical means of smoothing wind- or solar-power generation fluctuations. Such BESS-based hybrid power systems require a suitable control strategy that can effectively regulate power output levels and battery state of charge (SOC). To improve the smoothing performance of wind/PV/BESS hybrid power generation and the effectiveness of battery SOC control, a wind/photovoltaic (PV)/BESS hybrid power system simulation analysis have to be undertaken. A smoothing control method for reducing wind/PV hybrid output power fluctuations and regulating battery SOC under the typical conditions was proposed. Also novel real-time BESS-based power allocation method was proposed. The effectiveness of these methods was verified using MATLAB/SIMULINK software [17].

The digital signal processor (DSP) consists of solar cells, a wind turbine, a lead acid battery, and a buck–boost converter. This DSP can, day and night, be easily controlled and charged by a simple program, which can change the state of the system to reach a flexible application based on the reading weather conditions. The solar cells and wind turbine serve as the system's main power sources and the battery as an energy storage element. The output powers of solar cells and wind turbine have large fluctuations with the weather and climate conditions. These unstable powers can be adjusted by a buck–boost converter and thus the most suitable output powers can be obtained. A DSP for controlling a solar cell and wind-turbine hybrid charging system was developed. A booster was also designed in that regard. The DSP was controlled by the perturbation and observation methods to obtain an effective energy circuit with full charging system [18].

It is very important take into account these issues in order to obtain a technical well adopted solution, keeping the equilibrium among the user‟s need, the investment and the environmental constrains fulfillment. For example, equipment design not adapted to the environmental conditions has critical sustainability, due to frequent fails and expected growth of operational cost.

Factors that influence the design of a hybrid solar-wind power system relate mainly to political and social conditions, and to technical advances and economics. The analytic hierarchy process (AHP) is used to quantify the various divergences of opinions, practices and events that lead to confusion and uncertainties in planning HSWPS [19]. Linear programming techniques minimize the average production cost of electricity while taking environmental factors into consideration and meeting load requirements in a reliable manner. The environmental credit gained as compared to diesel alternatives can be obtained through direct optimization [20]. Unit size and costing of a solar-wind hybrid power system for a micro-grid depends on the availability of natural resources and should be considered comprehensively in designing such a hybrid power system.

1.3 OBJECTIVE

The objective of this work is to propose a design strategy for micro-grid powered by solar-wind hybrid power system, which consists of renewable energy sources (PV-arrays and wind generator) and energy storage bank (battery bank).

Internationally available comprehensive data set [5, 21] was used as the design input which shall include wind data, solar irradiation data and weather data and cost of different component will be collected from different manufacturer for the calculation of unit electricity cost.

1.4 THESIS OUTLINE

This thesis includes seven chapters. Chapter-1 contains general introduction to emphasize on the importance of this thesis, literature review to present the works which have been done so far and the objective of this thesis.

Chapter-2 discusses the theory of the power generating systems which is required to construct a solar-wind hybrid system, the elements of these power generating systems and different types of environmental effects on these power generating systems. Also this chapter discusses about the storage system.

Chapter-3 contains the design strategies of existing off-grid solar-wind hybrid power systems. Three types of existing strategies of standalone solar-wind hybrid power system are presented to gather the ideas about them.

Chapter-4 presents the drawbacks of the existing strategies. The design strategy of the proposed off-grid solar-wind hybrid power system is also presented in this chapter. To calculate the number of solar panels, wind turbines and batteries internationally available comprehensive data set is used for the existing strategy as well as the proposed strategy. Finally a comparison is done on the basis of surplus or deficiency of energy and the number of batteries.

Chapter-5 hosts the cost calculation of both these two types of hybrid system. To calculate the cost a life of twenty years is considered for both these strategies. Finally unit electricity cost is calculated and made a comparison among these two strategies.

Chapter-6 contains the yearly profiles of solar and wind of the two best places in Bangladesh and tried to implement the proposed strategy using these profiles. The unit electricity cost is also calculated for these two places for the six design scenarios which are considered in this work and tried to find out the suitable place to set up the off-grid solar-wind hybrid power system in Bangladesh.

Chapter-7 presents the conclusion of this thesis depending on the findings of this work. Finally future scope of work is presented.

Chapter 2

SOLAR AND WIND POWER

2.1 INTRODUCTION

Conventionally, the electric power is mainly generated from fossil fuels. However this kind of energy resources is highly limited, and will exhaust in the near future. With the rapid requirement of electricity and the increase of worse-and-worse energy crisis, it is of great urgency to replace fossil fuels with renewable energy. Among renewable resources, solar energy and wind power attract a great deal of interest owing to their easy acquirement.

One of the primary needs for socio-economic development in any nation in the world is the provision of reliable electricity supply systems. Here the discussion will be on the development of an indigenous technology hybrid Solar-Wind Power system that harnesses the renewable energies in Sun and Wind to generate electricity. In this technology electric DC energies produced from photovoltaic and wind turbine systems are transported to a DC disconnect energy Mix controller. The controller is bidirectional connected to a DC-AC float charging-inverter system that provides charging current to a heavy duty storage bank of Battery and at the same time produces inverted AC power to AC loads.

One of the primary needs for socio-economic development in any nation in the world is the provision of reliable electricity supply systems. In Bangladesh, the low level of electricity generation in the country from conventional fossil fuel has been the major constraint to rapid socio-economic development especially in rural communities. In Bangladesh, about sixty- five percent (65%) are rural dwellers with majority of them living far-off grid areas [22]. These rural dwellers are mostly farmers whose socio-economic lives can only be improved when provisions are made to preserve their wasting agricultural products and provide energy for their household equipment such as refrigerator, fan, lighting etc. There is also such a need to provide electricity for e-information infrastructures in our rural communities to service school, rural hospital, rural banking and rural e-library. Hence, there is the need to develop an indigenous technology to harness the renewable energies in Sun and Wind to generate electricity.

2.2 SOLAR ENERGY

Solar energy is energy from the Sun. It is renewable, inexhaustible, environmental pollution free. Solar energy, radiant light and heat from the sun, has been harnessed by humans since ancient times using a range of ever-evolving technologies. Solar energy technologies include solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis, which can make considerable contributions to solving some of the most urgent energy problems the world now faces.

2.2.1 SOLAR POWER SYSTEMS

Solar energy is energy from the Sun. It is renewable, inexhaustible, environmental pollution free. Solar energy, radiant light and heat from the sun, has been harnessed by humans since ancient times using a range of ever-evolving technologies. Solar energy technologies include solar heating, solar photovoltaic, solar thermal electricity, solar architecture and artificial photosynthesis, which can make considerable contributions to solving some of the most urgent energy problems the world now faces. Solar power is the conversion of sunlight into electricity, either directly using photovoltaic (PV), or indirectly using concentrated solar power (CSP). Concentrated solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. Photovoltaic convert light into electric current using the photoelectric effect [23].There are two types of solar power systems:

- Those that convert solar energy to D.C. power and
- Those that convert solar energy to heat

The Solar-generated electricity is called Photovoltaic (PV) power. Photovoltaic are solar cells that convert sunlight to D.C electricity. These solar cells in PV module are made from semiconductor materials. When light energy strikes the cell, electrons are emitted. The electrical conductor attached to the positive and negative scales of the material allow the electrons to be captured in the form of a D.C current. The generated electricity can be used to power a load or can be stored in a battery. Photovoltaic system is classified into two major types:

- Off-grid (standalone) systems and
- Grid-tie system

The off-grid (standalone) systems are mostly used where there is no utility grid service. It is very economical in providing electricity at remote locations especially rural banking, hospital and ICT in rural environments.

2.2.2 BASIC COMPONENTS OF SOLAR POWER SYSTEM

The major components include PV modules, battery and inverter shown in Fig 2.1. The most efficient way to determine the capacities of these components is to estimate the load to be supplied. The size of the battery bank required, the maximum discharge rate, and the minimum temperature at which the battery will be used. When designing a solar power system, all these factors are to be taken into consideration when battery size is to be chosen.

Lead-acid batteries are the most common in PV system because their initial cost is lower and also they are readily available nearly everywhere in the world. Deep cycle batteries are designed to be repeatedly discharged as much as 80 percent of their capacity and so they are a good choice for power systems.

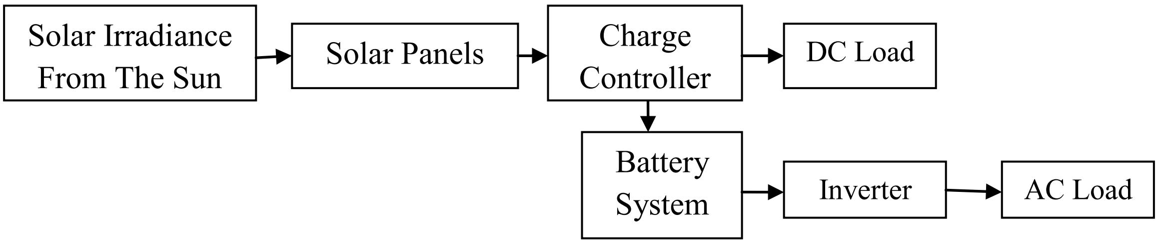


Figure 2.1: Off-Grid/ stand alone solar system

2.2.3 IRRADIANCE AND TEMPERATURE EFFECTS ON SOLR CELLS

There is a great effect of irradiance and temperature on solar cells.

The Effect of Irradiance

The amount of sunshine reaching the solar cells at any moment is referred to irradiance. The irradiance reaching the ground varies throughout the day with the movement of the sun and the clouds. Increasing the irradiance generates a proportionately higher current. Therefore the S.S.C. of the solar cell is directly proportional to the irradiance. The voltage variation is much smaller. Irradiance, or the brightness of the sun, also diminishes when the sun is at a low angle. Solar tracker systems that adjust the angle of the photovoltaic panel to maximize irradiance, may improve the ability to take advantage of the positive effects of cold on solar panel efficiency. The impact of irradiance on solar cell is shown in Fig 2.2.

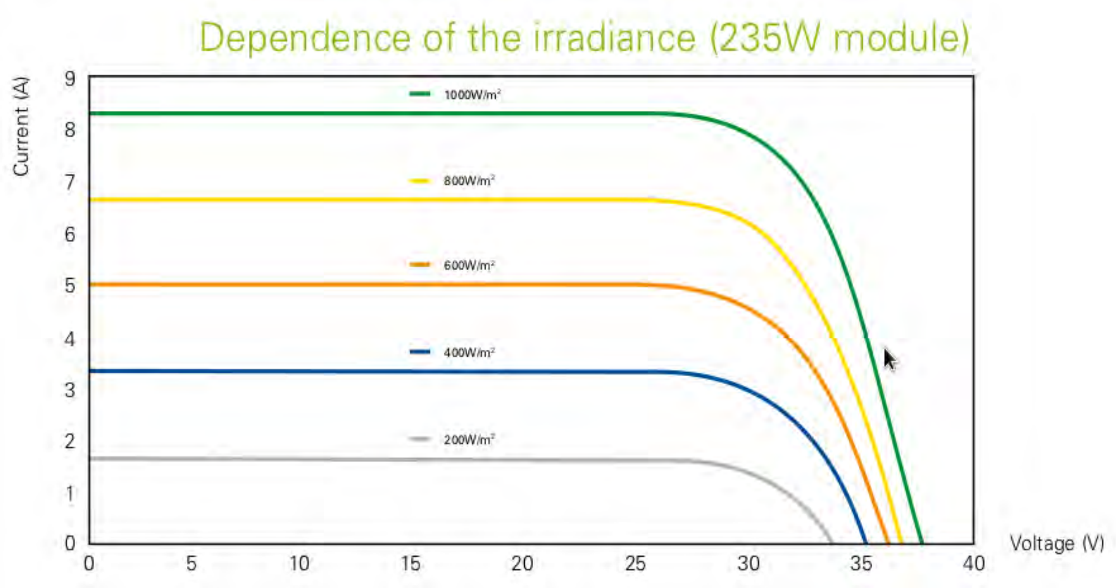


Figure 2.2: Irradiance effects on solar cells

In practical application, solar cells do not operate under standard conditions. Temperature and irradiance affects the performance of solar cells.

The Effect of Temperature

Solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore, increasing the temperature reduces the band gap energy. In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The open-circuit voltage decreases with temperature.

- **The Effect of High Temperatures**: The energy production efficiency of solar panels drops when the panel reaches hot temperatures. A field experiment in the United Kingdom found a drop of 1.1% of peak output for every increase in degrees Celsius of a home photovoltaic solar panel once the panel reached 42 degrees Celsius, or about 107 degrees Fahrenheit.
- **The Effect of Low Temperatures:** Photovoltaic solar panel power production works most efficiently in low temperatures. Cold, sunny environments provide optimal operating conditions for solar panels. Unfortunately, the coldest regions of the globe near the poles are areas with weaker sunshine and for, much of the year, shorter days.

The impact of increasing temperature is shown in the Fig 2.3.

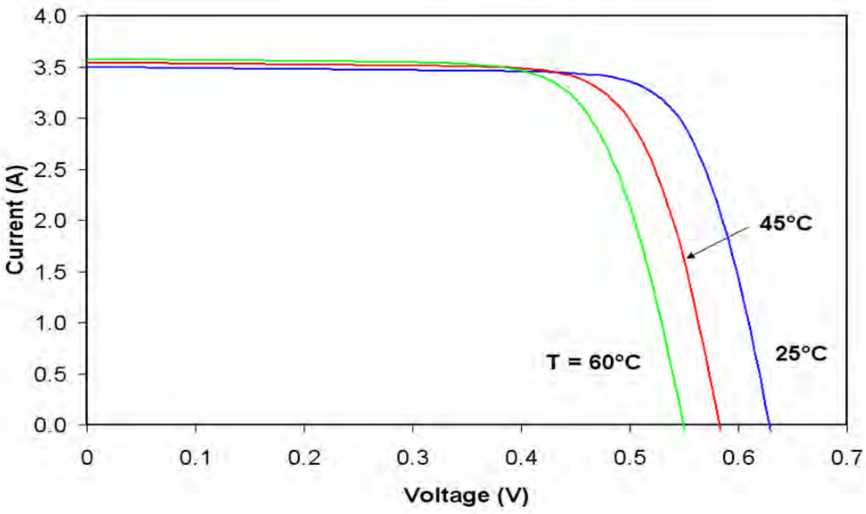


Figure 2.3: Temperature effects on solar cells

It should be noted that a higher temperature increases the mobility of electrons, which causes the flow of current to increase slightly.

2.2.4 PHOTOVOLTAIC (PV) SOLAR MODULES

The photovoltaic cell is also referred to as photocell or solar cell. The common photo cell is made of silicon, which is one of the most abundant element on earth, being a primary constituent of sand. A solar module is made up of several solar cells designed in weather proof unit. The solar cell is diode that allows incident light to be absorbed and consequently converted to electricity. The assembling of several modules will give rise to arrays of solar panels whose forms are electrically and physically connected together.

2.3 BATTERY

The batteries in use for solar systems are the storage batteries, otherwise deep cycle motive type. Various storages are available for use in photovoltaic power system, the batteries are meant to provide backups and when the radiance is low especially in the night hours and cloudy weather. The battery to be used:

- Must be able to withstand several charging and discharging cycles.
- Must be low self-discharge rate.
- Must be able to operate with the specified limits.

2.3.1 CHARGING CONTROLLER

The need for charging controllers is very important so that overcharging of the batteries can be prevented and controlled. The controllers to be used required the following features [24]:

- Prevent feedback from the batteries to PV modules.
- It should have also a connector for DC loads.
- It should have a work mode indicator.

2. 4 WIND POWER SYSTEM

The first use of wind power was to sail ships in the Nile some 5000 years ago. The Europeans used it to grind grains and pump water in the 1700s and 1800s. the first windmill to generate electricity in the rural U.S.A. was installed in 1890. Today, large wind-power plants are competing with electric utilities in supplying economical clean power in many parts of the world. The average turbine size of the wind installations has been 300 kW until the recent past. The newer machines of 500 to 2,000 kW capacities have been developed and are being installed. Prototypes of a few MW wind turbines are under test operations in several countries is a conceptual layout of modern multi megawatt wind tower suitable for utility scale applications. Wind Power is energy extracted from the wind, passing through a machine known as the windmill. Electrical energy can be generated from the wind energy. This is done by using the energy from wind to run a windmill, which in turn drives a generator to produce electricity. The windmill in this case is usually called a wind turbine. This turbine transforms the wind energy to mechanical energy, which in a generator is converted to electrical power. An integration of wind generator, wind turbine, aero generators is known as a wind energy conversion system (WECS).

2.4.1 COMPONENTS OF A WIND ENERGY SYSTEM

Modern wind energy systems consist of the following components:

- A tower on which the wind turbine is mounted
- A rotor that is turned by the wind
- The nacelle which houses the equipment including the generator
- Gear Box
- Generator that converts the mechanical energy in the spinning rotor into electricity
- Power Cables
- Transformer
- Switchyard

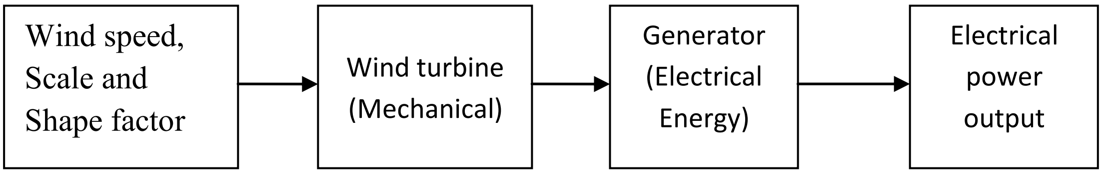


Figure 2.4: Block diagram of a wind turbine generation process [25]

The tower supporting the rotor and generator must be strong. Rotor blades need to be light and strong in order to be aerodynamically efficient and to withstand prolonged use in high winds. In addition to these, the wind speed data, air density, air temperature need to be known amongst others. The block diagram in Fig 2.4 shows the conversion process of wind energy to electrical energy.

Chapter 3

DESIGN STRATEGIES OF THE EXISTING OFF-GRID HYBRID SOLAR-WIND POWER SYSTEMS

3.1 INTRODUCTION

Conventionally, electric power is mainly generated from fossil fuels. However, this kind of energy resources is highly limited, and will exhaust in the near future. With the rapid requirement of electricity and the increase of worse-and-worse energy crisis, it is of great urgency to replace fossil fuels with renewable energy. Among renewable resources, solar-wind hybrid power system attracts a great deal of interest owing to its easy acquirement.

3.2 FIRST TYPE OF HYBRID SYSTEM CONFIGURATION

In this design strategy the analytic hierarchy process (AHP) is used to quantify the various divergences of opinions, practices and events that lead to confusion and uncertainties in planning hybrid solar wind power system (HSWPS). After deciding the priority of the design objectives, there is a need to know how the system components are simulated and what the operating strategy of the proposed design is. In this process, the HSWPS will be composed of wind turbine generator, PV arrays, batteries and a grid option [18]. Linear programming models are proposed in order to minimize the average production cost of electricity while meeting the load requirements in a reliable manner [18, 26]. Fig 3.1 shows the configuration of the hybrid power generation system under investigation.

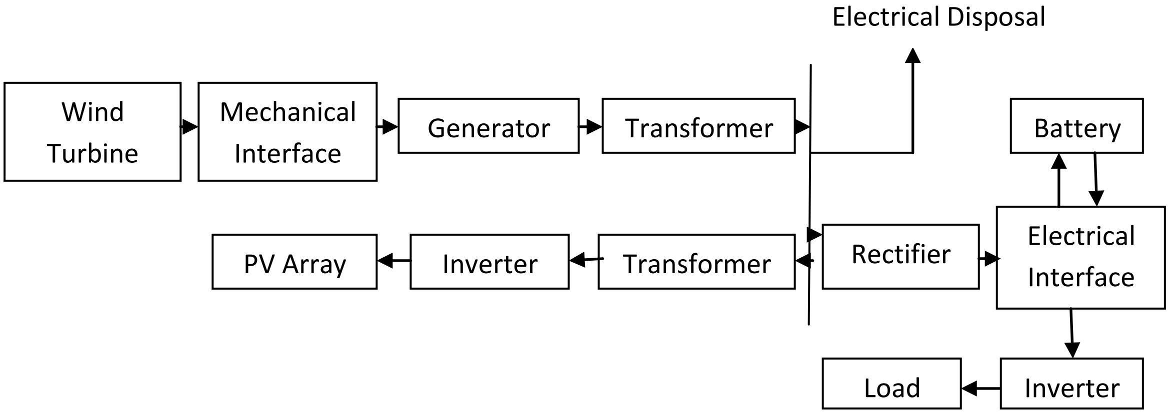


Figure 3.1: The grid-connected HSWPS

3.2.1 SYSTEM COMPONENTS

WTG: the following is the model used to calculate the output power P_w, (kW/m^2) generated by a WTG:

$$\begin{cases} P_w = 0 & V < Vci \\ P_w = a.V^3 - b.Pr & Vci < V < Vr \\ P_w = Pr & Vr < V < V\alpha \\ P_w = 0 & V > V\alpha \end{cases} \tag{3.1}$$

Where $a = \frac{Pr}{Vr^3 - Vci^3}$ and $b = \frac{Vci^3}{Vr^3 - Vci^3}$ and, Pr, Vci, Vr, and $V\alpha$ are the rated power, cut-in, rated and cut-out wind speed respectively.

The real electric power is calculated as:

$$P_{e.w} = P_w \times A_w \times eff_w \tag{3.2}$$

Where A_w is the swept area of the WTGs and eff_w is the efficiency of the WTGs and the corresponding converters shows in Fig 3.1.

PV arrays: the output power P_s, (kW) of a PV array of a area *'A_s'* when subjected to a horizontal irradiance H (kW/m^2) is given by

$$P_s = H \times A_s \times eff_s \tag{3.3}$$

Where, eff_s is the efficiency of the arrays and the corresponding converters shown in Fig 3.1.

Batteries: energy from batteries is needed whenever the renewable energy is insufficient to supply the load. On the other hand, energy is stored whenever the supply from the renewable system exceeds the load demand. The maximum allowable energy taken or added to the batteries is a percentage of the total capacity R_b, usually taken as 10% of R_b per hour [27]. In addition, to avoid deep discharges, the minimum storage level is limited to 20% of what is available in the battery before the discharging cycle begins.

3.3 SECOND TYPE OF HYBRID SYSTEM CONFIGURATION

Block diagram of an existing integrated wind-PV generating system is shown in Fig 3.2. This configuration can be used for the study of stand-alone system as well as network-connected systems [5]. For the network-connected configuration, the backup generator is not needed, and for the stand-alone system, the switch connecting the AC bus to the generating unit is off. In this case, if the demand is greater than the sum of generation and storage, then power must be supplied from the backup generator. Furthermore, if the total generated power is greater than the demand, and the storage is full, then the excess generation is dumped to an external voltage-controlled resistive load.

