Techno-Economic Optimum Sizing of Hybrid Renewable Energy System

Rural Electrification in Sri Lanka

K. M. Iromi Udumbara Ranaweera

Supervisor

Dr. Mohan Lal Kolhe

Department of Engineering Science
Faculty of Engineering and Science
University of Agder, 2013

Abstract

Using an off grid hybrid renewable energy-based power systems for rural electrification has become an attractive solution for areas where grid electricity is either not feasible or the cost of the grid extension is relatively high. A hybrid system uses one or several renewable energy technologies as primary energy sources and a conventional fossil fuel-based or biofuel-based generator as a backup source. Therefore, a hybrid system reduces the dependence on one energy source, resulting in reliable and affordable electricity for the rural consumers. As hybrid systems use several energy technologies, the selection of proper technologies and optimum sizing of the selected components is important in reducing the overall cost and increasing the reliability and availability of the service.

The objective of this study has been to find the optimum configuration of a hybrid system which can supply electricity to a rural community in Sri Lanka. A rural village from the Siyambalanduwa region in Sri Lanka containing approximately 150 households which results in a daily electricity demand of 270 kWh with a night-time peak of 25 kW has been chosen as target. The Siyambalanduwa region receives an abundance of solar radiation with an annual average of 5.0 $kWh/m^2/day$. In addition, the annual average wind speed of this region is 6.3 ms^{-1} which results in a wind power density of 300 W/m^2 at a height of 50 m above the ground. Several electricity generating technologies, including solar, wind and diesel generators have been studied, and the simulations have been performed for a large number of system configurations using the "HOMER" software. The total net present cost of each system configuration has been calculated for 20 years of systemic lifetime in order to examine the lowest energy cost option.

It has been found that the combination of wind turbines, PV system, a battery bank and a diesel generator gives the optimum hybrid system with following the rated capacities, wind – 40 kW, PV – 30 kW, battery bank – 222 kWh and the diesel generator – 25 kW. The wind turbines generate 67 % of the total annual energy output, which is approximately 116000 kWh/yr. The diesel generator is required to provide only 9 % of the total generation, resulting in 1240 hours of operation annually. The remaining 24 % is generated by the PV system. This hybrid system can supply electricity at an approximate levelized cost of 0.3 $/kWh and may be further reduced to 0.2 $/kWh, if state subsidies become available for covering 40 – 50 % of the capital investment. It has also been found that the optimized system can meet the energy demand without change in the energy cost of more than 0.1 $/kWh, even though the annual average wind speed varies in the range of 4.5 – 6.3 ms^{-1}. Consequently, the impact of the energy cost for changes in the annual average solar radiation in the range of 4.0 – 5.5 $kWh/m^2/day$ has been found to be negligible. The analysis has also been done by assuming that the national grid will be extended to the rural community after 10 years of off-grid operation. It has been found that the hybrid system is economically viable whether it is operated as off-grid or grid connected.

Preface

This thesis has been submitted in partial fulfillment of the degree of Master of Science in Renewable Energy at the University of Agder, Grimstad, Norway, comprising work done from January 2013 to June 2013. The thesis' main objective has been to investigate the techno – economic optimum size of a renewable energy-based hybrid system which can supply electricity for a selected rural community in Sri Lanka. The work described here has been conducted under the supervision of Professor Mohan Kolhe and Programme coordinator Stein Bergsmark.

I would like to express my sincere gratitude to my supervisor, Professor Mohan Kolhe for giving me great inspiration, ideas, comments and continuous support throughout the process of project completion. My special thanks also go to Stein Bergsmark for providing valuable guidance when writing this thesis. His comments and suggestions have greatly helped me to improve my writing. Last but not least, I would like to thank my husband and colleagues who helped me in numerous ways to make this thesis a success.

K. M. Iromi Udumbara Ranaweera
University of Agder
Grimstad, Norway
June 2013

Contents

Abstract .... **i**
Preface .... **ii**
List of Figures .... **v**
List of Tables .... **vii**
List of Abbreviations .... **viii**

1. Introduction **1**

1.1. Background and Motivation 1
1.2. Problem Statement 3
1.3. Goal and Objectives 5
1.4. Literature Review 5
1.5. Research Method 6
1.6. Key Assumptions and Limitations 7
1.7. Requirements 8
1.8. Thesis Outline 10

2. Data Collection **11**

2.1. Introduction 11
2.2. Village Load Profile 12
2.3. Solar Resource 14
2.3.1. Annual Solar Radiation Variation 14
2.3.2. Optimal Placement of Solar Arrays 17
2.3.3. Solar Radiation Incident on a Tilted PV Array 19
2.4. Wind Resource 21
2.4.1. Annual Wind Speed Variation 21
2.4.2. Wind Speed Variation with Height above Ground 23
2.4.3. Wind Speed Distribution 24
2.4.4. Wind Power Density at the Site 25

3. Hybrid System Components **29**

3.1. Introduction 29
3.2. Wind Turbine 31
3.2.1. Wind Turbine Power Curve 32
3.2.2. Wind Turbine Installation Cost 34
3.2.3. Operation and Maintenance Cost 35
3.3. PV Panels 36
3.3.1. Electrical Characteristics of PV Cells 36
3.3.2. Operating Temperature of a PV Cell 39

3.3.3. Power output of a PV Module 40
3.3.4. PV Cost 40
3.4. Diesel Generator 42
3.4.1. Operation and Maintenance of Diesel Generators 43
3.5. Storage Battery 43
3.6. Inverter 47
3.7. Distribution Grid 48

4. Hybrid System Modeling **49**
4.1. Introduction 49
4.2. Modeling of Hybrid System in HOMER 50
4.3. Dispatch Strategy 53
4.4. Search Space 54
4.5. Economics 55

5. Results **57**
5.1. Optimization Results 57
5.2. Sensitivity Results 60
5.2.1. Annual Average Solar Radiation and Wind Speed 60
5.2.2. Capital Cost of PV and Wind Systems 63
5.2.3. Misalignment of PV Array 64
5.3. Analysis of the Optimal Hybrid System 65
5.3.1. Performance of the Hybrid System 66
5.3.2. Effect of Changes in Annual Average Wind Speed and Solar Radiation 67
5.3.3. Effect of Load Changes 70
5.4. System Optimization Considering the Effect of Emission Costs 71
5.5. Connection of the Hybrid System to the National Grid in the Future 72
5.6. Replacing the Four Wind Turbines with a 50 kW Wind Turbine 74
5.7. Design of the Hybrid System 75
5.8. Economic Viability 78
5.9. Efficient Use of Electricity in the Microgrid 79
5.10. Comparison of Electricity Prices 80

6. Discussion **83**
7. Conclusions and Future Work **87**
Bibliography 89
Appendix A 93
Appendix B 96
Appendix C 98

List of Figures

Figure 1.1 : Hybrid system.......... 2
Figure 1.2 : Inhabitants in the Monaragala District without electricity, Sri Lanka.......... 4
Figure 2.1 : Map of the Siyambalanduwa Divisional Secretariat.......... 11
Figure 2.2 : Geography of the selected site.......... 12
Figure 2.3 : Closer view of the village.......... 12
Figure 2.4 : Load profile of the village.......... 14
Figure 2.5 : Annual average daily total sum of global horizontal radiation in kWh/m²/day for Sri Lanka [26].......... 15
Figure 2.6 : Daily average insolation incident on a horizontal surface throughout a year [25].......... 16
Figure 2.7 : Annual variation of the solar declination.......... 17
Figure 2.8 : Optimal tilt angle of a solar collector.......... 18
Figure 2.9 : Solar radiation on a tilted PV panel.......... 19
Figure 2.10 : Wind resource map of Sri Lanka [29].......... 22
Figure 2.11 : Annual average wind speed variation with height at site in Siyambalanduwa.......... 24
Figure 2.12 : Weibull probability distribution for different k values.......... 25
Figure 2.13 : Variation of the root mean cube wind speed with height at site in Siyambalanduwa. 27
Figure 2.14 : Variation of wind power density with height at site in Siyambalanduwa.......... 27
Figure 3.1 : DC coupled Hybrid system.......... 29
Figure 3.2 : DC/AC coupled hybrid system.......... 30
Figure 3.3 : AC coupled hybrid system.......... 31
Figure 3.4 : Wind power density and Betz limit variation with height at site in Siyambalanduwa... 33
Figure 3.5 : The power curve of the Anhui Hummer H8.0-10KW wind turbine.......... 34
Figure 3.6 : Equivalent circuit of a PV module.......... 37
Figure 3.7 : Typical Current vs Voltage and Power characteristics of a solar cell.......... 37
Figure 3.8 : Effect of solar irradiance and module temperature on the I–V curve of Canadian Solar CS6P-240P solar module.......... 38
Figure 3.9 : Solar PV ground mounted system.......... 41
Figure 3.10 : (a) Fuel consumption curve (b) Efficiency curve of a Centurion 25 kW diesel generator.......... 42
Figure 3.11 : Lifetime curve of the Surrette 6CS25P, 6V battery.......... 45
Figure 3.12 : Capacity curve of the Surrette 6CS25P, 6V battery.......... 46
Figure 4.1 : AC coupled hybrid system.......... 50
Figure 4.2 : Synthetic wind speed data.......... 51
Figure 4.3 : Synthetic solar radiation data.......... 52
Figure 4.4 : Modified wind turbine power curve.......... 52

Figure 4.5 : Changes in the real interest rate in Sri Lanka over the time 56
Figure 5.1 : Optimal system type at different annual average solar radiation and wind speed.......... 61
Figure 5.2 : Optimum PV Array capacity at different annual average solar radiation and wind speed 61
Figure 5.3 : Optimum Number of 10 kW wind turbines at different annual average solar radiation and wind speeds 62
Figure 5.4 : Optimum generator capacity at different annual average solar radiation and wind speed 62
Figure 5.5 : Optimum number of batteries at different annual average solar radiation and wind speed 62
Figure 5.6 : Optimum converter capacity at different annual average solar radiation and wind speed 63
Figure 5.7 : Optimal system type at different PV system cost and Wind turbine cost...................... 64
Figure 5.8 : HOMER Optimization results 65
Figure 5.9 : Cost summary of the project 66
Figure 5.10 : Discounted cash flow of the project throughout the lifetime 66
Figure 5.11 : Monthly average power production from different system components..................... 67
Figure 5.12 : LCOE and Renewable fraction at different annual average wind speeds 68
Figure 5.13 : LCOE and Renewable fraction at different annual average solar radiations 68
Figure 5.14 : Effect of changes in annual average wind speed and solar radiation on LCOE.......... 69
Figure 5.15 : Effect of changes in annual average wind speed and solar radiation on renewable fraction... 69
Figure 5.16 : Variation of LCOE for different daily average load 70
Figure 5.17 : Variation of Renewable fraction for different daily average load 71
Figure 5.18 : HOMER Optimization results 72
Figure 5.19 : Power curve of the Hummer H12.5-50 kW wind turbine 75
Figure 5.20 : An AC coupled hybrid power system 76
Figure 5.21 : Single line diagram of the hybrid system 77
Figure 5.22 : Comparison of electricity cost 80

List of Tables

Table 2.1 : Climate data in Siyambalanduwa region [25] ... 14
Table 2.2 : Monthly average insolation incident on a horizontal surface [25] ... 16
Table 2.3 : Monthly variation of optimal tilt angle ... 19
Table 2.4 : Monthly average wind speed at 50m and 10m above the ground [25] ... 23
Table 3.1 : Manufacturer's specification of Canadian Solar CS6P-240P solar module ... 38
Table 3.2 : Inverter specifications ... 47
Table 4.1 : Cost summary ... 53
Table 4.2 : HOMER search space ... 54
Table 5.1 : Optimum hybrid system architecture ... 58
Table 5.2 : HOMER optimization results ... 58
Table 5.3 : HOMER optimization results in categorized way ... 58
Table 5.4 : Optimization results when using only renewable resources ... 59
Table 5.5 : Optimal hybrid system configuration ... 64
Table 5.6 : Electrical performance of the hybrid system ... 67
Table 5.7 : Performance of the hybrid system with a 50 kW wind turbine ... 75
Table 5.8 : Effect of subsidies on the electricity price ... 79
Table 5.9 : Effect of system fixed O & M cost on the electricity price ... 79

List of Abbreviations

ACC	Annualized Capital Cost
CC	Cycle Discharging
CFL	Compact Fluorescent Light
DS	Divisional Secretariat
GHG	Green House Gas
IC	Inequality Coefficient
IPP	Independent Power Producer
LCC	Life Cycle Cost
LCOE	Levelized Cost of Energy
LED	Light Emitting Diode
LF	Load Following
MCB	Miniature Circuit Breaker
MCCB	Molded Case Circuit Breaker
MPP	Maximum Power Point
MPPT	Maximum Power Point Trackers
NGO	Non-Governmental Organizations
NOCT	Nominal Operating Cell Temperature
NPC	Net Present Cost
NPV	Net Present Value
NREL	National Renewable Energy Laboratory
O & M	Operation and Maintenance
PSO	Particle Swarm Optimization
PV	Photo-Voltaic
RMC	Root Mean Cube
SHS	Solar Home Systems

Chapter 1

Introduction

The application of renewable energy technologies for rural electric power supply has been increasing in recent years. However, due to large fluctuations and the intermittent nature of renewable energy resources, using them alone is relatively expensive and unreliable; moreover, there is sometimes the need for long term storage, especially due to these resources' seasonal variations. Therefore, hybrid systems have entered the scene for providing cost-effective and reliable electricity for remote communities.

1.1. Background and Motivation

More than 60 % of the world's electricity is generated by means of fossil fuels. The larger part of this is generated via coal, while oil and natural gas also make large contributions to producing electric power. The two main problems of using these fossil fuels as energy sources are, 1) they are finite, so they will be depleted over time and 2) burning fossil fuels releases pollutant gases into the environment. The pollutant gases CO, NO and NO_2 are harmful for animals and plants, and they also cause health problems in humans. Indeed, CO_2 emissions have caused "the green-house effect" through increasing the earth's temperature, can lead to several problems such as climate changes and melting glaciers resulting in the rise of sea-water levels. In the attempt to find a solution to these problems, the world's inhabitants have being looking to renewable energy resources for fulfilling their energy needs. Renewables include solar, wind, hydro and bio-energy as well as geothermal energy and tidal power. The sun is the source of all these renewable energy resources; for example, hydro power, solar and wind energy are widely used for electricity generation in many countries.

Development of renewable energy electricity production systems has opened the door for small community electrification in remote rural areas. There are many remote communities all over the world without electricity in many developed countries as well as developing ones. The major reason for remaining without electricity in such communities is the unavailability of a national grid nearby, due to the high cost involved in the extension of the transmitting and distributing infrastructure in these remote areas. In some countries, (particularly in developed ones) rural inhabitants generate their own electricity using diesel generators. However, the cost of the kWh generated by this type of generator is substantially higher than the cost of electricity from the utility grid; therefore, several inhabitants in remote communities cannot afford it. Due to the high cost involved with extending the national grid, it is not economical for utility companies to extend the grid to remote areas. When compared to the cost involved in grid extension, renewable energy systems have now become a cost-effective solution for supplying remote communities with electric power.

Widely used renewable energy systems are the Photo-Voltaic (PV) systems and small wind turbines. In addition, bio energy and mini hydro are also used. PV systems can be installed in almost any location because sunlight is sufficiently available in most of the earth's areas. But the other technologies can only be used in locations where the resources are sufficiently available. For example, a mini hydro plant requires a river with a sufficient flow rate, and a bio energy plant requires a sufficient amount of biomass plantation. Therefore, a suitable energy system in a certain geographical location must be chosen by considering the availability of resources throughout the year.

Renewable energy resources are highly intermittent in nature, meaning that most of them experience periodical as well as seasonal variations, thus being unable to guarantee a reliable and uninterrupted supply of electricity. On the other hand, the initial cost of investment in solar and wind systems is still relatively high in comparison to fossil fuel-based electricity. Interestingly, using multiple options of renewable energy resources provides more reliable electricity than a single renewable energy source has been identified as being one solution to these problems. By using a conventional energy source in connection with renewable sources the system becomes cost effective and more reliable. Combinations of such different but complementary energy generation systems based on renewable or mixed energy (renewable energy with a backup bio-fuel/diesel generator) are known as a renewable energy hybrid system. The grid formed by this system is known as a micro-offgrid due to its size when compared to the main grid. Figure 1.1 illustrates a typical hybrid system. It uses a wind turbine and a PV system as a primary energy sources and a diesel generator as a backup energy source. In addition, a battery bank is used as an energy storage medium.

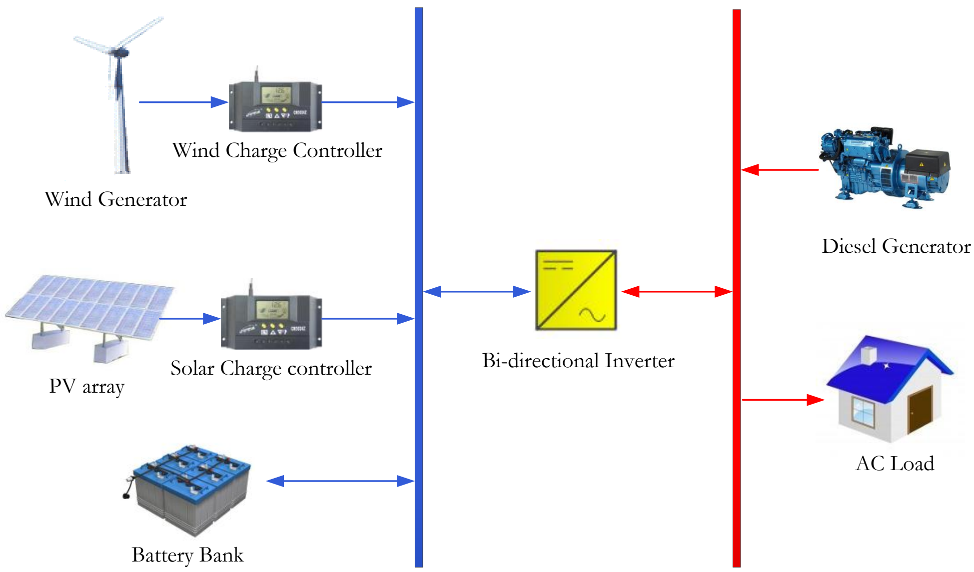


Figure 1.1 : Hybrid system

The combinations of electricity generation sources and components selected for a hybrid system have great influence on both the lifetime of the system and its affordability to the end users. In order to increase the efficiency of the system while reducing its cost, it is very important to correctly gauge the system's size. The most important element is the selection of energy sources. As mentioned earlier several types of renewable energy technologies can be utilized in a hybrid system, such as solar energy, wind energy, micro hydro and bio energy.

Batteries and conventional fossil fuel-based generators are the other important components of a hybrid system. Batteries are required to store surplus energy during times of high energy production from the renewable energy sources, which is used later for supplying the load when the power production from renewable sources is low. The generator is important to ensure quality of the service when the output from other technologies is low or when the demand is high. In addition, there should be some kind of automatic management technology built into the system to protect critical components from damage, for example, total depletion of the battery charge [1].

The total net present cost of the hybrid power system for its technical lifetime determines the energy cost and depends on the size of the generating systems and types of the energy resources used. Therefore selecting the proper combination of energy sources and the sizes of each generating system according to the electricity demand of the community is very important in order to make the system efficient and economical. This selection requires a detailed technical and economic analysis of the possible hybrid system configurations that can be applied to the given site location according to the availability of the renewable energy resources throughout the year.

Several approaches have been discussed in the literature for achieving the optimal configuration of hybrid systems. Further, a number of softwares have been developed by different institutions for analyzing the hybrid energy systems (e.g. HOMER, PVsysts, Geospatial Toolkit, Hybrid2… etc). Currently, these tools are widely used in sizing and analyzing the hybrid systems in several countries. Unfortunately, in Sri Lanka there is still not any successful hybrid energy systems in operation and the focus on studies of hybrid systems for rural electrification is minimal even though there has been a rapid growth in the renewable energy sector in Sri Lanka over the past few years.

1.2. Problem Statement

The Monaragala district is one of the poorest regions of Sri Lanka and is situated far from any urban areas. It is a district with a population of approximately 448000 [2] inhabitants whose income is mainly derived from agricultural activities in particular from paddy rice cultivation. There are many villages in this district without electricity which are located far from the urban centers in the region, for example villages from the Siyambalanduwa Divisional Secretariat (DS) which consists of 48 villages with a total population of 55200. According to the most recent publication from the Department of Census and Statistics in Sri Lanka, 6600 families in this DS get electricity from the national grid while 300 families get electricity from rural hydro power projects, 970 families get electricity using solar PV panels and 5700 families do not have access to any electricity in Siyambalanduwa, meaning that most of their villages remain without electricity. More ominously, not only does kerosene fuel consume a large part of a family's monthly budget, but lighting kerosene lamps also increases the risk of starting fires, not to mention that using kerosene is harmful for both people's health and the environment.

Electricity has now become a basic commodity of the people, and as such every single person in these rural areas should have the privilege of accessing this basic requirement at an affordable price, as doing so it helps to improve individual's lives in rural areas with regard to improved health care and education as well as local economic growth. At present, this has become possible through the implementation of renewable energy systems. Worldwide experience has shown that renewable energy systems can conveniently supply the electric energy requirement of the remote communities.

Figure 1.2 : Inhabitants in the Monaragala District without electricity, Sri Lanka

Under the rural electrification projects launched by the Ministry of Power and Energy during the past few years in Sri Lanka, 970 families in Siyambalanduwa have been provided with solar powered single home electrical systems, and more systems are planned to be distributed. The capacities of these systems are small, (around 20 – 50 Wp) and capable of supplying small DC loads for lighting and communication, such as CFL bulbs, radio and black and white television. On the other hand, the battery capacity of these systems is very small. Therefore during the seasons of low solar radiation, particularly in rainy seasons these systems are not able to meet the load, so these systems are not 100 % available.

Instead of providing isolated solar systems for each home, building a micro grid which can supply electricity to the whole community would be more economical and reliable. This micro grid can be powered by a renewable energy based hybrid system, into which several renewable energy technologies can be integrated. Additionally, some kind of dispatchable conventional technology can be used to increase the quality and availability of the service. However, the proper technologies should be carefully selected because the cost of the system must be minimized as much as possible to make the system economically viable. Further, the system components must be appropriately gauged in order to minimize the cost. Selecting suitable electricity generating sources and components' gauging process thus requires a detailed analysis of the renewable energy resource potential at the site location, daily load curve, possible technologies with their associated costs and technical operational characteristics of system components. The Levelized Cost of Energy (LCOE) approach must thereafter be applied to analyze the different technological solutions.

There have been a number of hybrid systems-based rural electrification projects implemented in several developing countries. Moreover, studies are continuously growing to address the viability of using hybrid system-based micro grids for rural electrification in various rural locations around the world; therefore, although this technology should be introduced to Sri Lanka, attention paid to hybrid systems-based micro grids is little in this country, even though there has been a large growth in the renewable industry within the past few years. Therefore, this work addresses the techno-economic possibility of using a hybrid system based micro grid for supplying electricity to a rural community in Siyambalanduwa.

1.3. Goal and Objectives

The main goal of this thesis is to propose an optimal off grid techno-economic design of a hybrid system which can provide affordable and reliable electricity for a rural community in Sri Lanka. This goal is achieved by accomplishing the following objectives:

- Studying the daily load profile of the selected community.
- Studying the potential of renewable energy resources in the selected area.
- Identifying the suitable renewable energy resources for the proposed hybrid system.
- Component selection and cost analysis.
- Modeling and simulation of the hybrid system using the HOMER software package.
- Optimization and sensitivity analysis of the hybrid system in HOMER.
- Performance evaluation of the optimal hybrid system.

1.4. Literature Review

Determination of the optimal design of the hybrid system in terms of cost and the reliability has become of great importance with the increase in usage of hybrid renewable energy systems, especially in remote area electrification. There have been a number of researches carried out in this regard over the last few decades.

Kamaruzzaman [3] has studied a simple genetic algorithm for unit sizing and cost analysis of a standalone hydro, wind and solar PV hybrid system. The algorithm randomly generates components sizes vector. Only the sizing vectors that can meet the load at any time during the time period of concern are used for the further analysis. The total net present cost of the selected combinations is calculated and then the optimal design is selected by sorting the results. This method does not account the limitations of the state of charging of the battery bank, which is a very important factor in determining the battery life time.

A. Ahmarinezhad et al [4] have developed an optimal design for a wind, solar PV and diesel hybrid system with battery backup. For the optimization of the life cycle cost they have used the Particle Swarm Optimization method (PSO). PSO has higher capacity and search efficiency. Combinations of several types of commercially available wind turbines, PV panels, batteries and diesel generators were chosen for the analysis. They have done the simulation for 20 year period with the time step of one hour. This paper does not consider the influence of fuel price variations on optimal design. They have used a fixed price for the fuel used by the diesel generator. Mohsen and Javed [5] also describe about optimization of wind, solar PV and battery hybrid system based on PSO. They have used 32 years wind speed data and solar radiation data for deriving the probability distribution functions. In addition they have considered the uncertainty of wind and photovoltaic power generation as well.

Abd El-Shafy [6] has proposed a method for optimal sizing of a solar PV, diesel hybrid system using a simple mathematical calculation. He has assumed that the diesel generator supplies the load only at the peak demand. According to the selected load profile the diesel generator capacity has been set to a value which is slightly above the peak load. The total cost of the system excluding the fuel cost has been selected as the objective function for minimization, because the fuel cost is constant for every combination of PV and battery sizes. Setting the size of the generator at a fixed value has simplified the calculations to a great extent compared to the methods discussed in other papers but this will not give an accurate result.

S. Farahat et al [7] have used a PSO based multi-objective algorithm which is called MOPSO for optimizing wind/PV hybrid system and the results have been validated by non-dominated sorting genetic algorithm (NAGA-II). Inequality coefficient (IC), correlation coefficient and annualized capital cost (ACC) have been used as the objective functions for optimization. This algorithm can evaluate only 32 different configurations of wind and solar PV devices.

Rachid et al [8] have developed a method using the DIRECT algorithm (Dividing RECTangles) for minimizing the total cost function subject to the constraints that the power produced by the system is greater or less than the load and the state of charge of the battery bank is maintained within the allowable limits. The same algorithm has been used by L. Zhang et al [9] in their research work on modeling and optimization of wind, solar PV and diesel hybrid system.

Hongxing et al [10] has proposed an optimal sizing of a hybrid system based on genetic algorithm. This algorithm has the ability to attain the global optimum with sufficient amount of computational simplicity. In their work they have selected PV module slope angle and the wind turbine height as the optimization variables other than the number of PV modules, wind turbine and batteries.

Similar optimization methods for hybrid systems have been discussed in [11], [12], [13]. In all of the research work mentioned above, the optimal design has found by minimizing the total cost function while satisfying certain constraints such as, loss of load probability and the state of charge of the battery. The accuracy of the final optimal design and the number of possible combinations that can be taken for the analysis are depend on the method used for the minimization of the objective function. One of the major weaknesses of these methods is that they have not considered the effect of possible changes in the fuel price in the future. Therefore sensitivity analysis is also very important in selecting the optimal design. Another thing is that any of these works have not calculated the CO_2 emission to the environment as well as CO_2 reduction incentive and carbon tax benefits. That is also an important issue to be considered in the case of hybrid systems using diesel backup generators.

Several other literatures [14], [15], [16], [17], [18], [19], [20], [21] have used the Homer software for techno-economic optimum sizing of hybrid systems. Homer optimization and sensitivity analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options and to account for uncertainty of technology costs, energy resource availability and other variables. It has also integrated with a product database with different products from a variety of manufactures. Hence this software is widely used for hybrid system optimization.

1.5. Research Method

The research method primarily consists of collecting renewable resource data, determination of village load profile, studying component characteristics and costs, studying hybrid system configurations, modeling and simulation of the hybrid system, selection of optimum system based on simulation results and the performance evaluation of the selected system. Initially, it is required to determine the daily load profile of the village. The seasonal variations of the load profile should also be taken into consideration if applicable. Determination of the load profile of the village could be done via conducting a survey in the village using parameters such as, the number of households and public utilities, family income, tendency and willingness to buy electrical appliances and possible small businesses that can arise if electricity is available will determine the load curve of the village. However, an estimated load curve can still be derived through making reasonable assumptions if actual surveyable data is not available.

The annual renewable resource variation data should be collected during the previous years to analyze the renewable resource potential of the site, hence to select the appropriate renewable electricity generating systems that can be integrated into the hybrid system. Renewable resource data can be obtained from the local meteorological stations or from the Internet. Several Internet-based renewable resource databases are available including meteorological data for worldwide sites. For example, NASA Surface Meteorological and Solar Energy, renewable energy resource website is a very good reference source for this purpose.

Subsequently, the different hybrid technological configurations for the interconnection of the system components should be studied and the required components should be selected accordingly. The specifications, characteristics and costs of these components should be studied and the system subsequently modeled in a hybrid system optimization software. Here I am using the micro grid optimization software "HOMER" which is developed by the National Renewable Energy Laboratory (NREL) in the USA. The simulations are required to make a large number of hybrid system configurations that consider several combinations of renewable resources, a diesel generator and battery bank with different capacities. The lifetime net present cost of the hybrid systems that can supply the village load with the required level of availability should be calculated to determine the lowest energy cost hybrid configuration. The sensitivity analysis of the uncertainties regarding the system inputs (primarily the wind speed and solar radiation) should be evaluated to examine the best system that can supply the load at the lowest energy cost for various conditions.

1.6. Key Assumptions and Limitations

The scope of this study is limited to determining the optimum capacities of the components in a hybrid system which can supply electricity to a selected community in Sri Lanka and performance evaluation of the system and will not address the complete design of the micro grid powered by this hybrid system. The analysis of the hybrid system has been done by making the following assumptions.

- NASA satellite-derived meteorology and solar energy data are reasonably accurate for gauging solar PV systems and wind systems for off-grid electrification systems.
- The same annual variations of solar radiation and wind speeds occur throughout the project lifetime.
- The consumers live according to a daily routine resulting the same load cycles every day.

- Rate of inflation has been considered the same for all types of costs (fuel cost, maintenance cost, labor cost,..etc.) occurring throughout the lifetime of the project.

The designed system has the following limitations.

- The hybrid configuration is location specific and will not be the optimal configuration for a different location where the renewable energy potential is not the same as the selected region even though the load profile may be the same.
- Only solar and wind energy will be chosen for the analysis due to the unavailability of other renewable resource data in the selected location. For example, this concerns the flow rate data of the water streams located within the area and the amount of biofuels available throughout the year which can be utilized to generate electricity via thermo chemical conversion.
- This study will not discuss the issues related to the micro grid stability and control.

1.7. Requirements

The requirements of the system can be divided into two; functional and nonfunctional requirements. A functional requirement specifies a function that a system or component must be able to perform, while a non-functional requirement specifies how a system must behave[1]. The hybrid system which has been studied in this work has the following functional and non-functional requirements.

Functional Requirements

FR 1 : Energy Demand – Peak 25 kW, daily average load 270 kWh/day

The system must be capable of continuously supplying enough energy according to the instantaneous demand within the established availability requirement. Consequently, the generation station must be properly gauged so that it can meet the maximum possible demand appearing during any time of the day. The derived daily profile for the selected community listed in section 2.2 has a peak load of 25 kW and an average daily demand of 270 kWh/day. The system must be able to supply this energy requirement without interruption.