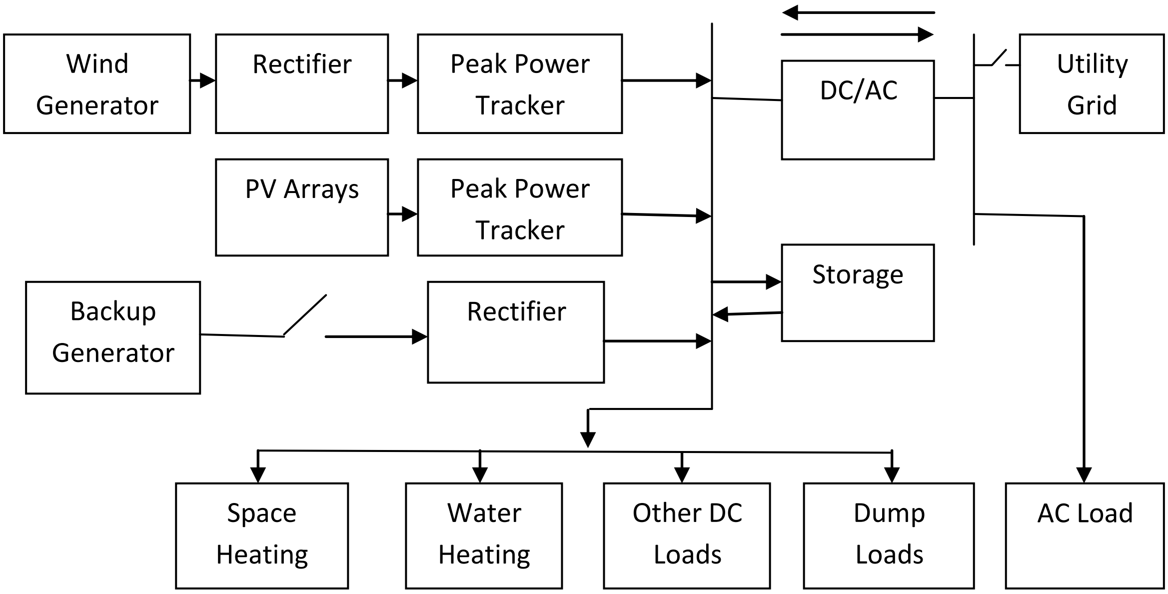


Figure 3.2: Integrated wind-PV generating system

The purpose of incorporating a dumped load into the system is to preserve the stability of the system frequency and voltage. If the excess energy cannot be dissipated usefully, then it must be disposed as heat by a controlled resistor [28]. The peak power „Trackers„keeps the wind and PV generators operating at their maximum power operating points.

3.3.1 SIZING OF WIND-PV GENERATION

In this section, an iterative algorithm is described for determining the wind generator capacity and the number of PV panels needed for the stand-alone system of Fig 3.2. The algorithm uses the hourly average wind, isolation, and power demand to determine the wind-PV generation capacities to meet the demand while minimizing an objective function which will be the total annual cost to the customer (F_c). F_c is the sum of the annual cost of capital (C_c) over the life of the generating system and its annual maintenance cost (C_m).

$$F_c = C_c + C_m \tag{3.4}$$

These costs can be broken up into the annual costs of the wind turbine, PV array, and backup generation as follows:

$$C_c = C_c^{pv} + C_c^{wind} + C_c^{store} + C_c^{backup} \tag{3.5}$$

$$C_m = C_m^{pv} + C_m^{wind} + C_m^{store} + C_m^{backup} \tag{3.6}$$

The objective function F_c is also constrained to minimize the magnitude of the difference between the generated power (P_{gen}) and the demand (P_{dem}) over a given period of time.

$$\Delta P = P_{gen} - P_{dem} \tag{3.7}$$

The total generated and demanded energy (W_{gen} , W_{dem}) over a 24-hour period can be written in terms of the generated wind and solar power and the power demand as follows:

$$W_{gen} = \sum_{n=1}^{24}[(\Delta t)(K_w P(n)_w + K_s P(n)_s)] \tag{3.8}$$

$$W_{dem} = \sum_{n=1}^{24}[(\Delta t)(P(n)_{dem})] \tag{3.9}$$

Where P_w and P_s are the power generated by a specific wind turbine and a single PV panel, respectively. K_w and K_s represent the number of wind turbine and PV panels used.

n is the sampling time (hour of day), and Δt is the time between the samples (in this case one hour).

In order to generation and load to balance over a given period of time, the curve of ΔP versus time must have an average of zero over the same time. Note that positive values of ΔP indicate the availability of generation and negative ΔP indicates generation deficiency. An equation of excess energy versus time (E_h) can be obtained by integrating ΔP.

$$E_h = \int \Delta P dt = W_{gen} - W_{dem} \tag{3.10}$$

The energy curves of equation (3.10) can be used to find the required storage capacity for the wind-PV system. On an average day, the battery is required to cycle between the positive and negative peaks of the energy curve. Therefore, the battery should at least have a capacity equal to the difference between the positive and negative peaks of the energy curve. For this type of application batteries designed specifically for cycling should be used. These batteries have a life time about 1500 cycles, and in order to obtain this life time, they should not be cycled through more than 80% of their rated capacity [29]. Hence, the number of batteries required for the needed storage capacity can be found as follows:

$$\text{Required Storage Capacity} = Max\int \Delta P dt \text{ - } Min\int \Delta P dt \tag{3.11}$$

$$\text{Number of batteries} = \frac{required\ storage\ capacity}{(0.8)(rated\ capacity\ of\ each\ battery)} \tag{3.12}$$

The iterative procedure adopted for selecting the wind turbine size and the number of PV panels needed for a stand-alone system to meet a specific load is as follows:

- Select commercially available unit sizes for wind turbine, PV panel, and storage battery.
- Since the rating for the wind turbine far exceeds that of a single PV panel, keep the number of turbine (K_w) constant and increase the number of PV panels (K_s) until the system is balanced, i.e. the curve of ΔP versus time for the system has an average of zero over a given period of time.
- Repeat step 2 for different number of wind turbines, i.e. K_w = 0,1,2,3,……..as needed.

- Calculate the total system annual cost for each contribution of K_w and K_s that satisfies the requirements in step 2.
- Choose the combination with lowest cost.

3.4 THIRD TYPE OF HYBRID SYSTEM CONFIGURATION

The major concern in this design of an electric power system that utilizes renewable energy sources is the accurate selection of system components that can economically satisfy the load demand [19]. While in autonomous systems, the environmental credit gained as compared to diesel alternatives can be obtained through direct optimization; in grid linked systems, emission is another variable to be minimized for the use of renewable energy be justified. Hence, system‟s components are found subject to:

- Minimize the electricity production cost.
- Ensuring that the load is served according to a certain reliability criteria and
- Minimize the power purchased from the grid.

The cost function is defined as [30]:

$$F \, \alpha \, (\textstyle\sum_{k=1}^{4} I_k - S_{pk} + OM_{pk}) \frac{1}{E_y \times N} \qquad (3.14)$$

Where, the index k is made to account for wind, solar, diesel generators or grid connection, and batteries.

The proposed analysis is composed of three modules, namely, the preprocessor, the optimization tool and the control module. To meet the above objectives, the user should have data on load demand, solar and wind resources averaged over several years as well as economic and technical data. Such information is analyzed and brought to the required format through the preprocessor. The selection of system components will be achieved via the optimization module and then the whole design will be tested in the control module through which the size of the storage will be determined as well as the environmental credit of the system. For this a chronological set of hourly load and resource data is assumed to be available.

In [31] a linear programming (LP) model for the design of integrated renewable energy system has been developed, and in [32] a similar LP model was used to arrive at an optimal mix of wind and photovoltaic for system design.

3.4.1 OPERTION POLICIES

Two different types of cases were considered in this strategy.

Case1. Autonomous System

The operation policy of the proposed system implies that the available energy from the wind turbines and solar panels in each sub period be used first, and excess energy to be stored in batteries. If the renewable energy is not sufficient to supply the load in a given sub period, two control policies are implemented to fill the void. In control policy 1 (*CP1*), energy is first drawn from the storage system. If this is not enough, the diesel generators should provide the remaining portion of the load. In control policy 2 (*CP2*), if the load cannot be met by the renewable supply, energy is drawn first from the diesel engines and, if possible, the batteries supply the remaining part of the demand. The main difference between the two approaches is that in *CP1*, the storage system acts as a fuel saver since the batteries are used before the diesel engine. This is done at the expense of having batteries that are already discharged in periods where diesel engines are not sufficient to supply the load. Hence, the unmet load is expected to be smaller in *CP2* but fuel costs are higher. In some sub periods, all of the available supply is not sufficient to serve the load; in such a case, the difference between the demand and the available energy is shed and an underflow cost is increased.

Case2. Grid-linked System

The control strategy for grid-linked system is similar to the one discussed in case 1 above in the sense that renewable energy must be exploit first and excess energy should be stored in batteries. However, if there is excess energy then, the later should be sold to the grid. Real spilled energy is the energy that cannot go to the grid because of the rating limit of the electric substation. If the renewable energy is not sufficient to supply the load in a given sub period, then the two control policies discussed in case 1 are applied but with the grid now replacing the diesel engines. It is to be mentioned the concept of fuel saving in *CP1* as discussed in case 1, leads to the concept of grid energy demand saving in case 2. Hence, better condition for the environment is guaranteed.

Chapter 4

PROPOSED DESIGN STRATEGY FOR OFF-GRID HYBRID SOLAR-WIND POWER SYSTEM

4.1 INTRODUCTION

Off-grid or standalone systems are associated to remote isolated small communities. Some geographically connected, others spatially distributed in a given-region with electrical service provided by a single or several sources such as: diesel generators, photovoltaic systems, wind turbines, hybrid systems, etc., frequently available only a few hours a day.

Off-grid or standalone systems are not connected with networks of grids of power generation system. These networks cannot always cooperate to meet the load requirements. For this reason, standalone systems should be strengthen and diversify their internal sources to ensure reliable supply of electrical energy to the load.

4.2 DRAWBACKS OF THE EXISTING DESIGN STRETAGIES

The first existing design strategy of solar-wind hybrid power system based on analytic hierarchy process (AHP) discussed in chapter 3 mainly related to political and social factors with technical advances and economics. The analytic hierarchy process is used to quantify the various divergences of opinions, practices and events that lead to confusion and uncertainties in planning hybrid solar-wind power system (HSWPS). Linear programming models are proposed in order to minimize the average production cost of electricity while meeting the load requirements in a reliable manner. A major drawback of this approach is that the reliability of the system is not accounted as the utility grid is not an infinite pool of energy.

The second existing design strategy of solar-wind hybrid power system based on a simple numerical algorithm is considered by taking wind turbine number fixed. It tries to find out the number of solar panels by iterative method which is discussed in section 3.3.1. It is used to determine the optimum generation capacity and storage needed for a stand-alone, wind, PV and hybrid wind/PV system for an experimental site in a remote area. As in the hybrid system the number of wind turbine is kept fixed, we can name it fixed sharing strategy. But the fixed sharing strategy does not consider the minimum unit electricity cost.

In the third existing design strategy of chapter 3, energy is first drawn from the storage system. If this is not enough, the diesel generators provides the remaining portion of the load and it is observed that the diesel generator has a great environmental impact due to the emission of CO_2 in the atmosphere.

In this work, the second existing design strategy of solar-wind hybrid power system is mainly analyzed and the other two design strategies are not taken into account for performance comparison with the proposed design strategy of hybrid solar-wind power system due to the major uncertainty of reliability of the first design strategy and severe environmental impact of the third design strategy.

4.3 PROPOSED DESIGN STRATEGY

On the availability of the natural resources proposed strategy divides the total load among the solar power generation system and the wind power generation system based on percentage concept. The summation of the power generated by the solar PV system and the power generated by the wind power generation system is taken as hundred (100) percent (%). Then calculating the percentage of power generated by the solar PV system and the percentage of power generated by the wind power generation system, the load can be shared between these two according to these percentages. This percentage concept of load sharing is called percentage sharing strategy.

Feasibility of a strategy to hybrid power system depends on the excess or deficiency of energy. If the strategy is able to produce excess energy for a particular time period (which is considered as one year) then the strategy is feasible for hybrid power system. Otherwise the strategy is not feasible.

The size of the solar PV system and the wind power generation system of solar-wind hybrid system are calculated. The sizing of the battery depends on excess or deficiency of energy. If the energy produced by the hybrid system is in excess after meeting the demand for a certain time interval, the excess energy can be stored in the battery which can be utilized when the deficiency of energy occur during another time interval. Finally the unit electricity cost is calculated for economic viability. A typical model of the hybrid power system considered in this work is shown in Fig 4.1.

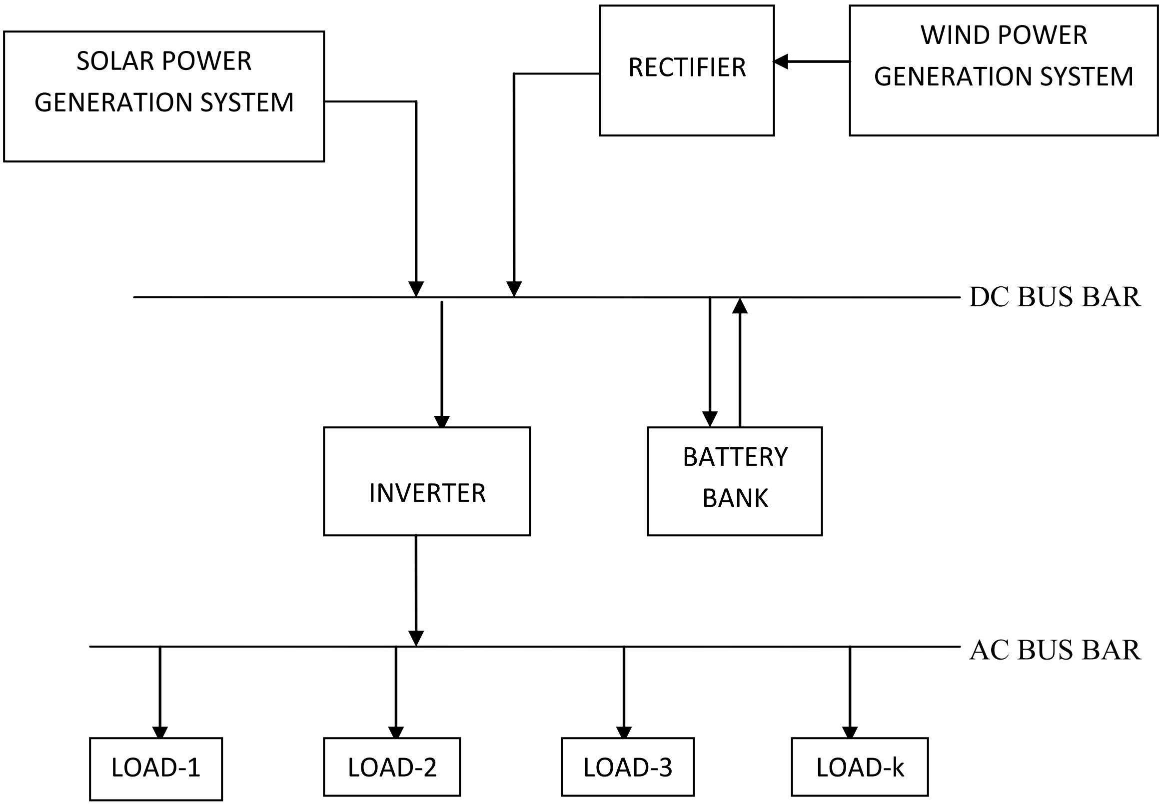


Figure 4.1: A typical model of hybrid solar-wind power system

The following energy flow which is similar as [19], is employed in this design strategy:

- The use of electric power generated by the photovoltaic arrays and wind turbine generators has priority in satisfying electricity demand over that provided by the batteries.
- If the total electric power generated by the photovoltaic arrays and wind turbine generators is higher than the demand, the additional electric power will be charged into the batteries.
- After charging the battery, the electric power that remains is disposed of.
- If the total electric power generated by the photovoltaic arrays and wind turbine generators is less than the demand, electric power will be discharged from the batteries to supply the demand.
- If the demand still cannot be satisfied, then this will result in an energy deficit.

For the feasibility test of a strategy to hybrid power system and to find out the minimum unit electricity cost of the proposed strategy, six different design scenarios are considered in this work. These are presented in Table 4.1

Table 4.1: Features of the six different design scenarios

Scenario	**Conditions**	
1	Peak Load	maximum solar irradiation and maximum wind speed
2		average solar irradiation and average wind speed
3		minimum solar irradiation and minimum wind speed
4	Average Load	maximum solar irradiation and maximum wind speed
5		average solar irradiation and average wind speed
6		minimum solar irradiation and minimum wind speed

In the first design scenario the peak load with maximum solar irradiation and maximum wind speed has been considered. In the second design scenario the peak load with average solar irradiation and average wind speed has been considered. In the third design scenario, the peak load with minimum solar irradiation and minimum wind speed is considered. In the fourth design scenario, the average load with maximum solar irradiation and maximum wind speed is considered. In the fifth and sixth design scenarios the average load with average solar irradiation, average wind speed and average load with minimum solar irradiation, minimum wind are considered, respectively.

The following steps are followed to compare the Unit Electricity Cost (UEC) of proposed strategy with the UEC of existing strategy:

1. At first load sharing by the solar power generation system and wind power generation system of each scenario for proposed strategy is calculated.
2. Then the sizing of the solar power generation system and the wind power generation system for each of the scenario is done.
3. For each scenario surplus or deficiency of power for a certain interval of time period is calculated.
4. From the surplus or deficiency of power, the surplus or deficiency of energy for that particular time period for all the scenarios is calculated.
5. Then the size of the battery bank is calculated depending on the surplus or deficiency of energy.
6. Finally the Unit Electricity Cost (UEC) for these six different design scenarios of the proposed strategy.
7. Steps 2 to 6 are repeated for fixed sharing existing strategy.
8. Eventually the UECs of both the strategies of the design scenarios which are feasible to the strategies are compared to find out the better strategy.

4.4 PV SYSTEM AND WIND POWER MODELING

To determine the generation of PV modules, the required energy consumption must be estimated. Therefore, the PV module generation in kW is calculated as:

$$P_s = \frac{U}{1000} \times s \times A \tag{4.1}$$

Where,

U = maximum output power from a solar panel in watt.

P_s = output power from a solar panel in kW.

s = solar irradiance in kWh/m$^{2.}$

A = Area required to produce per kWh energy in m^2/kWh.

Various mathematical models have been developed to assist in the predictions of the output power production of wind turbine generators (WTG), a statistical function known as Wiebull distribution function has been found to be more appropriate for this purpose. The function is used to determine the wind distribution in the selected site of the case study and the annual/monthly mean wind speed of the site. The Wiebull distribution function has been proposed as a more generally accepted model for this purpose.

The two-parameter Wiebull distribution function is expressed mathematically in equation (4.2) as:

$$F(v) = \frac{K}{C}\left(\frac{v}{C}\right)^{K-1} exp\left[-\left(\frac{v}{C}\right)^{K}\right] \tag{4.2}$$

It has a cumulative distribution function as expressed in equation (4.3), and is given as:

$$M(v) = 1 - exp\left[-\left(\frac{v}{C}\right)^{K}\right] \tag{4.3}$$

Where v is the wind speed, *K* is the shape parameter and *C*, the scale parameter of the distribution. The parameters *K* (dimensionless) and *C* (m/s) therefore characterized the Wiebull distribution. To determine *K* and *C*, the approximations widely accepted are given in equations (4.4) and (4.5) respectively.

$$K = \left(\frac{\partial}{v'}\right)^{-1.09} \tag{4.4}$$

$$C = \frac{v' \times K^{2.6674}}{(0.184+0.816K^{2.73859})} \tag{4.5}$$

Where, ∂ = Standard deviation of the wind speed for the site (ms^{-1}) and v' = Mean speed (ms^{-1})

The amount of power transferred to a wind turbine is directly proportional to the area swept out by the rotor, to the density of the air, and the cube of the wind speed. The power P_m in the wind is given by:

$$P_m = \tfrac{1}{2} (C_p \times \rho \times A \times V^3_{wind})$$

$$= \tfrac{1}{2} (C_p \times \rho \times \pi \times R^2 \times V^3_{wind}) \tag{4.6}$$

The electrical power output from the rotor of the wind turbine is

$$P_w = \eta \times P_m \tag{4.7}$$

The turbine power coefficient is

$$C_p = (0.44 - 0.0167\beta)\ Sin\ \frac{\pi(\lambda-2)}{13-0.3\beta} - 0.00184(\lambda - 2)\ \beta \tag{4.8}$$

The aerodynamic torque is maximum when $\beta = 0$. So the equation (4.8) becomes

$$C_p = 0.44 Sin\ \frac{\pi(\lambda-2)}{13} \tag{4.9}$$

The tip speed ratio (TSR) refers to the ratio between the wind speed and the speed of the tips of the wind turbine blades which is

$$\lambda = \frac{W_m \times R}{V_{wind}} \tag{4.10}$$

The torque T_m in the wind is given by:

$$T_m = \frac{P_m}{W_m} \tag{4.11}$$

Where,

β = Pitch angle in degree.

λ = Tip speed ratio.

R= Radius of the wind turbine in m.

ρ = Air density in kg/m^3.

η = Efficiency of electro-mechanical system.

V_{wind} = Wind speed in m/s.

w_m = Rotor speed in rad/s.

P_m = Mechanical power captured by the blades of wind turbine in watt.

P_w = Electrical power output from the rotor of the wind turbine in watt.

4.4.1 LOAD SHARING STRATEGY

If power generated by the solar panel is P_s and power generated by the wind turbine is $P_{w,}$ the load sharing by the solar power generation system and the wind power generation system of the proposed hybrid system are given by the equations (4.12) and (4.13) respectively.

Load sharing by the solar panel of the hybrid system is,

$$P_{sh} = \frac{P_s}{P_s + P_w} \times P \tag{4.12}$$

Load sharing by the wind turbine of the hybrid system is,

$$P_{wh} = \frac{P_w}{P_s + P_w} \times P \tag{4.13}$$

Where, P is the peak load or average load in kW.

4.4.2 SIZING OF WIND-PV GENERATION

If the load sharing by the solar panel of the hybrid system is P_{sh}, load sharing by the wind turbine of the hybrid system is P_{wh} then the number of solar panel and wind turbine require to serve the load is given by equations (4.14) and (4.15).

The number of solar panel required to serve the load is,

$$N_{sh} = \frac{P_{sh}}{P_s} \tag{4.14}$$

The number of wind turbine required to serve the load is,

$$N_{wh} = \frac{P_{wh}}{P_w} \tag{4.15}$$

Let $P_h(n)$,$P_s(n)$ and $P_w(n)$ are hybrid, solar and wind power generation for the time interval n in hour or month from equation (4.1) and (4.6). $P_l(n)$ is the load for that time interval n, Then the difference between the generation and demand for the given time interval is,

$$\begin{aligned} \Delta P_h(n) &= P_h(n) - P_l(n) \\ &= (N_{sh} \times P_s(n) + N_{wh} \times P_w(n)) - P_l(n) \end{aligned} \tag{4.16}$$

Where,

$$P_s(n) = \frac{U}{1000} \times s(n) \times A \tag{4.17}$$

$$P_w(n) = ½(C_p \times \rho \times \pi \times R^2 \times V^3_{wind}(n)) \tag{4.18}$$

Surplus energy generated by the hybrid system is,

$$\Delta E_h(n) = \Delta P_h(n) \times n \tag{4.19}$$

4.5 SIZING OF BATTERY

Sizing of battery is another challenge of the solar-wind off-grid hybrid power system. To face this challenge at first we have to find out the total surplus energy of the hybrid system E_{h1} and the total deficiency of energy of the hybrid system E_{h2} for a given time interval n.

Total surplus energy of the hybrid system for a given time interval n is

$$E_{h1} = \sum \Delta E_h(n) \times \gamma \tag{4.20}$$

Where,

$$\gamma = \begin{cases} 1 & for\ \Delta E_h(n) > 0 \\ 0 & otherwise \end{cases}$$

Total deficiency of energy of the hybrid system for a given time interval n is

$$E_{h2} = \sum \Delta E_h(n) \times \beta \tag{4.21}$$

Where,

$$\beta = \begin{cases} 1 & for\ \Delta E_h(n) < 0 \\ 0 & otherwise \end{cases}$$

The battery capacities are dependent on several factors which includes age and temperature. Batteries are rated in Ampere-hour (Ah) and the sizing depends on the required energy consumption. If the average value of the battery is known, and the average energy consumption per hour is determined.

The system capacity is determined by the equations (4.22) and (4.23):

$$C_{sys} = F \times W / V_{sys} \tag{4.22}$$

Where

C_{sys} = System Capacity

F = Depth of discharge of the battery

W = Daily Energy

V_{sys} = System DC voltage

The Ah rating of the battery is calculated as:

Ah rating = (Daily energy consumption (kW) / (Battery Rating (Ah) at a specific voltage) (4.23)

If $F \times E_{h1} > E_{h2}$

The number of the batteries for hybrid system is

$$B_h = E_{h2} / (F \times v_b \times i_b) \tag{4.24}$$

If $F \times E_{h1} < E_{h2}$ (It is not possible for the hybrid system configuration to support the demand)

The number of the batteries for hybrid system is

$$B_h = E_{h1} / (F \times v_b \times i_b) \tag{4.25}$$

Where v_b is the voltage of the battery, i_b is the ampere-hour of the battery and depth of discharge of the battery is taken 75%.

For the calculation of excess energy in percentage the equation (4.26) is used considering the depth of discharge of the battery 75%. The expected value of total excess energy in percentage is zero for the maximum utilization of the energy and minimum loss for a certain period of time. Total excess energy in percentage for a time period after utilization of the energy stored in the batteries during the deficiency of energy in that time period is given below:

$$\text{Surplus energy in percentage} = \frac{(F \times E_{h1}) - E_{h2}}{Demand\ of\ that\ perticular\ time\ period\ in\ kWh} \times 100 \tag{4.26}$$

Feasibility of a design scenario is similar as the feasibility of a strategy. For the feasibility test and to find out the minimum UEC the flow chart of Fig 4.2 among the six design scenarios is considered. The flow chart is followed for the existing strategy and also for the proposed strategy. Finally the results of existing strategy and the proposed strategy are compared.

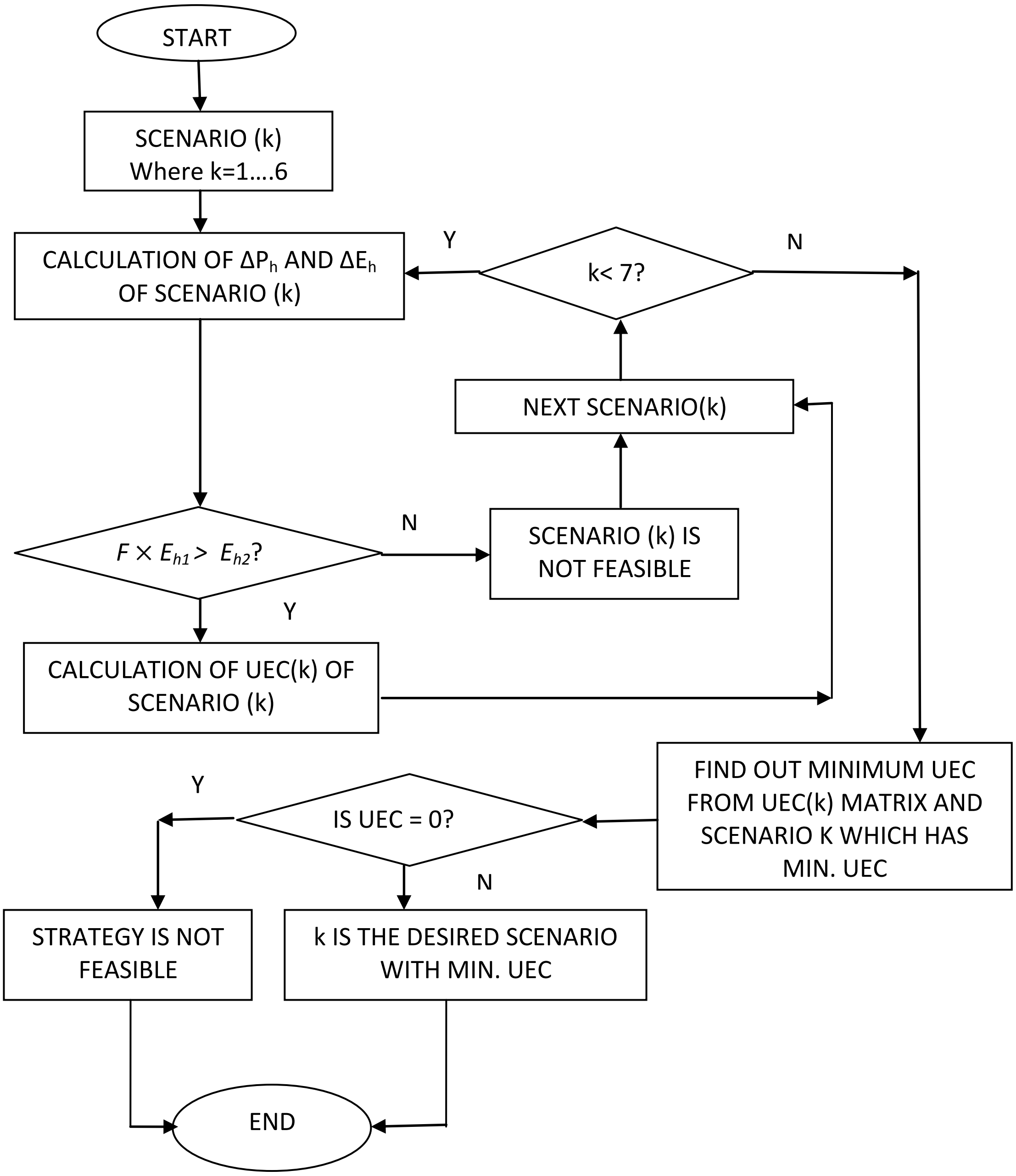


Figure 4.2: Flow chart of the feasibility test and minimum unit electricity cost

4.6 DATA SETS FOR SIMULATION (DAILY AND YEARLY LOAD DATA, SOLAR IRRADIATION DATA AND WIND SPEED DATA)

Two different types of data profile have been considered in this work. One is daily profile which includes daily load, solar irradiation and wind speed data and another is yearly profile with yearly load, solar irradiation and wind speed data.

Daily profile

The daily average hourly load profile of a house is shown in Fig 4.3. This data, taken from [33], is good representation of electrical demand of a typical residential home.

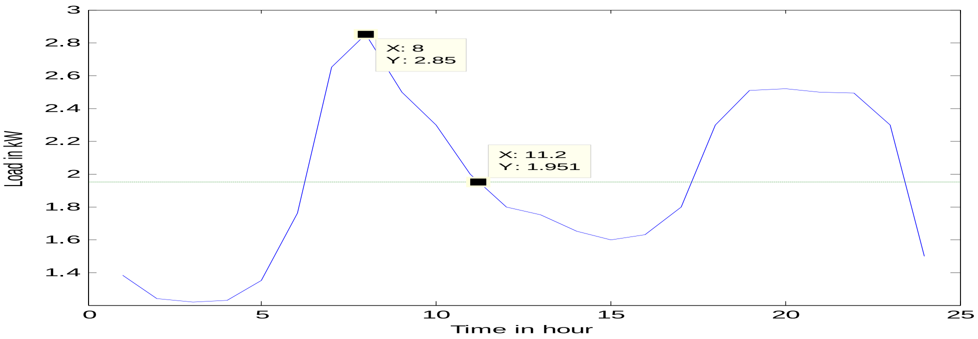


Figure 4.3: Hourly average demand of a typical residence [33]

Note that the curve of Fig 4.3, being an average hourly demand curve, is shown as a continuous plot. Therefore, the wind speed and solar irradiation curves [5] are also shown as continuous plots on Fig 4.4 and Fig 4.5. If the hourly demand data is assumed to be discontinuous (constant during each hour), then all the curves will be stair case plots.

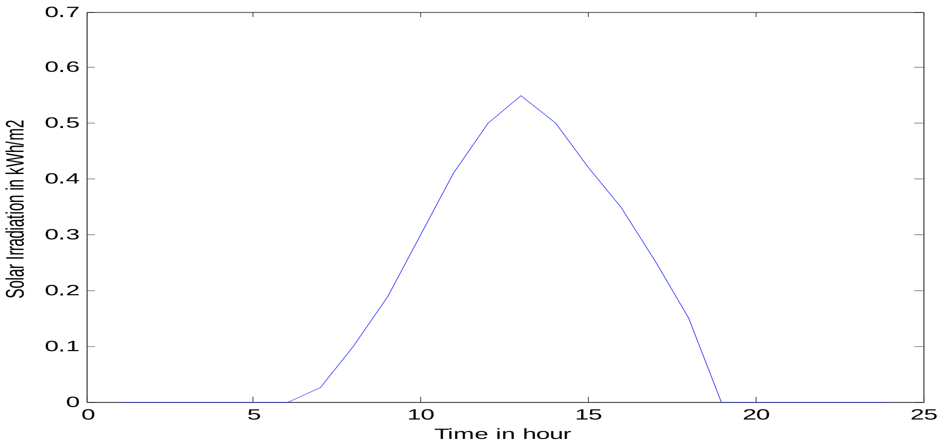


Figure 4.4: Hourly average solar irradiation [5]

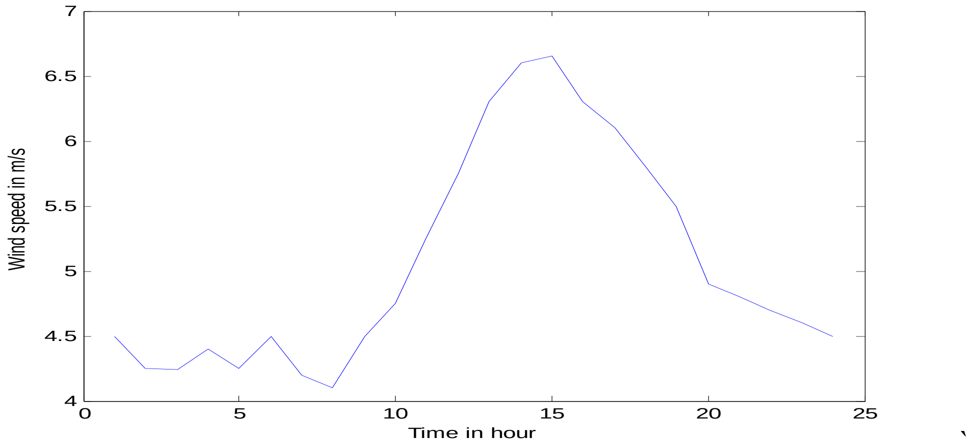


Figure 4.5: Hourly average wind speed [5]

Fig 4.5 shows the hourly average wind speed data over two years recorded by a data acquisition system installed in 1993 at the site of Pacific Northwest where the house is assumed to be located. These data were taken at a height of 4 meters. However, the wind turbine hub height was assumed to be 30 meters, thus, the wind data was collected using the power law expression [35] shown in equation (4.14).

$$\frac{S}{S_0} = \left(\frac{H}{H_0}\right)^{\alpha} \qquad (4.27)$$

Where H_o = 4m, S_o = 4m and S = 30m respectively. The expression α is a measure of surface friction and was taken as 0.13, as suggested in [34], was confirmed through experimental measurements.

Yearly Profile

Yearly solar irradiation and wind speed profiles are given in Table 4.2.The annual average monthly load profile for the house is shown in Fig 4.6.This data, taken from [33], is good representation of electrical demand of a typical residential home. Note the curve of Fig 4.6, being an average monthly demand curve, is shown as a continuous plot. Therefore, the wind speed and solar irradiation curves [35] are also shown as continuous plots on Fig 4.7 and Fig 4.8.

Table 4.2: Yearly profile of solar irradiance and wind speed

Month	Solar Irradiance	Wind Speed	Month	Solar Irradiance	Wind Speed
	$kWh/m^2/d$	m/s		$kWh/m^2/d$	m/s
January	4.36	1.9	July	4.23	2.2
February	4.92	2.1	August	4.29	1.9
March	5.59	2.2	September	4.02	1.7
April	5.76	2.5	October	4.32	1.5
May	5.30	2.5	November	4.28	1.6
June	4.53	2.4	December	4.21	1.7

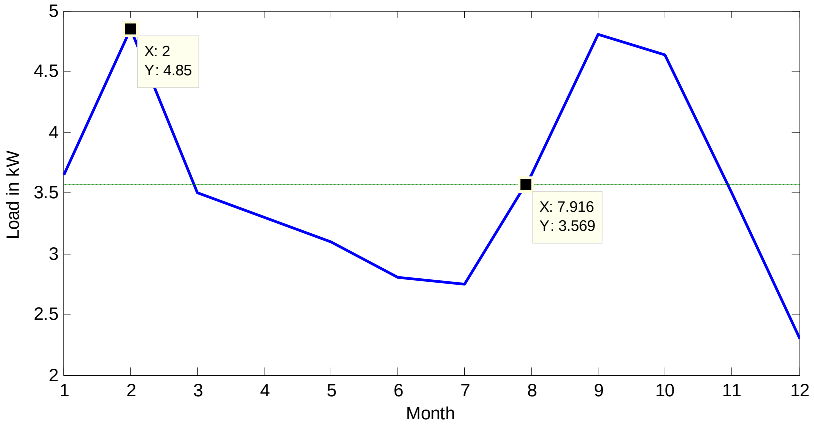


Figure 4.6: Monthly average demand of a typical residence [33]

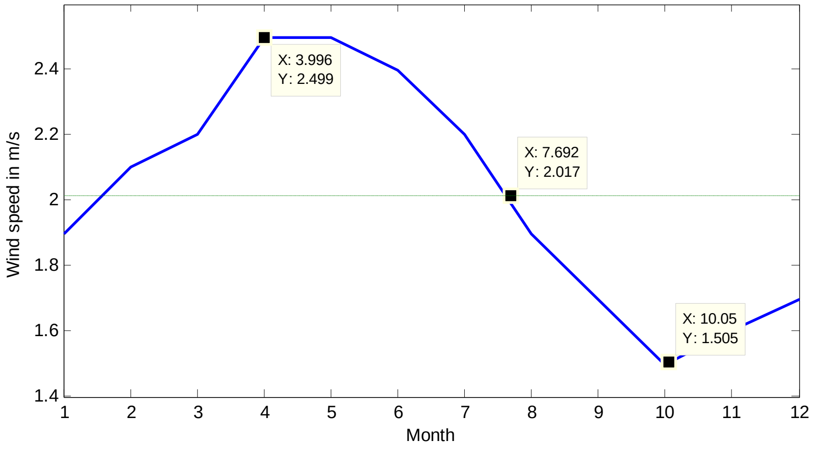


Figure 4.7: Monthly average wind speed [35]

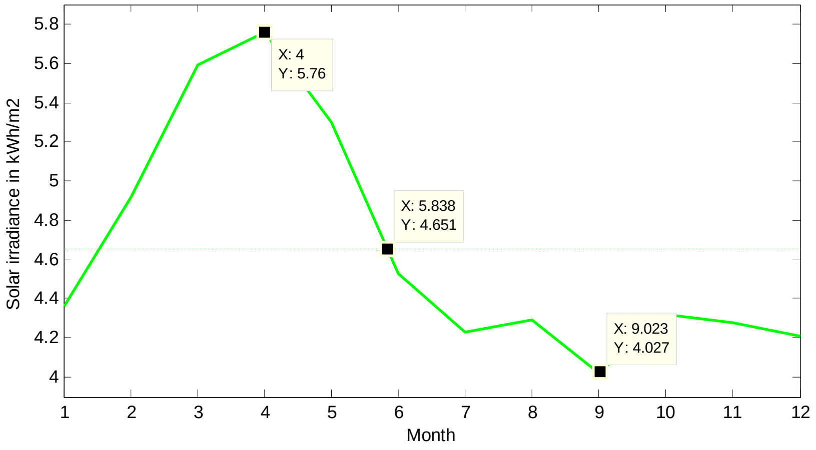


Figure 4.8: Monthly average solar irradiation [35]

If the monthly demand data is assumed to be discontinuous (constant during each month), then all the curves will be stair case plots. From the Fig 4.6 it is seen that the peak load is 4.85 kW and the average load is 3.5692kW.

4.7 MODIFICATION OF DAILY CURVES FOR TWELVE MONTHS

From the Table 4.2 it is seen that the average monthly daily load, solar irradiation and the wind speed are not same for the 12 months of a year. So the average values of the daily curves to the daily curves of any month have been converted such that the same average for that particular month can be obtained by multiplying a factor to each element of the daily curves. We can get the multiplying factor from the ratio of the average monthly value of any particular month and the average value of the daily curve.

$$\text{Multiplying factor} = \frac{\text{average monthly value of any particular month}}{\text{average value of the daily curve}} \tag{4.28}$$

After converting the daily curves for a particular month Fig 4.9- Fig 4.11 are found which represents daily load curves in kW, daily wind speed curves in m/s and daily solar radiation curves in kWh/m^2 of 12 months respectively and it is used for the calculation of surplus or deficiency of energy for any particular month, sizing of the battery and UEC.