FR 2 : Power Management

If the difference between the daily average power demand and the peak power demand is relatively higher then the cost of the system will increase, because the capacity of the system must be expanded to a limit which is capable of supplying the peak load, in such a situation a power management strategy should be implemented to reduce the peak load. Since a micro grid does not expand to a wide area, advanced power control mechanisms will not be required. Use of simple strategies will reduce the cost.

[1] www.lessons-from-history.com/node/83

FR 3 : Reserve Capacity - 10 %

The rated capacity of the hybrid system should not be determined through merely considering the load profile, as additional capacity to respond to sudden changes in the load is a constant requirement. Moreover, the renewable resources fluctuate greatly with time, and as a result the components must be gauged so that the overall system can meet the demand, even though power output from some components drops due to the renewable resource's fluctuating nature.

Nonfunctional Requirement

NFR 1 : Availibility – 99.8 %

While the minimum allowable annual outage hours caused due to shortages in the power generation is 18 hours which results in 99.8 % of the service availability, this excludes the interruptions caused by the network failures due to unavoidable reasons (natural hazards) and planned shutdowns for plant maintenance. The purpose of allowing the system to operate with a small percentage of capacity shortage is reducing the cost.

NFR 2 : Operating Reserve

The surplus operating capacity of the system that can instantly respond to a sudden increase in the electrical load or a sudden decrease in the renewable energy output is known as the operating reserve. Usually a power system always keeps an operating reserve to respond to sudden changes in the load or power generation. This is especially true, in the case of renewable energy systems, where it is essential to maintain considerable operating reserves to supply the load without frequent interruptions due to the fluctuating nature of the renewable sources. The required operating reserve of the system is defined in terms of the following indicators.

NFR 2.1 : As a percentage of hourly load – 10 %

The system must keep enough additional capacity to serve a sudden 10 % increase in the load each hour.

NFR 2.2 : A percentage of wind power output – 50 %

The system must keep additional capacity to serve the load even if the wind turbine output suddenly decreases to 50 %. As regards wind turbine output in general, it is better to maintain a higher operating reserve because wind turbine output is highly sensitive to the wind speed as the power contained in the wind is proportional to the cube of the wind speed. Thus a small sudden decrease in wind speed causes a large drop in the turbine power output.

NFR 2.3 : A percentage of solar power output – 25 %

The system must maintain additional capacity to serve the load when the output from the solar panels decreases by 25 %. This level does not need to be high as the percentage of the wind turbines, because the probability of sudden variation in sunshine is fairly low.

NFR 3 : Safety

Safety elements must be included to protect facilities from over currents created by high power demand and possible faults in the network. Current limiting devices such as Miniature Circuit Breakers (MCB) and fuses with proper ratings should be installed on both the generation side and the consumption side to protect the devices against over currents.

System Cost

The service should be affordable to the end users; meanwhile, the system should ensure sustainable operation during the project lifetime. Components must be carefully selected by considering their cost, efficiency and reliability for this reason. Less efficient and less reliable equipment reduces the initial investment, but over the course of a lifetime, selecting such equipments would not be a good decision.

1.8. Thesis Outline

The content of this thesis deals with the optimal sizing of a hybrid renewable energy system for electrifying a rural community in Sri Lanka. The thesis consists of 7 chapters and they are arranged in the following manner.

Chapter 1 gives a brief introduction about the requirement of renewable energy systems for rural electrification and the importance of hybrid energy systems in rural electrification. Following the problem statement, the chapter discusses the several methods developed for optimizing the hybrid systems under the literature review. It also discusses the research method, key assumptions and system requirements.

Chapter 2 discusses the data required for the analysis of the hybrid system which are basically the load profile of the village, wind resource, solar resource and the climate data of the village.

Chapter 3 has been devoted to explaining the main components used in the hybrid system. It describes the relevant characteristics of the system components such as electrical characteristics, costs, operation and maintenance issues. Next, modeling of the hybrid system in HOMER software is described in the Chapter 4.

The results obtained from the HOMER simulations are discussed in the Chapter 5. The results of the optimization and sensitivity analysis, the selection of the optimal hybrid configuration and the performance of the selected system for varying conditions of load, solar and wind resource have been discussed there. It has also provides a basic design of the hybrid system.

Finally, the Chapter 6 gives the discussion and Chapter 7 states the conclusions and the future scope of the work.

Chapter 2

Data Collection

Hybrid system design and optimization requires evaluation of load profile of the village and the renewable resources in the region. In this chapter we are going to discuss about the estimation of village load profile and the assessment of renewable resources, solar and wind at the site. The chapter discusses about the optimal placement of PV arrays, calculation of solar radiation on a tilted PV panel using horizontal radiation data and the derivation of the wind distribution and the wind power density curves as well.

2.1. Introduction

One of the villages from the Siyambalanduwa Divisional Secretariat in Monaragala District, Sri Lanka is selected for studying a renewable hybrid energy system for supplying electricity. The map of the Siyambalanduwa DS is given in Figure 2.1. As stated in the problem statement, Siyambalanduwa DS consists of 48 villages with a total population of 55200 which accounts 13600 households. From these total households, 5700 families do not have access to the electricity [22].

According to the publication of the Department of Census and Statistics in Sri Lanka Siyambalanduwa DS is the one of the poorest DS in Sri Lanka. The income of the people living there is mainly derived from paddy cultivation. Unavailability of basic facilities and the low income level have badly affected on the living standards and the education of the children in Siyambalanduwa. Therefore in order to improve the living standards, health, education and local economy of the people in the rural villages of Siyambalanduwa, it is very important to provide basic facilities including electricity for them.

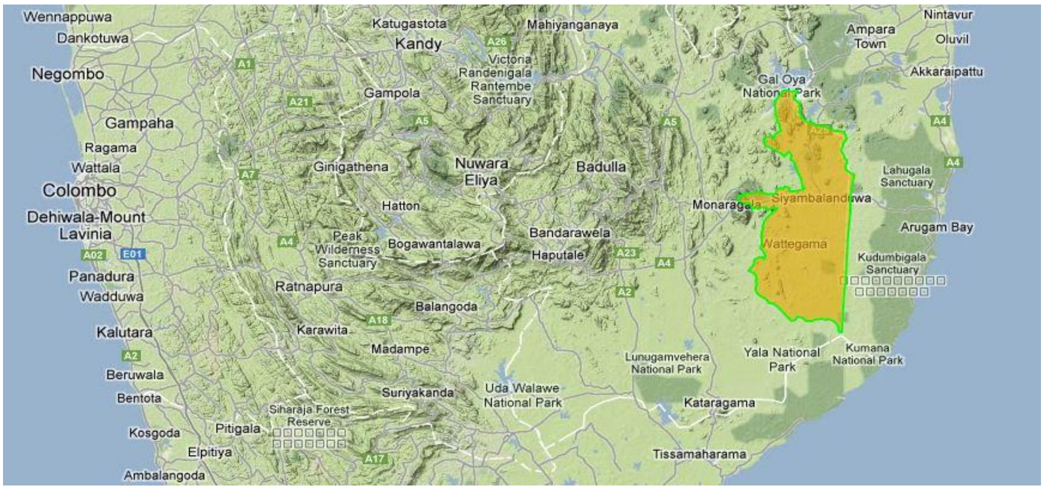


Figure 2.1 : Map of the Siyambalanduwa Divisional Secretariat (http://www.citypopulation.de/php/srilanka-admin.php?adm2id=8212)

In this research, a village located at 6.76^0 N latitude and 81.54^0 E longitude has been selected for studying the hybrid system. The geography of the selected site is shown in Figure 2.2 and 2.3. As shown in Figure 2.3, the electrical loads are scattered all over the village and most of the area in the village is covered by paddy fields.

Figure 2.2 : Geography of the selected site (maps.google.com)

Figure 2.3 : Closer view of the village (maps.google.com)

In order to model a hybrid renewable energy system for supplying electricity, firstly it is required to discover the potential of renewable energy resources in the selected area and the demand for the electricity of the selected community.

2.2. Village Load Profile

The proposed hybrid system is for supplying the electricity for a village consisting of about 150 households. In order to derive the load profile of the village which has had no electricity before, it is required to understand the living conditions of the people in the village. Basically the income of a family mainly affects on the load profile of a house. Other than income, the factors such as lifestyle of the people, willingness of buying electrical appliances and the size of the house will also affect on the load profile of a family. The village load is primarily determined by the number of houses in the village and the type of public utilities and commercial buildings available in the village. In addition, new commercial places that can emerge in the future if electricity is available also should be taken into account when deriving the load profile. A survey in the village will be required to conduct for collecting all these data. Since real surveyed data is not available, the load profile of the village has been derived based on the following assumptions and referring the load profiles available on the internet for different rural area electrification projects implemented in developing countries [18], [23], [24]. Usually the electricity demand in rural areas is not high as it in urban areas.

- The village consists of 10 rich families, 50 medium income families and 90 low income families. This assumption has been made because the most percentage of the people living in Siyambalanduwa are poor people.
- The village consists of a community center, temple, pre-school, primary school, 3 shops, street lights and two rice mills which consume daily electrical energy of about 60 kWh.
- Wealthy family uses electrical appliances mainly bulbs, color television, cassette, DVD player, fans, refrigerator, water heater, water pump, computer and an iron. Usually electricity is not used for cooking in rural villages in Sri Lanka. Instead they use firewood, because it is widely available and no cost. The daily energy consumption of this type is assumed as 4 kWh.
- Medium income families use electrical appliance basically bulbs, radio, television, fans, water heater and an iron. The medium income family's daily energy consumption is assumed as 2 kWh.
- The daily energy consumption of low income families would be very low. They will use electricity for fulfilling the basic requirements such as lighting, communication (radio and television) and maybe for ironing clothes and sometimes for water heating. Families in this category have very small houses as shown in Figure 1.2, therefore their lighting load also would be very small. Thus the daily energy consumption for low income families is assumed as 0.8 kWh.
- Since the village does not contain many public utilities and commercial industries that create a larger demand during the daytime, the load profile of the village will have a low early morning peak and a high night peak with the flat daytime load which is lower than the early morning peak.

Based on these assumptions a typical load curve for this village has been derived and it is given in Figure 2.4. According to the derived load profile, the maximum demand of the village is around 25 kW and daily energy consumption is around 270 kWh.

The monthly mean temperature of this area, which is given in Table 2.1 ranges from 25.6 ^{0}C to 27.1 ^{0}C throughout the year. Day and night temperature may vary by 3 ^{0}C to 5 ^{0}C. Thus this area is not affected by seasonal variations. Also the day length in Sri Lanka does not vary significantly throughout the year due to its geographical location near the equator. So there would not be significant changes in the load curve throughout the year. Therefore a constant daily load profile has been assumed for the entire year.

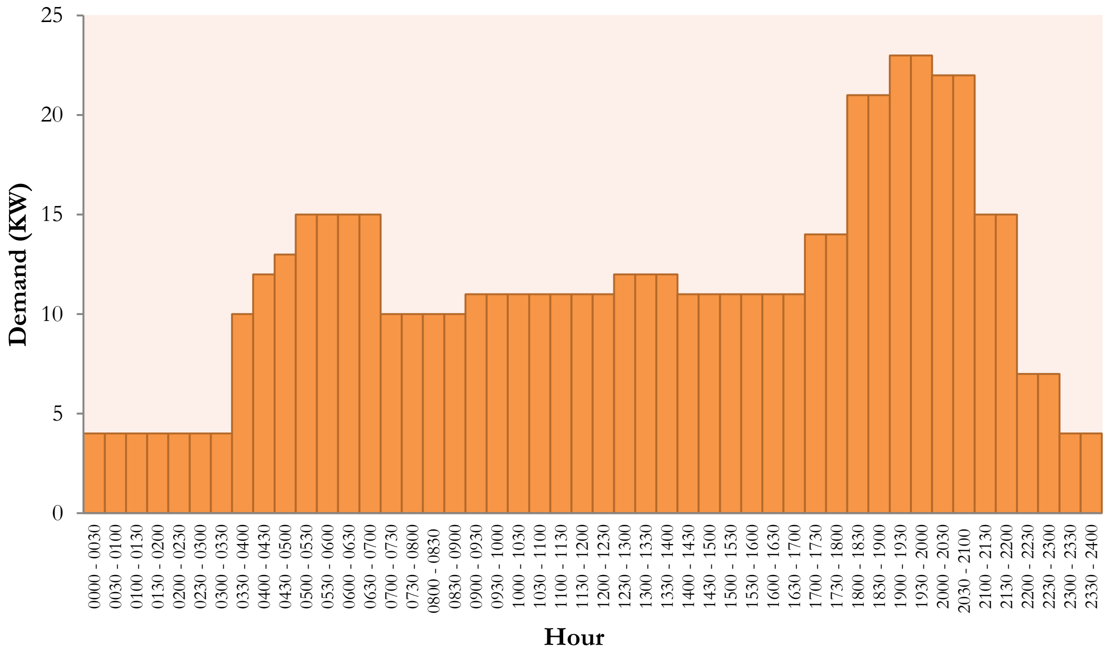


Figure 2.4 : Load profile of the village

Table 2.1 : Climate data in Siyambalanduwa region [25]

Month	Air temperature ^0C	Relative humidity %	Atmospheric pressure kPa	Earth temperature ^0C
January	25.6	77.1	99.8	26.5
February	25.7	76.0	99.8	27.1
March	26.3	75.0	99.7	28.3
April	26.7	80.0	99.6	28.8
May	27.1	80.2	99.5	28.2
June	26.8	77.5	99.5	27.7
July	26.6	76.7	99.5	27.5
August	26.5	76.7	99.6	27.3
September	26.4	77.9	99.7	27.5
October	26.2	79.7	99.7	27.6
November	26.0	80.7	99.7	27.4
December	25.9	78.6	99.8	26.7
Annual	**26.3**	**78.0**	**99.7**	**27.6**

2.3. Solar Resource

2.3.1. Annual Solar Radiation Variation

Sri Lanka is an island located closer to the equator, therefore it receives an abundant supply of solar radiation throughout the year. Solar radiation over the island does not show a notable seasonal variation but significant variation could be observed between the lowland and mountain regions in the country. As estimated in the solar resource map developed by the National Renewable Energy Laboratory in the USA, most part of the flat dry zone in the country receives 4 – 4.5 kWh/m²/day solar radiation and the hilly areas get solar radiation in the range of 2 – 3.5 kWh/m²/day. Thus a substantial potential exists in the dry zone of Sri Lanka for harnessing solar energy. Figure 2.5 shows annual average daily radiation sum in kWh/m²/day for Sri Lanka in 2003.

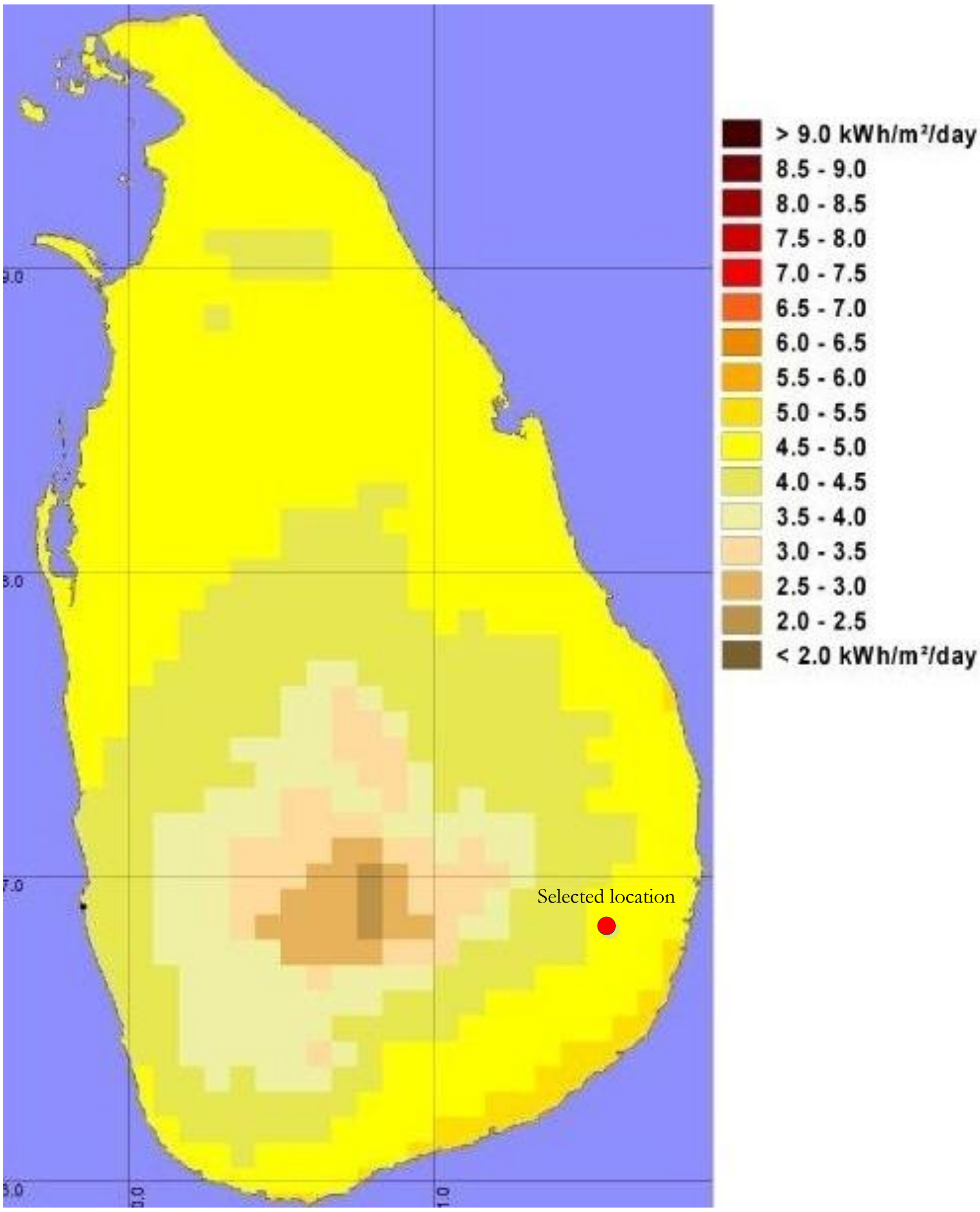


Figure 2.5 : Annual average daily total sum of global horizontal radiation in kWh/m²/day for Sri Lanka [26]

The selected site which is marked in Figure 2.5 is located at a latitude of 6.8⁰ N, longitude of 81.5⁰ E and altitudes of 85m. From Figure 2.5 it can be seen that the annual average daily total sum of global radiation at the site is relatively high. Therefore using solar PV for off grid hybrid energy system would be a better choice. However a detail analysis must be done in order to decide whether Solar PV is suitable or not and if it is suitable then what is the capacity of the PV system. For that annual solar radiation data on the site is required.

Due to the unavailability of ground measurement data of solar radiation at the selected location, data have been obtained from the NASA renewable energy resource website. Daily average insolation data on a horizontal surface obtained from the NASA database are plotted in Figure 2.6 throughout a year starting from 1st of January to 31st of December. Further, Table 2.2 tabulates monthly averaged insolation incident on a horizontal surface and the clearness index. The clearness index is a measure of the clearness of the atmosphere (i.e. the fraction of the solar radiation that is transmitted through the atmosphere to the earth's surface).

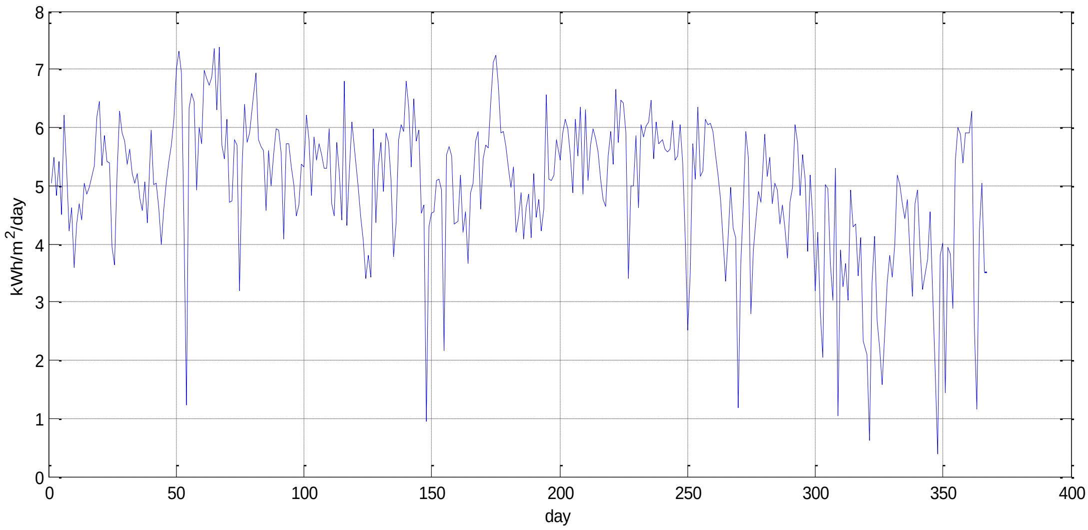


Figure 2.6 : Daily average insolation incident on a horizontal surface throughout a year [25]

Table 2.2 : Monthly average insolation incident on a horizontal surface [25]

Month	Monthly averaged global radiation (KWh/m²/day)	Clearness index
January	4.50	0.485
February	5.37	0.545
March	5.84	0.564
April	5.45	0.521
May	5.28	0.517
June	5.08	0.508
July	5.08	0.505
August	5.35	0.520
September	5.30	0.513
October	4.87	0.489
November	4.26	0.454
December	4.19	0.462
Annual average	**5.04**	**0.508**

According to solar radiation data, it can be seen that the average solar radiation in Siyambalanduwa is relatively high. This would give a relatively good possibility and opportunity to employ the photovoltaic technology as a component of the hybrid renewable energy system.

2.3.2. Optimal Placement of Solar Arrays

In order to capture the maximum amount of energy from the sun, solar panels should be placed pointing towards the sun. But the position of the sun in the sky varies over the day and also over the year. Therefore two axis solar tracker can be used to follow both of these sun's movements. Generally the costs of these two axis trackers are relatively high. Hence, they are not widely used in commercial applications. In most the applications, the panels are mounted with a fixed slope. Fixed slope solar collectors normally face towards the equator and the tilt angle is set to an angle which is equal to the geographical latitude of the collector location on the earth. This angle is a good approximation for the optimal angle to maximize the annual performance of the collector. By adjusting the tilt angle monthly or seasonally much more energy can be extracted than in the case of fixed tilt throughout the year. The adjustment of the angle depends on the geographical latitude and the declination angle.

The declination angle (δ) is the angle between the sun's direction and the equatorial plane. It varies from 23.45^0 to -23.45^0 within a year. The declination angle of a particular day in a year can be found using the following formula with an accuracy of 0.5^0. [27]

$$\delta = 23.45 \sin\left(\frac{360(284+n)}{365}\right) \qquad (2.1)$$

Where, n is the day in the year.

Annual variation of the solar declination angle is plotted in Figure 2.7 where angles measured in the counter-clockwise direction are positive and the clockwise measurements are negative.

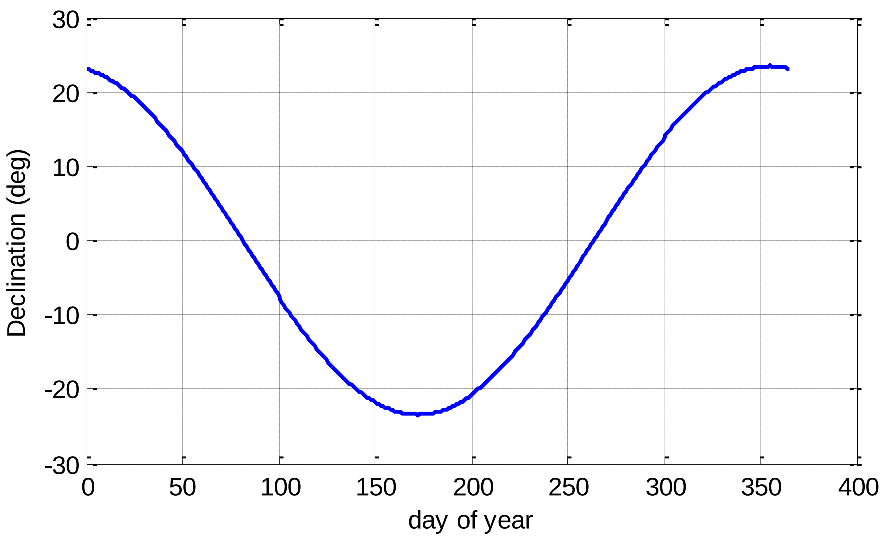


Figure 2.7 : Annual variation of the solar declination

Optimal tilt angle

Facing direction and the optimum tilt angle of a collector is dependent on the latitude (φ) and the declination angle (δ). The optimal tilt angle of a solar collector placed at a latitude of φ in the northern hemisphere is $\varphi + \delta$ and it is $|\varphi| - \delta$ for collectors placed in the southern hemisphere. The facing direction changes as follows.

- If $|\varphi| > \delta$, then collectors placed in northern hemisphere must face south and collectors placed in southern hemisphere must face north.
- A collector placed in the northern hemisphere (φ positive), if $|\delta| > \phi$ for negative δ then collector must face north.
- A collector placed in the southern hemisphere (φ negative), if $\delta > |\varphi|$ for positive δ then the collector must face south.

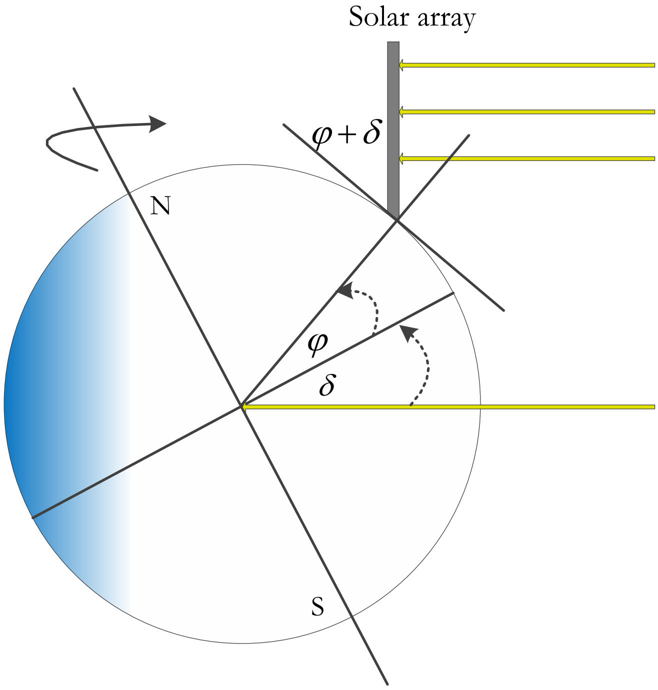


Figure 2.8 : Optimal tilt angle of a solar collector

According to these conditions the monthly optimal tilt angle variation of the site located at the latitude of 6.8^0 in Sri Lanka is given in Table 2.3. According to the data in Table 2.3 it can be seen that the collectors should be facing south during some months and north during other months. Therefore a high cost is involved in designing a monthly tilt angle adjustment system. Thus, I have decided to consider a PV system with a fixed tilt angle. For this location, the optimal tilt angle for a fixed tilt south facing collector is 6.8^0.

Table 2.3 : Monthly variation of optimal tilt angle

Month	Array tilt (deg)	Array points to
January	27	South
February	18	South
March	7	South
April	5	North
May	13	North
June	16	North
July	13	North
August	5	North
September	7	South
October	19	South
November	27	South
December	30	South

2.3.3. Solar Radiation Incident on a Tilted PV Array

Solar radiation data are generally available in terms of global horizontal radiation. But, usually in PV applications PV panels are not placed in horizontal. Therefore in order to find the power output from PV panels it is required to transform this global horizontal radiation data into solar radiation on tilted surfaces. The followings discuss the method of calculating the solar radiation on a tilted PV array using global horizontal radiation data.

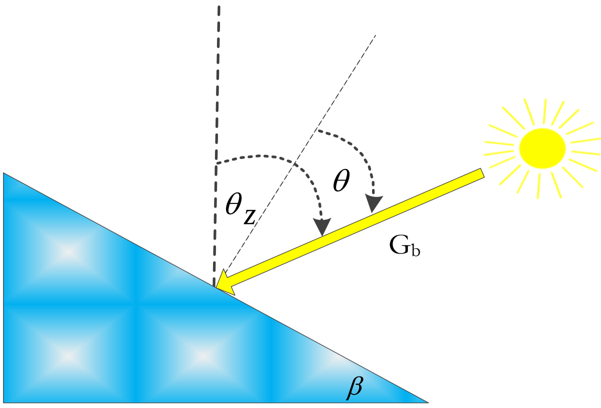


Figure 2.9 : Solar radiation on a tilted PV panel

In Figure 2.9, θ is the angle of incidence of a direct solar radiation on a tilted surface and it can be calculated using the following formula [27].

$$\begin{aligned}\cos\theta &= \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma + \cos\delta\cos\varphi\cos\beta\cos\omega \\ &+ \cos\delta\cos\varphi\cos\beta\cos\omega + \cos\delta\sin\varphi\cos\gamma\cos\omega + \cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \quad (2.2)$$

Where; β, φ and δ are the slope of the panel, latitude and the declination angle respectively. The parameter γ is the surface azimuth angle of the PV panel, which is the deviation of the projection on a plane of the normal to the surface from the local meridian. The other parameter ω is the hour angle. Hour angle is the angular displacement of the sun to the east or west from the local meridian due to rotation of the earth on its axis at 15^0 per hour.

The amount of solar radiation arriving at the top of the atmosphere is known as extraterrestrial radiation and it can be calculated using the equation;

$$G_{on} = G_{sc}\left(1 + 0.033 \cos\frac{360n}{365}\right) \tag{2.3}$$

Where ;

G_{on}	is the extraterrestrial normal radiation (kW/m^2)
G_{sc}	is the solar constant (1.367 kW/m^2)
n	is the day of the year

Using the extraterrestrial normal radiation, we can calculate the extraterrestrial horizontal radiation as follows.

$$G_o = G_{on}\ \cos\theta_z \tag{2.4}$$

Where, θ_z is the zenith angle and it is the angle between the vertical and the line of the sun or in other words angle of incidence of beam radiation on a horizontal surface, because a horizontal surface has a slope of zero, we can find an equation for the zenith angle by setting β = 0° in equation 2.2, which yields:

$$\cos\theta_z = \cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta \tag{2.5}$$

Integration of the equation 2.4 over a time period of one hour gives hourly average extraterrestrial horizontal radiation. That is; [28]

$$\overline{G_o} = \frac{12}{\pi}G_{on}\left[\cos\varphi\cos\delta\,(\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180^0}\sin\varphi\sin\delta\right] \tag{2.6}$$

Where ;

ω_1	is the hour angle at the beginning of the time step
ω_2	is the hour angle at the end of the time step

One of the other important parameter is the clearness index. The definition of the clearness index is, the fraction of global horizontal radiation on the earth's surface averaged over a time step to the extraterrestrial horizontal radiation averaged over a time step.

$$K_T = \frac{\overline{G}}{\overline{G_o}} \tag{2.7}$$

Where, $\overline{G}$ is the global horizontal radiation on the earth's surface averaged over a time step.