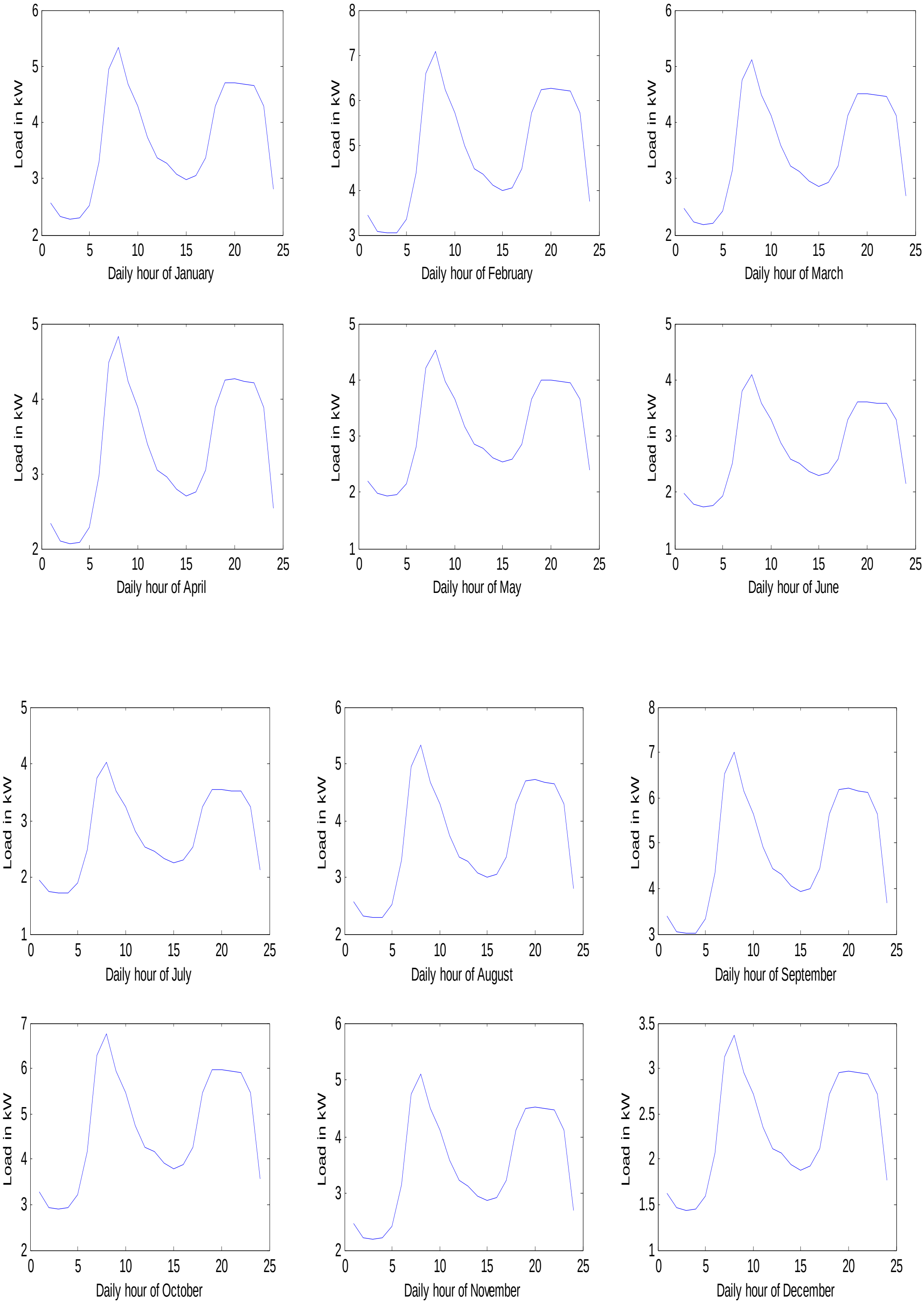


Figure 4.9: Daily load curves of 12 months

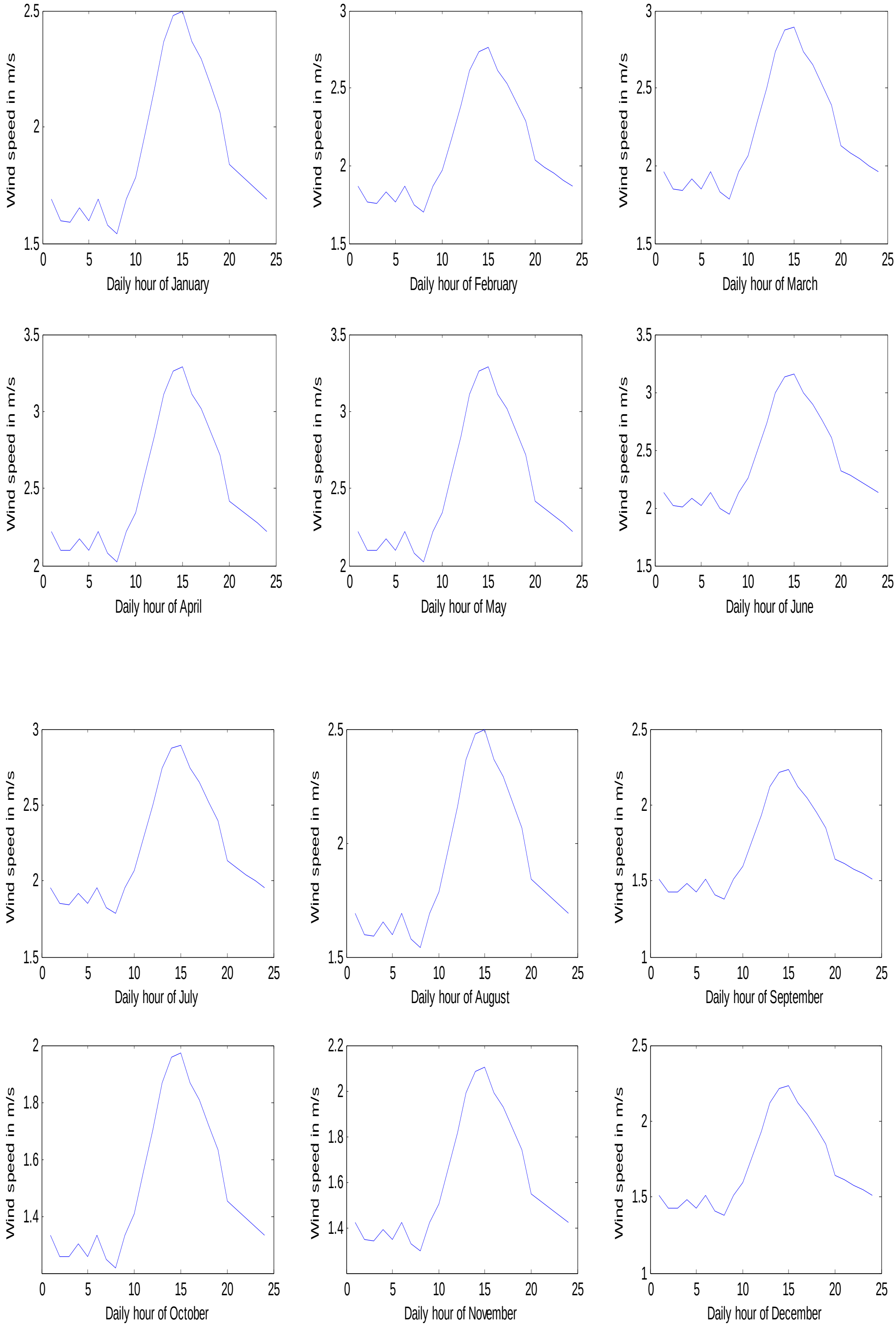


Figure 4.10: Daily wind speed curves of 12 months

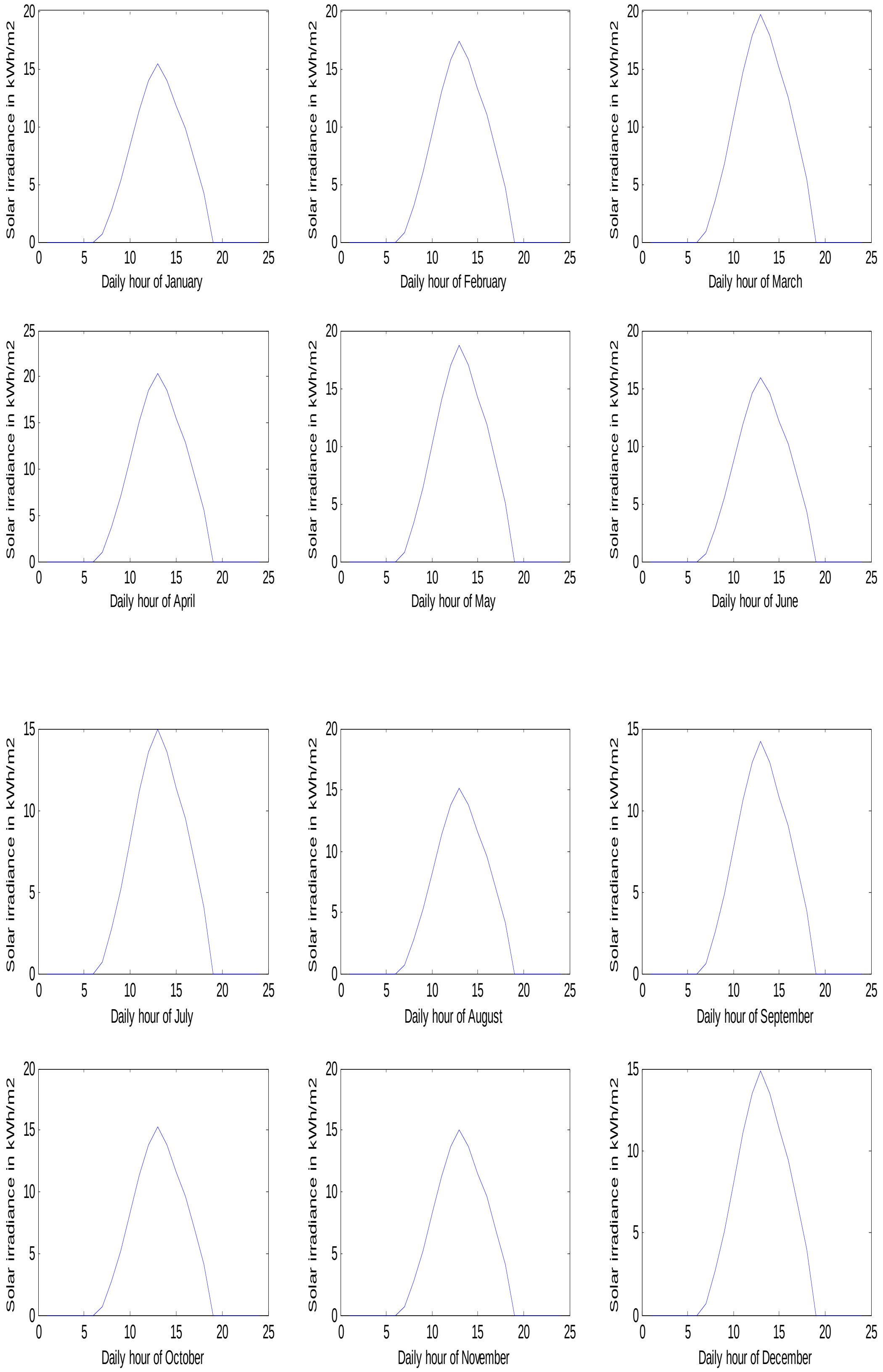


Figure 4.11: Daily solar irradiation curves of 12 months

4.8 IMPLEMENTATION OF THE EXISTING STRATEGY

The iterative optimization procedure was used for component sizing for a stand-alone hybrid (wind-PV) system of the existing strategy to supply the electrical power needs of a house. To analyze the implementation of the existing strategy, the analysis process needs to be divided into two cases for better understanding of the performances of the strategy in these two different cases. First case represents the works which are previously having been done [5] on the existing strategy and the second case depicts the performances of the same existing strategy but when implemented with the six different design scenarios considered in this work.

Case 1: At first the daily average hourly profile is considered for the calculation of excess or deficiency of power and excess or deficiency of energy for the existing strategy. To do so the fifth design scenario meaning the average load with average solar irradiation and average wind speed which is actually the only category of the daily average hourly profile considered in the existing strategy has been chosen.

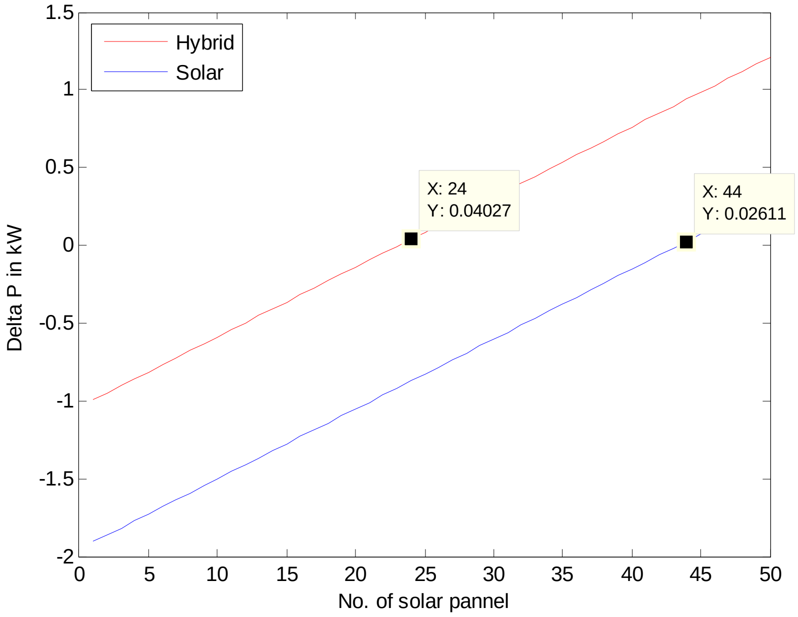


Figure 4.12: Average daily difference between the generated power and the demand versus number of solar panels

Fig 4.12 shows graphically the iterative procedure for sizing the components of a stand-alone hybrid generation system for the house under study. The number of PV panels (150-W panels) is increased from zero, and in each iteration the difference between the hourly average generation and demand ($\Delta P = P_{gen} - P_{dem}$) is calculated over a 24-hour period. The number of PV panels (K_s) required to meet the demand is at a point where the average of ΔP over the period under study is zero. For the example under study, only three cases have to be analyzed which are:

a) solar panels alone ($K_s = 44$) and no wind turbine ($K_w = 0$)

b) hybrid wind-PV ($K_w = 1$). As shown in Fig 4.12, the number of PV panels needed to make $\Delta P = 0$ over a 24-hour period are: $K_s = 24$ with 10-kW wind turbine for the hybrid configuration.

c) For the wind-alone configuration, 3 unit of 10-kW wind turbines have to be used ($K_w = 3$) because from one wind turbine is not sufficient to supply the house demand. However, when three turbines are used, the generated power exceeded the demand over 24-hour period. Therefore, for this configuration ΔP is positive without using any PV panels. $K_s = 0$.

- The daily curves of $\Delta P = P_{gen} - P_{dem}$ versus time for the three system configurations under study have been obtained which are shown in Fig 4.13.

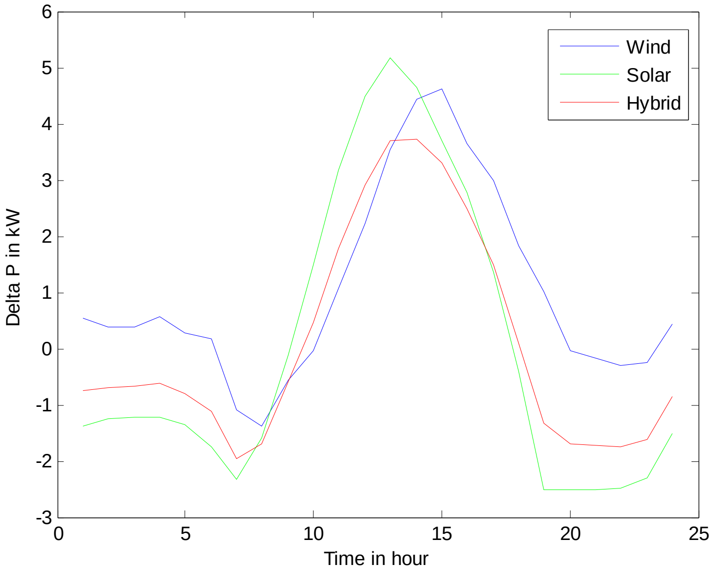
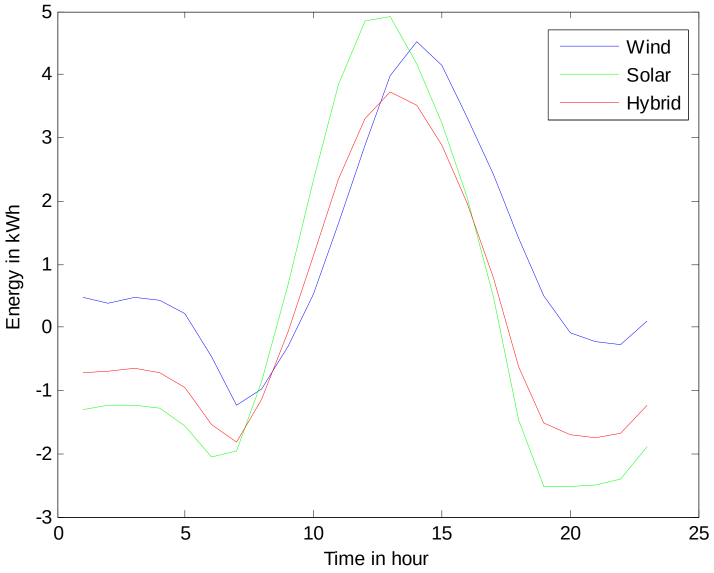


Figure 4.13: Average daily difference between the generated power and the demand

- The daily energy curves $E_h = \int \Delta P dt$ versus time for the three configurations have been obtained which are shown in Fig 4.14.



`Figure 4.14: Average daily difference between the generated energy and the demand energy

Note from Fig 4.14 that these curves for solar-alone and the hybrid system, the energy is balanced over 24 hours, meaning generation matches the demand. However, for wind-alone configuration, the average of the energy curve is positive, meaning that generation exceeds the demand.

- The number of batteries needed for each configuration is calculated using equations (3.11) and (3.12).

Case 2: Now the yearly average monthly profile has been used for the existing strategy or fixed sharing strategy. Also the daily curves for a particular month are used to calculate the surplus or deficiency of energy. The surplus or deficiency of energy for the whole year can be calculated just summing up the surplus or deficiency of energy of 12 months. For the calculation of yearly surplus or deficiency of energy the six different design scenarios have been considered which are discussed in section 4.3. Only solar-wind hybrid system is considered in this case.

Table 4.3: Surplus or deficiency of energy for fixed sharing strategy or existing strategy

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
	N_{sh}=69 N_{wh}=1 B_h=38	N_{sh}=86 N_{wh}=1 B_h=43	N_{sh}=101 N_{wh}=1 B_h=47	N_{sh}=51 N_{wh}=1 B_h=34	N_{sh}=63 N_{wh}=1 B_h=37	N_{sh}=74 N_{wh}=1 B_h=40
	P_s= 4.8384kW, P_w= 0.1101kW	P_s=5.0229kW, P_w=0.0578kW	P_s= 5.3064kW, P_w=0.0238kW	P_s=4.1472kW, P_w=0.1101kW	P_s=3.9067kW, P_w=0.0578kW	P_s= 3.8592kW, P_w=0.0238kW
Jan	0.0061	0.6465	1.2115	-0.6720	-0.2200	0.1944
Feb	-0.5119	0.2107	0.8484	-1.2771	-0.7670	-0.2994
Mar	0.8666	1.6876	2.4121	-0.0028	0.5768	1.1080
Apr	1.1372	1.9832	2.7297	0.2414	0.8386	1.3860
May	1.0069	1.7854	2.4723	0.1827	0.7322	1.2359
June	0.7547	1.4201	2.0072	0.0502	0.5199	0.9504
July	0.5958	1.2171	1.7653	-0.0621	0.3765	0.7785
Aug	-0.0357	0.5944	1.1504	-0.7029	-0.2581	0.1497
Sep	-1.0345	-0.4441	0.0769	-1.6597	-1.2429	-0.8608
Oct	-0.7411	-0.1065	0.4533	-1.4129	-0.9650	-0.5544
Nov	0.0523	0.6810	1.2357	-0.6133	-0.1695	0.2372
Dec	0.8788	1.4971	2.0427	0.2240	0.6605	1.0606
Tot	2.9752	11.173	18.406	-5.7044	0.8199	5.3862
Surplus energy in %	5.3526	26.7264	44.7640	-19.0642	-2.7373	11.7096

Table 4.3 represents yearly surplus or deficiency of energy for six different design scenarios of fixed sharing strategy or existing strategy. It has been seen from this table that, only scenario 4 and scenario 5 of solar-wind hybrid generation system of existing strategy cannot meet the demand. In scenario 1 the surplus energy is 5.3526% and the power generated by the solar system is 4.8384kW and the power generated by the wind system is 0.1101kW. As in this strategy the number of wind turbine is kept fixed in one unit of 500W, with that 69 solar panels with maximum output of 150W each are required. Also this design scenario required 38 batteries of 12V and 200Ah. In scenario 2 the surplus energy is 26.7264% and the power generated by the solar system is 5.0229kW and the power generated by the wind system is 0.0578kW. With one wind turbine this design scenario required 86 solar panels and 43 batteries. In scenario 3 the surplus energy is 44.7640% and the power generated by the solar system is 5.3064kW and the power generated by the wind system is 0.0238kW. With one wind turbine this scenario required 101 solar panels and 47 batteries. In scenario 6 the surplus energy is 11.7096% and the power generated by the solar system is 3.8592kW and the power generated by the wind system is 0.0238kW. This design scenario required 74 solar panels with wind turbine. Also this scenario required 40 batteries. The rating of the solar panel, wind turbine and

battery are same as of the ratings discussed in this section for scenario 1. The graphical representation of surplus or deficiency of energy for existing strategy is shown in Fig 4.15 and Fig 4.16 for peak load and average load respectively. Also we can see from the Table 4.2 that for yearly analysis scenario 5 which was considered in daily analysis of fixed sharing strategy cannot meet the demand.

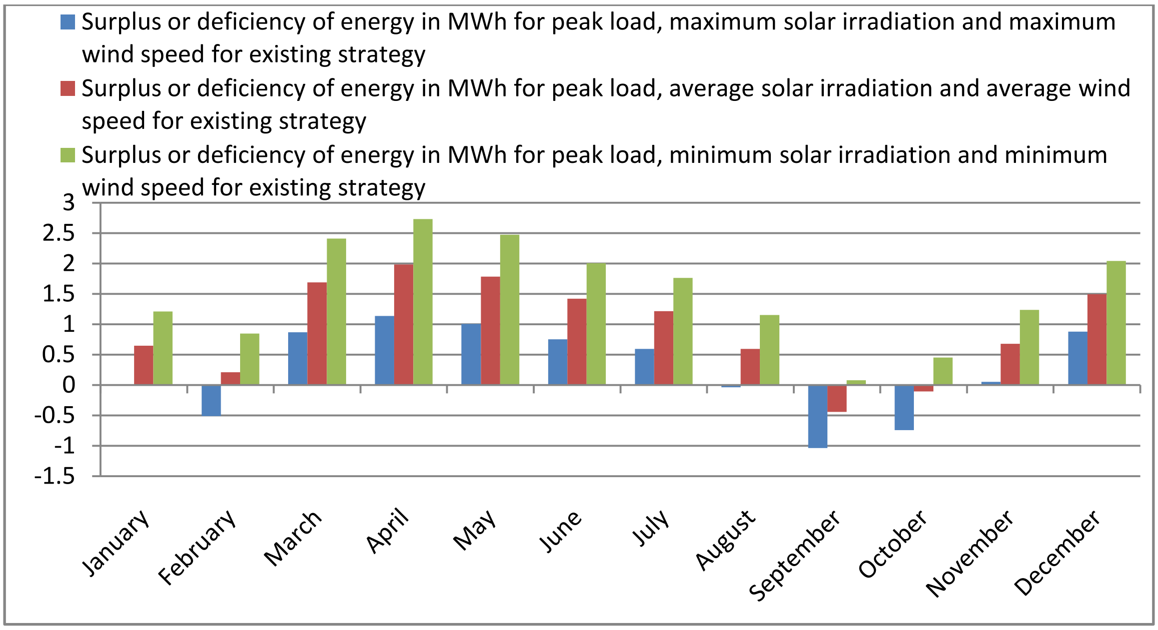


Figure 4.15: Surplus or deficiency of energy for peak load of existing strategy

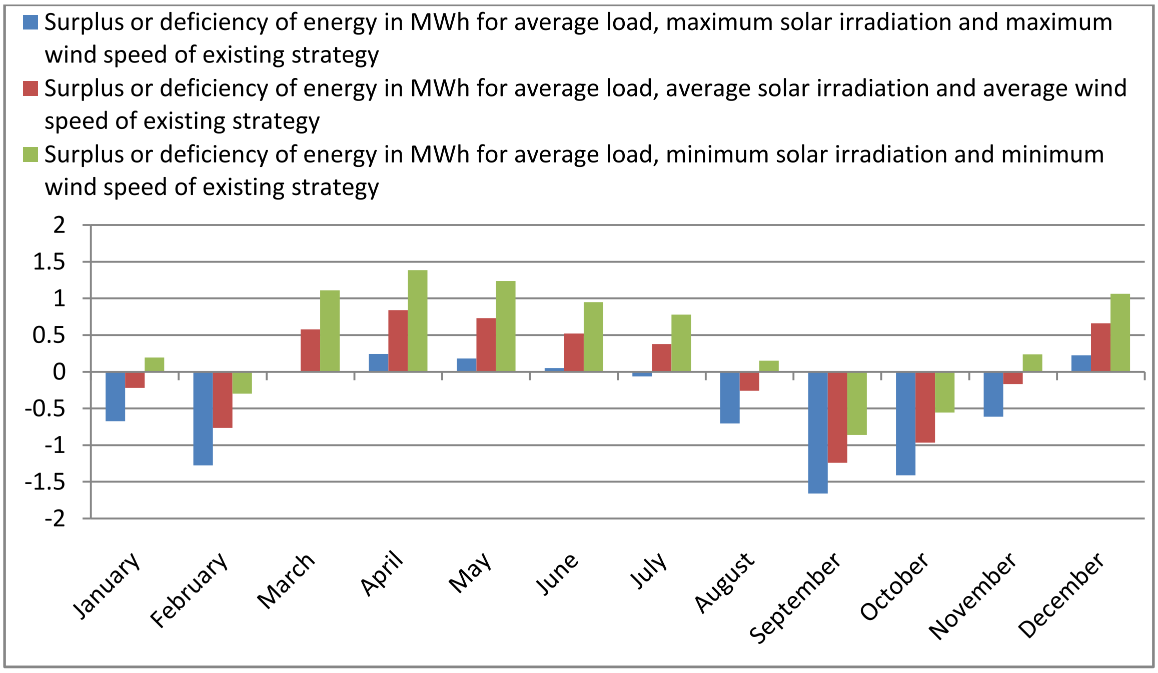


Figure 4.16: Surplus or deficiency of energy for average load of existing strategy

4.9 IMPLEMENTATION OF THE PROPOSED STRATEGY

Due to the local weather, geographical location, and environmental characteristics some places get good solar irradiation where as some places have good wind speed. Weather include sunshine, rain, cloud cover, winds, hail, snow, sleet, freezing rain, flooding, blizzards, ice storms, thunderstorms, steady rains from a cold front or warm front, excessive heat, heat waves, and more. These issues determine what kind of generating source is more appropriate. Good and regular wind speed is attractive for the exploration of wind energy. Analogously, in case of good solar incidence, the solar photovoltaic energy exploration is more appropriate. So, we may not get the energy required for the demand if we fix the unit size of the power generation system while designing the solar-wind hybrid power system which is done in existing strategy. In this proposed system the load sharing strategy totally depends on the availability of the solar radiation and the wind speed. Equations (4.12) and (4.13) are used to find out the load sharing strategy of the proposed system. Equations (4.14) and (4.15) are used to find out wind–PV sizing. Equations (4.24) and (4.25) are used to find out the sizes of the battery for the proposed strategy.

The same six design scenarios are used to calculate the yearly surplus or deficiency of energy for the proposed strategy so that the results of the yearly surplus or deficiency of energy for fixed sharing strategy can be compared.

Table 4.4 represents surplus or deficiency of energy for percentage sharing strategy or proposed strategy. It is seen from this table that except scenario 1 and scenario 4 of proposed strategy of solar-wind hybrid generation system all the design scenarios can meet the demand. In scenario 2 the surplus energy is 30.4607% and the power generated by the solar system is 4.4648kW and the power generated by the wind system is 0.4624kW. This scenario required 43 solar panels and 43 wind turbines. Also this scenario required 19 batteries. In scenario 3 the surplus energy is 94.2355% and the power generated by the solar system is 4.8240kW and the power generated by the wind system is 0.2378kW. With 68 wind turbines this scenario required 68 solar panels and 25 batteries. In scenario 5 the surplus energy is 0.5259% which is lower and the power generated by the solar system is 3.3486kW and the power generated by the wind system is 0.3468kW. This design scenario required 32 solar panels and 32 wind turbines. Also this scenario required 7 batteries. In scenario 6 the surplus energy is 48.5590% and the power generated by the solar system is 3.8592kW and the power generated by the wind system is 0.1903kW. With 50 wind turbines this design scenario required 50 solar panels and 14 batteries. The rating of solar panel, wind turbine and the battery are identical to that of the ratings of the existing strategy discussed in section 4.6. The graphical representation of surplus or deficiency of energy for this strategy is shown in Fig 4.17 and Fig 4.18 for peak load and average load respectively.