The total radiation on a horizontal surface consists of two components; direct radiation $(\overline{G}_b)$ and diffuse radiation $(\overline{G}_d)$.

$$\overline{G} = \overline{G}_b + \overline{G}_d \tag{2.8}$$

Direct radiation is the solar radiation received from the sun without having been scattered by the atmosphere while the diffuse radiation is the solar radiation received from the sun after its direction has been changed by scattering by the atmosphere. The diffuse radiation component can be found using the global horizontal radiation and the clearness index via the following relationships [28].

$$\frac{\overline{G}_d}{\overline{G}} = \begin{cases} 1.0 - 0.09K_T & \text{for } K_T \le 0.22 \\ 0.9511 - 0.1604K_T + 4.388K_T^2 - 16.638K_T^3 + 12.336K_T^4 & \text{for } 0.22 < K_T \le 0.80 \\ 0.165 & \text{for } K_T > 0.80 \end{cases} \tag{2.9}$$

The solar radiation striking the tilted surface of the PV array (G_T) consists of three components; direct radiation $(\overline{G}_{t,b})$, diffuse radiation $(\overline{G}_{t,d})$ and ground reflected radiation ($\overline{G}_{t,r}$). It can be calculated using the following formula [28].

$$\overline{G}_T = \overline{G}_{t,b} + \overline{G}_{t,d} + \overline{G}_{t,r} \tag{2.10}$$

$$\overline{G}_T = \overline{G}_b \frac{\cos\theta}{\cos\theta_z}\left(1 + \frac{\overline{G}_d}{\overline{G}_o}\right) + \overline{G}_d\left(1 - \frac{\overline{G}_b}{\overline{G}_o}\right)\left(\frac{1+\cos\beta}{2}\right)\left(1 + \sqrt{\frac{\overline{G}_b}{\overline{G}}}\sin^3\left(\frac{\beta}{2}\right)\right) + \overline{G}\rho_g\left(\frac{1-\cos\beta}{2}\right)$$

Where, ρ_g is the ground reflectance.

2.4. Wind Resource

2.4.1. Annual Wind Speed Variation

Sri Lanka is an island with substantial wind energy resources. Its wind climate is primarily determined by two Asian monsoons, the south west and northeast monsoons. The south west monsoon exists from May till early October while the northeast monsoon exists December to February. The south west is the stronger of the two monsoons and felt along the entire west coast of Sri Lanka as well as in interior areas and some mountain regions. While winds over mountain regions are highly site specific, turbulent and confined to the southwest monsoons, winds over flat landscapes in the southeastern and northwestern coastal belt are more consistent and occur during both monsoons[2]. Figure 2.10 gives the wind resource map for Sri Lanka and the wind power classification table. Wind resource areas of class 4 and higher are considered as suitable for utility scale wind power development. Rural or off grid applications require less wind resource for a

[2] www.windpower.lk

project to be viable. For these types of application, class 2 and higher resources may be sufficient for viable wind power development [29]. The site location marked on the map has marginal wind resources-class 2. Therefore wind turbines would be a better option for an off grid hybrid system.

Ground wind speed measurement data is not available for this site location. Hence the wind speed data have been obtained from the NASA renewable energy resource website. The data obtained from the NASA website is tabulated in Table 2.4.

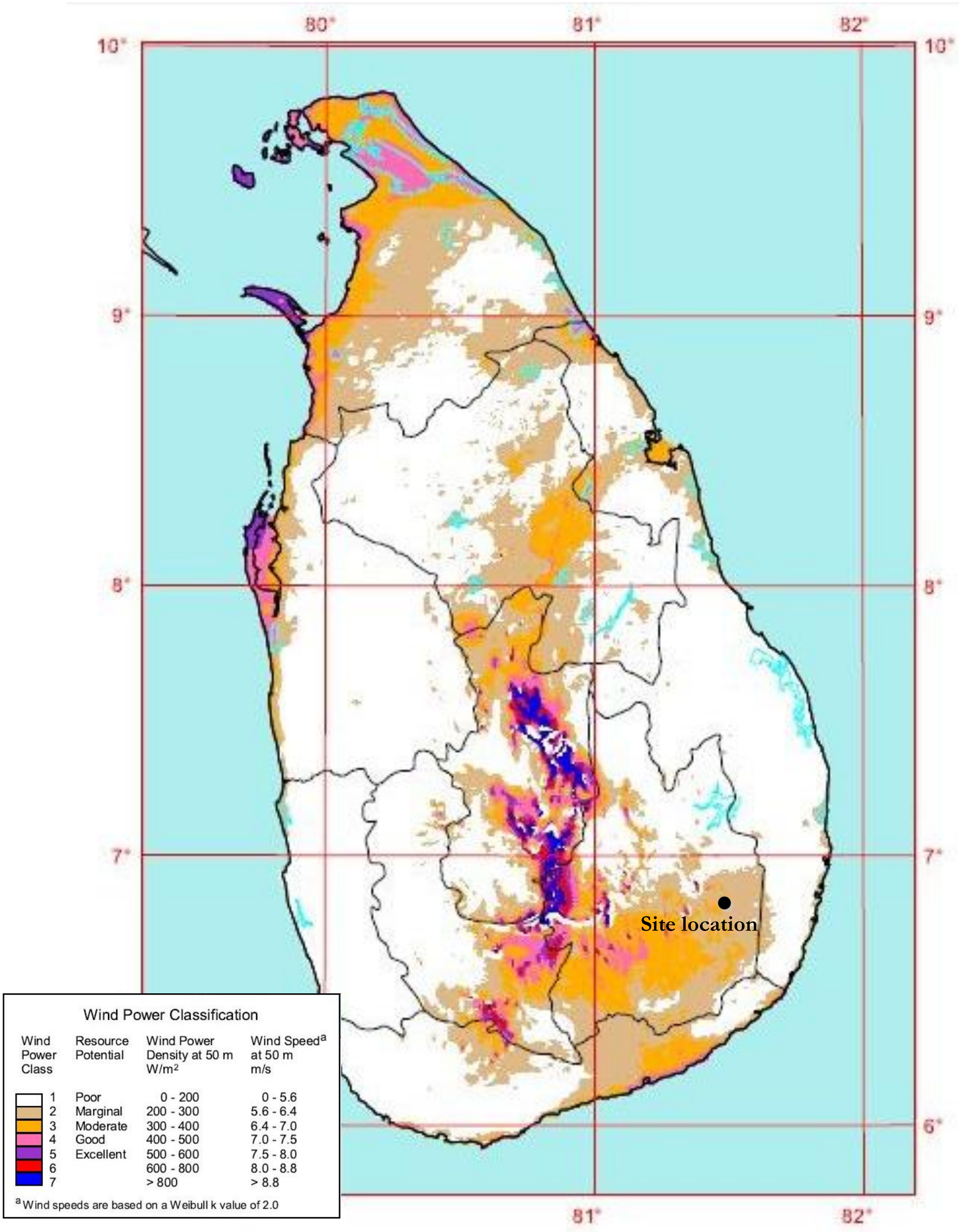


Figure 2.10 : Wind resource map of Sri Lanka [29]

Table 2.4 : Monthly average wind speed at 50m and 10m above the ground [25]

Month	Monthly Averaged Wind Speed (m/s) at 50m	Monthly Averaged Wind Speed (m/s) at 10m
January	6.50	5.6
February	5.17	4.4
March	3.94	3.4
April	3.95	3.4
May	7.15	6.1
June	8.84	7.6
July	7.82	6.7
August	8.32	7.1
September	7.41	6.3
October	5.71	4.9
November	4.66	4.0
December	5.66	4.8
Annual average	**6.27**	**5.4**

2.4.2. Wind Speed Variation with Height above Ground

From Table 2.4 it can be seen that the wind speed varies with the height above the ground. The effect of height on the wind speed is mainly due to the roughness of the earth's surface. This variation is described by the following equation [30].

$$u(h) = u(h_1)\,\frac{\ln\left(\frac{h}{z}\right)}{\ln\left(\frac{h_1}{z}\right)} \tag{2.11}$$

Where ;

h_1	Anemometer height
h	The height of the wind speed to be calculated
z	Surface roughness
$u(h)$	The wind speed to be calculated
$u(h_1)$	The wind speed at the anemometer height

Using equation 2.11, wind speed at any given height of the tower can be found if the surface roughness and wind measurements at different height are available. In this case we have wind speeds at two different height levels. Using these data we can calculate the surface roughness (z) of the site location. Since equation 2.11 is a nonlinear equation when solving for z, Matlab has been used to calculate the roughness value. The answer for z is 0.001.

Figure 2.11 plots the annual average wind speed variation with height above the ground at site in Siyambalanduwa.

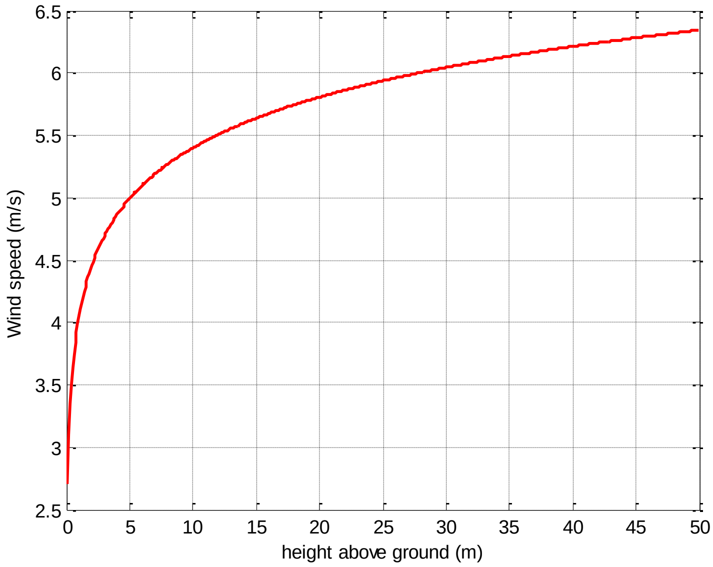


Figure 2.11 : Annual average wind speed variation with height at site in Siyambalanduwa

2.4.3. Wind Speed Distribution

The variation of wind speed at a particular site can be best described using the Weibull distribution function. Weibull distribution illustrates the probability of different mean wind speeds occurring at the site during a period of time. The probability density function is given by the following equation [31].

$$f(u) = \frac{k}{\lambda}\left(\frac{u}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{u}{\lambda}\right)^{k}\right) \tag{2.12}$$

Where ;

- u is the wind speed (m/s)
- k is the Weibull shape factor (unit less)
- λ is the Weibull scale parameter (m/s)

λ, the scale factor closely related to the mean wind speed and k is a measurement of the width of the distribution. The typical range of the Weibull k value is 1.5~2.5. The following equation relates two Weibull parameters and the average wind speed [31].

$$\bar{u} = \lambda\ \Gamma\left[\frac{1}{k}+1\right] \tag{2.13}$$

Where, Γ is the gamma function.

A Weibull distribution can be described by an average wind speed and Weibull k value. The graph below shows four Weibull distributions, all with the same average wind speed of 6 ms^{-1} but each with different Weibull k value. As the graph shows, lower k values correspond to broader distributions.

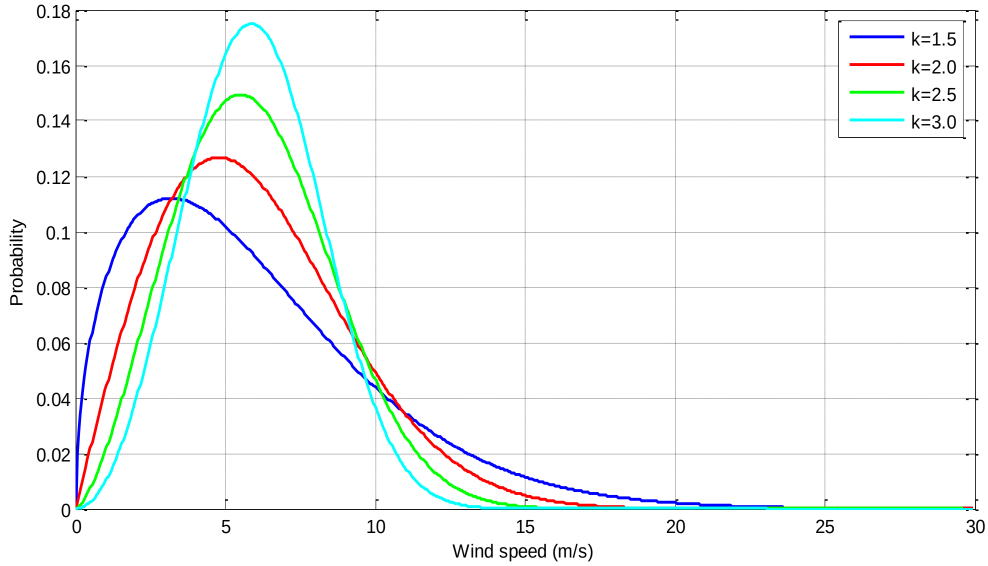


Figure 2.12 : Weibull probability distribution for different k values

The Weibull parameter k can be determined from the statistical analysis of measured wind data at the site. This requires a large set of data containing at least hourly wind speed averages to get an accurate result. In this work, I have only monthly average wind speeds containing 12 data points. This data set is not sufficient for finding a correct value for Weibull k. Thus I have selected the value of 2 for Weibull k,because 2 is most common for inland sites.

2.4.4. Wind Power Density at the Site

Wind power density provides an indication of a site's wind energy potential. It expresses the average wind power over one square meter (W/m^2). The power density is proportional to the cube of the wind speed and can be expressed as,

$$WPD = \frac{1}{2} \rho u^3 \tag{2.14}$$

Where ;

WPD	is the wind power density (W/m^2)
ρ	is the air density (kg/m^3)
u	is undisturbed wind speed (m/s)

The density of the air can be calculated using the following formula.

$$\rho = \frac{P}{RT} \tag{2.15}$$

Where ;

P	is the air pressure (N/m^2)
R	is the specific gas constant (287 Jkg^{-1}K^{-1})
T	is the temperature (K)

Expression 2.14 for wind power potential is a simplification under the assumption that the wind blows with speed u all the time. But wind speed is not constant over the time. To get an accurate estimate for the wind power density the average of the summation of wind speed data measured over time should be calculated as in the following formula.

$$WPD = \frac{1}{2n} \sum_{j=1}^{n} \rho_j \, u_j^3 \tag{2.16}$$

Where, n is the number of wind speed readings and ρ_j, u_j are the jth readings of the air density and wind speed.

Alternatively, if the wind speed frequency distribution of the site is known then the following equation can be used to calculate the wind power density.

$$WPD = \frac{1}{2} \sum_{j=1}^{n} \rho_j \, u_j^3 \, f(u_j) \tag{2.17}$$

Where, $f(u_j)$ is the frequency of occurrence of wind speed u_j during the selected time span. Using the Weibull distribution to describe the probability of different wind speeds occurring at the site, equation 2.17 can be modified as;

$$WPD = \frac{1}{2} \sum_{j=1}^{n} \rho_j \, u_j^3 \, \frac{k}{\lambda} \left(\frac{u_j}{\lambda} \right)^{k-1} \exp\left(-\left(\frac{u_j}{\lambda} \right)^{k} \right) \tag{2.18}$$

The Root Mean Cube (RMC) wind speed (V_{rmc}) is an another well known parameter using for describing the wind potential of the site. It is calculated using the following formula.

$$V_{rmc} = \sqrt[3]{\sum_{i=1}^{n} f(u_j) \, u_j^3} \tag{2.19}$$

Root Mean Cube wind speed can be used to quickly estimate the wind power density of the site by the following equation.

$$WPD = \frac{1}{2} \rho V_{rmc}^3 \tag{2.20}$$

Root Mean Cube Wind speed and the Wind Power Density variation with height

As discussed in Section 2.4.2 the wind speed varies with height. Therefore RMC wind speed and the wind power density also vary with the height above the ground. If the annual average wind speed at the site is known for a certain height (h_1), then the annual average wind speed at any height can be found using the equation 2.11 and from the equation 2.13 the relevant lemda (λ) value for each average wind speed can be calculated. By substituting calculated λ values for different heights, the RMC wind speed and the wind power density variation curve with the height can be obtained.

The annual average wind speed of the selected site, at a height of 10 m above the ground is 5.4 m/s, the surface roughness is 0.001 and k has been considered as 2. Using these data, RMC wind speed and the power density variation curve with the height above the ground has been derived for the selected site. The resulting graphs are given in Figure 2.13 and 2.14.

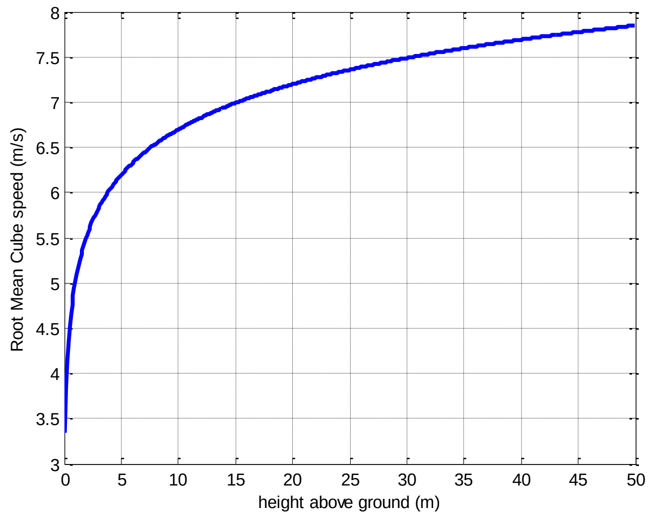


Figure 2.13 : Variation of the root mean cube wind speed with height at site in Siyambalanduwa

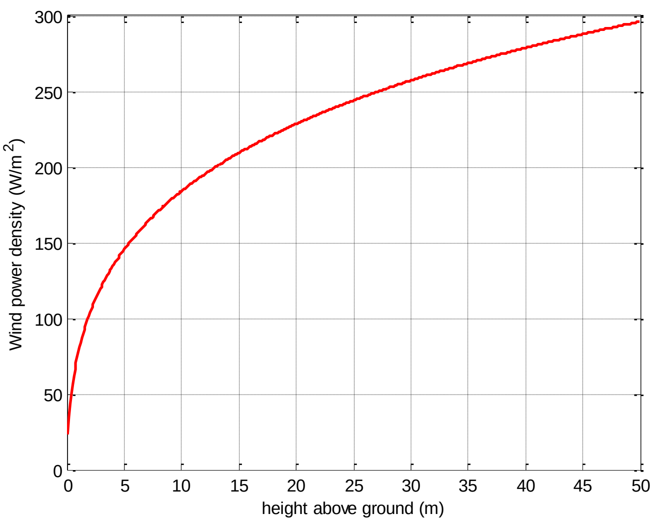


Figure 2.14 : Variation of wind power density with height at site in Siyambalanduwa

Chapter 3

Hybrid System Components

In this chapter we will discuss the characteristics, operation, maintenance and the relevant costs of the hybrid system components. At the beginning, chapter discusses the basic technological configurations of hybrid systems. Then it explains the characteristics of the components; wind turbine, PV panel, diesel generator, battery bank and the inverters. These are the primary components used in the hybrid system studied here.

3.1. Introduction

Hybrid energy systems generate AC electricity by combining renewable energy systems with an inverter, which can operate alternatively or in parallel with a conventional engine driven generator. As understood in the Chapter 2, the potential of solar and wind resources are relatively high in Siyambaladuwa region, thus they can be used for developing a renewable energy based electricity supply system for Siyambalanduwa. In addition to these resources a diesel generator and a battery bank have been selected for the hybrid system. According to the type of voltage and the type of bus that will link the different component together, hybrid systems can be classified as follows [32].

- DC coupled Hybrid system
- DC/AC coupled hybrid system
- AC coupled hybrid system

DC coupled hybrid system

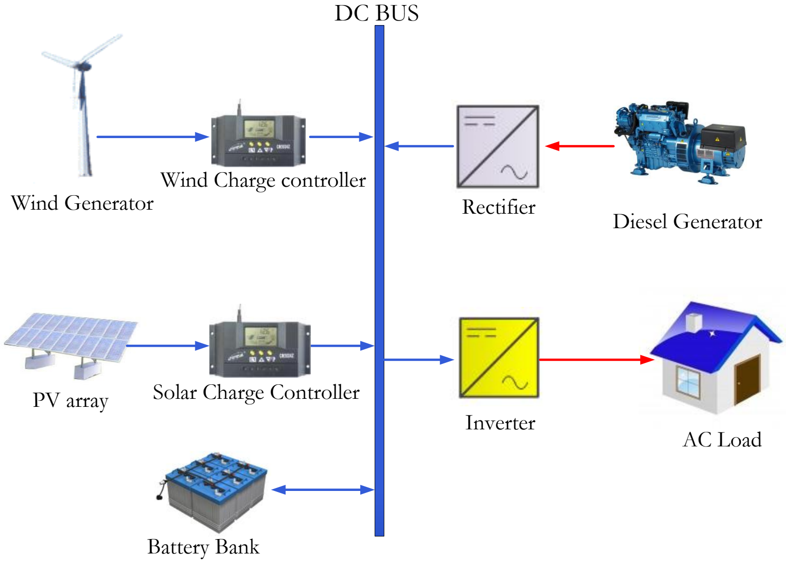


Figure 3.1 : DC coupled Hybrid system

Figure 3.1 illustrates a DC coupled hybrid system. In this configuration all electricity generating components are connected to the DC bus. Therefore DC generating systems are equipped with charging controllers and AC generating systems with rectifiers. In this configuration the power generated by the diesel generator is first rectified and then converted back to AC which reduces the efficiency of energy conversion due to several power processing stages. In addition the inverter cannot be operated in parallel with the diesel generator. Therefore inverter must be sized to supply the peak demand. Also inverter failure causes power interruption, unless the load can be supplied directly from the diesel generator for emergency conditions.

DC/AC coupled hybrid system

In DC/AC coupled hybrid system, electricity generating components can be connected to either DC or AC bus depending on their generating voltage. This system uses a bidirectional inverter to link the DC bus and the AC bus. In this configuration the inverter can be operated in parallel with the diesel generator, hence inverter may not be sized to meet the peak demand. The capability to operate the inverter in parallel with the diesel generator allows generator flexibility to optimize the operation of the system. Also the efficiency of the generator can be maximized.

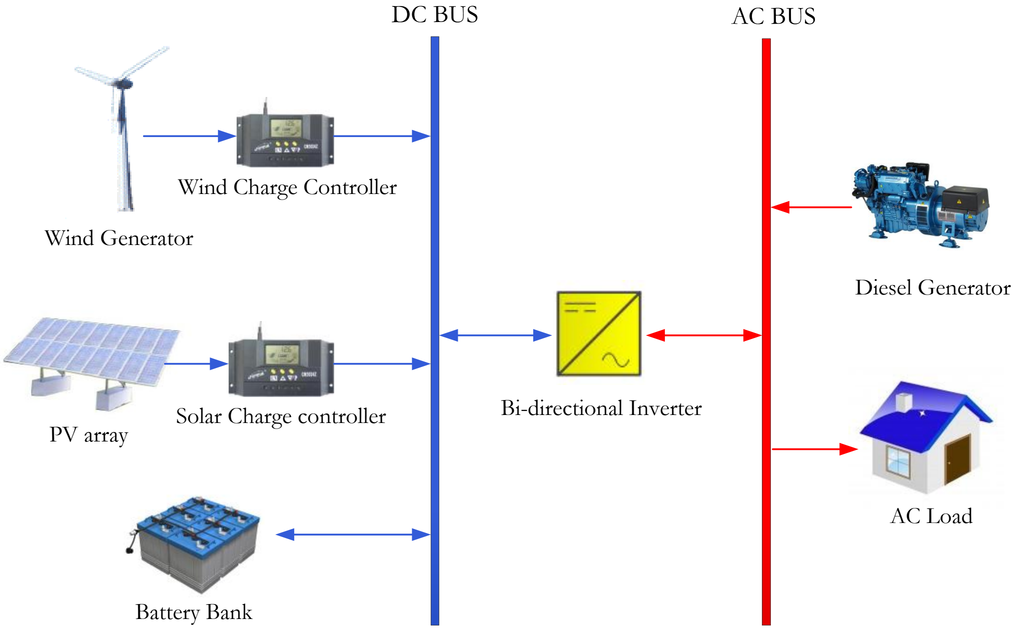


Figure 3.2 : DC/AC coupled hybrid system

AC coupled Hybrid system

In an AC coupled hybrid system, all electricity generating systems are connected to the AC bus. The DC generating systems are connected to the AC bus via inverters and AC generating components can be directly connected to the AC bus or may need an AC/AC converter to enable stable coupling. In this system the energy supply for the battery bank is controlled by a bidirectional inverter. AC coupled systems are easily expandable and also provides the benefits discussed in DC/AC coupling hybrid system. Also this system is easy to connect the grid if the grid extends to the remote area in the future. Therefore, most of the hybrid systems are using AC coupled hybrid configuration.

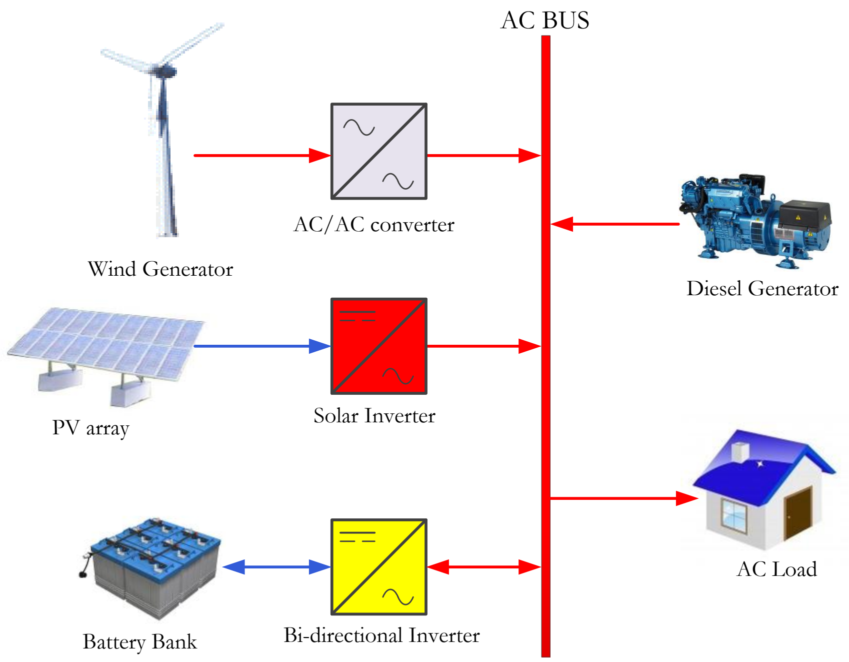


Figure 3.3 : AC coupled hybrid system

In this study I have selected the AC coupled hybrid configuration, because in addition to the advantages discussed above, it provides higher flexibility in selecting DC bus bar voltage, therefore the components in the hybrid system as well. But in a DC coupled system, DC bus bar voltage is determined by several components. In this system they are PV array, wind turbine, battery bank and the bi-directional inverter. The DC side voltage range of these components must be the same which determines the DC bus voltage. Therefore we have limited flexibility on selecting components for this system configuration in the market. Also in AC coupling, generating sources can be connected to almost any point in the network. In addition, this system has the advantage of easy connection to the grid without additional costs, if the grid may be extend to the selected area in the future.

According to the AC coupled hybrid system, the main components required in this study are; wind turbines, PV panels, batteries, diesel generator and inverters. For this system it is required 3 inverters which are basically a solar inverter, a wind inverter and a bidirectional battery inverter. The following sections discuss each of this component's functionalities, specifications and costs.

3.2. Wind Turbine

A wind turbine is a machine which converts the power in the wind into electricity. The generation capacity of modern wind turbines ranges from a few watts to megawatts (2MW). The larger wind turbines are typically used in utility scale applications and smaller wind turbines are used in residential and commercial applications either as grid connected or off grid. A typical wind turbine consists of following subsystems.

- The rotor and the supporting hub
- The drive train; Shaft, gear box, coupling, a mechanical brake and generator
- Nacelle and main frame including wind turbine housing, bed plate and yaw system.
- The tower and the foundation
- The main controls
- The balance of the electrical system including cables, switch gear and possible electronic power converters.

In modern wind turbines, the conversion process uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting first in the production of mechanical power and then in its transformation into electricity in a generator. The wind turbine can produce energy in response to the wind that is immediately available. The output of a wind turbine is thus inherently fluctuating and non-dispatchable [33].

Selection of a wind turbine for a certain application depends on several factors, such as; size, wind resource, availability, reliability, warranty, spare parts availability, proximity of operation and maintenance and transportation. In rural off grid applications, transportation of wind turbine components is the main difficulty arising when selecting high rating wind turbines, because higher rating wind turbines have blades with longer length which cannot be transported using conventional transportation facilities in rural areas. Therefore small wind turbines are preferred in most of the rural applications.

In this study, I have selected the Anhui Hummer H8.0-10 kW wind turbine. The specifications of this wind turbine are as follows.

Rated power	10 kW
Maximum output power	15 kW
Start up wind speed	3 ms^{-1}
Rated wind speed	10 ms^{-1}
Working wind speed	3 – 25 ms^{-1}
Generator efficiency	> 0.85
Generator type	Permanent Magnet Alternator
C_p	0.4
Blade diameter	8.0 m
Tower height	15 m

3.2.1. Wind Turbine Power Curve

As section 3.2 says, a wind turbine is a machine which converts the power in the wind into electricity. The conversion of wind energy to electrical energy involves primarily two stages. In the first stage, the kinetic energy in wind is converted into mechanical energy to drive the shaft of a wind generator. The power coefficient C_p deals with the conversion efficiency in the first stage. C_p is the ratio of actually captured mechanical power by blades to the available power in the wind [31].

$$C_p = \frac{P_{mech}}{P_{wind}} \tag{3.1}$$

There is a theoretical maximum limit for this power coefficient which is known as Betz limit. It has been found that no turbine can convert more than 16/27 (59.26 %) of the kinetic energy of wind into mechanical energy. Therefore the maximum power density available for converting to mechanical energy by a wind turbine located at the selected site location in Siyambalanduwa is limited to 59.26 % from the energy available in the wind. Figure 3.4 gives the variation of the Betz limit of the wind power density with the height above the ground at the site in Siyambalanduwa.

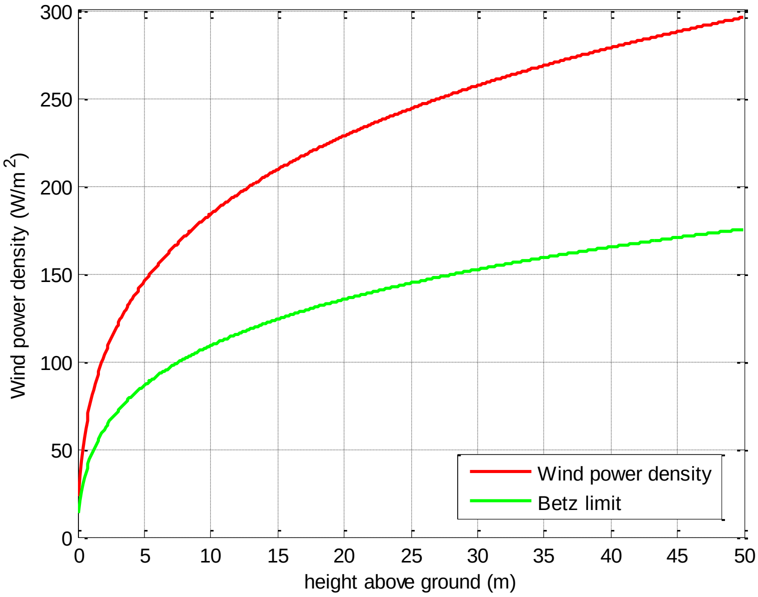


Figure 3.4 : Wind power density and Betz limit variation with height at site in Siyambalanduwa

The power in the wind coming to the turbine blades is proportional to the cube of the wind speed and can be expressed as,

$$P_{wind} = \frac{1}{2}\rho A u^3 \tag{3.2}$$

Where ;

- ρ is the air density (kg/m³)
- A is the area swept by the blades (m²)
- u is undisturbed wind speed (m/s)

In the second stage, mechanical energy captured by wind blades is converted into electrical energy via wind generators. At this stage, the conversion efficiency is determined by several parameters. They are;

- Gearbox efficiency - η_{gear}
- Generator efficiency - η_{gene}
- Electrical efficiency - η_{elec}

Therefore, the total power conversion efficiency of wind to electricity, η_t is the product of these parameters.

$$\eta_t = \eta_{gear}\, \eta_{gene}\, \eta_{elec} \tag{3.3}$$

Then the effective power output of the wind turbine is,

$$P_{eff} = \eta_t\, P_{wind} \tag{3.4}$$

The power curve of the wind turbine is derived from the equation 3.4. The power curve gives the power output of the wind turbine as a function of the mean wind speed. It is usually determined from laboratory measurements.

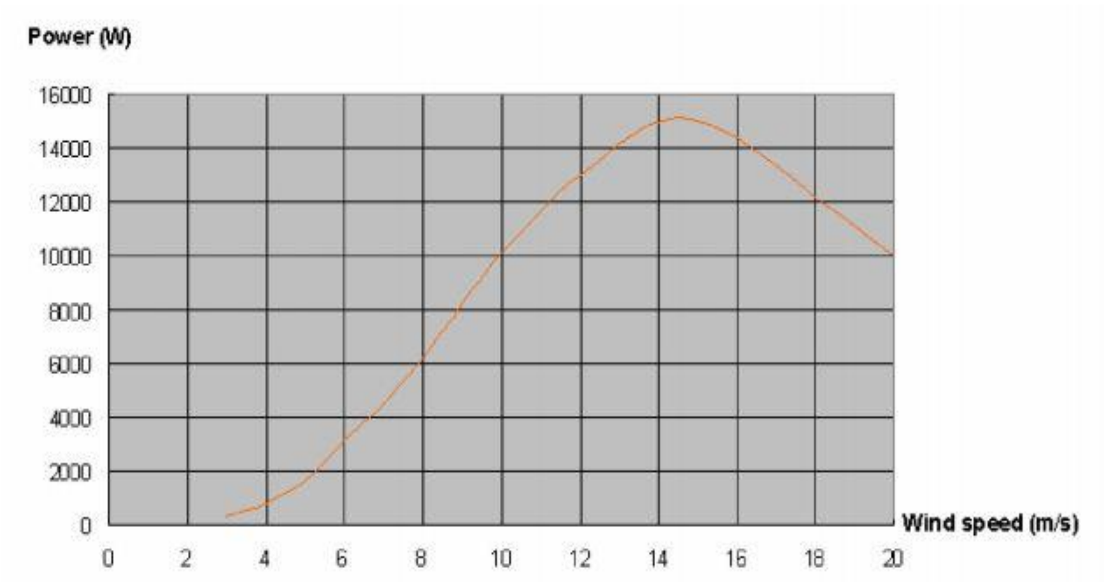


Figure 3.5 : The power curve of the Anhui Hummer H8.0-10KW wind turbine

The power curve of the Anhui Hummer H8.0-10KW wind turbine is given in Figure 3.5. As shown there, the wind turbine starts to produce usable power at a low wind speed, defined as the cut-in wind speed. For this turbine it is 3 ms^{-1}. The power output increases continuously with the increase in wind speed and reached to the rated power. The wind turbine delivers its rated power at the rated wind speed which is 10 ms^{-1} for this turbine. Beyond the rated wind speed, the output power of the turbine is determined by the control mechanism of the turbine. Theoretically it should be constant at its rated power. When the wind speed becomes too large the wind turbine need to be shut down immediately to avoid damaging the turbine. This wind speed is defined as the cut-off wind speed.

3.2.2. Wind Turbine Installation Cost

At present, the wind turbine prices in different countries are in the range of \$1100 to \$1400 per kW. According to the analysis of the different markets, there is quite a wide variation in wind turbine prices, depending on the cost structure of the local market. The reason for this wide variation include the impact of lower labor costs in some countries, local low cost manufactures, the degree of competition in a specific market, the nature and structure of support policies for wind, as well as site specific factors [34].

The selected wind turbine for this study is Hummer H8.0-10 kW and it has the following costs[3].

Generator	$ 8500
Siemens PLC	$ 900
Rectifier and dump controller	$ 700
Metal dump load	$ 800
10 kW wind inverter	$ 4000
15 m freestanding tower	$ 4100
12 m guy tower	$ 1610
16 m hydraulic tower	$ 7050

Hydraulic tower is the most expensive tower but installation and maintenance work is easy in this type because it does not require a crane to erect the tower.

The capital cost of a wind turbine includes turbine cost, shipment cost, imported taxes and duties, local transportation cost, turbine installation and cost for related civil works. An estimation for the shipment cost from China to Sri Lanka is $ 1000 [4] and local transportation cost is $ 250. In Sri Lanka, recently the government has removed the imported taxes and duty charges for renewable energy equipments for encouraging the renewable energy industry. Therefore there is no any imported levy for the wind turbines.

The wind turbine installation includes land acquisition, site preparation, assembling the turbine, laying the tower foundation, erecting the turbine and wiring. An estimated value for these tasks in Sri Lanka is aimed $ 4800. Then the capital cost for installing the wind turbine is approximately $ 25000 if 15 m free standing tower is selected.

3.2.3. Operation and Maintenance Cost

Small wind turbines require periodic maintenance such as lubrication, greasing and regular safety inspections. During the safety inspections, the bolts and electrical connections should be checked and tightened if necessary. Further, the machine should be checked for corrosion and the guy wires for proper tension. In addition, it is necessary to check for and replace any worn leading edge tape on the blades if appropriate. These actions must be taken once or twice a year. After about 10 years the blades and bearings may need to be replaced [35]. These maintenance work accounts significant Operation and Maintenance (O & M) cost over the lifetime of the turbine. According to the various sources on operating and maintenance of small wind turbines, the O & M cost lies in the range of 1.5 % to 3 % of the turbine cost in the early years after installation and increases with time as the turbine get older typically up to 5 %. The turbine considered in this study has a capital

[3] Email correspondence

[4] www.aliexpress.com

cost around $ 25000, therefore it's annual O & M cost would be in the range of $ 375 to $ 750. For the simulation it has been taken $ 500 as the annual O & M cost for 10 kW wind system installation.

3.3. PV Panels

The photovoltaic effect is the process of producing direct electrical current from the radiant energy of the sun using semiconductor cells. Semiconductor cells are basically large area p-n diodes and have a very small power output. The most common semiconductor material using for producing solar cells is the Silicon. Other than Silicon, Copper Indium Diselenide (CIS), Cadmium Telluride (CdTe) and Gallium Arsenide (GaAs) are used in the solar cell industry. The power output from a typical solar cell is about 1 W. Hence to generate the required amount of power a large number of cells are connected in series and parallel on a module.

3.3.1. Electrical Characteristics of PV Cells

The complex physics of a PV cell can be represented by the equivalent electrical circuit as shown in Figure 3.6. The corresponding I-V characteristic is described by the following equation [36].

$$I = I_{ph} - I_0 \left[\exp\left(\frac{V + IR_s}{K_B T / q} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \tag{3.5}$$

Where, I_{ph} is the photo current and it is related to the photon flux incident on the cell and dependent on the wavelength of the light. R_s is the series resistance and it represents the internal resistance to the current flow and depends on the p-n junction depth, impurities and contact resistance. R_{sh} is the shunt resistance and it is inversely related to the leakage current to the ground.

The other parameters;

- I_0 is the diode saturation current (A)
- K_B is the Boltzmann constant (1.38×10^{-23} m^2 kg s^{-2} K^{-1})
- T is the absolute temperature (K)
- I is the load current (A)
- V is the voltage at the terminals of the cell (V)
- q is the electronic charge (C)

A typical I-V characteristic and the power curve of a solar module is given in Figure 3.7. The basic two parameters that can be identified in this curve are the short circuit current (I_{sc}) and the open circuit voltage (V_{oc}). The open circuit voltage is the maximum voltage generated by the cell when no external load is connected to the cell and the short circuit current is the maximum current generated by the cell when the cell output is short circuited.

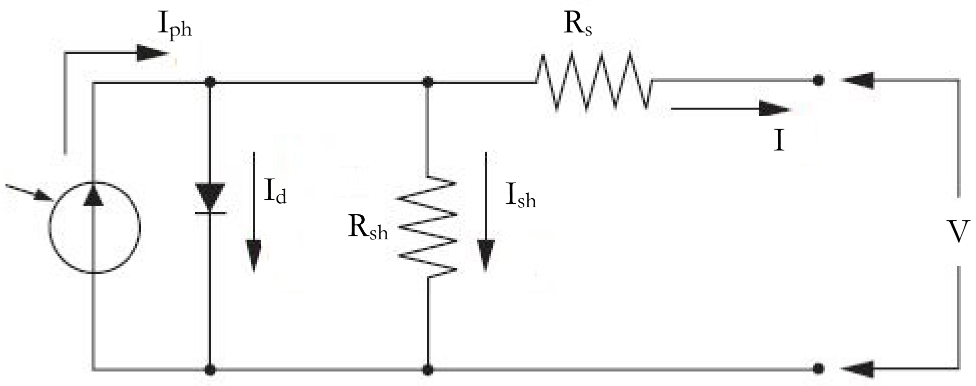


Figure 3.6 : Equivalent circuit of a PV module

In ideal case, small diode and the ground leakage current can be ignored in the equivalent electrical circuit, therefore the short circuit current I_{sc} equal to the photo generated current, hence the open circuit voltage is;

$$V_{oc} = \frac{K_B T}{q} \ln\left(1 + \frac{I_{ph}}{I_0}\right) \tag{3.6}$$

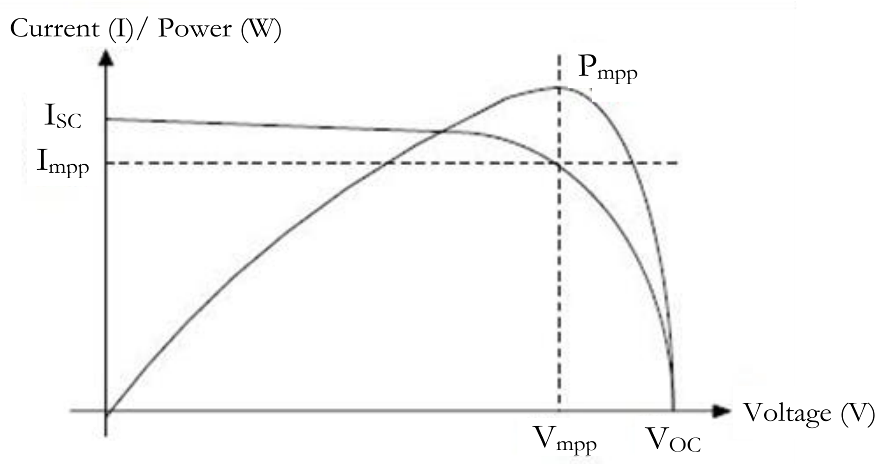


Figure 3.7 : Typical Current vs Voltage and Power characteristics of a solar cell

The power output of the cell is the product of the output voltage and the current. As can be seen in the Figure 3.7, the power output of the cell is zero at zero voltage and zero current. The module produces maximum power at a certain point which is known as Maximum Power Point (MPP). The respective voltage and current at this MPP are denoted as V_{mpp} and I_{mpp}. All these parameters are given in the manufacturer's data sheet of a solar module. An example for this is given in Table 3.1 which contains specifications of the Canadian Solar CS6P-240P solar module.

Table 3.1 : Manufacturer's specification of Canadian Solar CS6P-240P solar module (Under standard test conditions of irradiance 1000W/m^2, spectrum AM1.5 and cell temperature of 25 ^{0}C)

Nominal Maximum power (P_{mpp})	240 W
Optimum operating voltage (V_{mpp})	29.9 V
Optimum operating current (I_{mpp})	8.03 A
Open circuit voltage (V_{oc})	37.0 V
Short circuit current (I_{sc})	8.59 A
Module efficiency	14.92 %
Temperature coefficient at P_{mpp}	-0.43% $^0C^{-1}$
Nominal Operating Cell Temperature (NOCT)	45 ± 2^{0}C

Effect of solar irradiance and cell temperature on electrical characteristics

The power produced by a crystalline PV module is affected by two key parameters;

- Solar irradiance
- Cell temperature

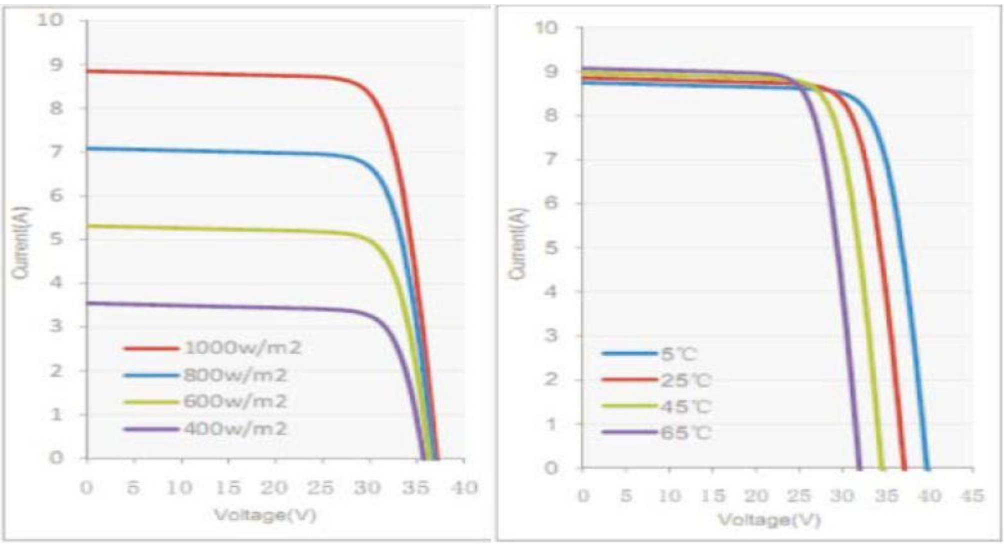


Figure 3.8 : Effect of solar irradiance and module temperature on the I–V curve of Canadian Solar CS6P-240P solar module

The effect of the solar irradiance and the module temperature on the I – V characteristic of the Canadian Solar CS6P-240P module is illustrated in Figure 3.8. As shown in the figure, the output current of the cell drops when the solar irradiance level decreases. Thus the output power also decreases but open circuit voltage does not change significantly. In contrast, the temperature increase in the module decreases the open circuit voltage but does not affect significantly on the short circuit current.

3.3.2. Operating Temperature of a PV Cell

The energy balance of the solar cell is used to calculate the operating temperature of the cell. The solar energy absorbed by the PV array is converted into electrical energy and heat energy which is transferred to the surroundings. This is given by the relationship [27];

$$\tau\,\alpha\,G_T = \eta_c\,G_T + U_L(T_c - T_a) \tag{3.7}$$

Where ;

- τ is the solar transmittance of the cover over the PV array (%)
- α is the solar absorptance of the PV array (%)
- G_T is the solar radiation striking the PV array (kW/m^2)
- η_c is the electrical conversion efficiency of the PV array (%)
- U_L is the coefficient of heat transfer to the surroundings (kW/m^2 ^{0}C)
- T_c is the PV cell temperature (^{0}C)
- T_a is the ambient temperature (^{0}C)

Solving 3.7 for T_c ;

$$T_c = T_a + G_T\left(\frac{\tau\alpha}{U_L}\right)\left(1 - \frac{\eta_c}{\tau\alpha}\right) \tag{3.8}$$

The term, $(\tau\alpha/U_L)$ in 3.8 is difficult to measure directly, but it can be found using the Nominal Operating Cell Temperature , which is usually mentioned in the manufacturer's data sheet. NOTC is the operating temperature of the cell at an incident irradiance of 0.8 kW/m^2 , an ambient temperature of 20 ^{0}C and no load operation ($\eta_c = 0$). Substituting these values into the equation 3.8; [28]

$$\frac{\tau\,\alpha}{U_L} = \frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOTC}} \tag{3.9}$$

Where ;

- $T_{c,NOCT}$ is the Nominal Operating Cell Temperature (^{0}C)
- $T_{a,NOCT}$ is the ambient temperature at which the NOTC is defined (20 ^{0}C)
- $G_{T,NOCT}$ is the solar radiation at which the NOCT is defined (0.8 kW/m^2)

If the solar panel is assumed to be operated at its maximum power point all the time then the electrical conversion efficiency of the PV module is the efficiency at MPP.

$$\eta_c = \eta_{mpp} \tag{3.10}$$

The efficiency at MPP changes as the cell temperature changes and the variation can be found by the following equation.

$$\eta_{mpp} = \eta_{mpp,STC}\ [1+\alpha_p (T_c - T_{c,STC})] \tag{3.11}$$

Where ;

$\eta_{mpp,STC}$ is the maximum power point efficiency under standard test conditions (%)

α_p is the temperature coefficient (%/^{0}C)

$T_{c,STC}$ is the cell temperature under standard test conditions (25^{0}C)

Substituting equations, 3.9, 3.10 and 3.11 into the equation 3.8, operating temperature of the cell at any irradiance can be found.

$$T_c = T_a + G_T \left(\frac{T_{c,NOCT} - T_{a,NOCT}}{G_{T,NOTC}} \right) \left(1 - \frac{\eta_{mpp,STC} \left[1+\alpha_p (T_c - T_{c,STC}) \right]}{\tau\,\alpha} \right)$$

$$T_c = \frac{T_a + \left(T_{c,NOCT} - T_{a,NOCT} \right) \left(\dfrac{G_T}{G_{T,NOCT}} \right) \left[1 - \dfrac{\eta_{mpp,STC}\ (1-\alpha_P\ T_{c,STC})}{\tau\,\alpha} \right]}{1 + \left(T_{c,NOTC} - T_{a,NOCT} \right) \left(\dfrac{G_T}{G_{T,NOCT}} \right) \left(\dfrac{\alpha_P\ \eta_{mpp,STC}}{\tau\,\alpha} \right)} \tag{3.12}$$

3.3.3. Power output of a PV Module

The power output of a PV module is a function of the solar irradiance and the cell temperature and can be calculated using the following formula where cell temperature can be found using 3.10. [28]

$$P_{PV} = Y_{PV}\ f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) \left[1+\alpha_P (T_c - T_{c,STC}) \right] \tag{3.13}$$

Where ;

Y_{PV} is the rated capacity of the PV module (kW)

f_{PV} is the PV derating factor (%)

$G_{T,STC}$ is the incident radiation at standard test condition (1 kW/m^2)

T_c is the PV cell temperature (^{0}C)

3.3.4. PV Cost

The cost of photovoltaic solar panels has been reduced drastically in the past years and is expected to continue for some time in the future. The great reduction observed in solar panel cost has been driven primarily by consecutive technological breakthroughs in the production of solar cells and the improvements in the manufacturing of solar panels. Current overall figures in recently updated prices range between $ 1700 - $ 2500 per kW of installed PV panels[5]. The following estimated costs have been considered for the analysis of the PV system in this work. The costs are given for a 10 kW fixed slope PV system.

- The price of the Canadian Solar CS6P-240P module in the Sri Lankan market is around $ 310. A 10 kW PV system requires 42 such modules having a worth of $ 13020 [6].
- The estimated cost for the solar ground mounting system with associated foundation work is $ 150 per module and therefore the cost for the 10 kW system is $ 6300 [6].
- The Local transportation cost of the PV modules and other equipments from Colombo to Siyambalanduwa is estimated as $ 300.
- The cost of a 10 kW solar inverter is around $ 3500 [7].
- The estimated installation cost including all wiring cost, combiner box cost, labor cost and other relevant cost is $ 5000.
- The land price of this selected area is very low and it is less than $ 150 per perch. If the cost is $ 150 per perch then the cost for the land is around $ 900.

The sum of the all the costs is around $ 29000 that is the estimated costs of a 10 kW solar PV system. Solar panels do not require any serious maintenance work as compared to other technologies incorporating moving parts. They require effective cleaning to increase the panel's efficiency, production rate and the panel's lifetime. Thus the operating and maintenance cost of a PV system is relatively small. In this analysis the annual operating and maintenance cost of a 10 kW PV system has been considered as $ 10.

Figure 3.9 : Solar PV ground mounted system

[5] www.renewablegreenenergypower.com/how-much-do-solar-panels-cost-2012-updated-prices/

[6] Email correspondence

[7] www.solarshop-europe.net/product_info.php?products_id=494

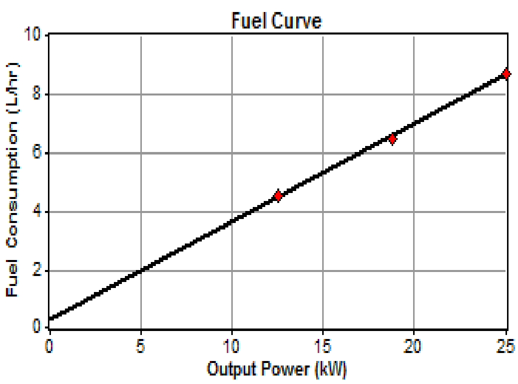
3.4. Diesel Generator

Diesel generators are important in renewable energy hybrid systems to improve the quality and the availability of the electricity supply. Since diesel generators are dispatchable they can be used to supply the load when the energy productions from the renewable sources are low or the state of the charge of the battery bank is not sufficient for supplying the load.

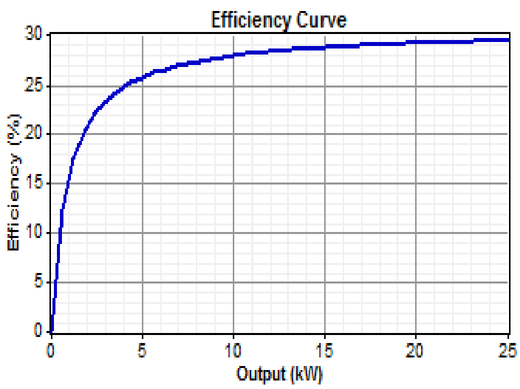
The initial investment for installing a diesel generator is relatively small when compared with the initial investment of the PV or wind energy system. However, the operating and maintenance cost of a diesel generator is relatively high as it requires a continuous supply of fuel (diesel), and frequent maintenance of the machine throughout its operating life. At present, in Sri Lanka the diesel price is Rs.121 ($ 0.95) [8] and the transportation cost also must be required to take into the account since diesel must be transported from the urban areas to the rural site. Thus for this analysis the fuel cost has been considered as $ 0.96.

The cost of the commercially available diesel generators is primarily dependent on the size of the generator. Such as, the smaller capacity generators have higher costs per kW and the larger capacity generators have a lower cost per kW. Therefore the cost curve of diesel generators does not vary linearly with the capacity, but increases with a gradually reducing gradient. These prices vary to some extent from brand to brand as well as according to the features included.

Usually diesel generators operate most efficiently near full load. Thus it is recommended to operate the generator above a certain load factor for maintaining the proper efficiency of the energy conversion hence lowering the fuel cost by reducing the utilization of fuels. The fuel consumption curve of a diesel generator is normally given by the manufacturer in the product specification data sheet and the efficiency curve can be derived using this. In this study I have selected Centurion generators. The fuel consumption curve and the efficiency curve of the Centurion 25 kW [9] diesel generator are given in Figure 3.10.



(a)



(b)

Figure 3.10 : (a) Fuel consumption curve (b) Efficiency curve of a Centurion 25 kW diesel generator

8 www.ceypetco.gov.lk/

9 www.generatorjoe.net/SpecSheet.asp?ID=3879

3.4.1. Operation and Maintenance of Diesel Generators

The lifetime of a diesel generator is specified in hours of operation and it depends on several factors, such as the operating condition, maintenance frequency, fuel quality and many others. A properly maintained diesel generator has an operating life of 20000 to 50000 hours[10]. To maintain the efficient operation and increased operating life of diesel generators it is necessary to carry out routine maintenance. The followings are the required routine maintenance for a diesel generator and their estimated costs [37].

- Changing oil and filter and also inspection of air and fuel filters, fuel systems, starter battery and system electrical connections. These should be done at a frequency of 250 hours of operation and the cost of this job is in the range of $ 18 to $ 70.
- Decarbonization: Replacement of the air and fuel filters, cleaning the cylinder head, nozzles, gaskets, etc.. should be performed at a frequency of 1500 hours and the cost for this work varies from $ 180 to $ 360.
- A full engine overhaul should be performed after 6000 hours of operation. This includes replacement of the crankshaft, bearings, valves, valve springs, injectors, fuel pumps, piston, piston rings, starter battery etc. This costs approximately $ 1030 - $ 2060 per event.

3.5. Storage Battery

An off grid hybrid system requires a storage to store the excess energy from the renewable sources for later utilization when enough power is not produced by the renewable sources. Batteries are the most common storage medium used in renewable applications. A battery is an electrochemical device that produces a voltage potential when placing different metals (electrodes) in an acid solution (electrolyte). When a circuit is formed between the electrodes, a current flow. This current is created by reversible chemical reactions between the electrodes and the electrolyte within the cell. There are two types of batteries, i.e. primary batteries and secondary batteries. The batteries which can only be used once are known as primary batteries while the batteries that can charge over and over again is known as secondary batteries [34]. Renewable applications use secondary batteries. The open circuit voltage of a battery is determined by the type of electrodes and the electrolyte used[11]. The voltage of a battery is not constant during charging and discharging of the battery. Typically the voltage of the battery at the equilibrium conditions is known as the nominal battery voltage.

Several types of batteries are available such as Lead-acid, Nickel Cadmium, Lithium, Zinc Bormide, Zinc Chloride, Sodium Sulfur, Nickel hydrogen and Vanadium batteries. From these types of batteries, Lead acid batteries are widely used in renewable applications due to its low cost, high voltage per cell and good capacity life. But these batteries are substantially heavy and have poor low temperature characteristics. Lead acid batteries can be categorized in several ways. One way is, non-spill Lead acid batteries and sealed Lead acid batteries. Non-spill Lead acid batteries require

---

[10] www.backwoodshome.com/articles/thomsen43.html

[11] batteryuniversity.com

proper maintenance including topping up electrolyte during their life span. They are extraordinarily resistant to frequent cycling operation, thus outstanding for requirement where regular use is required. They have an excellent lifetime even in the case of intensive use. Sealed lead acid battery uses a sophisticated battery charging method. In these batteries gassing is reduced to a minimum and topping is avoided. Any hydrogen and oxygen produced by gassing is fully recombined to water, thereby avoiding the loss of electrolyte volume [38].

The key properties of a battery are, its nominal voltage, State of Charge (SoC), minimum State of Charge, round trip efficiency, maximum discharge current, capacity curve and the lifetime curve. State of Charge is the percentage from the maximum possible charge that is present inside the battery. Depending on the energy available from the renewable sources and the load power requirement the SoC of a battery can be calculated from the following equations [3].

Battery charging;

$$\mathrm{SoC}(t) = \mathrm{SoC}(t-1) \times (1-\sigma) + \eta_B \left(E(t) - \frac{E_L(t)}{\eta_{inv}} \right) \tag{3.14}$$

Battery discharging;

$$\mathrm{SoC}(t) = \mathrm{SoC}(t-1) \times (1-\sigma) + \left(\frac{E_L(t)}{\eta_{inv}} - E(t) \right) \tag{3.15}$$

Where ;

SoC(t)	is the state of charge of the battery bank at the time t
SoC(t-1)	is the state of charge of the battery bank at the time t
σ	is the hourly discharge rate
$E(t)$	is the total energy generated by the renewable systems
$E_L(t)$	is the load demand at time t
η_{inv}	is the inverter efficiency
η_B	is the battery bank efficiency

The minimum state of charge is the state of charge below which the battery must not be discharged to avoid permanent damage. The round trip efficiency indicates the percentage of the energy going into the battery that can be withdrawn back out, because always some energy is lost in the discharging process as heat. The maximum discharge current of a battery refers to the maximum current that can be taken from a battery at any one time without significantly shortening the battery life. In this study I have selected Surrette 6CS-25PS battery which cost around \$ 1400 [12] (including shipment costs) and its properties are given below [39].

Nominal voltage	6 V
Round trip efficiency	80 %
Min. State of charge	40 %
Nominal capacity	1156 Ah
Maximum discharge current	41 A

[12] store.renewableenergysys.com/browse.cfm/battery-surrette-6v-1156-solar-battery-6-cs-25ps/4,45.html

The life of a battery primarily affected by the depth of discharge and the operating temperature. Depth of discharge is the level at which batteries are discharged in a cycle before they are charged again. Usually the manufacturer specifies the nominal number of complete charge and discharge cycles as a function of the depth of discharge in the product data sheet. For example, Figure 3.11 gives the lifetime curve of the Surrette 6CS25P battery [39]. As shown in Figure 3.11, the number of cycles to failure drops rapidly with increasing depth of discharge. Figure 3.11 also plots the lifetime throughput of the battery which also depends on the number of cycles to failure and can be calculated using the following equation.

$$Q_{lifetime,i} = f_i \; d_i \left(\frac{q_{\max} \; V_{nom}}{1000} \right) \tag{3.16}$$

Where ;

$Q_{lifetime,i}$	is the lifetime throughput (kWh)
f_i	is the number of cycles to failure
d_i	is the depth of discharge (%)
$q_{\max}$	is the maximum capacity of the battery (Ah)
V_{nom}	is the nominal voltage of the battery (V)

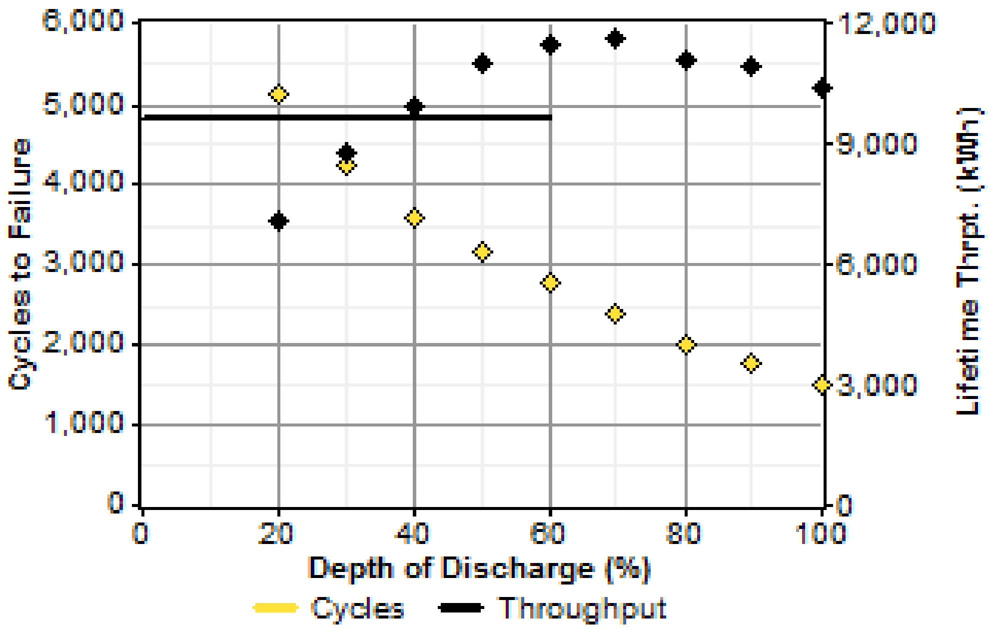


Figure 3.11 : Lifetime curve of the Surrette 6CS25P, 6V battery

In addition to the depth of discharge, daily cycles and operating temperature; battery life is also affected by sulfation and corrosion. When the batteries have been in a low state of charge for a long time, sulfate crystals which formed by the chemical reactions of the battery converts to stable crystalline and they deposit on negative plates. Sulfation reduces the battery capacity and increases the battery resistance. Corrosion is also a natural phenomenon which cannot be eliminated but can be slowed down. Corrosion occurs in the grids as well as in the battery terminals. A. Cherif [40] has developed a battery ageing model for deep cycle batteries in renewable applications. His model account the effect of the battery age on the battery charging and discharging characteristics. The paper also gives an expression for the lifetime reduction due to sulfation and corrosion. These models can be used to calculate the exact lifetime of the battery used in renewable applications by considering not only the number of operational cycles based on load profile and energy availability from sources but also the sulfation and corrosion effect.