Table 4.4: Surplus or deficiency of energy for percentage sharing method or proposed method

	Scenario 1	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
	N_{sh}=28 N_{wh}=28 B_h=15	N_{sh}=43 N_{wh}=43 B_h= 19	N_{sh}=68 N_{wh}=68 B_h=25	N_{sh}=20 N_{wh}=20 B_h=3	N_{sh}=32 N_{wh}=32 B_h=7	N_{sh}=50 N_{wh}=50 B_h=14
	P_s= 4.8384kW, P_w= 0.7708kW	P_s=4.4648kW, P_w=0.4624kW	P_s= 4.8240kW, P_w=0.2378kW	P_s=3.4560kW, P_w=0.5505kW	P_s=3.3486kW, P_w=0.3468kW	P_s= 3.8592kW, P_w=0.1903kW
Jan	-0.5988	0.4883	2.3001	-1.1786	-0.3089	0.9956
Feb	-0.9861	0.3564	2.5938	-1.7021	-0.6281	0.9829
Mar	0.3451	1.8799	4.4380	-0.4735	0.7543	2.5962
Apr	1.2372	3.1729	6.3990	0.2049	1.7534	4.0762
May	1.2700	3.1460	6.2728	0.2694	1.7702	4.0215
June	1.0438	2.6830	5.4150	0.1696	1.4809	3.4480
July	0.5560	1.9146	4.1790	-0.1685	0.9183	2.5486
Aug	-0.6157	0.4623	2.2589	-1.1907	-0.3283	0.9653
Sep	-1.7855	-0.8906	0.6009	-2.2628	-1.5469	-0.4730
Oct	-1.8090	-0.9923	0.3689	-2.2446	-1.5912	-0.6112
Nov	-0.9027	-0.0363	1.4078	-1.3648	-0.6716	0.3681
Dec	0.0605	0.9800	2.5125	-0.4300	0.3057	1.4091
Tot	-2.1853	13.164	38.747	-10.372	1.9079	20.327
Surplus energy in %	-10.7447	30.4607	94.2355	-34.1551	0.5259	48.5590

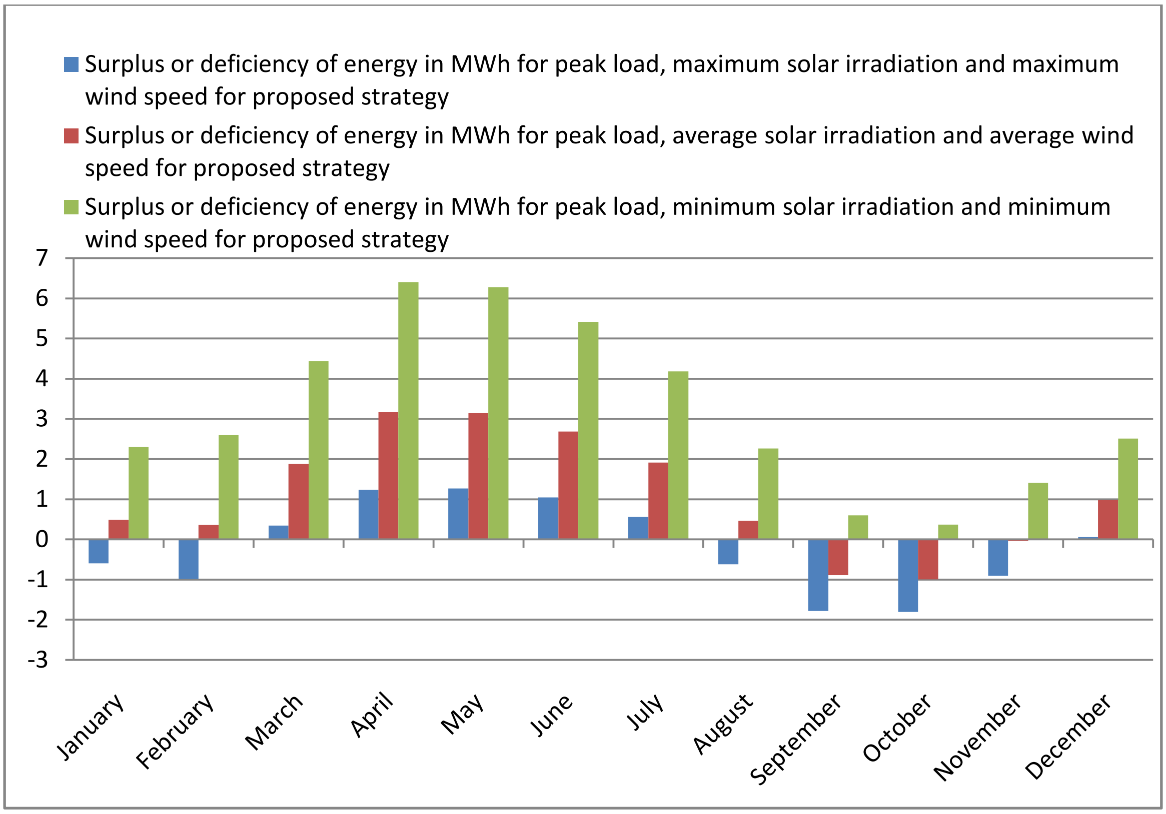


Figure 4.17: Surplus or deficiency of energy for peak load of proposed strategy

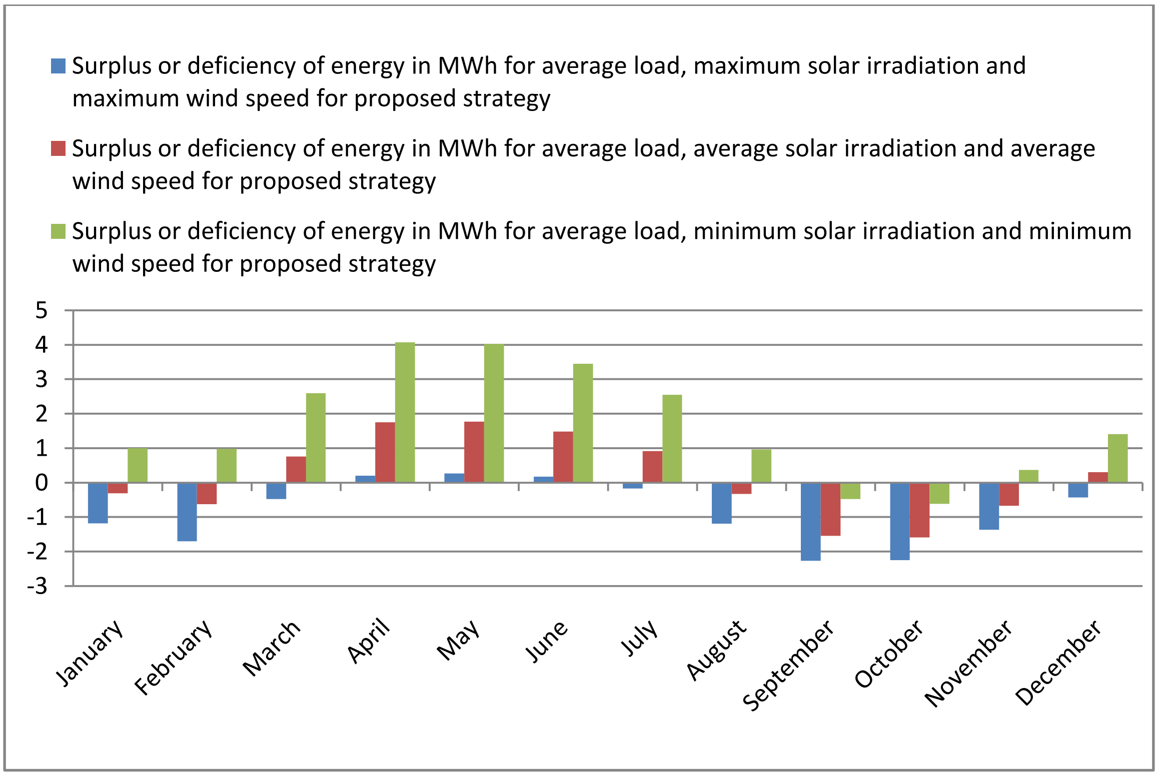


Figure 4.18: Surplus or deficiency of energy for average load of proposed strategy

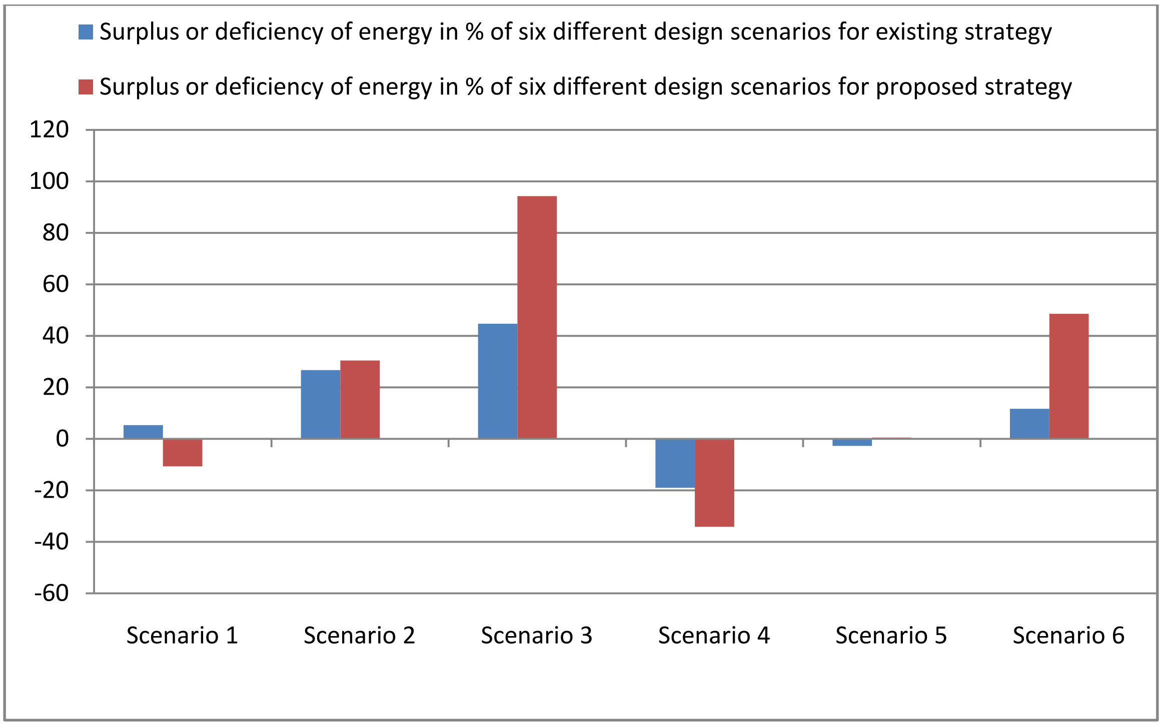


Figure 4.19: Surplus or deficiency of energy in percentage for six scenarios of fix sharing strategy and proposed strategy

The comparison of the excess energy expressed in percentage (%) of the existing strategy and the proposed strategy is shown in Fig 4.19 and it is found that except scenario 1 and scenario 4 the surplus energy produced by the proposed strategy is positive. That means for proposed strategy all the design scenarios except scenario 1 and scenario 4, are feasible to design solar-wind hybrid power system. Among these design scenarios scenario 5 has lower surplus energy that means the maximum utilization of energy and minimum loss for the time interval *n*. The surplus energy expressed in percentage (%) for this scenario is 0.5259% which is almost near to zero. On the other hand except scenario 4 and scenario 5 the surplus energy produced by the existing strategy is positive and scenario 1 has lower surplus energy which is 5.3526%. If all the design scenarios which are feasible to design solar-wind hybrid system of proposed and existing strategy, are considered then it is found that the surplus energy is lowest in scenario 5 of proposed deign strategy. It is also seen from Table 4.2 and Table 4.3 that the number of batteries of all scenarios for proposed strategy is lower than the existing strategy. Graphical representation of the number of batteries comparison between the six scenarios of existing strategy and the proposed strategy is shown in Fig 4.20.

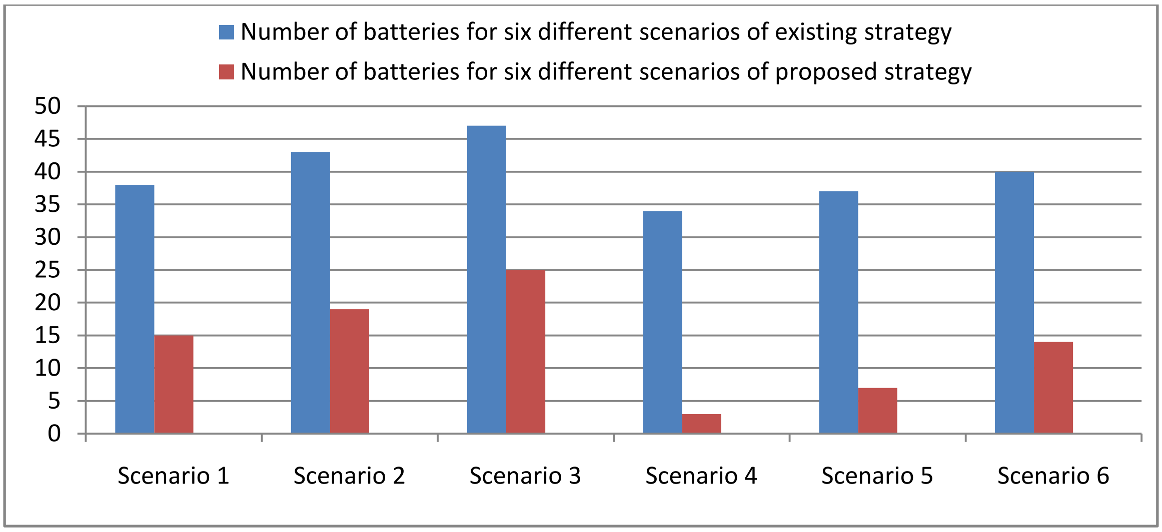


Figure 4.20: Number of batteries comparison between the six scenarios of existing strategy and the proposed strategy

4.10 ENVIRONMENTAL IMPACT

From the point of view of environmental safety grid tied solar PV provides a positive impact by reducing greenhouse gas (CO_2) emission to the atmosphere [36].Conventional sources emit Green House Gas (CO_2) that affects our environment badly.

We know that, every liter of diesel fuel when burned produces 2.7 kg of carbon dioxide [37].It has been calculated that, if the diesel generator is consuming 1 liter of diesel per hour then 8760 × 20 = 1,75,200 liter diesel in 20 years. So, the amount of CO_2 produced in 20 years by the diesel generator is = 2.7 ×1,75,200 = 4,73, 040 kg.

Also, for each liter of petrol fuel when burned produces 2.4 kg of carbon dioxide [37]. It has been calculated that, if the petrol generator is consuming 1 liter of petrol per hour then the petrol generator is consuming 8760 × 20= 1,75,200 liter petrol in 20 years. So, the amount of CO_2 produced in 20 years by the petrol generator is = 1,75,200 × 2.4 = 4,20,480 kg.

As in the proposed strategy, the diesel and the petrol generator were not used; there is less possibility of facing severe environmental impact due to CO_2 emission by the implementation of the proposed strategy.

Chapter 5

COST CALCULATION

5.1 THEORY OF LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis (LCCA) covers the total cost of a power source in three phases: construction phase, operational phase and decommissioning phase. The construction phase includes the initial investment cost.

Operational phase contains the fuel cost and the cost incurred due to operation and maintenance. The decommissioning phase covers the cost related to termination of the project and disposal of the equipment. All these costs are summed up to provide the total life cycle cost of the project. The overall cost incurred over the lifetime is then converted into unit cost per kWh of energy [38]. This approach has gained popularity among the researchers and been followed in a number of research projects related to energy production.

5.2 NET PRESENT VALUE

As LCCA comprises not only the initial cost of a project but also all future costs for the entire operation of a system, the Net Present Value (NPV) of the components has to be taken into account to make a meaningful comparison. For this reason, all future costs are discounted in LCCA to their equivalent value in the present economy and the present worth of the costs is calculated. Thus the LCC analysis takes into account the changing value of money as well as cost escalations due to inflation.

5.3 OVERALL SYSTEM COST

The overall system cost associated with a power system operating for a number of years can be classified into four branches. They are: a) initial capital cost; b) fuel cost; c) recurring cost and d) non-recurring cost.

5.3.1 INITIAL CAPITAL COST

The first classification is the initial capital cost of purchasing equipment that includes cost of PV modules and wiring for a PV system. In case of diesel or petrol generator based power system the capital cost comprises of paying for generator, circuit breaker and other equipment and installation cost. For calculation of capital cost, cost of different component is collected from different manufacturer [39-42].

i) Cost of hybrid system is

$$CH = a_1 \times P_s \times N_{sh} + a_2 \times P_w \times N_{wh} \tag{5.1}$$

ii) Cost of inverter is

$$CI = b_1 \times P_s \times N_{sh} + b_2 \times P_w \times N_{wh} \tag{5.2}$$

iii) Cable and installation cost is

$$CC = c_1 \times P_s \times N_{sh} + c_2 \times P_w \times N_{wh} \tag{5.3}$$

iv) Cost of mounting is

$$CHM = d_1 \times P_s \times N_{sh} + d_2 \times P_w \times N_{wh} \tag{5.4}$$

v) Miscellaneous cost is

$$CM = e_1 \times P_s \times N_{sh} + e_2 \times P_w \times N_{wh} \tag{5.5}$$

vi) Battery cost is

$$CB = f_1 \times B_h \times v_b \times i_b \tag{5.6}$$

Total capital cost is

$$Th_1 = (CH + CI + CC + CHM + CM + CB) \tag{5.7}$$

Where,

a_1= per kW solar panel cost in BDT/kW=80,000 BDT/kW

b_1= per kW solar inverter cost in BDT/kW=55,000 BDT/kW

c_1= per kW solar installation cost in BDT/kW = 50,000 BDT/kW

d_1= per kW solar mounting cost in BDT/kW = 20,000 BDT/kW

e_1= per kW miscellaneous cost for solar in BDT/kW = 20,000 BDT/kW

a_2= per kW wind turbine cost in BDT/kW = 70,000 BDT/kW

b_2= per kW wind turbine inverter cost in BDT/kW = 55,000 BDT/kW

c_2= per kW wind turbine installation cost in BDT/kW = 50,000 BDT/kW

d_2= per kW wind turbine mounting cost in BDT/kW = 20,000 BDT/kW

e_2= per kW miscellaneous cost for wind turbine in BDT/kW = 20,000 BDT/kW

f_1= per kWh battery cost in BDT/kWh = 7500 BDT/kWh

Th_1 = total capital cost in BDT

5.3.2 FUEL COST

Fuel cost is one of the important factors for calculation of the unit electricity cost. For the power generation system based on renewable energy no fuel cost is required.

For solar-wind hybrid system, Th_2 = 0.00 BDT

Where, Th_2 is the total fuel cost in BDT for the life time of this hybrid system.

5.3.3 RECURRING COST

Secondly, recurring costs that occur every year of operation are primarily due to maintenance of equipment, site and overall system supervision. In case of generator-based system, the generator is checked at regular intervals whether it requires overhauling. In a PV system the batteries require inspection and topping up at about three month‟s interval.

5.3.4 NON-RECURRING COST

Finally non-recurring costs are those that occur on an irregular basis. The expenditure of replacement of major components of a system like battery or other equipment is referred as non-recurring or single payment cost.

5.4 ECONOMIC FACTORS

A number of economic factors have to be taken into account while calculating the life cycle cost. The period of analysis is the lifetime of the longest-living system under comparison. In case of PV system the lifetime is about 20 years and for petrol generator the lifetime is about 5 years [43]. So, for LCC analysis the period is taken to be 20 years. As the components and services get expensive over time, the excess inflation factor takes into account this cost escalation. In this calculation inflation factor is applied to fuel cost and other maintenance and replacement costs. The last factor is the discount rate which is the rate at which money would increase in value if it was invested in other projects rather than in power system.

5.5 UNIT ELECTRICITY COST

For the calculation of LCC at first the total net present worth of recurring and non-recurring cost has to be calculated. To do this, the future cost is multiplied by a factor to incorporate the inflation and discount rate. For a non-recurring single future cost *Cr*, paid after *N* years, the present worth (*PW*) is given by [44]

$$PW = Cr \times Pr = Cr \times \left(\frac{1+i}{1+d}\right)^{N} \tag{5.8}$$

For a recurring payment *Ca*, which occurs annually for a period of *N* years, the present worth (*PW*) is

$$PW = Ca \times Pa = Ca \times \left(\frac{\left(\frac{1+i}{1+d}\right)\left(\left|\frac{1+i}{1+d}\right|^{N} - 1\right)}{\left(\frac{1+i}{1+d} - 1\right)}\right) \tag{5.9}$$

Here Pr and Pa is the present worth factors for non-recurring and recurring costs respectively. Pa is called the Annualization Factor. Here the present worth factors for non-recurring and recurring costs are given by equation (5.10) and (5.11)

$$Pr = \left(\frac{1+i}{1+d}\right)^{N} \tag{5.10}$$

$$Pa = \left(\frac{\left(\frac{1+i}{1+d}\right)\left(\left|\frac{1+i}{1+d}\right|^{N} -1\right)}{\left(\frac{1+i}{1+d}-1\right)}\right) \tag{5.11}$$

i) Inverter replacement cost is

$$CI = b_1 \times P_s \times N_{sh} + b_2 \times P_w \times N_{wh} \tag{5.12}$$

ii) Battery replacement cost is

$$CB = f_1 \times B_h \times v_b \times i_b \tag{5.13}$$

iii) Component replacement cost is, CR

∴ Replacement cost is

$$Cr_3 = (CI + CB + CR) \tag{5.14}$$

Present worth factor is

$$Pr_3\,(n) = \left(\frac{1+i}{1+d}\right)^{n}{}_{3} \tag{5.15}$$

Total Replacement cost is

$$Th_4 = Cr_3 \times Pr_3\,(n) \tag{5.16}$$

Where,

Th_4 = Total replacement cost in BDT

n_3= Replacement years = 5, 10 and 15 (life time of battery and inverter are 5 year [43]).

Annual maintenance cost of the hybrid system is Ca_3

Annualizaion factor is

$$Pa_3 = \left(\frac{\left(\frac{1+i}{1+d}\right)\left(\left|\frac{1+i}{1+d}\right|^{N_3} - 1\right)}{\left(\frac{1+i}{1+d} - 1\right)} \right) \tag{5.17}$$

Total annual cost of the hybrid system is

$$Th_3 = Ca_3 \times Pa_3 \qquad (5.18).$$

Where,

$Th_3 =$ Total annual cost in BDT

N_3 = Life span of hybrid system in year

i = Inflation rate

d = Discount rate

The sum of individual present worth expenses (*PW*), calculated from equations (5.8) and (5.9), and gives the total life cycle cost of the system. From the overall life cycle cost the annualized life cycle cost (*ALCC*) and unit electricity cost (*UEC*) are calculated using the annualization factor (*AF*) and daily load (*DL*) using

$$ALCC = \frac{LCC}{AF} \tag{5.19}$$

$$UEC = \frac{ALCC}{DL \times 365} \tag{5.20}$$

According to the above discussion, life cycle cost analysis has been done for the grid tied SHSs and conventional sources. From this, unit electricity cost for each of the system is calculated and compared among the systems.

Life cycle cost is

$$LCC = (Th_1 + Th_2 + Th_3 + Th_4) \tag{5.21}$$

Annual life cycle cost is

$$ALCC = LCC/Pa_3 \tag{5.22}$$

Unit electric cost is

$$UEC = \frac{ALCC}{\sum ML(n)} \tag{5.23}$$

To illustrate an example of UEC estimation for particular loads the following values of economic parameters are considered for analysis, period of analysis: 20 years, annualization factor: 1.46, discount rate: 20 %, inflation rate: 6.7% [45].

Six different scenarios are considered in this thesis for the existing strategy and also for the proposed strategy. Each time it is tried to find out the unit electricity cost by using equations from (5.1) to (5.23). Table 5.1 contains the values obtained from these calculations. Graphical representation of UEC comparison between the six scenarios of existing strategy and the proposed strategy is shown in Fig 5.1.