The capacity of a battery is defined as the amount of energy that can be withdrawn from starting to fully-charged state and it is measured in Amp-hours. But the capacity of a battery depends on the rate at which energy is withdrawn from it. The higher the discharge current, the lower the capacity. For example, the capacity curve of the Surrette 6CS25P battery is given in Figure 3.12. The nominal capacity of this battery is given as 1156 Ah by the manufacturer and it is just one point on this capacity curve.

When batteries are left standing without charging, the batteries lose charge slowly by self discharging. This occurs due to the reactions within the cells of a battery. The self discharge rate depends on the temperature, the type of battery and their age. As batteries get older, self discharge rate increases. To avoid self discharge the top surface of the battery and the battery terminals must be kept clean [34].

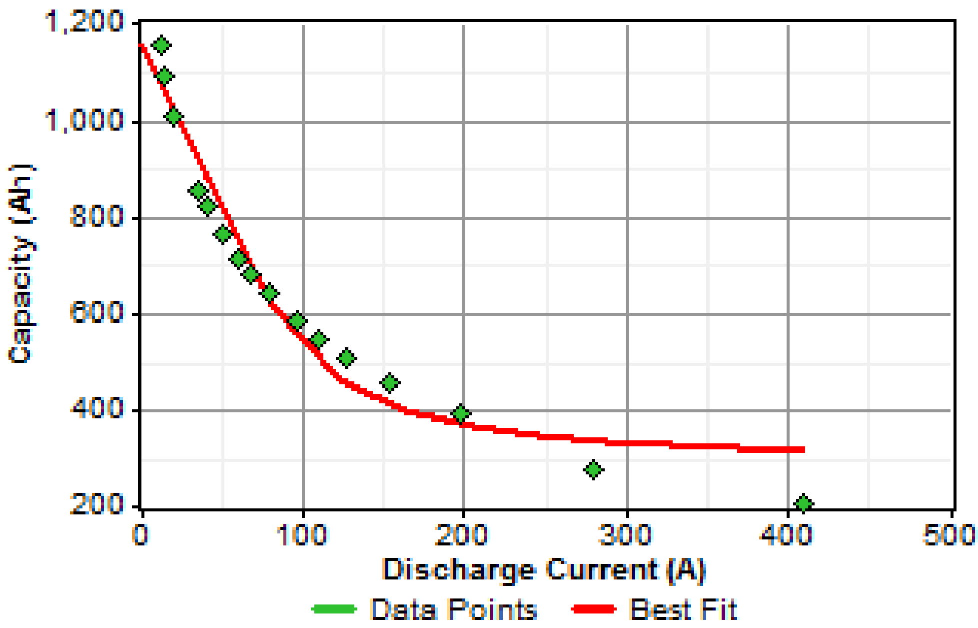


Figure 3.12 : Capacity curve of the Surrette 6CS25P, 6V battery

Batteries require regular maintenance in order to maintain proper operation within its useful lifetime. The maintenance requirement for batteries varies significantly depending on the battery design and application. Generally batteries require maintenances, cleaning of cases, cable and terminals, tightening terminals, distill water addition and performance checks. Performance checks include specific gravity recordings, conductance readings, temperature measurements, cell voltage reading and capacity test.

3.6. Inverter

A hybrid system needs an inverter to convert DC voltage from the batteries to AC voltage required by the load. There are several factors need to be considered when selecting an inverter for a certain application. Usually the inverters used in renewable applications can be divided into two; that is grid tied inverters and off grid inverters. Also there are inverters which are specifically designed for PV applications and they are integrated with Maximum Power Point Trackers (MPPT). Some inverters for off-grid PV systems come with integrated charge controllers. Further some inverters are bidirectional, that is they are able to operate in both inverting and rectifying modes. Therefore a right inverter must be carefully selected for an off grid hybrid system according to the requirement and also paying attention to the hybrid system configuration as well.

Further inverters can be categorized according to the type of waveform they produce. Three most common waveforms are the square wave, modified square wave and sine wave. Square wave inverters are less costly but only suitable for small appliances. They provide little output voltage control, limited surge capacity and considerable harmonic distortion. The presence of frequency components which are integer multiples of the input signal those are not present in the input signal is known as harmonic distortion. The presence of the harmonic distortion, distort the current waveform drawn from the supply. Modified sine wave inverters are better than square wave inverters and can handle large surges and produce output with much less harmonic distortion. Sine wave inverters are the most expensive one but have a wave shape that is very close to the grid voltage therefore used in grid connected applications [41].

The DC side voltage of a battery inverter must be matched to the battery bank voltage. Generally stand alone battery inverters operate at 12, 24, 48, 96, 120 or 240 V, DC depending on the power level. For high power applications it is better to use an inverter with a higher DC voltage because then the current ratings of the wires and the rated capacities of other DC components such as fuses, breakers decrease. The efficiency of the inverter is also very important. At present the inverter efficiencies have improved a lot and the typical efficiency figures are well above 90 %. Nevertheless, the efficiency of the inverter varies depending on the load and usually the manufacturer specifies the efficiency curve of the inverter.

Table 3.2 : Inverter specifications

	Solar Inverter	**Battery Inverter**
Brand	SMA	SMA
Model	Sunny Mini Central 10000 TL	Sunny Island SI 8.0H
Rated Capacity	10 kW	8.0 kW
Maximum Efficiency	97.2 %	95 %
DC voltage	333 V – 700 V	41 V – 63 V
AC voltage	230 V, 50 Hz	230 V, 50 Hz
Price[13]	$ 3500	$ 5300

[13] www.solarshop-europe.net

The AC coupled hybrid configuration requires inverters for connecting PV panels, wind turbines and battery bank to the micro grid. The inverters with the specifications given in Table 3.2 have been selected for solar and battery system and the selected wind turbine, Hummer H8.0-10 kW comes with a grid-tie inverter.

3.7. Distribution Grid

A distribution grid transmits the electrical power from the generating station to the consumer end. Generally in Sr Lanka, overhead all aluminum conductors supported by concrete or wooden poles are used for distribution of electrical power to consumers. Power can be transmitted using single phase or three phase lines. Single phase power distribution requires conductors with higher current ratings and creates more power losses than a three phase system. Three phase system allows larger loads to be connected but the design process is more complex than a single phase system design, because loads must be balanced between the three phases in order to attain better performance of the power system.

Chapter 4

Hybrid System Modeling

In this chapter we will discuss about the modeling of hybrid system using the micro grid optimization software "HOMER". Preceding sections explain the relevant inputs that describe the technical specifications, resource data and costs which are required when modeling the system in HOMER and it also briefly discusses how the software calculates the levelized cost of energy using the economics inputs.

4.1. Introduction

The main components of the hybrid system with their technical details and relevant costs have been discussed earlier in Chapter 3. As stated in problem statement the objective of this work is to find out the best hybrid system which can supply the electricity at the lowest price with an accepted level of availability. For this, it is required to consider several combinations of renewable energy systems and diesel generator with different component capacities. This is done by using the software "HOMER", which is developed by the National Renewable Energy Laboratory in the United State.

HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid connected power systems for remote, stand-alone and distributed generation applications. It facilitates a range of renewable energy and conventional technologies including solar PV, wind turbine, hydro power, generator (diesel, gasoline, biogas), battery bank and hydrogen. HOMER's optimization analysis algorithms allow the user to evaluate the economic and technical feasibility of a large number of technology options. The sensitivity analysis also can be performed in HOMER and it allows finding the effect of uncertainty in the input variables to the energy cost and the optimal configuration[14].

HOMER hybrid model requires several inputs which basically describe the technology options, component costs, component specifications and resource availability. HOMER uses the energy balance in optimization calculations. It compares hourly electric and thermal demand to the energy that the system produces in that hour and calculates the flow of energy to and from each component of the system. This comparison is done for each of the 8760 hours in a year for each system configuration that the user wants to consider. It then determines whether the hybrid configuration can supply the demand under the conditions that the user has specified. If it can, then HOMER calculates the net present value of installation and operating cost of the project over its lifetime and the cost of the energy based on the Levelized Cost of Energy (LCOE). The resulting hybrid configuration that has the least LCOE or the least total net present value of the project is considered as the optimum hybrid system.

[14] analysis.nrel.gov/homer/

4.2. Modeling of Hybrid System in HOMER

The hybrid system has been modeled in HOMER using AC coupled hybrid configuration as discussed in section 3.1 as shown in Figure 4.1. The DC bus bar voltage of this configuration has been set to 48 V by connecting 8 batteries in series, each having 6 V, DC voltage.

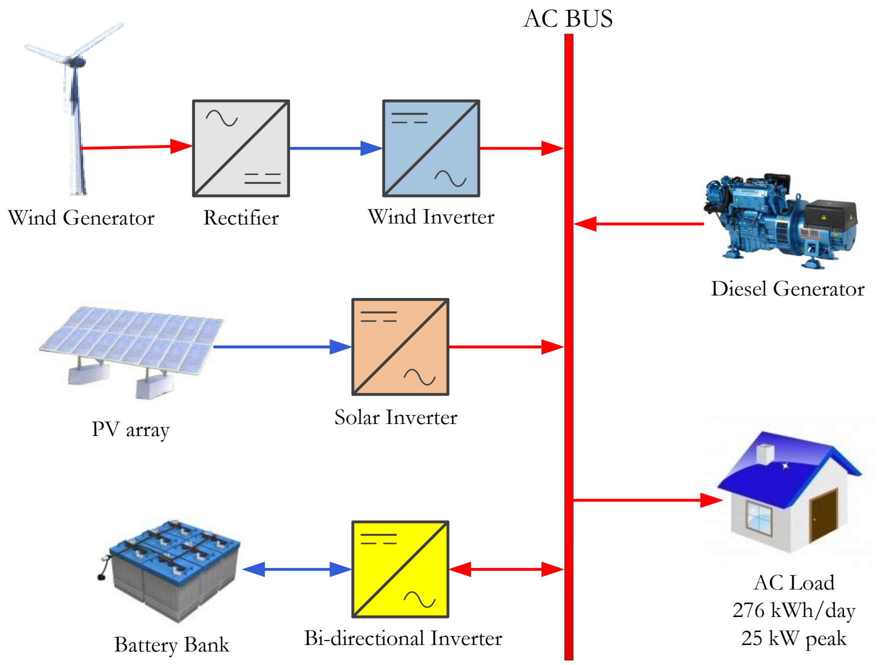


Figure 4.1 : AC coupled hybrid system

Once the required components of the hybrid system are selected as in Figure 4.1, then several inputs must be entered in each of the component input windows in HOMER. These inputs basically describe the costs, technical specifications and resource data that have been already discussed in Chapter 2 and 3. A summary of these data is given in Appendix A and only the important points are discussed below.

Load

As decided in section 2.2 , a constant load profile has been assumed throughout the year, but we can add hourly and daily randomness to this load profile in HOMER to make the load profile realistic. I have added 10 % randomness for both these cases. Adding 10 % randomness to the load profile results increase in annual peak demand to 33 kW. HOMER calculates the parameters, annual average of the daily demand, peak load and load factor based on the load profile and the random variability inputs given by the user.

Wind resource

In this work I have obtained solar radiation and wind speed data from the NASA database. This database contains only monthly average values of solar and wind data. HOMER can generate synthetic hourly data using these monthly averages when hourly solar radiation and wind speed data are not available. In order to calculate synthetic hourly wind data HOMER requires four parameters, Weibull k (described in section 2.4.3), autocorrelation factor, diurnal pattern strength and hour of peak wind speed.

- Autocorrelation factor

  This is a measure of how strongly the wind speed in one hour depends on the wind speed in the previous hour. The complexity of local topography has a significant effect on the autocorrelation factor. Usually areas surrounded more uniform topography tend to have high autocorrelation factors (0.9 – 0.97) [28]. Siyambalanduwa area has more uniform topography covering most of the area by paddy fields. Hence 0.94 selected as the autocorrelation factor.

- Diurnal pattern strength

  This is a measure of how strongly the wind speed tends to depend on the time of day. The typical range of this variable is 0 to 0.4 and 0.25 was selected for this analysis.

- Hour of peak wind speed

  This is the hour that tends to be the windiest on average. Hour 20:00 is the windiest hour at this site according to [29] and [25].

Figure 4.2 illustrates the synthetic annual wind speed data calculated by HOMER using the above input parameters and average monthly wind speed data obtained from NASA solar radiation data base.

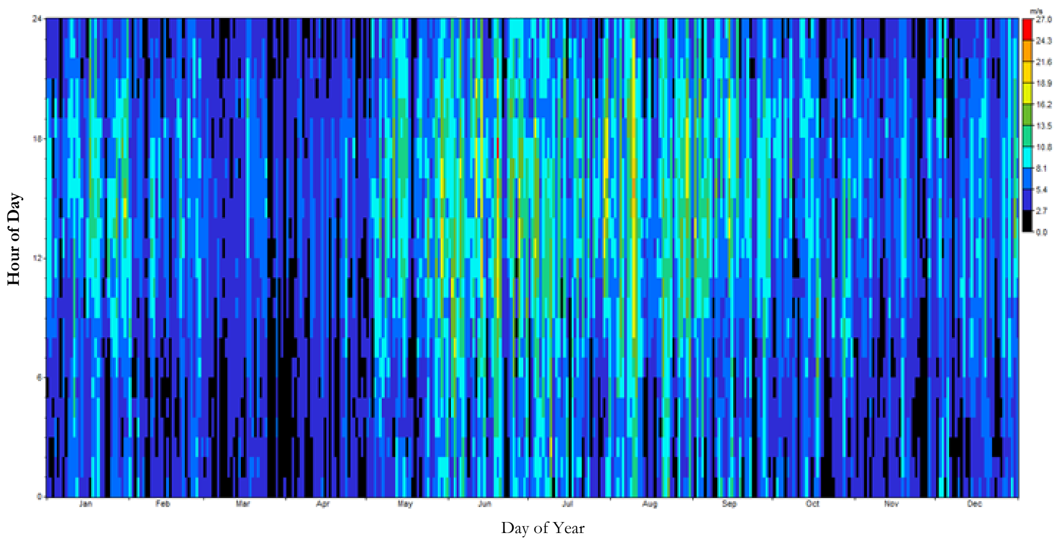


Figure 4.2 : Synthetic wind speed data

Solar resource

HOMER also can calculate hourly solar radiation data based on the monthly average radiation and clearness index. It uses the method described in [42] to generate synthetic hourly solar radiation data. Figure 4.3 shows the synthetic hourly solar radiation data in Siyambalanduwa which is calculated by HOMER using the NASA monthly average solar radiation data.

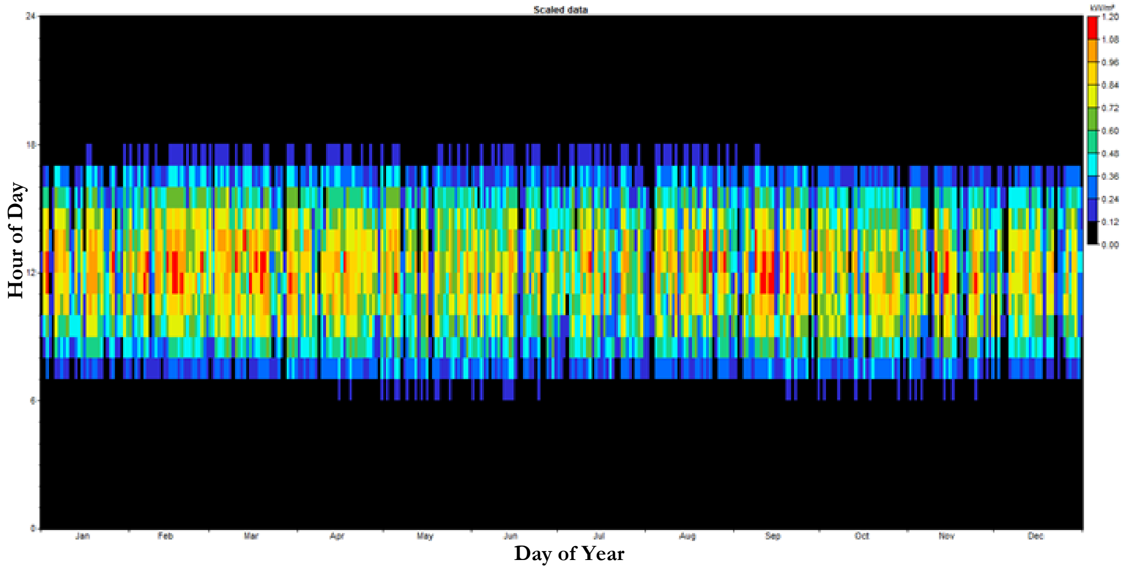


Figure 4.3 : Synthetic solar radiation data

Wind turbine

The power curve of the wind turbine has been modified by multiplying each point on the power curve by the efficiency of the wind inverter, because in AC coupled hybrid configuration given in Figure 4.1 the wind turbine has been connected to the AC bus bar via an inverter, but HOMER does not facilitate connecting separate inverter for a wind turbine. Therefore the efficiency of the inverter has been integrated to the wind turbine efficiency. The power curve of the wind turbine obtained after multiplying by the inverter efficiency is given in Figure 4.4.

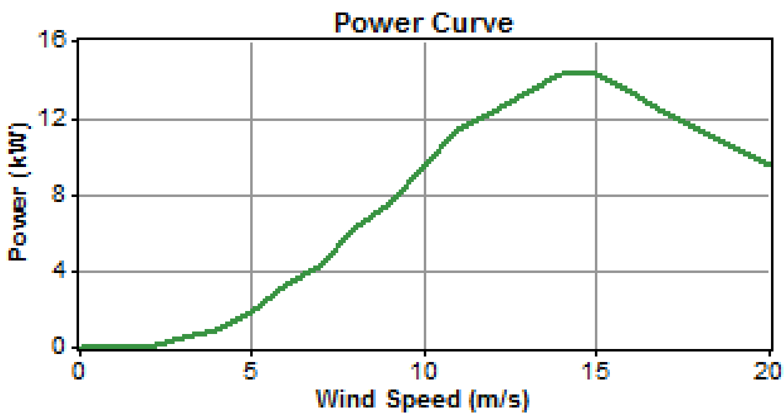


Figure 4.4 : Modified wind turbine power curve

PV array

Derate factor of the PV array has been set to 80 % accounting the efficiency of the solar inverter, soiling of the panels, wiring losses, shading, aging and so on.

Component costs

The following Table 4.1 gives a summary of the costs of components and other relevant costs.

Table 4.1 : Cost summary

Component	Capacity	Capital Cost $	O & M Cost	Replacement Cost $
PV system	10 kW	29000	10 $/year	23000
Wind turbine	10 kW	25000	500 $/year	20000
Battery	1156 Ah	1400	10 $/year	1400
Generator[15]	10 kW	6300	0.5 $/hr	6300
	15 kW	9700	0.6 $/hr	9700
	21 kW	12000	0.7 $/hr	12000
	25 kW	14000	0.8 $/hr	14000
	29 kW	14500	0.9 $/hr	14500
Inverter				
Solar inverter	10 kW	3500	0	3500
Wind Inverter	10 kW	4000	0	4000
Battery Inverter	6 kW	5300	0	5300

System fixed capital cost

The fixed capital cost of the system is mainly allocated for constructing a building for keeping the battery bank, charge controllers, generator, inverter and other relevant electrical instruments and constructing the distribution lines throughout the village. It also includes the site preparation cost, labor cost, engineering design cost and other miscellaneous cost. An estimate of the fixed capital cost by considering 2 km long single phase distribution lines has been taken as $ 30000.

System fixed operation and maintenance cost

System fixed O & M cost primarily includes fixed labor cost and insurance costs. If a full time engineer or a technician is working in the hybrid system premises then he has to be paid a monthly wage. However the O & M costs of the wind turbine, PV panels, Battery and the diesel generator are excluded from the system fixed O & M cost, because they are included separately. Assuming a technician is full time employing in the premises annual fixed O & M cost has been taken as $ 6000.

4.3. Dispatch Strategy

The diesel generator is the only dispatchable energy source used in this hybrid energy system. Since the energy output from renewable sources is highly intermittent and cannot be controlled by the user, it must be used when it is available, to supply the load or to charge the battery bank. If renewable energy systems or the battery bank is not able to meet the load then the diesel generator

[15] www.generatorjoe.net/subcatmfgprod.asp?0=503&1=469&2=-1

has to be turned on to supply the load without causing power interruptions. Therefore using a diesel generator is essential in hybrid systems to supply the load in a controlled manner to improve the availability of the system. However controlling the operation of a diesel generator is rather complicated due to several aspects. The main thing is the energy conversion efficiency of the generator. As I have discussed in section 3.4, the efficiency of the generator is very low at low load factors. Therefore if the generator is chosen to supply the load that cannot be supplied by the renewable sources then generator may operate in a low load factor so that at a low efficiency. Sometimes operating the generator at its full capacity when required and using the excess energy to charge the battery bank may be more economical than the previous case. Which is the optimal strategy depends on many factors, including the size of the generator and battery bank, the price of fuel, the O & M cost of the generator and the amount of renewable power in the system. Therefore, dispatch strategy also should be developed when optimizing the hybrid system. HOMER can model two dispatch strategies; i.e. "Load following" and "Cycle charging".

- Load Following (LF)

  The diesel generator starts when required and produce only the required amount of power that cannot be produced by the renewable sources or battery bank to supply the load.

- Cycle Discharging (CC)

  The diesel generator starts when required and operates at its full capacity and excess energy is sent to the battery bank to charge the batteries.

4.4. Search Space

In order to find the optimal system, we need to consider several combinations of different capacities of hybrid system components. We can provide a wide range of capacities to the HOMER. The larger the number of inputs, the higher the time that HOMER takes to simulate the system. Table 4.2 specifies the capacities of the system components that I have chosen for the simulation.

Table 4.2 : HOMER search space

PV Array (kW)	Wind turbine-10 kW (Quantity)	Generator (kW)	Battery (Strings)	Converter (kW)
0.0	0	0.0	0	15.0
10.0	1	10.0	1	20.0
15.0	2	15.0	2	25.0
20.0	3	20.0	3	30.0
25.0	4	25.0	4	35.0
30.0	5	29.0	5	
40.0	6	35.0	6	
50.0	7		7	
60.0	8		8	
70.0	9		10	

4.5. Economics

In order to evaluate the economic viability of micro-grids supplied by hybrid power systems, the levelized energy cost analysis of the feasible systems must be done by considering the lifetime of the system, because hybrid systems with renewable technologies have a higher capital cost, but small O & M cost during the lifetime of the system. In contrast, fossil fuel based electricity generation systems have lower capital cost but higher O & M cost due to fuel costs, generator maintenance and replacement costs. Thus, LCOE analysis can compare the economics of different technological solutions.

HOMER optimization algorithms are based on the LCOE analysis. It finds the optimum system by calculating the Net Present Value (NPV) of the lifetime cost of the project by including all the costs that occur within the lifetime of the project for every system configurations considered in the search space by the user. Then it ranks all the feasible systems according to increasing net present cost and levelized cost of energy. The following gives a brief description about the total net present cost and the levelized cost of energy.

The total Net Present Cost

The total Net Present Cost (NPC) of the system is the difference between the present value of all the costs occurs over the lifetime of the project and the present value of all the revenue earns over its lifetime. The present value of the costs that will make n-year later can be calculated by the following formula.

$$C_{NPC} = C\left(\frac{1+i'}{1+d}\right)^{n} \tag{4.1}$$

Where ;

i' is the annual inflation rate (%)

d is the nominal interest rate (%)

In order to find the LCOE, the total NPC of the project must be converted to series of equal annual cash flows which is known as total annualized cost. The following equation is used to calculate the total annualized cost.

$$\text{Total annualized cost (\$/year)} = \text{Total NPC} \times \text{CPF} \tag{4.2}$$

Where, CPF is the capital recovery factor and it is given by the formula,

$$\text{Capital recovery factor} = \frac{i\,(1+i)^{N}}{(1+i)^{N}-1} \tag{4.3}$$

Where, N is the number of years and i is the real interest rate, that is the discount rate used to convert between one-time costs and annualized costs. The lifetime of the project has been studied here is 20 years. Therefore N is 20. The real interest rate is determined using the nominal interest rate (d) and the annual inflation rate (i') by the following formula.

$$i = \frac{d - i'}{1 + i'} \tag{4.4}$$

HOMER assumes the rate of inflation is same for all types of costs (fuel cost, maintenance cost, labor cost, etc.) occurring throughout the lifetime of the project. The variation of the real interest rate in Sri Lanka over the years is given in Figure 4.5 [16]. According to Figure 4.5 the average real interest rate in Sri Lanka during the past 10 years (2002 – 2011) has been below 2.5 %, unless the effect of the peak occurred in 2009 is considered. Thus the real interest rate of 2 % has been selected for the analysis.

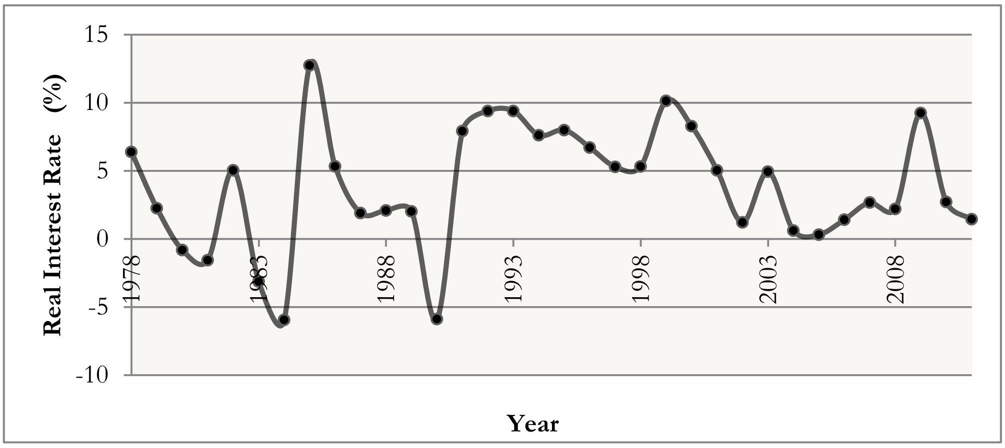


Figure 4.5 : Changes in the real interest rate in Sri Lanka over the time

Levelized Cost of Energy (LCOE)

Levelized cost of energy is the cost per kWh of electrical energy, such that the total NPC of the useful energy generated throughout the whole lifetime of the hybrid project is equal to the total net present cost of the project. LCOE of the electricity generated by an off grid hybrid energy project can be calculated from the following equation.

$$\text{LCOE} = \frac{\text{Total Annualized Cost (USD/yr)}}{\text{Annual load served (kWh/yr)}} \tag{4.5}$$

[16] www.quandl.com/WORLDBANK-World-Bank/LKA_FR_INR_RINR-Sri-Lanka-Real-interest-rate

Chapter 5

Results

The optimum hybrid system is the one which can supply electricity at the lowest price or in other words, the system which is having the lowest total net present value, at the mean time supplying the electricity at the required level of availability. In this chapter we will discuss the results obtained from the HOMER simulations and the selection of the optimal system based on the simulation results. The chapter also discusses the performance of the optimal hybrid system, hybrid system design, economic viability of the project and a brief introduction to the energy management in the micro grid.

5.1. Optimization Results

HOMER simulation results of the hybrid system optimization are given in Table 5.2 and Table 5.3. In order to make the description easier we will define two terms; i.e. system type and system configuration.

- System type

  A system type is a combination of technologies. For example, wind/diesel/battery describes a system type that includes wind turbines, diesel generators and batteries.

- System configuration

  A system configuration is a combination of particular numbers and sizes of components. For example, a system with a 10 kW wind turbine, 15 kW diesel generator, 16 batteries and a 25 kW inverter describes a configuration of the wind/diesel/battery system type. The same system type with 32 batteries is a different system configuration.

Table 5.2 gives part of the overall optimization results. It displays the list of system configurations which are ranked according to the increasing NPC of the project. Table 5.3 gives the categorized optimization results and it displays most cost effective configuration of each system type. According to the HOMER simulation results, the optimum system type is PV/wind/diesel generator/battery system and its system configuration is given in Table 5.1. This system can supply the electricity at an LCOE of 0.34 $/kWh and the system annual capacity shortage is only 0.1 %. In this analysis I have not accounted the penalty cost for the emissions of pollutants. At the later analysis in section 5.4, I will consider this effect as well.

Table 5.1 : Optimum hybrid system architecture

PV system capacity	25 kW
Number of 10 kW Wind turbines	4
Generator capacity	25 kW
Battery bank	24 batteries, 166 kWh
Converter capacity	25 kW
Dispatch Strategy	Load Following
Renewable fraction	0.88
Capacity shortage	0.1 %

Table 5.2 : HOMER optimization results

PV (kW)	H10kW	Gene (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gene (hrs)
25	4	25	24	25	LF	$ 270,500	17,262	$ 552,752	0.336	0.88	7,231	1,548
30	4	25	32	25	LF	$ 296,200	15,711	$ 553,102	0.336	0.91	5,803	1,237
25	4	25	32	25	LF	$ 281,700	16,633	$ 553,672	0.336	0.89	6,542	1,391
30	4	25	24	25	LF	$ 285,000	16,501	$ 554,819	0.337	0.90	6,579	1,410
25	4	25	24	15	LF	$ 262,100	17,959	$ 555,760	0.337	0.87	7,798	1,680
30	3	25	32	25	LF	$ 271,200	17,422	$ 556,073	0.338	0.86	7,556	1,613
25	4	25	24	30	LF	$ 274,100	17,262	$ 556,352	0.338	0.88	7,231	1,548
30	4	29	32	25	LF	$ 296,700	15,901	$ 556,702	0.338	0.90	5,998	1,129
30	4	25	32	30	LF	$ 299,800	15,711	$ 556,703	0.338	0.91	5,803	1,237
25	4	25	32	30	LF	$ 285,300	16,633	$ 557,272	0.338	0.89	6,542	1,391
20	4	25	24	25	LF	$ 256,000	18,425	$ 557,275	0.338	0.86	8,188	1,750
35	4	25	32	25	LF	$ 310,700	15,096	$ 557,548	0.339	0.92	5,292	1,135
35	3	25	32	25	LF	$ 285,700	16,641	$ 557,812	0.339	0.87	6,915	1,487
25	4	29	32	25	LF	$ 282,200	16,869	$ 558,037	0.339	0.89	6,790	1,277
30	4	25	24	15	LF	$ 276,600	17,214	$ 558,078	0.339	0.89	7,196	1,555
25	4	29	24	25	LF	$ 271,000	17,577	$ 558,406	0.339	0.88	7,527	1,419
30	4	25	24	30	LF	$ 288,600	16,501	$ 558,419	0.339	0.90	6,579	1,410
20	4	25	24	15	LF	$ 247,600	19,013	$ 558,495	0.339	0.86	8,649	1,857
20	4	25	32	25	LF	$ 267,200	17,817	$ 558,530	0.339	0.87	7,483	1,595
30	3	29	32	25	LF	$ 271,700	17,589	$ 559,301	0.340	0.86	7,760	1,458
25	4	25	40	25	LF	$ 292,900	16,312	$ 559,627	0.340	0.90	6,069	1,287
30	3	25	32	30	LF	$ 274,800	17,423	$ 559,690	0.340	0.86	7,557	1,613
25	5	25	24	25	LF	$ 295,500	16,165	$ 559,822	0.340	0.91	5,987	1,283

Table 5.3 : HOMER optimization results in categorized way

PV (kW)	H10kW	Gene (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gene (hrs)
25	4	25	24	25	LF	$ 270,500	17,262	$ 552,752	0.336	0.88	7,231	1,548
	4	15	16	15	CC	$ 174,100	26,098	$ 600,835	0.365	0.73	15,147	3,511
60		29	48	15	LF	$ 297,700	29,625	$ 782,117	0.475	0.62	18,181	3,410
40	6	29			CC	$ 310,500	36,220	$ 902,741	0.548	0.79	22,407	4,236
		21	16	15	CC	$ 76,400	51,541	$ 919,177	0.558	0.00	38,356	7,154
	6	29			CC	$ 194,500	47,385	$ 969,320	0.588	0.67	31,378	5,956
60		35			CC	$ 220,000	56,965	$ 1,151,451	0.699	0.41	42,066	6,446
		35			CC	$ 46,000	74,914	$ 1,270,949	0.772	0.00	56,591	8,760

As shown in the results in Table 5.3, a diesel only system requires a small capital investment ($ 46,000) compared to hybrid systems. But due to its large operating and maintenance cost ($ 74,914), the lifetime net present cost of the system ($ 1,270,949) is very much higher than the hybrid system ($ 552,752). Thus the LCOE is also becoming larger which is approximately 0.8 $/kWh and it is more than twice higher than the energy cost of the optimum renewable energy based hybrid system given in Table 5.1. By connecting a battery bank with the diesel generator the energy cost can be reduced to 0.56 $/kWh but the cost is still 0.22 $/kWh higher. Therefore, from an economic perspective stand alone power systems based on renewable sources, storage battery bank and a diesel generator is considerably more cost effective than systems which use diesel generators only. The simulations have been also done by removing the diesel generator from the system to find the energy cost of a hybrid system which uses only renewable systems. The results are shown in Table 5.4. According to the simulation results, energy cost of the optimized hybrid system which uses only renewable sources is 0.51 $/kWh which is still higher than the energy cost (0.34 $/kWh) of the optimized renewable energy based hybrid system which uses a diesel generator which is given in Table 5.1. The primary objective of using a diesel generator in hybrid system is to supply the peak demand therefore reduction in the rated capacities of the battery bank and renewable systems is possible . If a diesel generator is not used, then a large storage is required to supply the peak as shown in the results (128 batteries) including large capacity PV system and many wind turbines. The installed capital of this system is more than 2 times higher than the installed capital of the hybrid system which uses a diesel generator. On the other hand, a large percentage of the energy generated is wasted as excess energy because peak demand occurs only within a small period of time during the day. According to the simulation results excess energy generated from the system which uses only renewable systems is 59 %. Therefore, in this system most percentage of the generated energy is excess energy. But the percentage of excess energy generated by the hybrid system which uses a diesel generator given in Table 5.1 is 35 %.

Table 5.4 : Optimization results when using only renewable resources

PV (kW)	H10kW	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.
80	6	128	30	CC	$ 615,200	13,586	$ 837,351	0.509	1.00
80	6	128	30	LF	$ 615,200	13,586	$ 837,351	0.509	1.00
75	6	136	30	CC	$ 611,900	13,863	$ 838,575	0.509	1.00
75	6	136	30	LF	$ 611,900	13,863	$ 838,575	0.509	1.00
80	5	144	35	CC	$ 616,200	13,649	$ 839,386	0.510	1.00
80	5	144	35	LF	$ 616,200	13,649	$ 839,386	0.510	1.00
75	7	120	30	CC	$ 614,500	13,799	$ 840,140	0.510	1.00
75	7	120	30	LF	$ 614,500	13,799	$ 840,140	0.510	1.00

According to the above observations we can see that the hybrid systems which use both renewable sources and a diesel generator are more economical than systems with only renewable energy sources or only diesel generators. But the important matter is the sizing of the hybrid components in a right way to reduce the energy cost or net present cost of the project. If sizing is not done properly then we may end up with a system having larger NPC than the base system was in concern.

The optimal hybrid system configuration obtained from the HOMER optimization algorithm is given in Table 5.1. However, finding the optimum hybrid configuration requires more analysis because the inputs given to the HOMER may not 100 % accurate. Especially the renewable resource inputs, solar radiation and wind speed data. In this study these data have been obtained from the NASA surface meteorology and solar database. Therefore there may be little variations between these and the actual data. Moreover, there may be uncertainty in the cost inputs as well. Thus the sensitivity analysis is required to validate the results obtained from the optimization analysis by considering the sensitivities of the input variables.

5.2. Sensitivity Results

HOMER sensitivity algorithms can be used to evaluate the effect of uncertainties in the input variables those discussed in section 4.2, in selecting the optimum hybrid system configuration. Here, I have analyzed the uncertainties of the following variables when selecting the optimal hybrid configuration.

- Annual average solar radiation

  According to the solar radiation maps developed by NREL for Sri Lanka, the Siyambalanduwa region is located in the region of annual average daily solar radiation sum of 4.5 – 5.0 kWh/m^2/day. Therefore the sensitivity analysis has been done for the variation in solar radiation in this range.

- Annual average wind speed

  According to the wind resource maps developed by NREL for Sri Lanka, the Siyambalanduwa region is located in the region of annual average wind speed 5.5 – 6.4 m/s. Therefore the sensitivity analysis has been done for the variation in wind speed in this range.

- Capital cost of the PV system

  As there can be uncertainties in the estimated installed cost of the PV system, the sensitivity analysis has been done for the uncertainties of $\pm 15\%$ of the estimated installed cost.

- Capital cost of the wind system

  As there can be uncertainties in the estimated installed cost of the Wind turbine, the sensitivity analysis has been done for the uncertainties of $\pm 15\%$ of the estimated installed cost.

- Misalignment of the PV array

  The sensitivity analysis has also been done to evaluate the effect of misalignment of the PV array by $\pm 1^0$.

5.2.1. Annual Average Solar Radiation and Wind Speed

According to the solar radiation and wind resource maps developed by NREL for Sri Lanka, the selected site is located in the region of solar radiation 4.5 – 5.0 kWh/m^2/day and wind speed of 5.6 – 6.4 ms^{-1}. Therefore the sensitivity analysis has been done for the annual average solar radiation changes of 4.5 – 5.0 kWh/m^2/day and wind speed variation of 5.5 – 6.4 ms^{-1}. Figure 5.1 gives the sensitivity plot for varying annual average wind speed and solar radiation in the range mentioned above. The whole area of the sensitivity plot is green implying that the optimal system type is same for all the variations considered in the analysis. Therefore the optimal system type is Wind/PV/ Generator/Battery hybrid system.

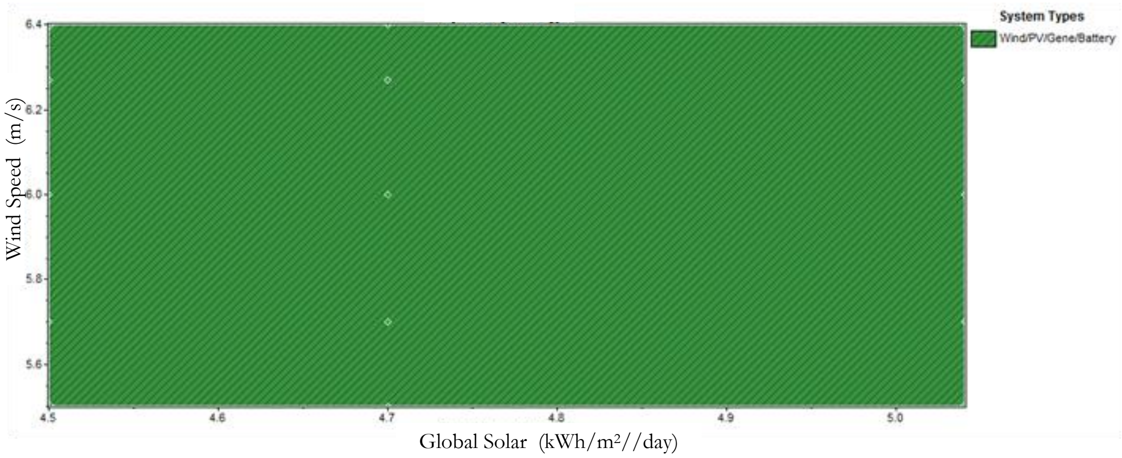


Figure 5.1 : Optimal system type at different annual average solar radiation and wind speed

Afterwards, it is required to check whether the optimal hybrid system configuration considered before in Table 5.1 is still valid for the variations in the annual average solar radiation and wind speed values. This is illustrated below. The following figures plot the optimum capacities of the different components relevant to the optimum configuration at different points on the plot. In the following plots the numbers on the figure represents the optimum capacity of the component relevant to the optimal configuration at each point.

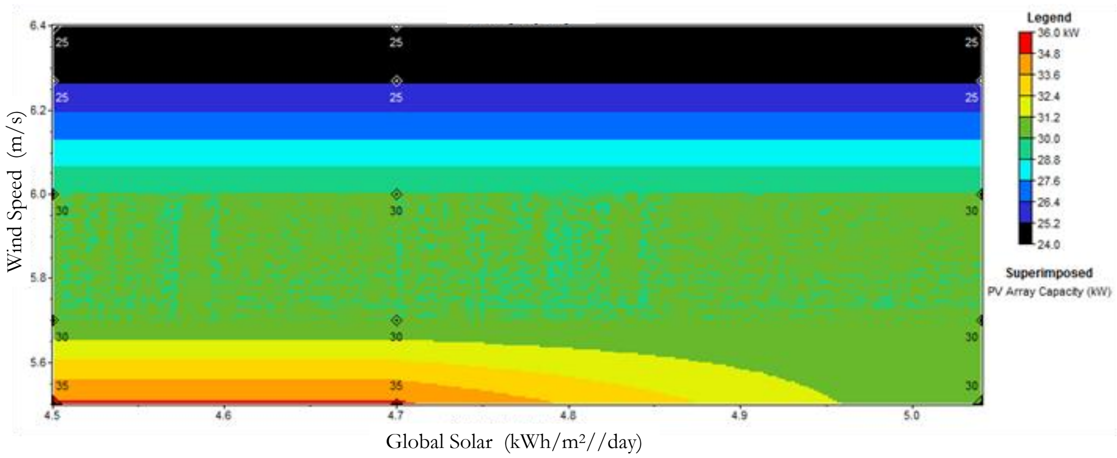


Figure 5.2 : Optimum PV Array capacity at different annual average solar radiation and wind speed

According to the HOMER optimization results given in Table 5.1, 25 kW was the optimum capacity of the PV system when the annual average solar radiation is 5.0 kWh/m^2/day and annual average wind speed is 6.3 ms^{-1}. As shown in the sensitivity plot in Figure 5.2, if the annual average wind speed drops below 6 ms^{-1} then the optimum capacity of the PV system increases to 30 kW. Since the wind speed has a relatively high probability of changing the annual average, 30 kW has been selected as the optimum capacity, because then the system can supply the electricity at a lower price even though the annual average wind speed drops below 6.0 ms^{-1}.

Figure 5.3 and 5.4 illustrate the optimum number of wind turbines and the generator capacity in the optimum hybrid system configurations relevant to each point on the sensitivity plot. According to these sensitivity results, the optimum number of wind turbines and generator capacity do not change within the selected range of variations in the annual average wind speed and solar radiation. Therefore 4 numbers of 10 kW wind turbines and the generator capacity of 25 kW have been validated as the optimum results.

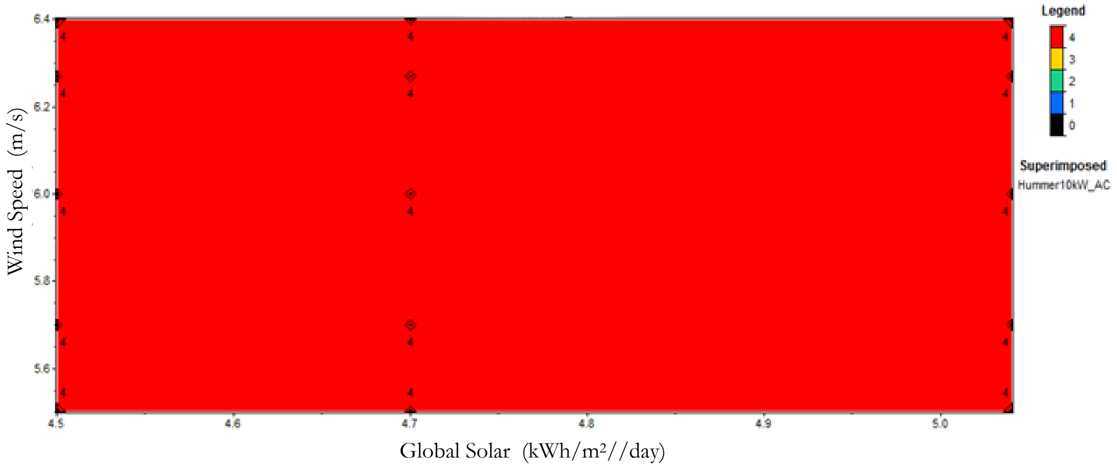


Figure 5.3 : Optimum Number of 10 kW wind turbines at different annual average solar radiation and wind speeds

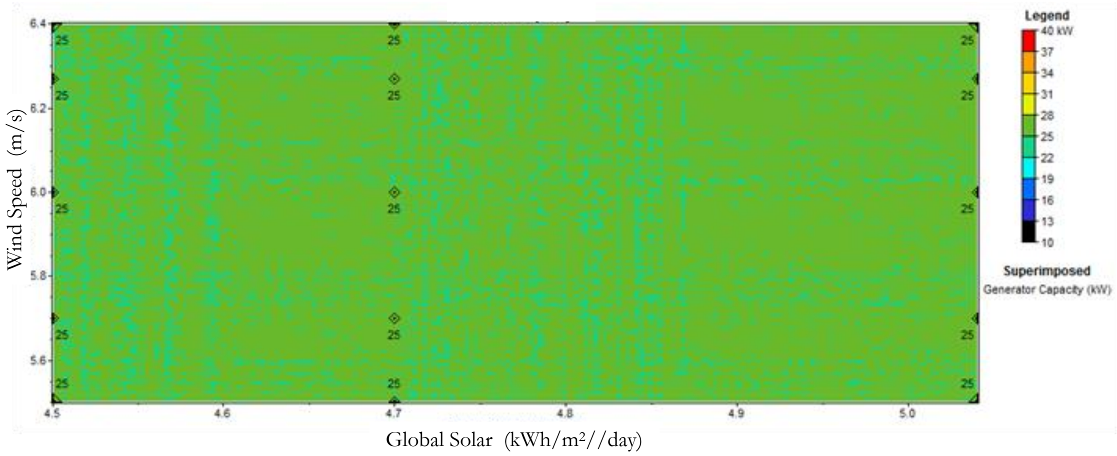


Figure 5.4 : Optimum generator capacity at different annual average solar radiation and wind speed

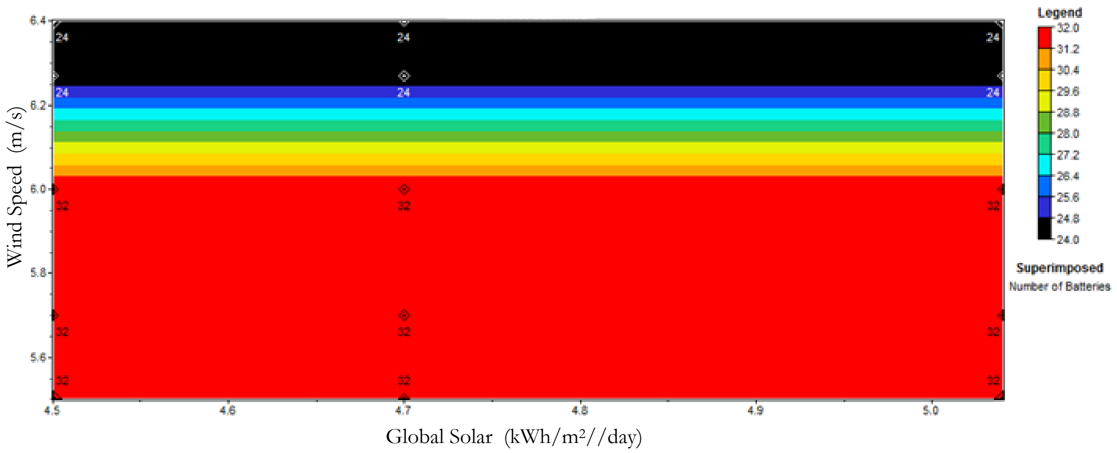


Figure 5.5 : Optimum number of batteries at different annual average solar radiation and wind speed

Figure 5.5 illustrates how the optimum number of Surrette 1156 Ah, 6 V batteries changes as the annual average wind speed and the solar radiation changes. Since the optimum size of the battery bank changes from 24 to 32 as the annual average wind speed drops below 6.0 ms^{-1} the optimum size of the battery bank has been increased to 32 batteries.

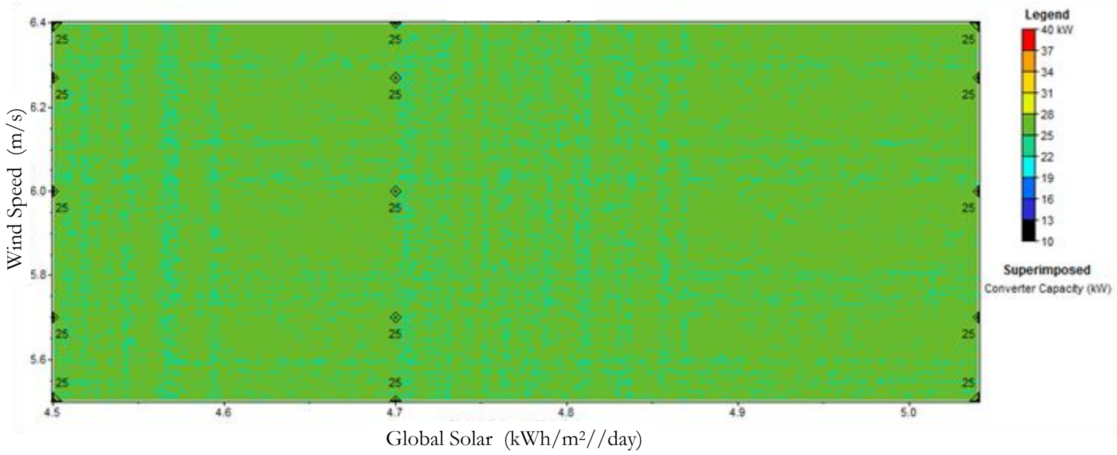


Figure 5.6 : Optimum converter capacity at different annual average solar radiation and wind speed

The other major component in the hybrid system is the bi-directional inverter. HOMER optimization analysis gave 25 kW as the optimal capacity of the bi-directional inverter. According to the sensitivity plot shown in the Figure 5.6, 25 kW is the optimum capacity for all the cases considered in the sensitivity analysis. Therefore the optimum capacity of the converter has been selected as 25 kW.

According to the sensitivity analysis for the variation in the annual average wind speed and solar radiation, the following system configuration has been selected as the optimum system configuration.

PV system capacity	30 kW
Number of 10 kW Wind turbines	4
Generator capacity	25 kW
Battery bank	32 batteries , 222 kWh
Converter capacity	25 kW

5.2.2. Capital Cost of PV and Wind Systems

Sensitivity analysis has been done for analyzing the effect of uncertainties in the estimated capital cost of the PV system and the wind turbine. Here I have considered $\pm 15\%$ variations in the costs from the estimated nominal costs considered before in section 4.2 for optimization analysis. Figure 5.7 illustrates the results obtained for the sensitivity analysis. According to Figure 5.7, it can be seen that the optimal system type does not change even though the estimated cost inputs change within the range of $\pm 15\%$. Therefore the system type Wind/PV/Generator/Battery has been the optimal system type.

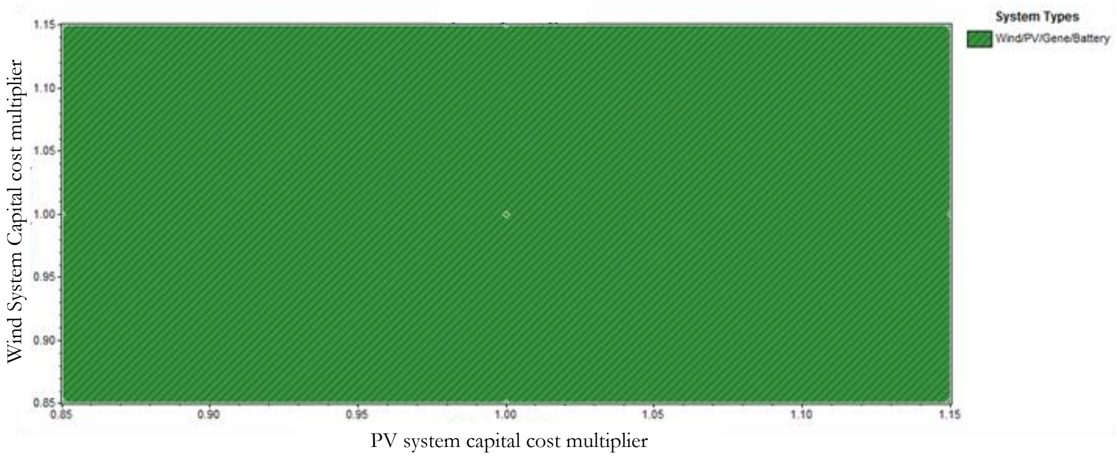


Figure 5.7 : Optimal system type at different PV system cost and Wind turbine cost

Studying the optimization and sensitivity results obtained from the HOMER simulations, it can be concluded that the optimal hybrid system is the Wind/PV/Generator/Battery configuration with the capacities given in Table 5.5.

Table 5.5 : Optimal hybrid system configuration

PV capacity	30 kW
Number of 10 kW wind turbines	4
Generator capacity	25 kW
Battery bank	32 batteries, 222 kWh
Converter capacity	25 kW
Dispatch strategy	Load Following
Renewable fraction	0.91
Capacity shortage	0.1 %

5.2.3. Misalignment of PV Array

As stated in section 2.3.2, it has been decided to mount the PV array with a fixed tilt angle of 6.8^0 which is the optimal tilt angle that maximizes the annual performance of the PV array. However, misalignment could happen when installing the PV arrays. Therefore, I have analyzed the effect of changes in tilt angle by $\pm 1^0$ in selecting the optimal hybrid system configuration. According to the simulation results, changes in tilt angle by $\pm 1^0$ does not affect the optimum hybrid configuration. Therefore, the hybrid system configuration given in Table 5.5 is optimized for changes in the tilt angle by $\pm 10\,\%$ from the optimum tilt angle as well. As said by the simulation results, drop in annual energy production by the PV array due to $\pm 1^0$ misalignment is less than 10 kWh/yr which is negligible. This drop is compensated by increasing the operating hours of the diesel generator so that the observed increase in annual operating hours of the generator is below 5 hours. Hence, we can see that the effect of $\pm 1^0$ misalignment of the PV array does not affect in the selection of the optimal system type and also there is no significant changes in the performance of the hybrid system as well.

5.3. Analysis of the Optimal Hybrid System

The techno economically optimum configuration of the hybrid system which can supply the electricity to a community in Siyambalanduwa region having an approximate load profile given in Figure 2.4, has been found using the HOMER optimization and sensitivity analysis. The architecture of this system is given in Table 5.5. As can be seen in the HOMER optimization results given in Figure 5.8, this configuration is ranked in the 2nd place. But there is no difference between the energy costs of this system configuration and the system configuration ranked in the 1st place. But the renewable fraction of this system (91 %) is higher than the renewable fraction (89 %) of the system configuration given in Table 5.1 which is advantageous. According to the simulation results, this project requires an initial capital of approximately $ 296000 and the total NPC of the project is $ 553000. This system can supply the electricity for a levelized cost of 0.34 $/kWh.

PV (kW)	H10kW	Gene (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gene (hrs)
25	4	25	24	25	LF	$ 270,500	17,262	$ 552,752	0.336	0.88	7,231	1,548
30	4	25	32	25	LF	$ 296,200	15,711	$ 553,102	0.336	0.91	5,803	1,237
25	4	25	32	25	LF	$ 281,700	16,633	$ 553,672	0.336	0.89	6,542	1,391
30	4	25	24	25	LF	$ 285,000	16,501	$ 554,819	0.337	0.90	6,579	1,410
25	4	25	24	15	LF	$ 262,100	17,959	$ 555,760	0.337	0.87	7,798	1,680
30	3	25	32	25	LF	$ 271,200	17,422	$ 556,073	0.338	0.86	7,556	1,613
25	4	25	24	30	LF	$ 274,100	17,262	$ 556,352	0.338	0.88	7,231	1,548
30	4	29	32	25	LF	$ 296,700	15,901	$ 556,702	0.338	0.90	5,998	1,129
30	4	25	32	30	LF	$ 299,800	15,711	$ 556,703	0.338	0.91	5,803	1,237
25	4	25	32	30	LF	$ 285,300	16,633	$ 557,272	0.338	0.89	6,542	1,391
20	4	25	24	25	LF	$ 256,000	18,425	$ 557,275	0.338	0.86	8,188	1,750
35	4	25	32	25	LF	$ 310,700	15,096	$ 557,548	0.339	0.92	5,292	1,135
35	3	25	32	25	LF	$ 285,700	16,641	$ 557,812	0.339	0.87	6,915	1,487
25	4	29	32	25	LF	$ 282,200	16,869	$ 558,037	0.339	0.89	6,790	1,277
30	4	25	24	15	LF	$ 276,600	17,214	$ 558,078	0.339	0.89	7,196	1,555
25	4	29	24	25	LF	$ 271,000	17,577	$ 558,406	0.339	0.88	7,527	1,419
30	4	25	24	30	LF	$ 288,600	16,501	$ 558,419	0.339	0.90	6,579	1,410
20	4	25	24	15	LF	$ 247,600	19,013	$ 558,495	0.339	0.86	8,649	1,857
20	4	25	32	25	LF	$ 267,200	17,817	$ 558,530	0.339	0.87	7,483	1,595
30	3	29	32	25	LF	$ 271,700	17,589	$ 559,301	0.340	0.86	7,760	1,458
25	4	25	40	25	LF	$ 292,900	16,312	$ 559,627	0.340	0.90	6,069	1,287
30	3	25	32	30	LF	$ 274,800	17,423	$ 559,690	0.340	0.86	7,557	1,613
25	5	25	24	25	LF	$ 295,500	16,165	$ 559,822	0.340	0.91	5,987	1,283

Figure 5.8 : HOMER Optimization results

Figure 5.9 gives a comprehensive summary of the net present values of different costs involved in the project throughout its lifetime of 20 years. These costs are further illustrated in Figure 5.10 as a discounted cash flow graph for the project lifetime. Here we can see, after 15 years battery replacement occurs. But the diesel generator replacement does not occur within 20 years lifetime of the project, because the hours of operation of the generator during a year is about 1240 and therefore the total operating hours of the generator during the project lifetime is 24800 which is less than the lifetime operating hours of the generator (25000 hrs).

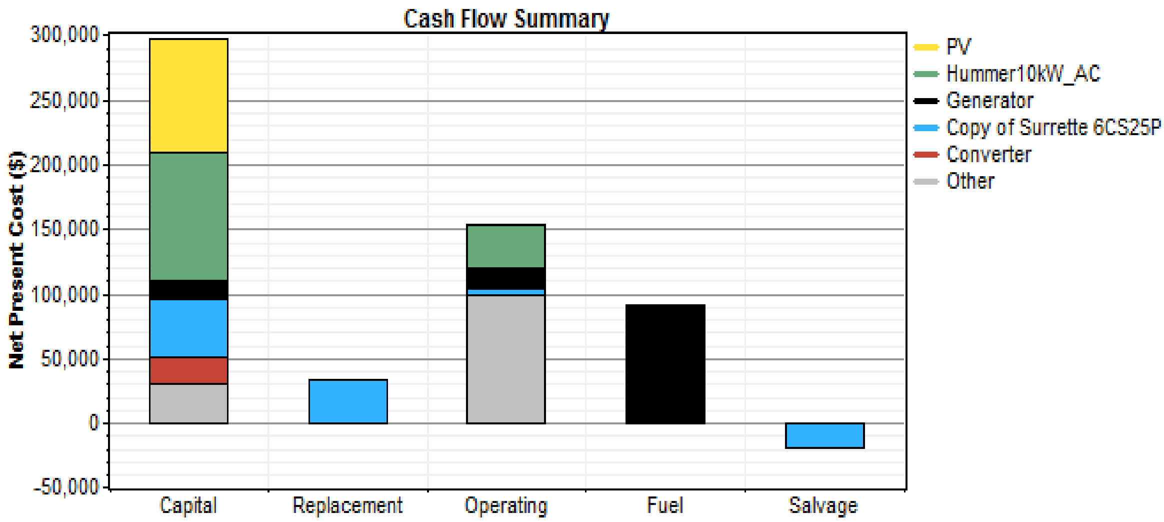


Figure 5.9 : Cost summary of the project

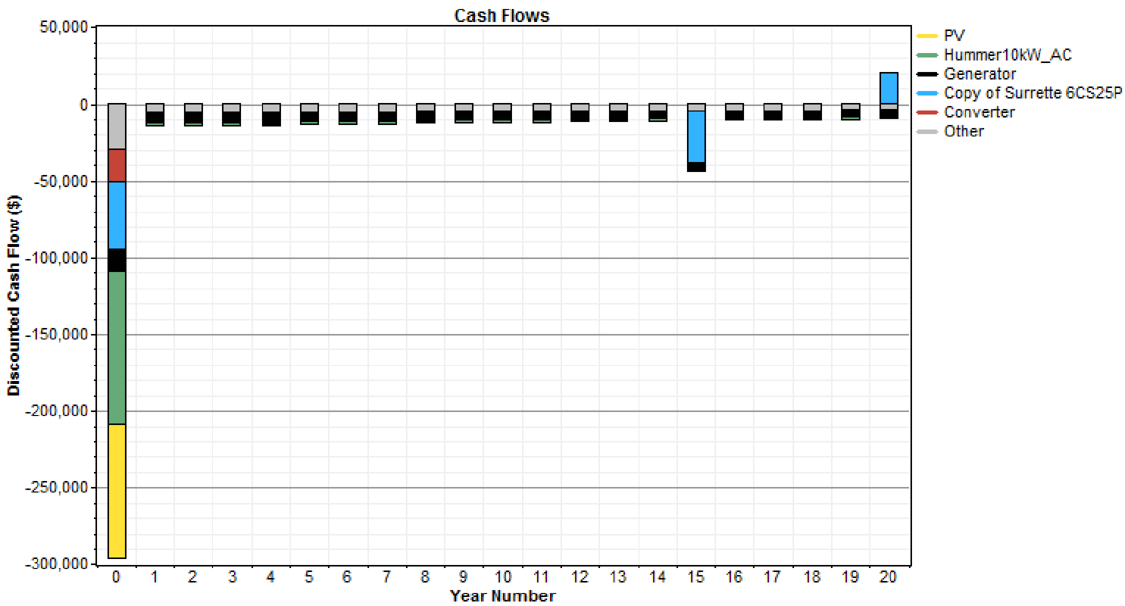


Figure 5.10 : Discounted cash flow of the project throughout the lifetime

5.3.1. Performance of the Hybrid System

Monthly average electric power production from each of the system components in the hybrid system is shown in Figure 5.11. Here we can see that the largest percentage of the power is generated by the wind turbines. Especially the generated power from the wind turbines is considerably higher during the months from May to September. On the other hand the average power generated from the wind turbines is relatively small during the period of March to April. Therefore, the diesel generator has to produce much more energy during March to April than the other month. As can be seen in the figure, energy generation from the renewable systems is considerably high during May to September. But still there is a contribution from the diesel generator. That implies that the diesel generator is still required to supply the peak demand during this period.