Table5.1: Unit electricity cost of six scenarios of existing and proposed strategy

Existing Strategy		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**	**Scenario 5**	**Scenario 6**
		$N_{sh}=69$ $N_{wh}=1$ $B_h=38$	$N_{sh}=86$ $N_{wh}=1$ $B_h=43$	$N_{sh}=101$ $N_{wh}=1$ $B_h=47$	$N_{sh}=51$ $N_{wh}=1$ $B_h=34$	$N_{sh}=63$ $N_{wh}=1$ $B_h=37$	$N_{sh}=74$ $N_{wh}=1$ $B_h=40$
		P_s= 4.8384kW, P_w= 0.1101kw	P_s=5.0229kW, P_w=0.0578kw	P_s= 5.3064kW, P_w=0.0238kW	P_s=4.1472kW, P_w=0.1101kW	P_s=3.9067kW, P_w=0.0578kW	P_s=3.8592kW, P_w=0.0238kW
	UEC	51.4997	62.6795	72.4129	54.4554	64.9499	74.6781
Proposed Strategy		$N_{sh}=28$ $N_{wh}=28$ $B_h=15$	$N_{sh}=43$ $N_{wh}=43$ $B_h= 19$	$N_{sh}=68$ $N_{wh}=68$ $B_h=25$	$N_{sh}=20$ $N_{wh}=20$ $B_h=3$	$N_{sh}=32$ $N_{wh}=32$ $B_h=7$	$N_{sh}=50$ $N_{wh}=50$ $B_h=14$
		P_s= 4.8384kW, P_w= 0.7708kW	P_s=4.4648kW, P_w=0.4624kW	P_s= 4.8240kW, P_w=0.2378kW	P_s=3.4560kW, P_w=0.5505kW	P_s=3.3486kW, P_w=0.3468kW	P_s=3.8592kW, P_w=0.1903kW
	UEC	30.7622	45.8896	70.8896	26.5694	43.3604	68.9794

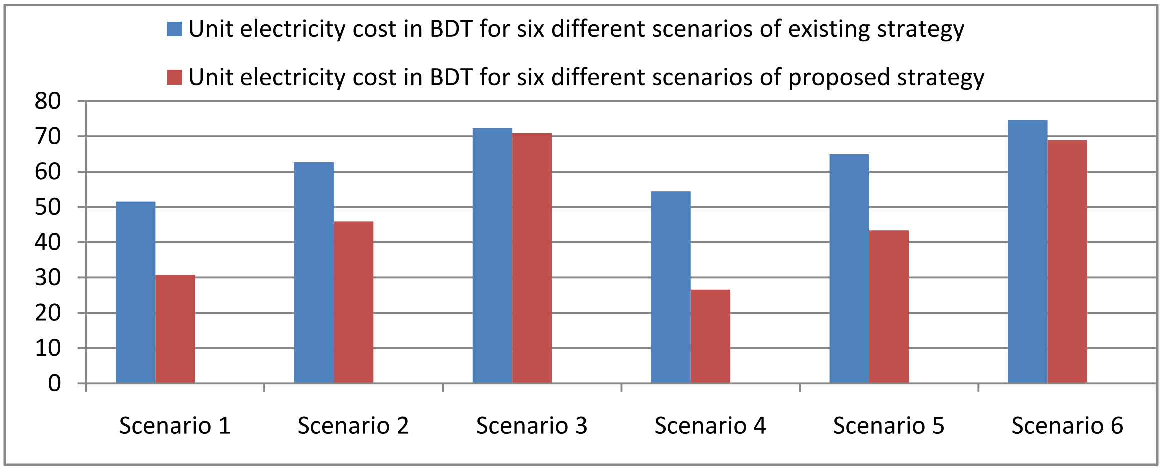


Figure 5.1: Unit Electricity Cost comparison between the six scenarios of existing strategy and the proposed strategy

It is observed from Fig 5.1 that the UEC of all scenarios for proposed strategy is lower than the existing strategy. From the Table 4.5 it has been observed that scenario 2, 3, 5 and 6 of proposed strategy can meet the demand and the surplus energy in percentage of scenario 5 is lowest among these design scenarios. From Fig 5.1 it is seen that the UEC is lowest in scenario 5 than scenario 2, 3 and 6. The UEC of scenario 5 of proposed strategy is also lowest than the UEC of all the feasible scenarios of existing strategy. So if the average load with average solar irradiation and average wind speed (means category 5) is considered for designing an off-grid solar-wind hybrid power system then we get lowest UEC which is 43.3604BDT with lowest surplus energy in percentage which is 0.5259%.

Chapter 6

OPTIMIZATION OF UNIT ELECTRICITY COST FOR BANGLADESH USING PROPOSED STRATEGY

6.1 INTRODUCTION

At the present time the electricity companies of Bangladesh are unable to produce enough electricity to meet the domestic, industrial and development needs. The generation capacity is about 8005MW (as on March 2012) and maximum demand served so far is 6066 MW (March 22, 2012) [46] whereas the total demand is 9023MW [46]. According to USAID, the demand for energy is growing at a rate of 10% annually. In 1971, 3% of the total population in Bangladesh had access to electricity. Today, approximately 33% of the population has access, which is also low compared to many developing countries [47]. This crisis is partly due to over-dependence on gas. The present gas deficit against the national demand on a daily basis is expected to increase further in the upcoming future. The crisis will deepen unless a greater share of indigenous coal is included in the energy mix [48]. But burning fossil fuels emits poisonous gases and toxic metals into our atmosphere, directly causing increasing incidents of lung disease, polluting soils and waters, damaging crops. Bangladesh is one of those countries where carbon emission is increasing day by day and for the sake of creating more power by using the limited fossil fuel would make the situation worse. So, to fulfill this omnipresent electricity demand of this country without increasing the effect of global warming, renewable sources can be used in a wide range. In renewable, energy from the sun is one of the promising options for electricity generation. It can be used as the source of light in photovoltaic and it helps wind to flow. Solar-wind hybrid power has two big advantages over fossil fuels. The first one is, it is never going to run out. The average power consumed by humans is 15 TW whereas the amount of sunlight reaching the Earth is 89,000 TW [49] which is about 6000 times higher. So it is understandable that solar-wind hybrid energy is very plentiful. It has the highest power density among renewable energies. The second one is its positive effect on the environment. Solar-wind power system is free of pollution during use.

The Solar Home System (SHS) distribution agenda in Bangladesh is considered to be one of the most efficacious of its kind in the world, bringing power to rural areas where grid electricity supply is neither available nor expected in the medium term. [50] Solar-wind electricity can be used in cities too where grid connection is available as the electricity companies of Bangladesh are insufficient to ensure 24/7 electricity. Load shedding for almost six to ten hours a day in the grid-connected areas has become a usual phenomenon.[51] In the FY 2010, load shedding was imposed on 354 days, and in FY 2011 the deficiency of power was about 1335 MW [46] which is a very alarming state.

6.2 ANALYSIS

For the optimization of Unit Electricity Cost for Bangladesh the yearly profiles of solar irradiation in $kW/m^2/day$ and wind speed in m/sec from the year 2004-2012 of Khulna and Chittagong in Bangladesh provided by Bangladesh Meteorological Department have been analyzed. It has been found that Khulna has got best solar irradiation and wind speed respectively. On the other side Chittagong has next best wind speed but the solar irradiation here is not so good. Nine years average monthly solar irradiation profile of these two sites is presented in Table 6.1 and nine years average monthly wind speed profile of these two sites is presented in Table 6.2. Two cases are considered to find out the minimum UEC of the six design scenario. In case one the best site of solar irradiation and wind speed is considered and in the second case the next best site is considered for the proposed solar-wind hybrid power system.

Table 6.1: Solar irradiance of Khulna and Chittagong of Bangladesh in $kWh/m^2/day$

Months	Khulna	Chittagong
January	4.58	2.15
February	5.53	2.92
March	5.92	3.06
April	6.11	3.33
May	6.20	3.70
June	4.95	2.45
July	4.14	2.57
August	4.67	2.49
September	4.72	2.40
October	4.81	2.53
November	4.38	2.28
December	4.15	2.13
Yearly avg. m/sec	5.01	2.67

Table 6.2: Wind speed of Khulna and Chittagong of Bangladesh in m/sec

Months	Khulna	Chittagong
January	8.33	8.83
February	8.35	10.05
March	11.35	10.28
April	11.98	10.4
May	13.28	10.08
June	12.03	11.03
July	10.08	11
August	9.53	9.8
September	9.75	8.9
October	10.5	7.63
November	8.05	8
December	7.68	7.75
Yearly avg. m/sec	10.08	9.48

Case I

In this case the best site of solar irradiation and wind speed is considered for the proposed solar-wind hybrid power system. The graphical presentation of 9 years monthly average of best sites of solar irradiation and wind speed profile are shown in Fig 6.1 and Fig 6.2 respectively. It is seen that, maximum solar irradiation and wind speed is harvested in the month of May whereas the minimum solar irradiation and wind speed is harvested in the month of July and December respectively. The similar yearly load profile of which is considered in chapter-4 is also considered here. To calculate the surplus or deficiency of energy in MWh Equations (4.20), (4.13) and (4.26) are used, to calculate the number of solar panel and number of wind turbine Equations (4.14) and (4.15) are used, to calculate the number of batteries Equations (4.24) and (4.25) are used and to calculate UEC in BDT Equations (5.1) - (5.23) are used. Results obtained from the calculation are presented in Table 6.3 and shown graphically in Fig 6.3 – Fig 6.6.

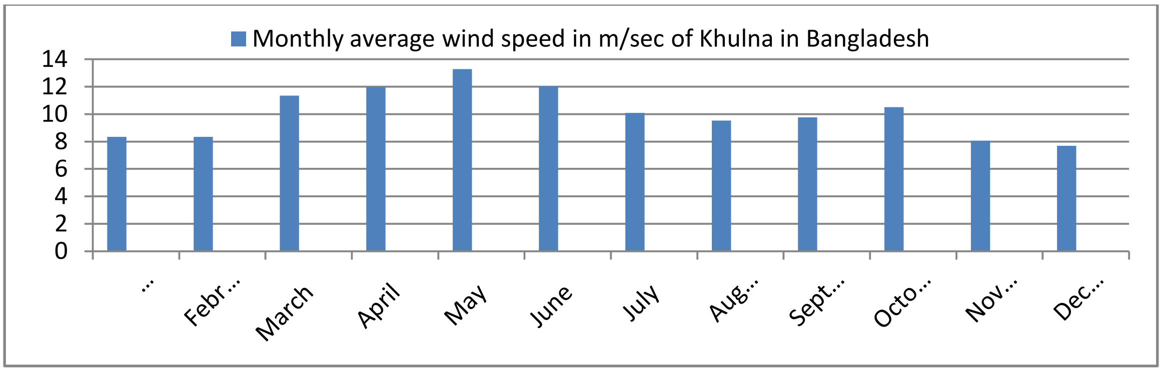


Figure 6.1: Monthly average wind speed of Khulna in Bangladesh

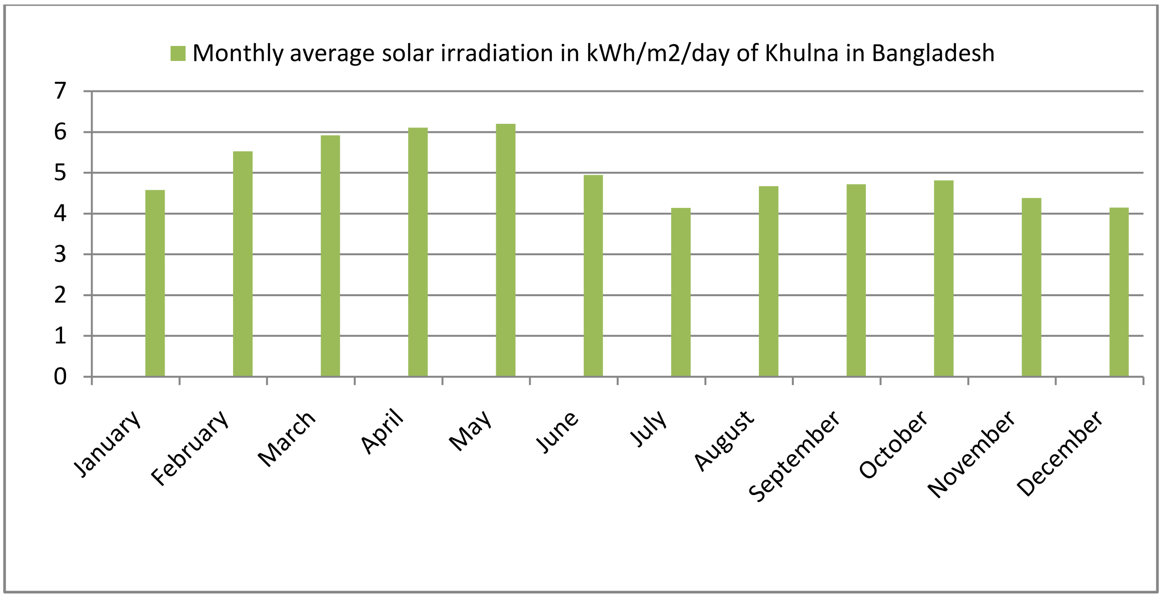


Figure 6.2: Monthly average solar irradiation of Khulna in Bangladesh

Table 6.3: Surplus or deficiency of energy of Khulna in Bangladesh using percentage sharing method or proposed method

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	N_{sh}=4 N_{wh}=4 B_h=25	N_{sh}=7 N_{wh}=7 B_h= 13	N_{sh}=14 N_{wh}=14 B_h=5	N_{sh}=3 N_{wh}=3 B_h=15	N_{sh}=5 N_{wh}=5 B_h=16	N_{sh}=10 N_{wh}=10 B_h=9
	P_s= 0.4960kW, P_w= 5.9223kW	P_s=0.7019kW, P_w=4.5267kW	P_s= 1.1592kW, P_w=4.0091kW	P_s=0.3720kW, P_w=4.4418kW	P_s= 0.5013kW, P_w=3.2333kW	P_s=0.8280kW, P_w=2.8637kW
Jan	1.8999	1.0929	1.1819	0.7679	0.0297	0.0934
Feb	1.0906	0.3246	0.5094	-0.0550	-0.7658	-0.6338
Mar	2.0851	1.3359	1.5600	0.9338	0.2342	0.3943
Apr	2.2400	1.4991	1.7424	1.0860	0.3919	0.5657
May	2.3892	1.6522	1.9045	1.2339	0.5424	0.7226
June	2.5332	1.7422	1.8685	1.3959	0.6684	0.7586
July	2.5225	1.6965	1.7412	1.3969	0.6460	0.6780
Aug	1.9051	1.1019	1.2000	0.7718	0.0362	0.1063
Sep	1.0800	0.2790	0.3821	-0.0540	-0.7881	-0.7145
Oct	1.2075	0.4105	0.5227	0.0723	-0.6592	-0.5791
Nov	1.9964	1.1807	1.2496	0.8673	0.1233	0.1726
Dec	2.8471	2.0215	2.0672	1.7213	0.9708	1.0034
Tot	23.797	14.337	15.930	10.138	1.4300	2.5675
Surplus energy in %	61.7340	37.1937	41.3251	26.2298	2.2744	5.4107
UEC	25.5591	25.0527	36.6070	22.8462	30.1753	40.2775

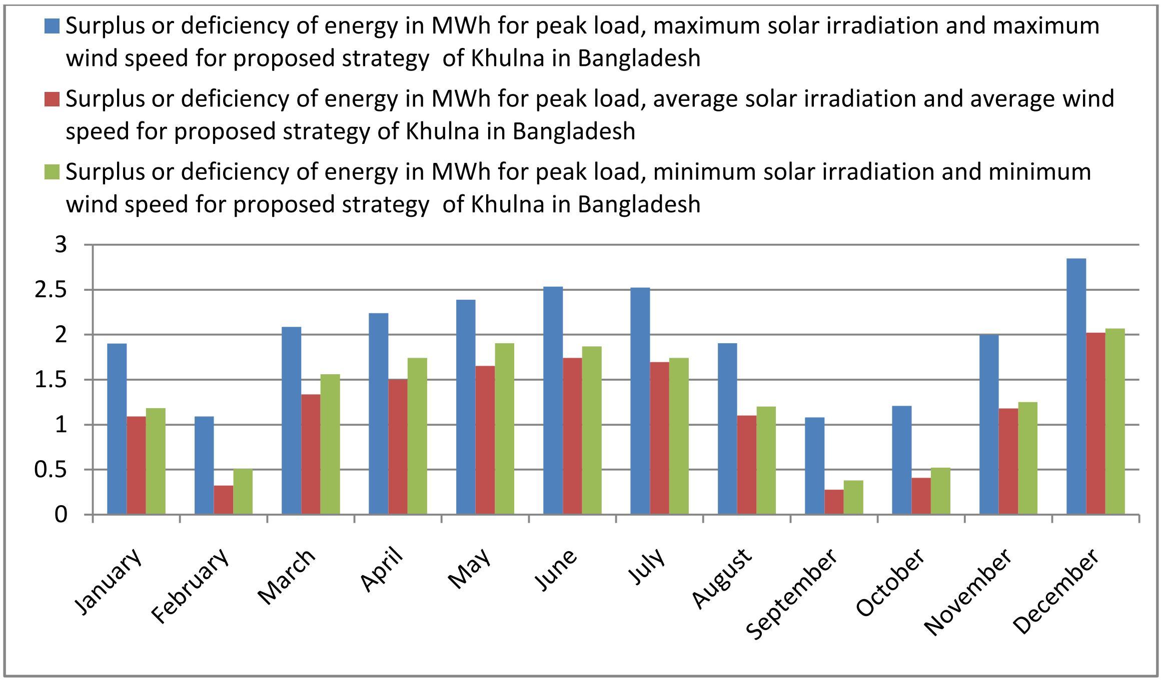


Figure 6.3: Surplus or deficiency of energy for peak load of Khulna in Bangladesh using proposed strategy

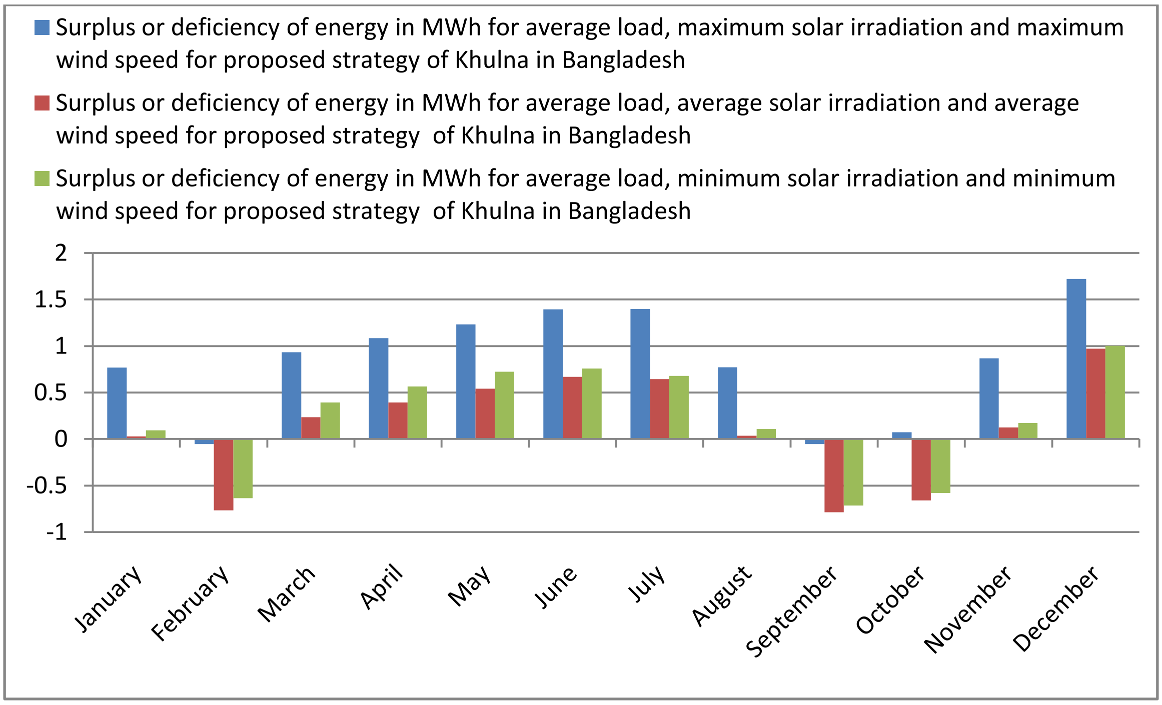


Figure 6.4: Surplus or deficiency of energy for average load of Khulna in Bangladesh using proposed strategy

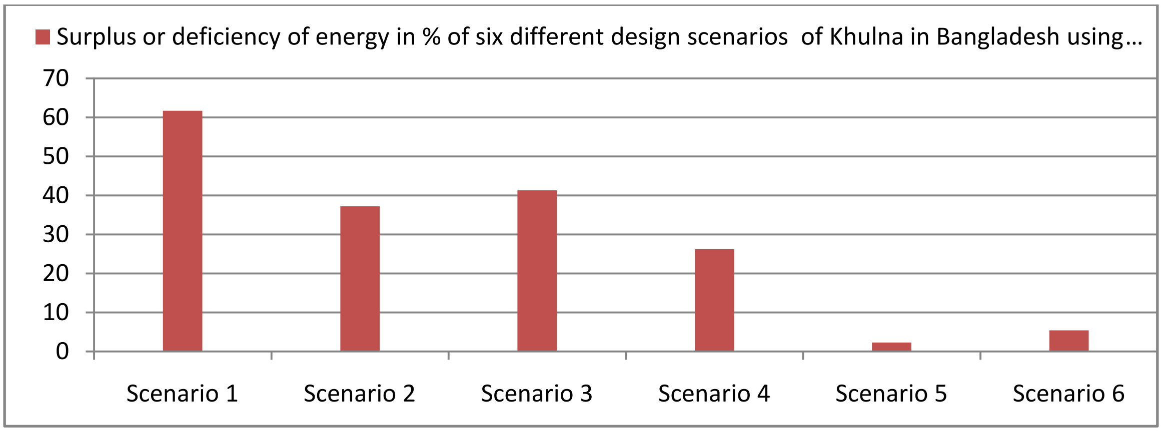


Figure 6.5: Surplus or deficiency of energy in percentage for six scenarios of Khulna in Bangladesh

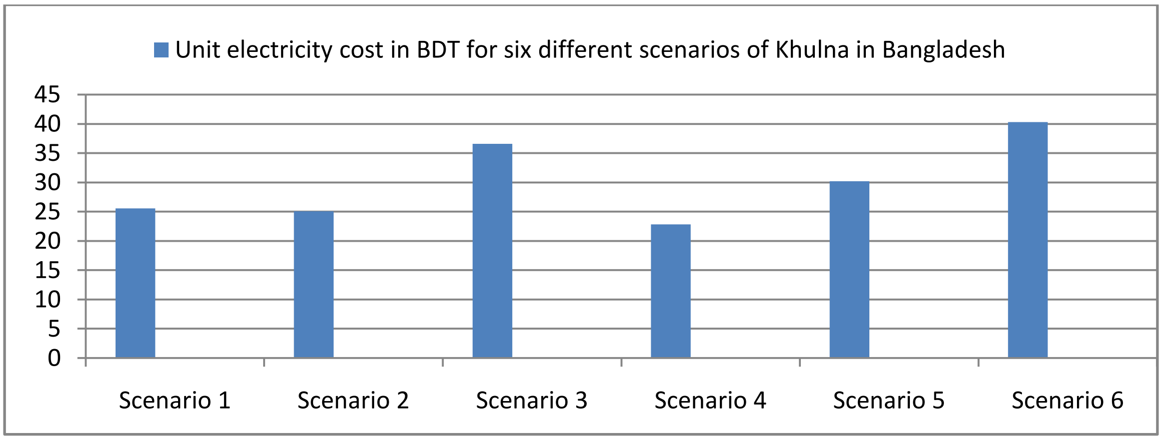


Figure 6.6: Unit Electricity Cost for six scenarios of Khulna in Bangladesh

Case II

In this case the next best site of wind speed is considered for the proposed solar-wind hybrid power system. But the solar irradiation is very poor in Chittagong. The graphical presentation of 9 years monthly average of solar irradiation and wind speed profile are shown in Fig 6.5 and Fig 6.6 respectively. It is seen that, maximum solar irradiation is harvested in the month of May and wind speed is harvested in the month of June whereas the minimum solar irradiation is harvested in the month of December and wind speed is harvested in the month of October. Same equations of Case-I are used to calculate the surplus or deficiency of energy in MWh, to calculate the number of solar panel and number of wind turbine, to calculate the number and to calculate UEC in BDT. Results obtained from the calculation are presented in Table 6.4 and shown graphically in Fig 6.7 – Fig 6.10.