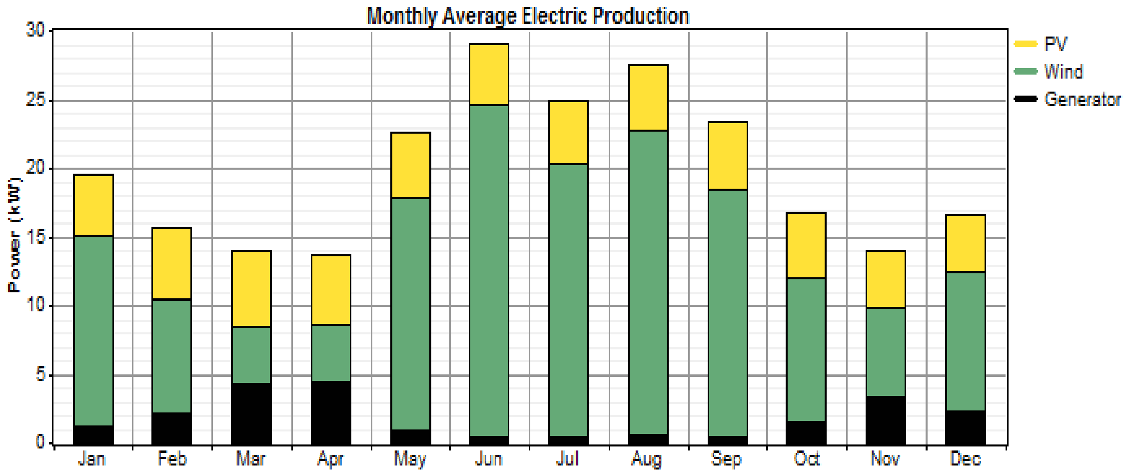


Figure 5.11 : Monthly average power production from different system components

Table 5.6 summarizes the annual energy generation figures from the different components and other relevant performance indicators of the hybrid system. The wind turbines generate the highest percentage of 67 % of the total annual energy generation while the diesel generator generates only 9 % of the total. Therefore the renewable fraction of the system is 0.91. As stated in the table, 35 % of the total annual energy generation is excess energy. The capacity shortage of this system is only 0.1 % which is very small resulting only 9 hours of load shedding during the whole year caused due to inability of producing enough power to meet the load. The generator dispatching strategy used here is the load following criteria, therefore the generator must be operated such that it produces only the required amount of power to cover the shortage capacity that cannot be supplied from the renewable systems or battery bank to meet the load. Further, the capacity factor of the PV system is 15.8 % which is relatively low and for wind turbines it is 33.1 % while for the diesel generator it is 7.5 %.

Table 5.6 : Electrical performance of the hybrid system

PV array energy production	41490 kWh/yr	24 %
Wind turbines energy production	116050 kWh/yr	67%
Diesel Generator energy production	16250 kWh/yr	9 %
AC primary load	100740 kWh/yr	
Excess electricity	60670 kWh/yr	35 %
Capacity shortage	65 kWh/yr	0.1 %
Renewable fraction	0.91	
Generator dispatch strategy	Load following	
Hours of operation of the diesel generator	1240 hrs/yr	

5.3.2. Effect of Changes in Annual Average Wind Speed and Solar Radiation

The selected hybrid system configuration is optimized for the annual average wind speed and the annual average solar radiation of 6.3 ms^{-1} and 5.0 $kWh/m^2/day$ respectively. Even though this system is not the optimum configuration outside this nominal solar radiation and wind speed figures, it can still meet the demand but with a higher cost of energy. Figure 5.12 and 5.13 illustrate how the energy cost of this system varies according to the variation of the annual average wind speed and solar radiation. They also show the variation of renewable fraction.

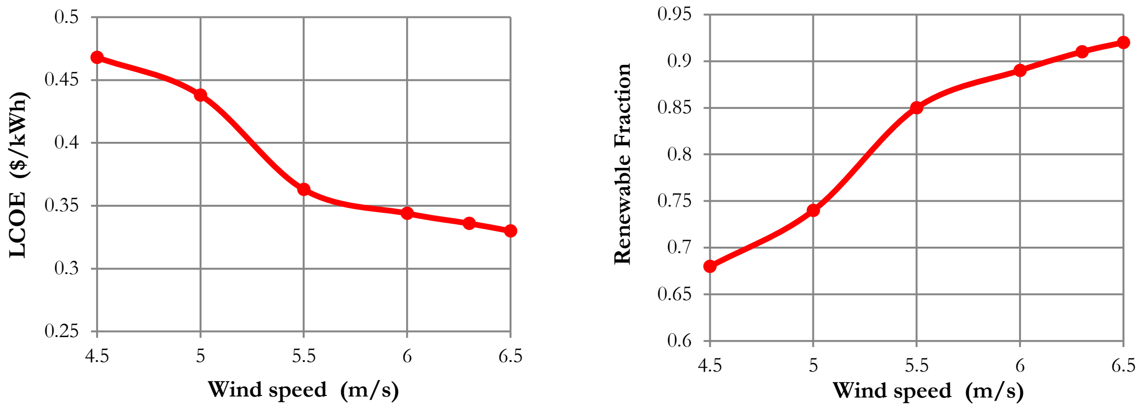


Figure 5.12 : LCOE and Renewable fraction at different annual average wind speeds

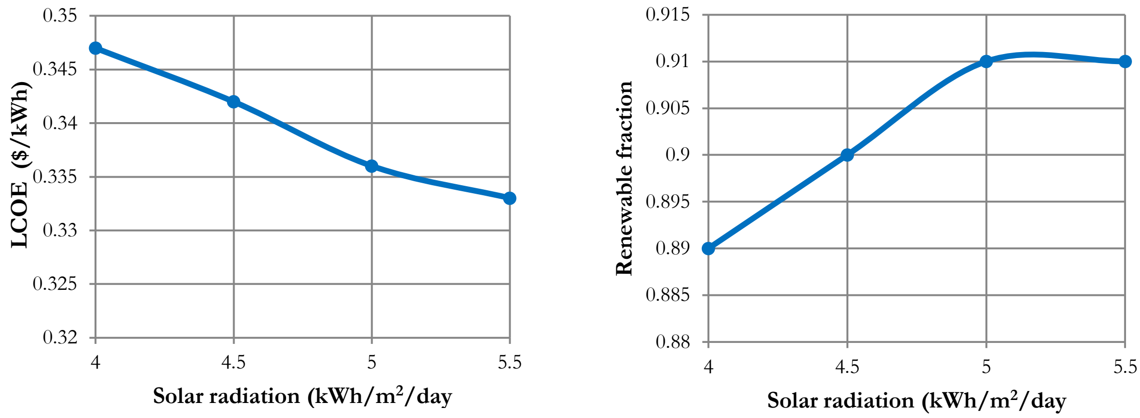


Figure 5.13 : LCOE and Renewable fraction at different annual average solar radiations

According to Figure 5.12 we can see that the LCOE increases as the annual average wind speed decreases and also we can observe decrease in the renewable fraction. Decreasing the renewable fraction implies that the hybrid system compensates the power reduction of the wind turbines due drop in annual average wind speed by increasing the power generation from the diesel generator. Therefore the cost of energy increases due to increase in the fuel cost. The increase in the cost for the variation in the annual average wind speed in the range of 4.5 ms^{-1} – 6.5 ms^{-1} is approximately 0.15 $/kWh (18 Rs/kWh). Similar variations can be observed for different annual average solar radiations too. But the change in the cost is not as high as in the case of wind speed. The reason is that the power output of the wind turbine is proportional to the cube of the wind speed. Therefore a small change in the wind speed results a large drop in the output power of the turbine thus affecting noticeably on the system performance. The power output of the PV array is proportional to the solar radiation thus a small change in the solar radiation does not change the power output of the PV array considerably. Therefore the effect of the energy cost is also not significant as shown in Figure 5.13. Within the range considered it is only about 0.01 $/kWh which is negligible.

Figure 5.14 and 5.15 further illustrate the variation of the LCOE and the renewable fraction with the variation of parameters, wind speed and solar radiation.

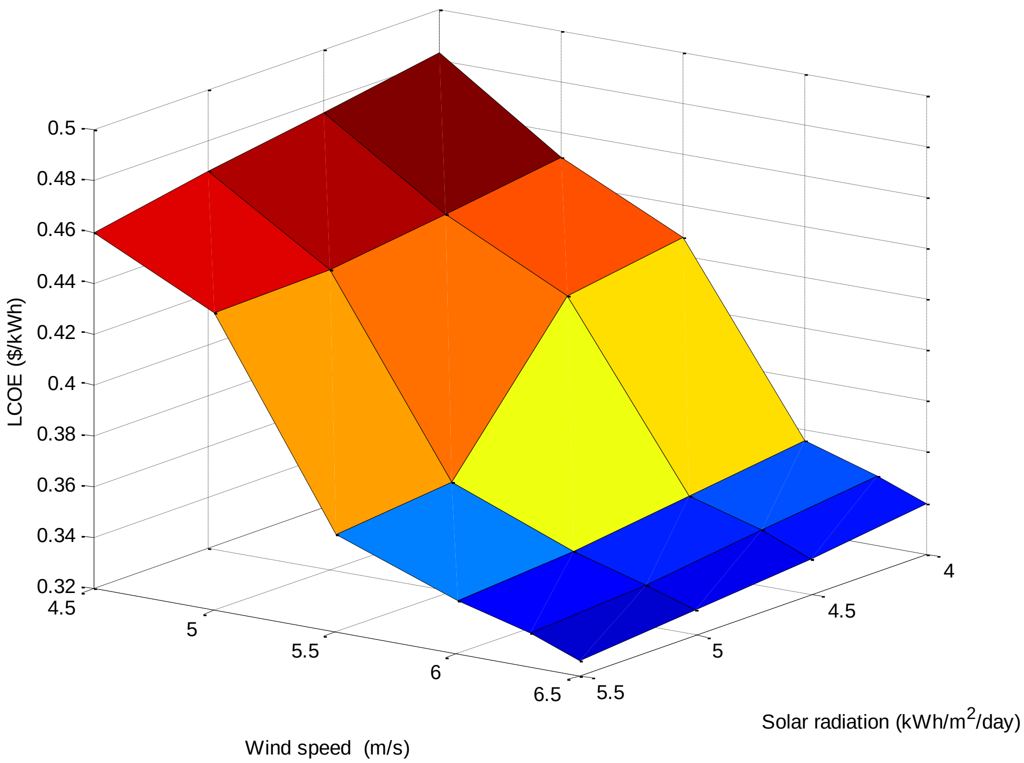


Figure 5.14 : Effect of changes in annual average wind speed and solar radiation on LCOE

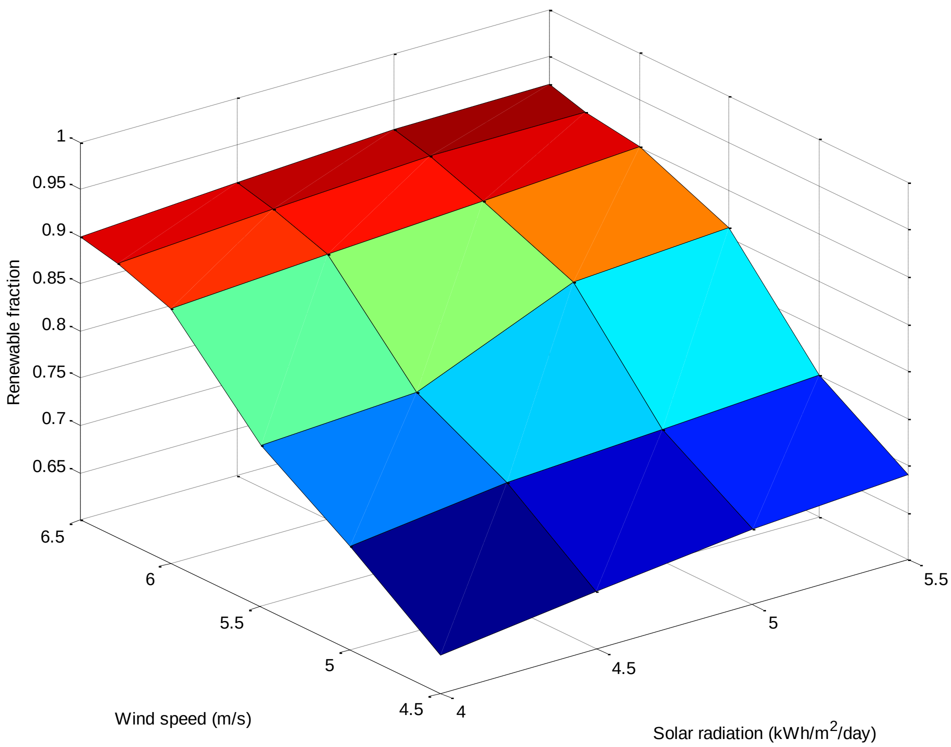


Figure 5.15 : Effect of changes in annual average wind speed and solar radiation on renewable fraction

5.3.3. Effect of Load Changes

In section, 2.2 I have derived the load profile of the village based on the certain assumptions. Thus, there might be some variations in this load profile in comparison with the actual load profile, which can be found only after implementing the project. On the other hand possibly there will be a load growth in the future. Thus it is important to analyze the optimized hybrid system for different average load profiles other than the nominal load profile considered earlier. This will help to find out whether this system is capable of supplying the growing demand or not and also in understanding how the LCOE varies for different annual average load conditions. HOMER analysis also helps to find the feasible solutions for growing demand as well. For example if it is required to augment the capacity of the system, then HOMER helps to determine which is the most economical solution under the specified conditions.

Here I have analyzed the effect of the load with respect to different annual average wind speeds. The reason for doing so is, because wind resource is more critical than solar resource. That is, the probability of changing the annual wind resource is typically higher than the solar resource. Besides, even small changes in the wind speed causes large variation in the turbine output power as discussed in section 5.3.2. Specially, in this study the optimum hybrid system has the largest power contribution from the wind turbines which is 67 % from the total generation. Therefore analyzing the effect of the load corresponding to the wind speed is important. The results of this analysis are illustrated in Figure 5.16 and 5.17.

From Figure 5.16, it can be seen that the selected hybrid system can supply the load without significant change in the cost of energy at a certain annual average wind speed even though the daily average load increases to 320 kWh/day. As the daily average load increases a reduction in the renewable fraction can be observed which implies that the hybrid system meets the growing demand by increasing the power generation by the diesel generator. However there is no big change in the LCOE as load grows for a certain annual average wind speed. Even though the average annual wind speed drops to 4.5 ms^{-1} the maximum change observed in the LCOE is about 0.15 $/kWh within the selected range in the load growth.

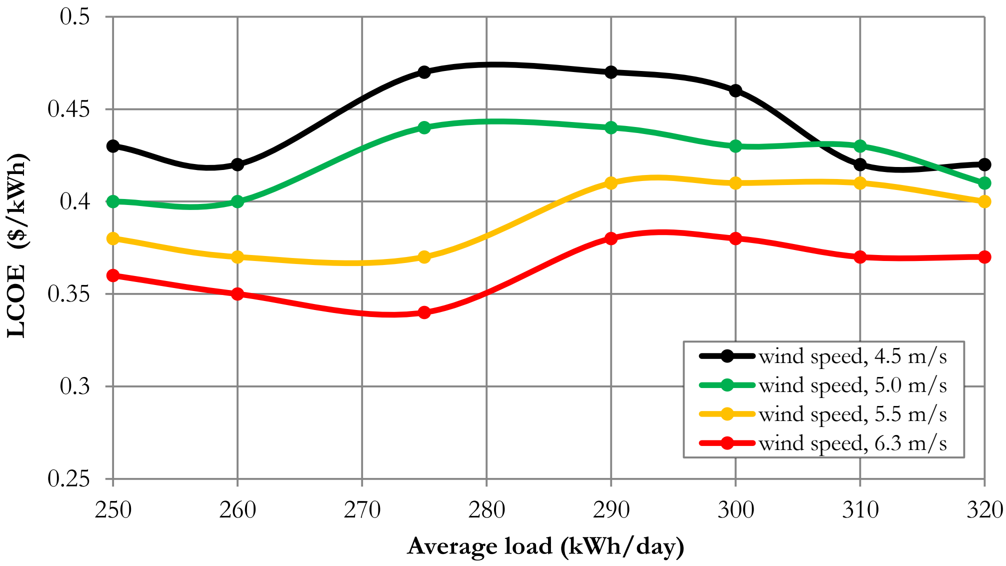


Figure 5.16 : Variation of LCOE for different daily average load

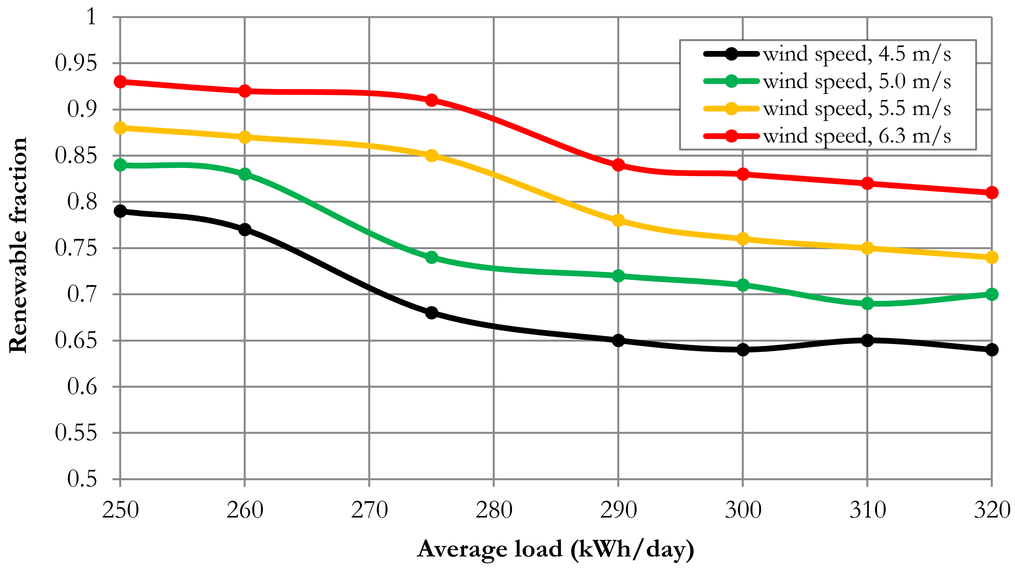


Figure 5.17 : Variation of Renewable fraction for different daily average load

5.4. System Optimization Considering the Effect of Emission Costs

All of the analysis that I have discussed so far were done without taking the benefits of reduction in the Green House Gas (GHG) emissions. But, when designing a renewable energy project it is important to account environmental benefits as well, because many countries put their efforts on mitigating the climate change with the associated increase in global temperature and sea level rise by taking precautionary measures to reduce GHG emissions. These precautionary actions include implementing policies in the sectors which produces GHGs and moving towards alternatives such as renewable energy. Thus, renewable energy acts a main role in reducing GHG emission targets defined by the countries. Already in several countries especially in developed countries, users are charged for each ton of GHG emission to encourage them for reducing the GHG emissions by changing their behaviors. Even though there is no such direct charging scheme for GHG emissions in Sri Lanka there have been many policy measures implemented so far in this context [43]. Therefore, it is worth to analyze this hybrid system by taking account the GHG emission costs as well. Here main concern has been given to Carbon Dioxide which is produced from the burning of diesel in the generator.

The current prices of CO_2 per ton are varying from country to country. For example the recent prices per ton of carbon emissions in EU countries are hovering around $ 11 [17] and in Australia it is about $ 24 while in the US the price is floating around $ 21 [18] . China is also going to introduce carbon tax of 10 yuan ($ 1.6) per ton of CO_2 but still the start date is undecided[19]. By looking at these figures and comparing the economic situation in Sri Lanka with these countries it is fairly

17 www.spiegel.de/international/europe/europe-looks-to-fix-problems-with-its-carbon-emissions-trading- system-a-863609.html

18 www.huffingtonpost.com/2012/09/20/carbon-dioxide-cost-per-ton_n_1898306.html

19 www.oilseedcrops.org/2013/02/19/china-to-introduce-carbon-tax-of-10-yuan-per-ton-start-date-undecided/

difficult to decide a price per ton of CO_2 in Sri Lanka's point of view. However I have assumed a value of $ 10 per ton and have done the analysis.

PV (kW)	H10kW	Gene (kW)	S6CS25P	Conv. (kW)	Disp. Strgy	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Gene (hrs)
30	4	25	32	25	LF	$ 296,200	15,864	$ 555,601	0.337	0.91	5,803	1,237
25	4	25	24	25	LF	$ 270,500	17,452	$ 555,866	0.337	0.88	7,231	1,548
25	4	25	32	25	LF	$ 281,700	16,805	$ 556,488	0.338	0.89	6,542	1,391
30	4	25	24	25	LF	$ 285,000	16,674	$ 557,651	0.339	0.90	6,579	1,410
25	4	25	24	15	LF	$ 262,100	18,165	$ 559,118	0.339	0.87	7,798	1,680
30	4	25	32	30	LF	$ 299,800	15,864	$ 559,202	0.340	0.91	5,803	1,237
30	4	29	32	25	LF	$ 296,700	16,059	$ 559,285	0.340	0.90	5,998	1,129
30	3	25	32	25	LF	$ 271,200	17,621	$ 559,327	0.340	0.86	7,556	1,613
25	4	25	24	30	LF	$ 274,100	17,452	$ 559,466	0.340	0.88	7,231	1,548
35	4	25	32	25	LF	$ 310,700	15,236	$ 559,827	0.340	0.92	5,292	1,135
25	4	25	32	30	LF	$ 285,300	16,805	$ 560,088	0.340	0.89	6,542	1,391
35	3	25	32	25	LF	$ 285,700	16,824	$ 560,790	0.340	0.87	6,915	1,487
20	4	25	24	25	LF	$ 256,000	18,641	$ 560,800	0.340	0.86	8,188	1,750
25	4	29	32	25	LF	$ 282,200	17,048	$ 560,961	0.341	0.89	6,790	1,277
30	4	25	24	15	LF	$ 276,600	17,404	$ 561,177	0.341	0.89	7,196	1,555
30	4	25	24	30	LF	$ 288,600	16,674	$ 561,251	0.341	0.90	6,579	1,410
25	4	29	24	25	LF	$ 271,000	17,775	$ 561,647	0.341	0.88	7,527	1,419

Figure 5.18 : HOMER Optimization results

According to the HOMER simulation results shown in Figure 5.18, it can be seen that the selected hybrid system has now been ranked in the 1st place and the total Net Present Cost of the project has increased slightly due to the addition of the emission cost, but there is no significant change in the LCOE. Therefore, it can be concluded that there is no significant effect of emission costs on the optimal hybrid configuration and the LCOE. The reason for this is that the capacity of the diesel generator using for this system is typically small and the contribution of this generator to the total energy generation is substantially low (9 %). Therefore, the diesel consumption of the generator is also low and thus the emissions as well. However, when compared to the diesel generator/battery power plant which can supply the electric energy requirement of the selected community, the annual CO_2 emission by the renewable energy based hybrid system given in Table 5.5 is particularly less which is about 1/6 order of the CO_2 emission by the diesel/battery system. Therefore renewable energy based hybrid systems are comparatively environmentally friendly when compared with diesel only power systems even though the hybrid system uses a small diesel generator.

5.5. Connection of the Hybrid System to the National Grid in the Future

The selected rural community in Sri Lanka for this study has not yet been electrified by the national grid. But, in the future the government may invest money for the extension of the national grid to this remote village as well. But how long it will take to accomplish this task is uncertain. However, if the grid is extended to the selected rural village during the lifetime of the hybrid system, then it will affect the cost returns of the project. It can influence either positively or negatively, because once the grid is available, the community will buy electricity from the national grid. On the other hand all the energy generated by the hybrid system can be sold to the grid. Therefore it is important to analyze the effect on the LCOE if the national grid is available in the future.

For this analysis I have made the assumptions that the community will have access to the electricity from the national grid after 10 years and the hybrid power system is developed and operated by an Independent Power Producer (IPP). Under these assumptions, the community will buy electricity from the micro grid which is based on the hybrid system or in other words from the Independent Power Producer during the first 10 years and then from the national grid. Hence the IPP can sell the electricity generated by the hybrid power system to the community during the period where national grid is not available. Once the national grid is available, the hybrid system can be connected to the grid and all the energy generated by the hybrid system can be sold to the national grid. When the hybrid system is connected to the grid, the diesel generator and the battery bank will not be required any longer, thus they can be decommissioned. Then the hybrid system will consist only renewable systems that is, 4 wind turbines with the total capacity of 40 kW and the PV system with the capacity of 30 kW.

The LCOE analysis of the project has been made considering off grid operation of the hybrid system for the first 10 years and grid connected operation for the next 10 years. All relevant costs including the initial capital investment, operating and maintenance cost, battery and generator replacement costs, salvage values and the earnings made by selling electricity to the grid after connection to the grid has been taken to the LCOE analysis. HOMER simulation has been made to find the amount of energy that the hybrid system can sell to the national grid annually. According to the HOMER simulations it has been found that both wind turbines and PV system together can generate 157500 kWh of energy during a year. The purchasing cost of the energy has been considered as 0.16 $/kWh which is the current purchasing price of the energy generated from wind and solar by the Ceylon Electricity Board.

The present value of each cost that will make n-year later is calculated by the following equation.

$$C_{NPC} = C\left(\frac{1+i'}{1+d}\right)^n \tag{5.1}$$

Where ;

i' is the inflation rate (%)

d is the interest rate (%)

It has been assumed that the inflation rate is 5 % and the interest rate is 7 %. The detailed calculations of the net present value of the system lifetime cost are given in the Appendix B. It has been found that the net present value of the lifetime cost of the project is $ 269000. In order to find the LCOE, the total net present cost of the project must be converted to series of equal annual cash flows which is known as total annualized cost. The following equation is used to calculate the total annualized cost.

$$\text{Total annualized cost (\$/year)} = \text{Total NPC} \times \text{CPF} \tag{5.2}$$

Where, CPF is the Capital Recovery Factor and it is calculated by the formula 4.3. Once the total annualized cost is found, the LCOE of the electricity generated by the hybrid energy system can be calculated using the equation 4.5. Since the electricity generated by the hybrid system can be sold to the community only before connection to the grid, the total annualized cost has been calculated considering 10 years. That is the first 10 years of operation of the hybrid system after commissioning the project. It has been found that the annualized cost of the project is 30000 $/year and the LCOE is 0.3 $/kWh. This cost is less than the LCOE obtained for the case of off grid operation (0.34 $/kWh) of the hybrid system during the whole lifetime of 20 years. Therefore it can be concluded that this system is economical to implement even though the grid will be extended to the Siyambalanduwa area in the future. That is the effect of connecting the hybrid system to the national grid after some time of off-grid operation affects positively on the cost returns. If the electricity is sold at a price which is higher than the calculated LCOE mentioned in section 5.3 for the off-grid operation during the whole lifetime, then the project will make profits for both off grid and grid connected operation.

5.6. Replacing the Four Wind Turbines with a 50 kW Wind Turbine

The optimal hybrid system selected before consisting of 4 wind turbines with each rated capacity of 10 kW resulting total capacity of 40 kW. This 4 wind turbines can be replaced by a single wind turbine having rated capacity of 40 kW. Using a single turbine instead of 4 wind turbines will reduce the installation cost as well as the maintenance cost. Therefore I have performed simulations by considering one 50 kW wind turbine rather than four 10 kW wind turbines. I have chosen a 50 kW wind turbine, because 50 kW wind turbines are more widely available in the market than 40 kW wind turbines. I have selected the Hummer H12.5-50 kW wind turbine which costs around $ 78900 [20]. The specifications of this wind turbine are given below and the power curve of the turbine is given in Figure 5.19.

Rated power	50 kW
Maximum output power	75 kW
Start up wind speed	3 ms^{-1}
Rated wind speed	11 ms^{-1}
Working wind speed	3 – 25 ms^{-1}
Generator efficiency	> 0.92
Generator type	Permanent Magnet Alternator
Blade diameter	12.0 m
Tower height	18 m
Design lifetime	20 years

The total installed cost of the turbine including shipment cost, local transportation cost, turbine installation cost and wiring cost has been considered as $ 95000 and the annual operating and maintenance cost has been considered as $ 800. HOMER simulation results for this hybrid configuration is given in Table 5.7. As shown in Table 5.7, it can be seen that the energy cost can be reduced to 0.28 $/kWh by replacing the 4, 10 kW wind turbines with a 50 kW wind turbine. The renewable fraction of this system is 0.97 which is very good. Therefore, the diesel generator supplies only 3 % of the total annual load resulting total annual operating hours of the diesel generator of 530 hours. Further, the installed capital of the system is $ 291200 and the total net present cost of the system for 20 years of lifetime is $ 461000 which is $ 92000 less than the net present cost of the system given in Table 5.5.