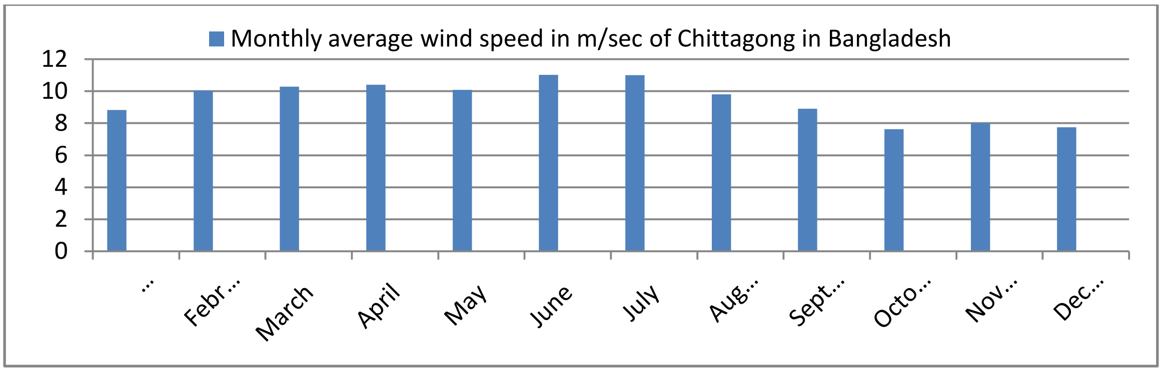


Figure 6.7: Monthly average wind speed of Chittagong in Bangladesh

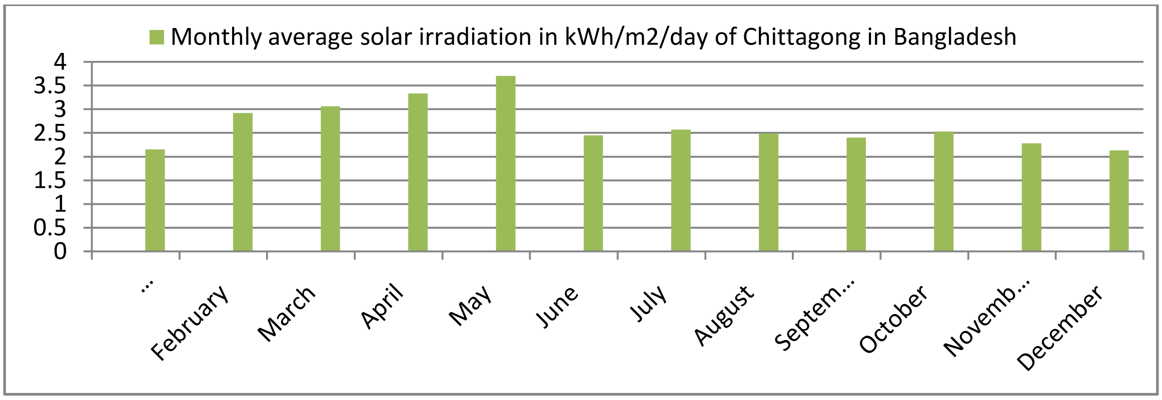


Figure 6.8: Monthly average solar irradiation of Chittagong in Bangladesh

Table 6.4: Surplus or deficiency of energy of Chittagong in Bangladesh using percentage sharing method or proposed method

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
	$N_{sh}=6$ $N_{wh}=6$ $B_h=17$	$N_{sh}=9$ $N_{wh}=9$ $B_h= 13$	$N_{sh}=15$ $N_{wh}=15$ $B_h=7$	$N_{sh}=4$ $N_{wh}=4$ $B_h=9$	$N_{sh}=7$ $N_{wh}=7$ $B_h=15$	$N_{sh}=12$ $N_{wh}=12$ $B_h=10$
	$P_s= 0.4440$kW, $P_w= 5.0900$kW	$P_s=0.4802$kW, $P_w=4.8461$kW	$P_s= 0.6390$kW, $P_w=4.2121$kW	$P_s=0.2960$kW, $P_w=3.3933$kW	$P_s= 0.3735$kW, $P_w=3.7692$kW	$P_s= 0.5112$kW, $P_w=3.3697$kW
Jan	1.2226	1.1398	0.8691	-0.0609	0.3025	0.1697
Feb	0.4251	0.3756	0.1715	-0.8806	-0.4839	-0.5612
Mar	1.4092	1.3658	1.1737	0.0994	0.5023	0.4350
Apr	1.5765	1.5448	1.3760	0.2590	0.6735	0.6256
May	1.7525	1.7367	1.5999	0.4243	0.8548	0.8336
June	1.8605	1.7907	1.5459	0.5683	0.9448	0.8336
July	1.9068	1.8423	1.6079	0.6112	0.9929	0.8903
Aug	1.2519	1.1839	0.9426	-0.0413	0.3368	0.2285
Sep	0.4162	0.3442	0.0951	-0.8745	-0.5003	-0.6151
Oct	0.5498	0.4835	0.2456	-0.7446	-0.3648	-0.4702
Nov	1.3418	1.2647	1.0052	0.0545	0.4236	0.3002
Dec	2.1928	2.1092	1.8368	0.9098	1.2725	1.1383
Tot	15.906	15.181	12.470	0.324	4.9548	3.8081
Surplus energy in %	41.2628	39.3835	32.3489	0.8458	11.9790	8.8113
UEC	25.2215	29.8094	40.2590	20.8862	35.7737	47.6066

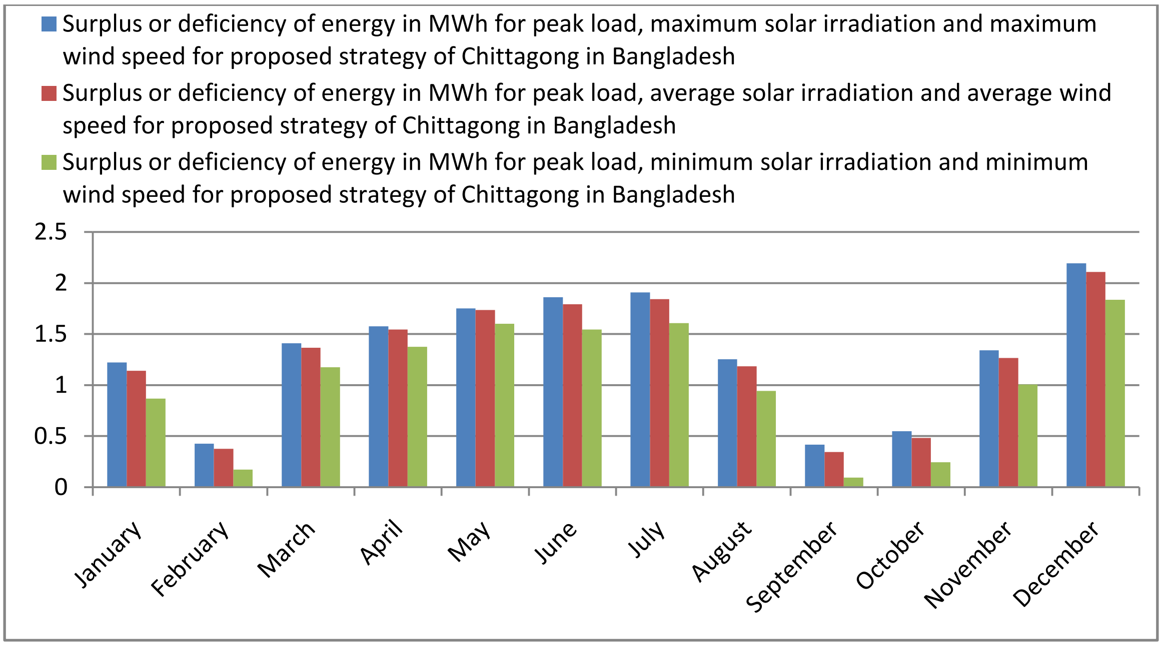


Figure 6.9: Surplus or deficiency of energy for peak load of Chittagong in Bangladesh using proposed strategy

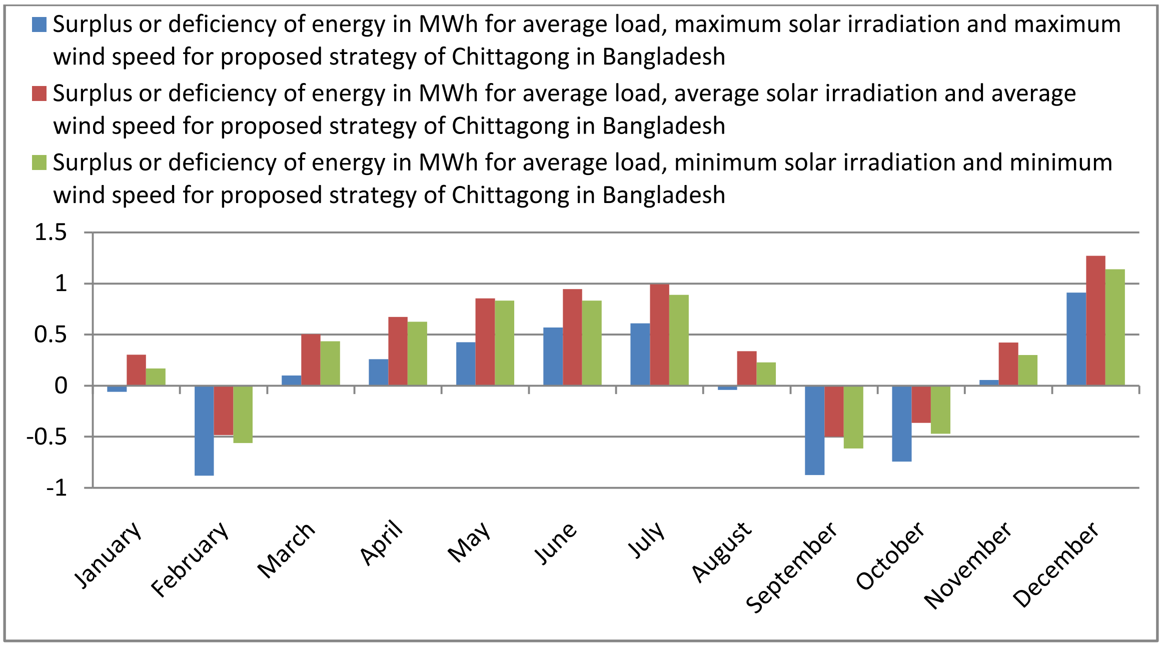


Figure 6.10: Surplus or deficiency of energy for average load of Chittagong in Bangladesh using proposed strategy

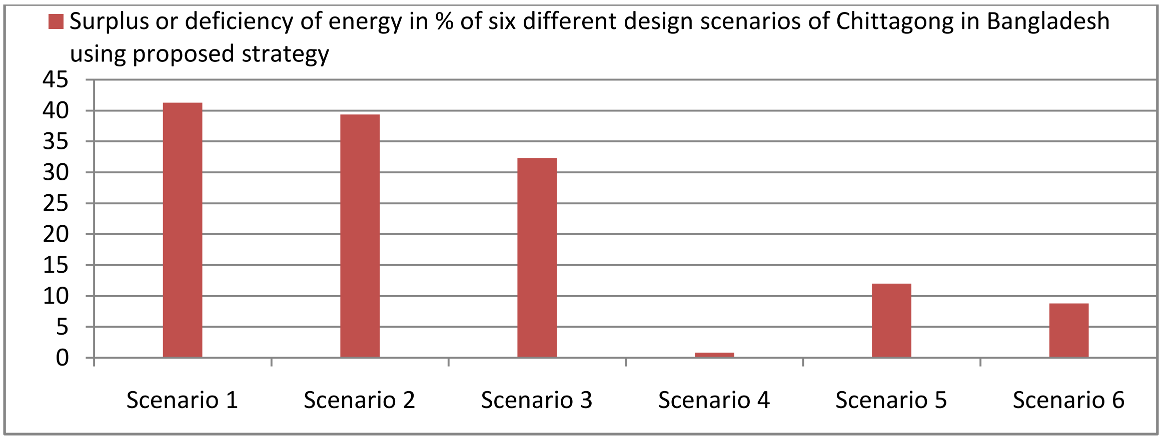


Figure 6.11: Surplus or deficiency of energy in percentage for six scenarios of Chittagong in Bangladesh

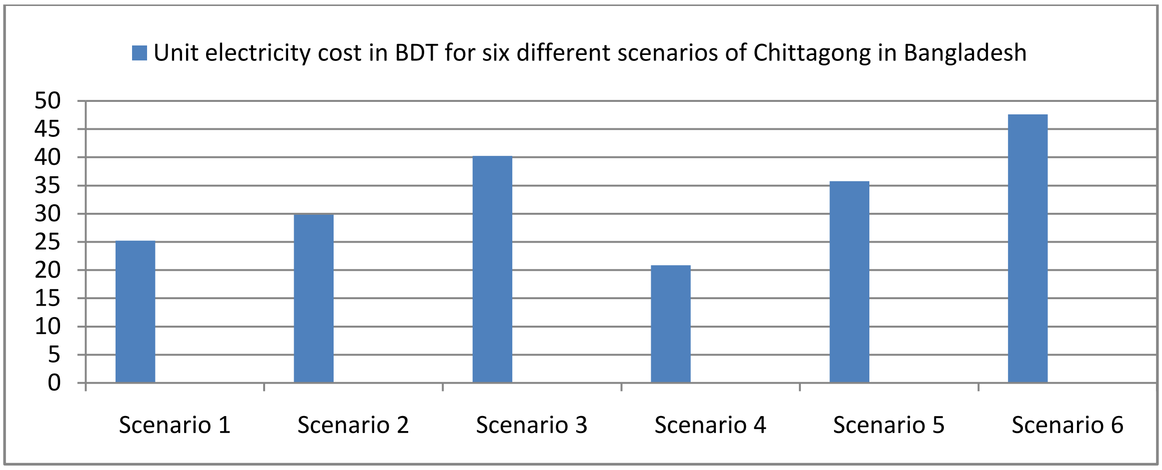


Figure 6.12: Unit Electricity Cost for six scenarios of Chittagong in Bangladesh

6.3 RESULT DISCUSSION

In Case-I, all the six scenarios are feasible to design SWHPS as the surplus energies in percentage are positive and the minimum UEC is achieved in scenario 4 which is 22.8462 BDT. This design scenario required 3 solar panels of 250W peak with 3 wind turbines of 400W. The diameter of the wind turbine is 1.17m. 15 batteries of 24V, 200Ah are also required with it. In Case-II, also all the six scenarios are feasible to design SWHPS as the surplus energies in percentage are positive and again the minimum UEC is achieved in scenario 4 which is 20.8862 BDT. This design scenario required 4 solar panels and 4 wind turbines. Nine batteries are also required with it. The rating of solar panel, wind turbine and the battery are identical to that of the ratings of Case-I.

Chapter 7

CONCLUSION

7.1 CONCLUSION

The goal of this work is to propose a design strategy of an off-grid solar-wind hybrid power system and to evaluate the performance of the strategy. The primary focus of this study is the development of dynamic models for a small standalone hybrid power generation system. The developed model of the solar-wind hybrid power system consists of a combination of solar energy generation system and a wind power generation system with a storage bank. A detail model of the wind-solar hybrid power generation system is presented in this work. With typical load profiles, solar irradiation and wind speed profiles of a typical site, the sizing approaches of each energy sources and the battery bank capacities are also discussed in this work. These data were used for the discussion of total energy generation and distribution in load.

Six different scenarios have been considered in this work for the existing strategy and also for the proposed strategy. In first scenario peak load with maximum solar irradiation and maximum wind speed has been considered, in second scenario peak load with average solar irradiation and average wind speed has been considered. In third scenario peak load with minimum solar irradiation and minimum wind speed has been considered. For the rest of the three scenarios average load with the previous three combinations of solar irradiation and wind speed have been considered.

These six different design scenarios of both types of strategies were modeled using MATLAB from mathematical model. For each scenarios the load sharing strategy, sizing of wind-PV generation, sizing of battery and unit electricity cost were calculated.

It is observed that if Khulna of Bangladesh is considered then minimum UEC is achieved by using the scenario 4 and if Chittagong is considered then minimum UEC is also achieved by using the scenario 4. But if the international data sets of solar irradiation and wind speed are considered then the minimum UEC is achieved by using the scenario 5. From this work it is also observed that, the minimum Unit Electricity Cost (UEC) varies from scenario to scenario depending on the availability of solar irradiation and wind speed.

It has been found that the unit electricity cost and number of batteries of proposed method is lower than the existing method in all the scenarios.

The proposed strategy has proved to be the best option to deliver "high quality" community energy services at the lowest economic cost, and with maximum social and environmental benefits. Indeed, by choosing this proposed strategy, developing countries can stabilize their CO_2 emission while increasing consumption through economic growth.

7.2 SCOPE OF FUTURE WORKS

The plan that has been proposed in this work is about Solar-Wind Hybrid System that can be used where now a days the scarcity of electricity is clearly noticeable and sometimes some users attempt to own their personal home electric power generation system. So it is high time to give importance in future works, researches on designing, implementation, modification and improvement of Solar-Wind Hybrid System. Some future works that can contribute to design better Solar-Wind Hybrid Systems are mentioned below:

(a) In this work only the design strategy of an off-grid solar-wind hybrid system has been proposed. This work may be extended for the grid tied solar-wind hybrid system.
(b) To analyze system stability due to the injection of power from the solar-wind power system. This can contribute to develop better design strategies.

References

[1] Onar, O. C. ;Uzunoglu, M. ; Alam, M. S. “Dynamic Modelling, Design and Simulation of a Wind/Fuel cell/Ultra-capacitor-Based Hybrid Power Generation System”, *Journal of Power Sources-Science Direct*, vol. 161, p.p. 707-722, 28 March 2006.

[2] Phuangpornpitak, N. and Kumar, S. “PV hybrid systems for rural electrifications in Thailand” *Renewable and Sustainable Energy Reviews*, vol. 11, Issue: 7, pp. 1530-1543, September 2007.

[3] de Souza Ribeiro, L.A. ; Saavedra, O.R. ; de Lima, S.L. ; Gomes de Matos, J.“Isolated Micro-Grids With Renewable Hybrid Generation: The Case of Lençóis Island” , *IEEE Transactions on Sustainable Energy*, Vol. 2, Issue: 1, pp. 1-11, 2011.

[4] Lin Xu ; XinboRuan ; Chengxiong Mao ; Buhan Zhang ; Yi Luo “An Improved Optimal Sizing Method for Wind-Solar-Battery Hybrid Power System” , *IEEE Transactions on Sustainable Energy* , Vol. 4, Issue: 3 , pp.774 – 785, 2013.

[5] Kellogg, W.D. ; Nehrir, M.H. ; Venkataramanan, G. ; Gerez, V. “Generation unit sizing and cost analysis for stand-alone wind, photovoltaic, and hybrid wind/PV systems” **,** *IEEE Transactions on Energy Conversion*, Vol. 13, Issue: 1, pp. 70-75, 1998.

[6] Chakraborty, S. ; Ito, T. ; Senjyu, T. ; Saber, A.Y.“Intelligent Economic Operation of Smart-Grid Facilitating Fuzzy Advanced Quantum Evolutionary Method”, *IEEE Transactions on Sustainable Energy*, Vol. 4 , Issue: 4, pp. 905 – 916, 2013

[7] Sungwoo, Bae; Kwasinski ,A.”Dynamic Modeling and Operation Strategy for a Microgrid With Wind and Photovoltaic Resources”, *IEEE Transactions on Smart Grid* , Vol. 3, Issue: 4, pp. 1867-1876, 2012.

[8] Bonanno, F. ; Consoli, A. ; Lombardo, S. ; Raciti, A.” A logistical model for performance evaluations of hybrid generation systems”, *IEEE Transactions on Industry Applications*, Vol. 34 , Issue: 6, pp. 1397 – 1403, 1998.

[9] Whei-Min Lin ; Chih-Ming Hong ; Chiung-Hsing Chen. “Neural-Network-Based MPPT Control of a Stand-Alone Hybrid Power Generation System”, *IEEE Transactions on Power Electronics*, Vol. 26, Issue: 12, pp. 3571 – 3581, 2011

[10] Wei Qi ; Jinfeng Liu ; Xianzhong Chen ; Christofides, P.D. “Supervisory Predictive Control of Standalone Wind/Solar Energy Generation Systems”, *IEEE Transactions onControl Systems Technology*, Vol. 19 , Issue: 1, pp. 199 - 207 ,2011

[11] Billinton, R. ; Karki, R. ” Capacity expansion of small isolated power systems using PV and wind energy”, *IEEE Transactions on Power Systems*, Vol. 16 , Issue: 4, pp. 892 – 897, 2001.

[12] Xiong Liu ; Peng Wang ; Poh Chiang Loh “A Hybrid AC/DC Micro grid and Its Coordination Control”, *IEEE Transactions on Smart Grid*, Vol. 2, Issue: 2, pp. 278-286, 2011.

[13] Wang, J. ; Yang, F.“Optimal capacity allocation of standalone wind/solar/battery hybrid power system based on improved particle swarm optimization algorithm”, *IEEE Transactions on Renewable Power Generation*, Vol. 7 , Issue: 5, pp. 443 – 448, 2013.

[14] Chunhua Liu ; Chau, K.T. ; Xiaodong Zhang “An Efficient Wind–Photovoltaic Hybrid Generation System Using Doubly Excited Permanent-Magnet Brushless Machine”, *IEEE Transactions on Industrial Electronics*, Vol. 57 , Issue: 3, pp. 831 – 839, 2010.

[15] Sioshansi, R. ; Denholm, P. “Benefits of Colocating Concentrating Solar Power and Wind”, *IEEE Transactions on Sustainable Energy*, Vol. 4, Issue: 4 , pp. 877 – 885, 2013.

[16] Hirose, T. ; Matsuo, H. ” Standalone Hybrid Wind-Solar Power Generation System Applying Dump Power Control Without Dump Load”, *IEEE Transactions on Industrial Electronics*, Vol. 59, Issue: 2, pp. 988 – 997, 2012.

[17] Xiangjun Li ; Dong Hui ; Xiaokang Lai “Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations” , *IEEE Transactions on Sustainable Energy*, Vol. 4, Issue: 2, pp. 464 – 473, 2013.

[18] Chang Chien, Jia-Ren ; Kuo-Ching Tseng ; Yan, Bo-Yi, "Design of a hybrid battery charger system fed by a wind-turbine and photovoltaic power generators” , *Review of Scientific Instruments*, Vol. 82 , Issue: 3 , pp. 035107 - 035107-7, 2011.

[19] Chedid, R. ; Akiki, H. ; Rahman, S. ” A decision support technique for the design of hybrid solar-wind power systems “, *IEEE Transactions on Energy Conversion*, Vol. 13 , Issue: 1, pp. 76 – 83, 1998.

[20] Chedid, R. ; Rahman, S. "Unit sizing and control of hybrid wind-solar power systems", *IEEE Transactions on Energy Conversion*, Vol. 12 , Issue: 1, pp. 79 – 85, 1997.

[21] Widen, J. “Correlations Between Large-Scale Solar and Wind Power in a Future Scenario for Sweden”, *IEEE Transactions on Sustainable Energy*, Vol. 2,Issue: 2, pp. 177 – 184, 2011.

[22] Islam, M. S.; Islam, M. R.”Reducing Biomass Usage in Rural Areas of Bangladesh”, South Asia Energy Network, Practical Action, Colombo, p.p. 4-5, July 2011.

[23] Article on “Solar Power”, website: http://en.wikipedia.org/wiki/Solar_power

[24] Thomas (Ed), M. “Solar-Electricity”, John Wiley and Sons Ltd, Chichester, 2nd Edition, 2004.

[25] Olajide, M. B.; Oni, J. O.”Application of Solar Energy for Officers and Homes”, *International Training School and Workshop on Solar Energy*, University of Agriculture, Abeokuta, p.p. 18-29, June 2009.

[26] Chedid, R.;Saliba, Y.”Optimization and Control of Autonomous Renewable Energy Systems,” *International Journal of Energy Research*, Vol. 20, N0. 7, July, 1996.

[27] Musgrove, A. R. “The optimization of Hybrid Energy Conversion Systems Using the Dynamic Programming. Model RAPSODY”, *Int. Journal of Energy Research*, Vol.17, No.2, April-June, 1993.

[28] Hunter, R.; Elliot, G. “Wind-Diesel Systems”, Press Syndicate of the University of Cambridge, 1994.

[29] Linden, D. (Editor), “Handbook of Batteries”, 2nd Edition, McGraw Hill, Inc., New York, 1994.

[30] Bussey, L.;Eschenbach,T. “The Economic Analysis of Industrial Projects”, 2nd Edition, Prentice-hall Inc., New Jersey, 1992.

[31] Ramakumer, R.;ShudhakarShetty, P.; Shenayi, K. “A Linear Programming Approach to the Design of Integrated Renewable Energy Systems for Developing Countries”, *IEEE Trans. on Energy Conversion*, EC-01, p.p. 18-24, 1986.

[32] Swift, A. H. P.; Holder, M. R. “Design of Hybrid Energy Systems”, *7th ASME Wind Symposium*, New York, 1998.

[33] Chill, J.;Ritland, K. ; Kelly, W. "Description of Electric Energy Use in Single Family Residences in the Pacific Northwest 1986-1992”, Office of Energy Resources, Bonneville Power Administration, December 1992, Portland, OR.

[34] Gipe, P.”Wind Power For Home & Business”, Chelsea Green Publishing Company, 1993.

[35] RETScreen, *International clean energy decision support centre* available at: http//www.retscreen.net.

[36] Kabir, M. A.;Dey, H. S. ; Farby, H. M. "Microfinance: The Sustainable Financing System for Electrification and Socio-economic Development of Remote localities by Solar Home Systems (SHSs) in Bangladesh," in *Proc.SYSCON'10*, pp 82-84, April2010.

[37] James Miller, "Making the Most of the Internet And the Other Less/More Important Things in Life," Daisy Analysis Ltd., United Kingdom, pp. 189.

[38] Kannan, R. ; Leong, K. C. ; Osman, R. ; Hoand, H. K. ; Tso, C. P. "Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore," *Solar Energy,* Vol. 80 No. 5, pp.555 – 563, May 2006.

[39] B –Trac Engineering Ltd. *A business concern of Bangla Trac Ltd.* available at: http://www.btraceng.com/

[40] RAHIMAFROOZ, *The Manufacturer, Distributor and Importers of IPS and batteries items based in Bangladesh* available at: http://www.bdips.com/

[41] "Ningbo Qixin Solar Electrical Appliance Co. ltd" *manufacturer of solar panels* available at: http://www.nbqxsolar.com

[42] "Wenzhou Nova New Energy Co. Ltd" *manufacturer of wind turbines* available at: http://www. novanewenergy.com

[43] Bhuyian, M. M. H.;Asgar, M. A ;Mazumder, R. K. ; Hussain, M. "Eco- nomic evaluation of a stand-alone residential photovoltaic power system in Bangladesh," *Renewable Energy*, vol. 21, pp. 403-410, January 2000.

[44] Tomas Markvart, Editor, "Solar Electricity", John Wiley and Sons, 2nd Edition, pp. 115-127.

[45] KALER KANTHA, *The daily news paper of Bangladesh* available at: http//www.kalerkantha.com

[46] (2013) Bangladesh Power Development Board website available at: http://www.bpdb.gov.bd/bpdb/index.php?option=com_content&view

[47] (2013) U. S. Energy Information Administration website available at: http://www.eia.gov/countries/country-data.cfm?fips=BG&trk=m.

[48] B. Imam, “Energy Crisis and Potential in Bangladesh”, *Strategic Analysis*, Vol. 35 No.2, pp.248 – 264, March 2011.

[49] GOB (March 2008) *National Energy Policy*, Ministry of Power, Energy and Mineral Resources of Bangladesh.

[50] Kabir, M. A.; Dey, H. S. and Farby, H. M. “Microfinance: The Sustainable Financing System for Electrification and Socio-economic Development of Remote localities by Solar Home Systems (SHSs) in Bangladesh,” in *Proc. SYSCON’10*, pp. 82-84. April 2010.

[51] Kowsar, A.; Islam, M. S.; Mehzabeen, K. R. and Mahmood, Z. H.“Solar Energy to Meet the Energy Crisis in Bangladesh” in *Proc. International Conference on Environmental Aspects of Bangladesh (ICEAB), Japan*, pp. 113-115, September 2010.

Appendix-A

MATLab code for fixed sharing method:

```
clearall;

%Yearly curves data
pl=[3.65 4.85 3.5 3.3 3.1 2.8 2.75 3.65 4.8 4.63 3.5 2.3];
v=[1.9 2.1 2.2 2.5 2.5 2.4 2.2 1.9 1.7 1.5 1.6 1.7];
s=[4.36 4.92 5.59 5.76 5.30 4.53 4.23 4.29 4.02 4.32 4.28 4.21];


%Finding out the average value of the yearly curves
n=length(pl)
t=1:1:n;
sum=0;
sum2=0;
sum3=0;

for i=1:1:n;
sum=sum+pl(i);
    sum2=sum2+v(i);
    sum3=sum3+s(i);
end

avg=sum/n;
avg2=sum2/n;
avg3=sum3/n;

PL=avg;
V=max(v);
S=max(s);

%Power generation by the wind power system
W=500;
R=1.5;
Row=1.225;
NgNr=1;
Vwind=V;
Wm=2.295*Vwind;
L=Wm*R/Vwind;
Cp=0.44*sin((pi*(L-2))/13);
Pm=(Cp*Row*pi*R^5*Wm^3)/(2*L^3);
Pr=NgNr*Pm/1000;

%Power generation by the solar power system
U=150;
A=0.08;
Ps=(U/1000*S*A);

%Sizing of the hybrid system
Nhw=1;
Nhs=ceil((PL-Pr*Nhw)/(Ps));

NS=1:1:150;
for k=1:1:150;
```

```
deltaP1(k)=((k*Ps))-PL;
deltaP2(k)=((k*Ps))-PL+Pr*Nhw;
end

%Finding out the excess or deficiency of energy of the yearly curves
h=1*24*30;
energy=0;
f61=0;
f62=0;

for i=1:1:n;

Wm=2.295*v(i);
    L=Wm*R/v(i);
Cp=0.44*sin((pi*(L-2))/13);

DHe(i)=Nhs*(U*s(i)*A/1000)-
pl(i)+NgNr*((Cp*Row*pi*R^5*Wm^3)/(2*L^3))/1000*Nhw;

    h=1*24*30;

energy  = energy + pl(i)*h;

ENG3(i)=DHe(i)*h;

if ENG3(i)<0;
       f61=f61+ENG3(i);
end
if ENG3(i)>0;
       f62=f62+ENG3(i);
end

end

%Sizing of the battery
vb=12;
ib=.2;
Nbh=ceil((max(ENG3)-min(ENG3))/(0.80*vb*ib*30))

%Excess ehergy in parcentage
eeh=(f62*.75+f61)/energy*100


%UEC for Hybrid

%INITIAL CAPITAL COST
SC=80;
WC=70;
IC=55;
CC=50;
M=20;
MC=20;
BC=7500;

A3=WC*W*Nhw+SC*U*Nhs;
B3=IC*(W*Nhw+U*Nhs);
C3=CC*(W*Nhw+U*Nhs);
D3=M*(W*Nhw+U*Nhs);
```

```
E3=MC*(W*Nhw+U*Nhs);
F3=BC*Nbh*vb*ib;

TH1=(A3+B3+C3+D3+E3+F3);

%FUEL COST
TH2=0;

%ECONOMIC FACTORS
I=0.067;
D =.2;

%RECURRING COST
N=20;
CA=5000;
PA=((1+I)/(1+D))*(abs((1+I)/(1+D))^N-1)/((1+I)/(1+D)-1);

TH3=CA*PA;

%NON-RECURRING COST
n1=5;
PR1=((1+I)/(1+D))^n1;
n2=10;
PR2=((1+I)/(1+D))^n2;
n3=15;
PR3=((1+I)/(1+D))^n3;
PRH=(PR1+PR2+PR3);

CRC=5000;
CRH=(B3+F3+CRC);

TH4=CRH*PRH;

%UNIT ELECTRICITY COST
AF=PA;
DL=PL*h;
LCCH=TH1+TH2+TH3+TH4;
ALCCH=LCCH/AF;
UECH=ALCCH/(DL*12);


figure(1)
plot(t,pl,'LineWidth',2)
xlabel('Month')
ylabel('Load in KW')


figure(2)
plot(t,v,'LineWidth',2)
xlabel('Month')
ylabel('Wind speed in m/s')

figure(3)
plot(t,s,'g','LineWidth',2)
xlabel('Month')
ylabel('Solar irradiance in KWh/m2')
```

```
figure(4)
plot(NS,deltaP2,'r','LineWidth',2)
holdon
plot(NS,deltaP1,'g','LineWidth',2)
xlabel('No. of solar pannel')
ylabel('Delta P in KW')
LEGEND('Hybrid','Solar','Location','Best')
clc

figure(5)
plot(t,DHe,'r','LineWidth',2)
xlabel('Month')
ylabel('Hourly excess power in KW')
clc

figure(6)
plot(t,ENG3,'r','LineWidth',2)
xlabel('Month')
ylabel('Monthly excess energy in KWh')
```

MATLab code for percentage sharing method:

```
clearall;

%Daily curves data
pl1=[1.38 1.24 1.22 1.23 1.35 1.76 2.65 2.85 2.5 2.3 2 1.8 1.75 1.65 1.6
1.63 1.8 2.3 2.51 2.52 2.5 2.49 2.3 1.5];
v11=[4.5 4.25 4.24 4.4 4.25 4.5 4.2 4.1 4.5 4.75 5.25 5.75 6.3 6.6 6.65
6.3 6.1 5.8 5.5 4.9 4.8 4.7 4.6 4.5];
s11=[0 0 0 0 0 0 0.025 0.1 0.19 0.3 0.41 0.5 0.55 0.5 0.42 0.35 0.25
0.15 0 0 0 0 0 0];
y1=length(pl1);
t1=1:1:y1;

%Finding out the average value of the daily curves
sum1=0;
sum22=0;
sum33=0;
for j=1:1:y1;
    sum1=sum1+pl1(j);
    sum22=sum22+v11(j);
    sum33=sum33+s11(j);
end

avg1=sum1/y1
avg22=sum22/y1
avg33=sum33/y1

%Yearly curves data
pl=[3.65 4.85 3.5 3.3 3.1 2.8 2.75 3.65 4.8 4.63 3.5 2.3];
v=[1.9 2.1 2.2 2.5 2.5 2.4 2.2 1.9 1.7 1.5 1.6 1.7];
s=[4.36 4.92 5.59 5.76 5.30 4.53 4.23 4.29 4.02 4.32 4.28 4.21];
n=length(pl)
t=1:1:n;

%Finding out the average value of the yearly curves
sum=0;
sum2=0;
sum3=0;
for i=1:1:n;
sum=sum+pl(i);
    sum2=sum2+v(i);
    sum3=sum3+s(i);
end

avg=sum/n;
avg2=sum2/n;
avg3=sum3/n;


%Finding out the multipling factor for the modification of the daily
curves for a perticular month
for i=1:1:n;
m(i)=pl(i)/avg1;
m2(i)=v(i)/avg22;
m3(i)=s(i)/avg33;
end

PL=avg;
```

```
V=avg2;
S=avg3;

%Power generation by the wind power system
W=500
R=1.5;
Row=1.225;
NgNr=1;
Vwind=V;
Wm=2.295*Vwind;
L=Wm*R/Vwind;
Cp=0.44*sin((pi*(L-2))/13);
Pm=(Cp*Row*pi*R^5*Wm^3)/(2*L^3);
Pr=NgNr*Pm/1000;

%Power generation by the solar power system
U=150;
A=0.08;
Ps=(U/1000*S*A);

%Load sharing by the wind and solar power generation system
w1=Pr/(Pr+Ps)*PL;
s1=Ps/(Pr+Ps)*PL;

%Sizing of the hybrid system
Nhw=ceil(w1/Pr)
Nhs=ceil(s1/Ps)

%Finding out the excess or deficiency of energy of the yearly curves
h=1*24*30;
energy = 0;
f61=0;
f62=0;

for i=1:1:n;
Wm=2.295*v(i);
    L=Wm*R/v(i);
Cp=0.44*sin((pi*(L-2))/13);

DHe(i)=Nhs*(U*s(i)*A/1000)-
pl(i)+NgNr*((Cp*Row*pi*R^5*Wm^3)/(2*L^3))/1000*Nhw;

    h=1*24*30;

energy  = energy + pl(i)*h;

ENG3(i)=DHe(i)*h;

if ENG3(i)<0;
       f61=f61+ENG3(i);
end
if ENG3(i)>0;
       f62=f62+ENG3(i);
end

end

%Excess ehergy in parcentage
eeh=(f62*.75+f61)/energy*100
```

```
%Sizing of the battery
vb=12;
ib=.2;
for i=1:1:n;
for j=1:1:y1;

    Wm1=2.295*v11(j)*m2(i);
    L1=Wm*R/(v11(j)*m2(i));
    Cp1=0.44*sin((pi*(L-2))/13);
    DHe1(i,j)=Nhs*(U*s11(j)*m3(i)*A/1000)-
pl1(j)*m(i)+NgNr*((Cp*Row*pi*R^5*Wm^3)/(2*L^3))/1000*Nhw;

end
end

f611=0;
f621=0;
fmh=0;
ffh=0;
fnh=0;
fgh=0;

h1=1*30;
energy1 = 0;

for i=1:1:n
for j=1:1:y1

energy1  = energy1 + pl1(j)*m(i)*h1;
ENG31(i,j)=DHe1(i,j)*h1;

if ENG31(i,j)<0;
ffh=ffh+ENG31(i,j);
       f611=f611+ENG31(i,j);
fmhm(i)=ffh;
end

if ENG31(i,j)>0;
fgh=fgh+ENG31(i,j);
       f621=f621+ENG31(i,j);
fnhn(i)=fgh;
end

end
ffh=0;
fgh=0;
end

fmh=min(fmhm);
fnh=min(fnhn);

if abs(f621*.75)>abs(f611)
Nbh=ceil(abs(fmh)/(0.75*vb*ib*30));
end

if abs(f621*.75)<abs(f611)
Nbh=ceil(abs(fnh)/(0.75*vb*ib*30));
end
```

```
%UEC for Hybrid
%INITIAL CAPITAL COST
SC=80;
WC=70;
IC=55;
CC=50;
M=20;
MC=20;
BC=7500;

A3=WC*W*Nhw+SC*U*Nhs;
B3=IC*(W*Nhw+U*Nhs);
C3=CC*(W*Nhw+U*Nhs);
D3=M*(W*Nhw+U*Nhs);
E3=MC*(W*Nhw+U*Nhs);
F3=BC*Nbh*vb*ib;
TH1=(A3+B3+C3+D3+E3+F3);

%FUEL COST
TH2=0;

%ECONOMIC FACTORS
I=0.067;
D =.2;

%RECURRING COST
N=20;
CA=5000;
PA=((1+I)/(1+D))*(abs((1+I)/(1+D))^N-1)/((1+I)/(1+D)-1);
TH3=CA*PA;

%NON-RECURRING COST
n1=5;
PR1=((1+I)/(1+D))^n1;
n2=10;
PR2=((1+I)/(1+D))^n2;
n3=15;
PR3=((1+I)/(1+D))^n3;
PRH=(PR1+PR2+PR3);

CRC=5000;
CRH=(B3+F3+CRC);

TH4=CRH*PRH;

%UNIT ELECTRICITY COST
AF=PA;
DL=PL*h;
LCCH=TH1+TH2+TH3+TH4;
ALCCH=LCCH/AF;
UECH=ALCCH/(DL*12);

figure(1)
plot(t,pl,'LineWidth',2)

xlabel('Month')
ylabel('Load in kW')
```

```
figure(2)
plot(t,v,'LineWidth',2)
xlabel('Month')
ylabel('Wind speed in m/s')

figure(3)
plot(t,s,'g','LineWidth',2)
xlabel('Month')
ylabel('Solar irradiance in kWh/m2')

figure(4)
plot(t,DHe,'r','LineWidth',2)
xlabel('Month')
ylabel('Monthly excess power in kW')
clc

figure(5)
plot(t,ENG3,'r','LineWidth',2)
xlabel('Month')
ylabel('Monthly excess energy in kWh')

figure(61)
subplot(2,3,1)
plot(t1,m(1)*pl1)
xlabel('Daily hour of January')
ylabel('Load in kW')
subplot(2,3,2)
plot(t1,m(2)*pl1)
xlabel('Daily hour of February')
ylabel('Load in kW')
subplot(2,3,3)
plot(t1,m(3)*pl1)
xlabel('Daily hour of March')
ylabel('Load in kW')
subplot(2,3,4)
plot(t1,m(4)*pl1)
xlabel('Daily hour of April')
ylabel('Load in kW')
subplot(2,3,5)
plot(t1,m(5)*pl1)
xlabel('Daily hour of May')
ylabel('Load in kW')
subplot(2,3,6)
plot(t1,m(6)*pl1)
xlabel('Daily hour of June')
ylabel('Load in kW')

figure(62)
subplot(2,3,1)
plot(t1,m(7)*pl1)
xlabel('Daily hour of July')
ylabel('Load in kW')
subplot(2,3,2)
plot(t1,m(8)*pl1)
xlabel('Daily hour of August')
ylabel('Load in kW')
subplot(2,3,3)
plot(t1,m(9)*pl1)
xlabel('Daily hour of September')
ylabel('Load in kW')
```

```
subplot(2,3,4)
plot(t1,m(10)*pl1)
xlabel('Daily hour of October')
ylabel('Load in kW')
subplot(2,3,5)
plot(t1,m(11)*pl1)
xlabel('Daily hour of November')
ylabel('Load in kW')
subplot(2,3,6)
plot(t1,m(12)*pl1)
xlabel('Daily hour of December')
ylabel('Load in kW')

figure(71)
subplot(2,3,1)
plot(t1,m2(1)*v11)
xlabel('Daily hour of January')
ylabel('Wind speed in m/s')
subplot(2,3,2)
plot(t1,m2(2)*v11)
xlabel('Daily hour of February')
ylabel('Wind speed in m/s')
subplot(2,3,3)
plot(t1,m2(3)*v11)
xlabel('Daily hour of March')
ylabel('Wind speed in m/s')
subplot(2,3,4)
plot(t1,m2(4)*v11)
xlabel('Daily hour of April')
ylabel('Wind speed in m/s')
subplot(2,3,5)
plot(t1,m2(5)*v11)
xlabel('Daily hour of May')
ylabel('Wind speed in m/s')
subplot(2,3,6)
plot(t1,m2(6)*v11)
xlabel('Daily hour of June')
ylabel('Wind speed in m/s')

figure(72)
subplot(2,3,1)
plot(t1,m2(7)*v11)
xlabel('Daily hour of July')
ylabel('Wind speed in m/s')
subplot(2,3,2)
plot(t1,m2(8)*v11)
xlabel('Daily hour of August')
ylabel('Wind speed in m/s')
subplot(2,3,3)
plot(t1,m2(9)*v11)
xlabel('Daily hour of September')
ylabel('Wind speed in m/s')
subplot(2,3,4)
plot(t1,m2(10)*v11)
xlabel('Daily hour of October')
ylabel('Wind speed in m/s')
subplot(2,3,5)
plot(t1,m2(11)*v11)
xlabel('Daily hour of November')
ylabel('Wind speed in m/s')
subplot(2,3,6)
```

```
plot(t1,m2(12)*v11)
xlabel('Daily hour of December')
ylabel('Wind speed in m/s')

figure(81)
subplot(2,3,1)
plot(t1,m3(1)*s11)
xlabel('Daily hour of January')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,2)
plot(t1,m3(2)*s11)
xlabel('Daily hour of February')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,3)
plot(t1,m3(3)*s11)
xlabel('Daily hour of March')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,4)
plot(t1,m3(4)*s11)
xlabel('Daily hour of April')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,5)
plot(t1,m3(5)*s11)
xlabel('Daily hour of May')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,6)
plot(t1,m3(6)*s11)
xlabel('Daily hour of June')
ylabel('Solar irradiance in kWh/m2')

figure(82)
subplot(2,3,1)
plot(t1,m3(7)*s11)
xlabel('Daily hour of July')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,2)
plot(t1,m3(8)*s11)
xlabel('Daily hour of August')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,3)
plot(t1,m3(9)*s11)
xlabel('Daily hour of September')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,4)
plot(t1,m3(10)*s11)
xlabel('Daily hour of October')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,5)
plot(t1,m3(11)*s11)
xlabel('Daily hour of November')
ylabel('Solar irradiance in kWh/m2')
subplot(2,3,6)
plot(t1,m3(12)*s11)
xlabel('Daily hour of December')
ylabel('Solar irradiance in kWh/m2')
```

Appendix-B

Specifications of solar panel:

Manufacturer: Ningbo Qixin Solar Electrical Appliance Co.,ltd
Web Site: http://www.nbqxsolar.com
Module (SL150TU-18P) Specifications
18V 150W 156 156 Poly- Silicon Solar Module Solar Energy Cells panel

Electrical Data

Maximum Power(W): 150W
Optimum Power Voltage(Vmp): 18.61V
Optimum Operating Current(Imp): 8.06A
Open Circuit Voltage(Voc): 22.19V
Short Circuit Current(Isc): 8.62A
Cell Efficiency (%): 17.46%
Module Efficiency (%): 15.12%
Tolerance Wattage(%): 0~+3%
NOCT: 47° C +/-2° C

Components & Mechanical Data

Solar Cell: 156*156 Poly
Number of Cell(pcs): 4*9
Size of Module(mm): 1485*668*35
Front Glass Thikness(mm): 3.2
Surface Maximum Load Capacity: 2400-5400Pa
Allowable Hail Load: 23m/s, 7.53g
Weight Per Piece(KG): 11.6
Bypass Diode Rating(A): 10
Frame(Material Corners, etc.): 35#
Backing (Brand Type): TPT
Temperature Range: -40° C to +85° C
FF (%): 70-76%
Standard Test Conditions: AM1.5 1000W/ 25 +/-2° C

Warranty & Certifications

Warranty 20 year limited power warranty
2 year limited product warranty
Certifications IEC 61215, IEC 61730

Specifications of wind turbine:

Manufacturer:Wenzhou Nova New Energy Co. Ltd
Web Site: http://www. novanewenergy.com
NOVAS-700-2 Specifications
500W 12/24V DC Residential Permanent Magnet Small Wind Power Generator

- Small wind generator
- Suitable for homes and boats
- Voltage: 12 or 24V DC
- Rated power: 400 to 600W
- Maximum power: 550 to 750W
- Configuration: 3 blades and upwind
- Rotor diameter: 118.14 inches (3m)
- Blade material: CFRP
- High-speed protection: hysteresis braking (slowdown)
- Over-speed protection: hysteresis braking (shutdown)
- Start up wind speed: 1.5m/second (3.35mph)
- Start charging wind speed: 1.2m/second (2.69mph)
- Rated wind speed: 12.5m/second (28 mph)
- Incision wind speed: 25m/second (56mph)
- Survival wind speed: 60m/sec (134mph)

Specifications of battery:

Manufacturer:Lucus Battery
Web Site: http://www.bdips.com
APL AP 200 Specifications

Volt: 12 Volt
Plate/cell: 29
AHC@20 Hrs: 200
Dimensions (mm) Approximate:

1. Length: 505mm
2. Width: 220mm
3. Height: 240mm