[20] Email correspondence

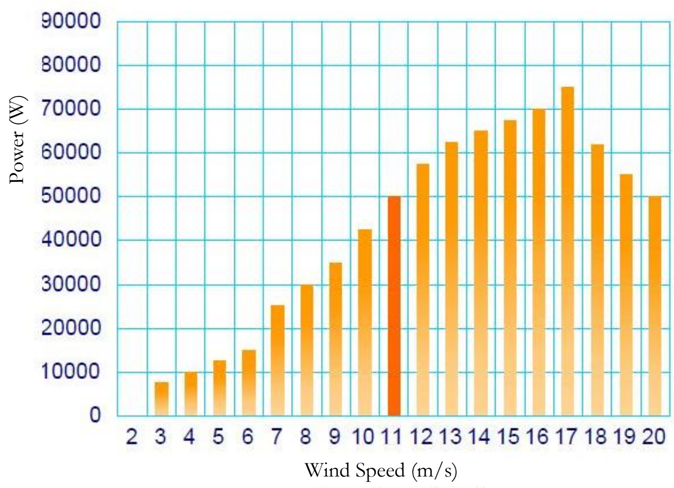


Figure 5.19 : Power curve of the Hummer H12.5-50 kW wind turbine

Table 5.7 : Performance of the hybrid system with a 50 kW wind turbine

LCOE	0.28 $/kWh	
Renewable fraction	0.97	
Diesel generator operating hours	530 hrs/yr	
Dispatch strategy	Load Following	
Annual generation		
PV array	41500 kWh/yr	(21 %)
Wind turbine	147800 kWh/yr	(75 %)
Diesel generator	6850 kWh/yr	(3 %)
Capacity shortage	0 %	

However, before selecting a 50 kW wind turbine instead four 10 kW wind turbines it should be ensured that whether proper transportation facilities are available or not to reach the rural village considered, because the size of a 50 kW wind turbine is relatively large, having a radius of the turbine blades of about 6 m. Therefore proper roads are required to transport this turbine to the site. Hence, attention must be given to this issue when replacing several small turbines with a large wind turbine.

5.7. Design of the Hybrid System

According to the HOMER simulations it has been found that the following hybrid configuration is the optimal hybrid configuration which can supply the electricity at a lowest cost with an accepted level of availability to the selected community from the Siyambalanduwa region in Sri Lanka.

PV capacity	30 kW
Number of 10 kW wind turbines	4
Diesel Generator capacity	25 kW
Battery bank/Number of 1156 Ah batteries	222 kWh/32
Capacity of the bi-directional inverter	25 kW

The connection diagram of these components is given in Figure 5.20. An AC coupled hybrid configuration is used in designing the system. In this connection, all electricity generating components are connected to the AC bus. As PV arrays generate DC electricity, they are connected to the AC bus via solar inverters. Since the capacity of the PV system is 30 kW, 3 SMA Sunny Boy inverters having capacity of 10 kW each have been used as shown in Figure 5.20. More details on the connection of 10 kW PV system is given in Figure 5.21. The MPP voltage range on the DC side of the sunny boy inverter is 333 V – 500 V and the MPP voltage of the Canadian solar 240 W module is 29.9 V. Thus, 14 solar modules have been connected in series to adjust the array output voltage in the range of DC input voltage range of the inverter. Since 10 kW PV system requires 42 PV modules, they have been arranged into 3 strings and each string contains 14 series connected PV modules. The optimum operating current of a single PV module at standard condition is 8.03 A. Thus, the maximum total input current to the inverter by three strings at MPP operation is 24.09 A, which is less than the rated input current of the inverter (31 A).

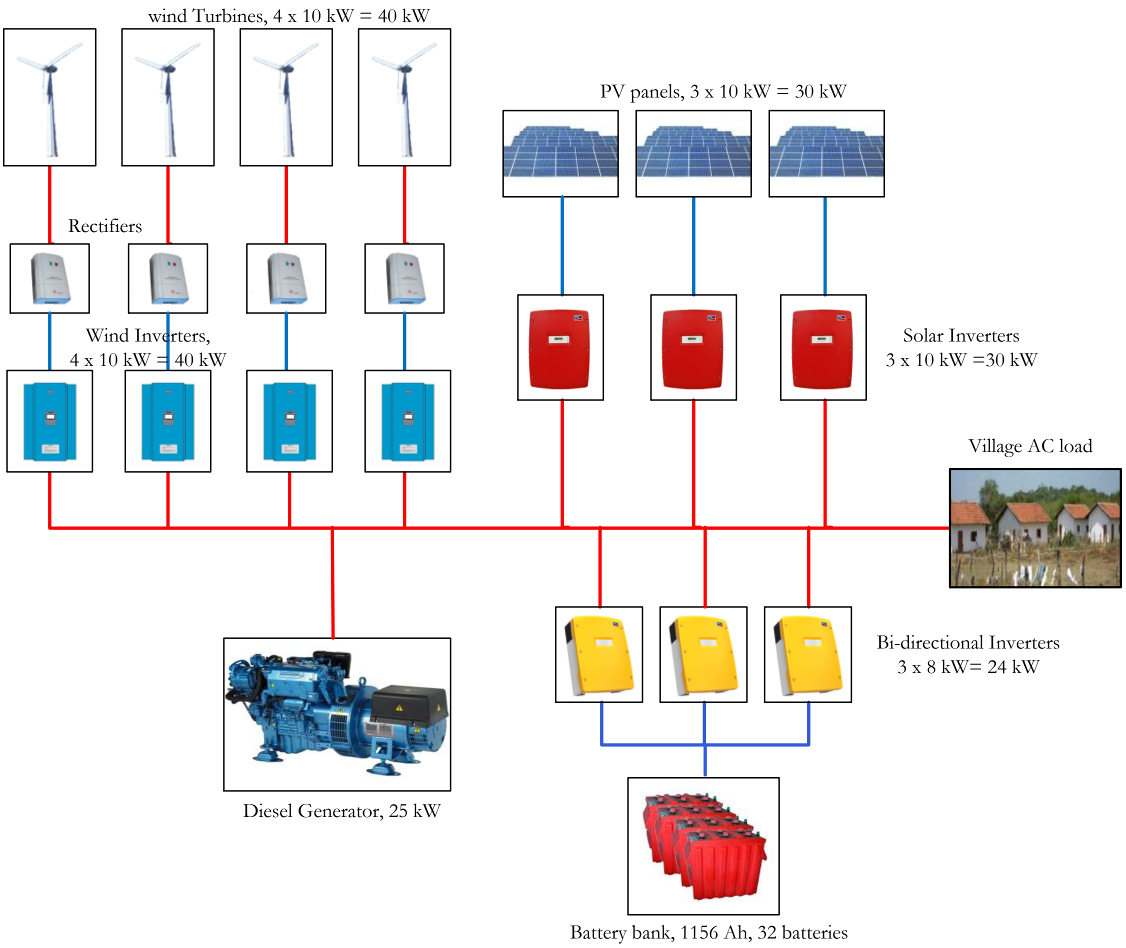


Figure 5.20 : An AC coupled hybrid power system

The wind turbine contains a permanent magnet alternator type generator which generates single phase AC electricity. This AC is rectified and fed into the inverters. The controller monitors and adjust the status of the generator with respect to the changes in the wind resource. The power requirement of the controller can be supplied from the grid. The controller itself contains a DC power supply that converts AC input from the grid to 24 V, DC power. The excess energy generated from the turbine that is not required by the grid is diverted to the dump load by the dump load controller.

The battery bank consists of 32 Surrette 1156 Ah, 6 V flooded lead acid deep cycle batteries. The selected voltage of the DC bus is 48 V. Therefore 8 batteries have been connected in series to obtain the nominal voltage of the DC bus of 48 V. Four sets of series connected batteries are connected in parallel which gives altogether 32 batteries resulting nominal capacity of the battery bank of 222 kWh.

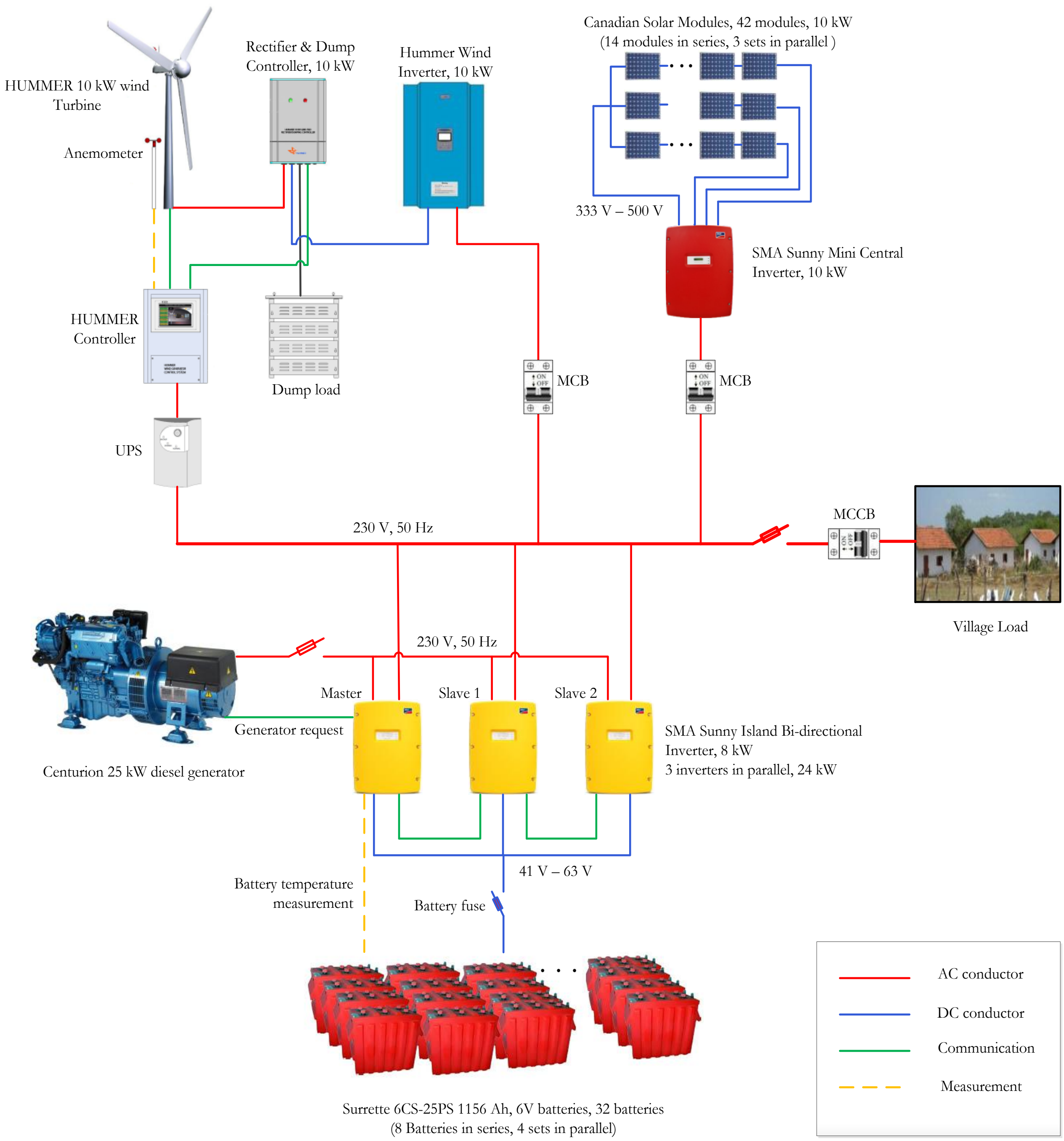


Figure 5.21 : Single line diagram of the hybrid system

Three parallel connected SMA Sunny Island–8 kW inverters have been used as the bidirectional inverter. This arrangement results total capacity of 24 kW as the rated capacity of the bi-directional inverter, which is less than the optimal capacity obtained from the HOMER simulation. But there is no significant difference in the operation of the overall system if a 24 kW inverter is used instead of a 25 kW unit according to the HOMER simulations. Thus this arrangement has been used.

Fuses, Miniature Circuit Breakers (MCB) and a Molded Case Circuit Breaker (MCCB) are employed in the system to protect the equipments and conductors from overload and over current conditions. A MCCB is used to limit the total load of the micro grid to the required level and also to protect the equipments from over currents created due to faults in the micro grid. According to the load profile, the maximum demand of the village is about 25 kW. By keeping 5 kW additional capacity for the uncertainty of the load, a MCCB with a nominal rated capacity of 130 A is selected. The thermal release setting (for overload) and magnetic release setting (for over current) can be set with respect to the nominal rated capacity in the MCCB.

In order to maintain the proper operation of the hybrid system by maximizing the energy utilization generated by the renewable sources and minimizing the operating hours and fuel consumption by the diesel generator, the interactive operation of the individual components should be controlled by an intelligent hybrid management system. Energy Management System (EMS) can be either automatically or manually operated. A manually operated system requires well trained operator for controlling the system operation. On the other hand automatic system does not require human involvement. However, the design of the energy management system of the hybrid system is not in the scope of this thesis.

5.8. Economic Viability

Development of a rural electrification scheme based on a renewable hybrid power system in Siyambalanduwa region entails an initial capital investment of approximately $ 296000. This system can feed approximately 150 – 175 households including public utilities and several small businesses. This type of rural electrification schemes can be implemented either private sector based, utility based or as a combination of private sector and utility based. However, the government subsidies will be essential to make the service affordable to the end users and to ensure the sustainability of the system even though the project is developed in either way, because the levelized cost of electricity (0.35 $/kWh) is substantially higher than the average price of the electricity from the national grid. In reality, the electricity price of rural electrification schemes cannot be equalized with the national grid tariff which already incorporates subsidies, particularly in developing countries. Nevertheless, development of proper tariff structure is a crucial factor in the design stage of the project in order to attract the private sector investors. Simultaneously, sustainable financing for O & M of the system must be ensured by the regulated purchase tariff. Generally the basic rule in the rural electrification project is that the tariff structure must cover at least the capital and the lifetime O & M cost of the project. The LCOE is the indicator that represents the flat electricity tariff that can cover the capital and the O & M cost of the project during the project lifetime.

Table 5.8 illustrates how the levelized cost of energy can be brought down with the capital subsidies from the government or Non-Governmental Organizations (NGO). Other than capital investment based subsidy, several subsidy schemes are available, for example connection based, output based and operation based [32]. Different schemes can lower the energy cost by different amounts. As showed in Table 5.8, the LCOE can be reduced by 0.1 $/kWh if subsidy is available for covering 40 – 50 % of the capital cost.

Table 5.8 : Effect of subsidies on the electricity price

Subsidy as a percentage of capital cost (%)	0	25	40	50	60
LCOE ($/kWh)	0.35	0.29	0.26	0.24	0.22

In contrast to the financial scheme, proper O & M scheme must be developed to ensure the sustainable operation of the rural electrification project. Local people can be trained for doing basic maintenance of the system and even for collecting the monthly fees from the consumers. O & M cost can be brought down by incorporating well trained local people. However, the service of skilled technicians will be required for major maintenance activities especially in the wind turbines and the diesel generator. Table 5.9 illustrates how the costs can be brought down by involving local trained people for maintaining the system. Training local people for monitoring the system operation and doing routine maintenance of the system will avoid the necessity of employing a full time technician thus reduces the administrative cost.

Table 5.9 : Effect of system fixed O & M cost on the electricity price

System fixed O & M cost ($/year)	6000	4000	2000	1000
LCOE ($/kWh)	0.34	0.32	0.30	0.29

If the annual fixed O & M cost can be brought down approximately to $ 1000 then the energy cost drops to 0.3 $/kWh, and with the capital subsidies of 40 – 50 %, the energy cost can be brought down approximately to 0.2 $/kWh. This is an acceptable and affordable price for the rural consumers.

5.9. Efficient Use of Electricity in the Microgrid

Efficient use of electricity is a key issue in rural electrification systems which are based on the hybrid power systems, because, the rated capacity of the generating systems is increasing as the peak demand of the community increases which then increase the capital cost substantially. In order to reduce the capital investment, the peak and the average load must be minimized as much as possible. Therefore, the inhabitants must be educated about the energy efficiency measures. At the same time, people should aware about their responsibilities and the system limitations. Usually in rural communities, lighting loads make the largest contribution to the total load. Thus people should be educated about the energy efficient bulbs (LED) and their long lifetime to eliminate purchasing cheap low efficient incandescent bulbs. In addition people should be given an understanding about the right time of using the certain electrical appliances such as electric irons and water pumps. By operating them during off peak hours the peak demand can be reduced. In addition, people must be encouraged to iron cloths of few days and avoid daily ironing. Further, suitable water pumps must be selected according to the pump lift and flow rate. All these can be done by conducting awareness programs for the inhabitant in the village. So, awareness programs also should be a part of the micro grid development scheme.

On the other hand an alarm system can be designed to avoid unwanted tripping of the main circuit breaker due to increase in load above the rated capacity of the hybrid system. For this, the village load should be continuously monitored and as it is about to reach the limits, a siren horn can be activated to encourage the people to switch off some electrical appliances for clipping the peak load. The people may give positive feedbacks on these alarms, because they know otherwise they have to face supply interruptions.

5.10. Comparison of Electricity Prices

Solar Home Systems (SHS) provide huge benefits to the people in rural communities where national grid electricity is not available. These systems are available from 10 Wp – 100 Wp and the prices vary depending on the size and the complexity of the system. However the costs of these systems are typically higher and cannot be afforded by low income rural inhabitants for a one time payment. Therefore, several loan schemes are available to make these systems viable for rural low income families in Sri Lanka. The cost of energy generated by these systems typically lies in the range of 0.28 – 0.30 $/kWh which is higher than the energy price of the micro grid based electricity (0.2 $/kWh with subsidies). In comparison with SHS, micro grid based electricity offers several benefits to the consumers. SHS can power only limited number of appliances including few CFL/LED bulbs, radio and a television. If users need to power many appliances then a system having a large capacity PV system and a battery must be purchased and they are high cost, thus rarely affordable.

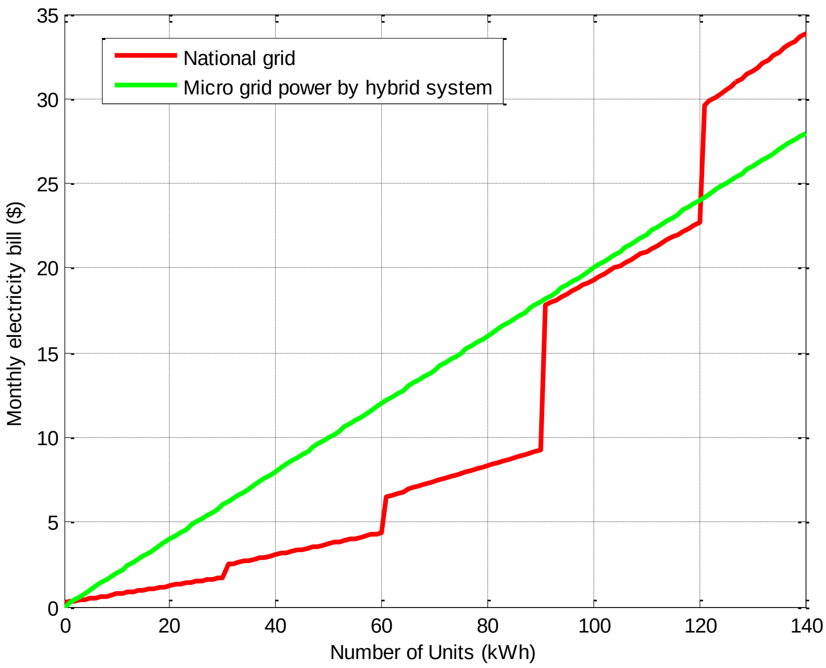


Figure 5.22 : Comparison of electricity cost

However, the cost of the electricity from the hybrid power system cannot be brought down to a price which is similar to the national grid price. Currently, the cost of electricity from the national grid for the domestic user lies in the range of 0.05 – 0.2 $/kWh depending on the number of monthly units consumed. In addition to the unit price, a monthly fixed charge of 0.24 $ – 2.5 $ is added and it also depends on the number of units consumed during a month. Figure 5.22 gives a comparison of the monthly total electricity costs from the national grid and the hybrid power system versus the number of units consumed per month for the domestic user. Here the cost of the electricity from the hybrid system has been assumed to be 0.2 $/kWh assuming that the government subsidies have been given for covering the 40 – 50 % of the capital cost of the project. It can be seen that the cost of electricity of the hybrid system is substantially higher than the electricity price from the national grid even with the capital subsidies, when the monthly electricity consumption is less than 120 kWh. Generally the electricity consumption in rural areas is not as high as in urban areas and probably lies below 80 kWh/month. Therefore, rural households cannot get electricity to a price like the national grid price. But practically, this is the most economical solution for electrifying rural communities where the grid extension is expensive and impractical.

Chapter 6

Discussion

The objective of the thesis has been to investigate the optimum size of a renewable energy-based hybrid power system which can supply electricity for a selected rural community in Sri Lanka. A rural village from the Siyambalanduwa region in Sri Lanka comprising approximately 150 households including several small businesses and public utilities has been selected for the analysis. The average daily load of this village is 270 kWh/day and an approximate maximum demand of 25 kW has been observed during the evening between 7:00 – 8:00 PM. A constant load profile listed in Figure 2.4 has been assumed throughout the year because the region is not affected by seasonal variations and the day length does not vary significantly because Sri Lanka is located close to the equator.

The Siyambalanduwa region receives an abundance of sunlight with an annual average solar radiation of 5.0 $kWh/m^2/day$. In addition, the annual average wind speed in the region is 6.3 ms^{-1} which results in a wind power density of 300 W/m^2 at a height of 50 m above the ground. Therefore solar and wind technologies have been selected as the candidate resources for electricity generation in the hybrid system except for the diesel generator and battery bank. Subsequently, simulations have been made for a large number of hybrid system configurations, and the net present value of the lifetime cost and the LCOE of each configuration have been calculated for a technical lifetime of 20 years in order to identify the lowest cost option.

Diesel powered micro grids seem to be economical based on the initial capital investment, because they require a very small capital investment when compared to renewable energy based hybrid systems. But lifetime cost analysis reveals that the fossil fuel-based micro grid has the highest lifetime cost due to its large O & M cost for fuels, generator maintenance and replacements. In contrast, hybrid systems entail a large capital investment, but lower O & M cost. Thus the lifetime cost analysis clearly shows that the hybrid systems are more economical than diesel powered micro grids. According to the results, the lifetime cost of a certain hybrid configuration greatly depends on the type of generating systems involved and their rated capacities. However, the least costly option that can meet the community's electricity demand under the specific requirements is the optimum solution. The decision concerning the final selection of the optimum configuration has been made based on both optimization and sensitivity analysis, which has not been done in most of the previous studies on hybrid system optimization using HOMER. The optimum configuration derived here is dependent on the load profile of the village and the potential of renewable resources on the site, thus this result is only valid for this site and should not be extrapolated to other communities. According to the simulation results, the following hybrid system configuration is found to be the optimized solution.

PV capacity	30 kW
Number of 10 kW wind turbines	4
Generator capacity	25 kW

Battery bank (1156 Ah, 48 V)	222 kWh
Converter capacity	25 kW

The renewable fraction of the optimized hybrid system mentioned above is 0.91, hence the diesel generator is required to supply only 9 % of the total annual load. The wind turbines generate annual energy of 116000 kWh which is the highest percentage (67 %) from the total annual energy generation. The remaining 24 % is generated by the PV system, which is approximately 41500 kWh/yr. This system can meet the load with an availability of 99.9 % resulting in only 9 hours of power outage during a year, however this excludes the power interruptions caused due to natural hazards or shut-downs for plant maintenance.

The optimal dispatch strategy of the diesel generator has been found to be "Load following" and the diesel generator should therefore be operated at a load such that it supply only the shortage capacity that cannot be supplied by the renewable energy system and battery bank. According to the simulation results, the hours of operation of the diesel generator during one year is approximately 1240 hours, which results in the total number of operating hours of the generator during the project lifetime of 20 years to be approximately 24800 hours. The lifetime operating hours of the diesel generator are 25000 hours, which is higher than the operating hours of the diesel generator during the entire lifetime of the project. Therefore, while it is not required to replace the diesel generator within the project life span, the battery bank should be replaced after 15 years, a procedure which costs around $ 33300. The lifetime cost analysis of the system showed that the project requires a capital investment of $ 297000. The net present value of the lifetime fuel cost is $ 91000 while the total O & M cost of the hybrid power system which primarily accounts O & M of the diesel generator, batteries and wind turbine is $ 153000. On the whole, the project is worth the net present cost of $ 553000 including the salvage values of the components.

According to the results, the hybrid power system can supply the electricity at an approximate levelized energy cost of 0.34 $/kWh. Moreover, the system can meet the demand without change in the LCOE more than 0.1 $/kWh for changes in the annual average wind speed in the range of 4.5 – 6.5 ms^{-1}. However, according to the obtained results there is no significant influence on the LCOE for the variation in the annual average solar radiation in the range of 4.0 – 5.5 $kWh/m^2/day$. In addition, the hybrid system can supply the load even though the average daily load increased by 15 % and the observed increase in the LCOE for the increase in load is below 0.05 $/kWh, which is negligible. Nonetheless, as the load increases, the renewable fraction drops more than by 10 %, thus increasing the power generation of the diesel generator. Further, analysis of the hybrid system by connecting to the utility grid assuming that the utility grid will extend to the rural village after 10 years reveals that it is beneficial for both rural consumers and the Independent Power Producer, because the villagers can then buy low cost electricity from the national grid, and IPP can increase revenue by selling all the power generated by the hybrid system to the grid. Moreover, the analysis has been made by replacing the 4 wind turbines by a single wind turbine having a rated capacity of 50 kW. The results reveal that the levelized energy cost can be approximately reduced to 0.28 $/kWh by replacing the 4 wind turbines with a 50 kW wind turbine. In addition, the renewable fraction has been improved to 0.97, resulting in annual operating hours of the diesel generator to 530 hours, which covers only the 3 % of the total annual load.

One of the important point revealed by this analysis is that, developing this kind of rural electrification scheme in Sri Lanka requires government subsidies to make the service affordable to the end user due to the fact that the energy cost obtained from the analysis is typically higher than the electricity price of the national grid. The present national grid electricity price for the domestic user lies in the range of 0.05 – 0.2 $/kWh depending on the number of kWh consumed during one month. In addition, a fixed charge of 0.24 – 2.5 $/month depending on the number of kWh consumed is also charged. When compared to this price, the levelized cost of electricity of the hybrid system (0.34 $/kWh) is relatively higher. However, in addition to subsidies, the active involvement of the local people to maintain the system is very important for reducing the operating and maintenance costs. As the results show, the energy costs can be lowered to approximately 0.2 $/kWh if the government funds become available for covering 40 – 50 % of the capital investment and by involving the local people to maintain the system.

Chapter 7

Conclusions and Future Work

The key objective of this thesis has been to find a techno-economic optimum sizing of an off grid hybrid power system for electrifying a rural community in Sri Lanka. The work was started by defining the typical load profile of the selected community. At the same time possible renewable resources that can be used to produce electricity have been identified by analyzing past data on the annual variations of solar radiation and wind speed. However, due to the unavailability of the hydro resource data, it is not considered in the analysis.

Off-grid renewable energy-based power systems cannot provide a continuous supply of electricity without a storage medium, due to the intermittent nature of the renewable resources. Thus, a battery bank has also been added to the hybrid system. In order to ensure the continuity of the supply without putting severe stress on the battery bank for a reduced overall cost, a diesel generator has also been included. Further, while various component configurations for the hybrid system have been studied, the AC coupled hybrid configuration has been selected mainly due to its easy expandability and the maximized efficiency of the diesel generator. After selecting the appropriate components and studying their characteristics, the hybrid system has been modeled in HOMER, and simulations have been made to determine the preeminent system which can supply the village load with the required level of availability. The lifetime cost of each hybrid configuration that can meet the continuous load demand has been calculated to determine the system which provides the lowest cost.

A PV/wind/battery bank/diesel generator hybrid system has been found as the optimum system with capacities of 30 kW, 40 kW, 222 kWh and 25 kW respectively. The estimated value of the levelized cost of energy obtained from the lifetime cost analysis is 0.34 $/kWh. It has been found that the cost can be further lowered approximately to 0.2 $/kWh with the reduction of O & M cost and with the help of the government subsidies. The energy cost of 0.2 $/kWh is acceptable and affordable for rural consumers, even though it is not as low as the price of the electricity from the national grid in Sri Lanka.

However, expanding the grid to the rural areas also requires a huge work incorporating large capital investment in building the medium voltage transmission lines, expanding the generation and grid substation capacities, building the low voltage distribution network and a great deal of other related tasks. On the other hand, in Sri Lanka more than 50 % of electricity generation is made by thermal power stations which are based on fossil fuels, and the remaining is generated by hydro power stations. In addition, the total installed capacity of the utility scale renewable energy systems is about 50 MW, and this is only 1.5 % of the total installed capacity. Nevertheless, Sri Lanka does not have any fossil fuel reserves; therefore, fuels for its thermal power stations have to be imported. Additionally, according to the Ceylon Electricity Board the hydro power potential within the country that can be used to generate electricity has already been exploited, and there is no possibility of building MW level power plants using hydro resources However, the comparison has finally been forced be made with fossil fuel-based electricity. As compared with the costs and losses involved when transmitting power from long distances to rural villages the renewable system based micro grids are more economical than the grid extension.

However, the analysis has also been performed by assuming that the grid will extend to the selected rural community after 10 years, and the micro grid has been developed by an IPP. According to the results obtained from this analysis, it can be concluded that the development of this micro grid rural electrification system is economically attractive whether it is connected to the grid or operated as an off-grid system. Further, the possibility of replacing the four wind turbines with a 50 kW wind turbine has been considered. The energy cost can be reduced from 0.34 $/kWh to 0.29 $/kWh by using a single large capacity wind turbine instead of four wind turbines.

Renewable energy systems are environmentally friendly, because they do not release any pollutant gases into the environment. The diesel generator used in the hybrid system generates only a small percentage (9 %) of the total load, thus a great reduction in the emissions of carbon and other greenhouse gases can be obtained when compared to the fossil fuel based electricity from the grid. That is also an added advantage of renewable energy based hybrid systems. Finally, it may be concluded that the hybrid power system is more economically attractive than grid electricity for electrifying the selected rural community in Sri Lanka under the condition that the system is properly gauged in accordance with the renewable resource potential and load condition in the village.

While this work has addressed the techno-economic optimal sizing section of the hybrid power system design for electrifying a rural community from the Siyambalanduwa region in Sri Lanka, it may move in several possible directions in the future. The interesting focuses for the future work are;

- Developing an energy management system for the micro grid.
- Developing a proper financial and business model by analyzing the economic condition in Sri Lanka as well as the selected rural community.
- Proposing a suitable operation and maintenance scheme which can ensure the sustainable operation of the system.
- Addressing the possibility of replacing the diesel generator in the hybrid system by locally generated biofuels.
- This system has not been delegated a hydro resource as a component in the hybrid system due to the unavailability of hydro resource potential data. Therefore, future analysis may be made by including the hydro resource in the hybrid system.

Bibliography

[1] S. Rolland and G. Glania, "Hybrid Mini-grids for Rural Electrification: Lessons Learned," Alliance for Rural Electrification, Brussels, 2011.

[2] "Population of Sri Lanka by District," Department of Census and Statistics , 2012.

[3] K. Sopian, A. Zaharim, Y. Ali, Z. M. Nopiah, J. A. Razak and N. S. Muhammad, "Optimal Operational Strategy for Hybrid Renewable Energy System Using Genetic Algorithms," *WSEAS Transactions on Mathematics,* vol. 7, no. 4, pp. 130-140, 2008.

[4] A. Ahmarinezhad, A. A. Tehranifard, W. Ehsan and F. Firuzabad, "Optimal sizing of a stand alone hybrid system for Ardabil area of Iran," *Technical and Physical Problems of Engineering,* vol. 4, no. 12, pp. 118-125, 2012.

[5] M. Bashir and J. Sadeh, "Optimal Sizing of Hybrid Wind/Photovoltaic/Battery Considering the Uncertainty of Wind and Photovoltaic Power Using Monte Carlo," in *Environment and Electrical Engineering (EEEIC)*, Venice, 2012.

[6] A. E. S. A. Nafeh, "Proposed Technique for Optimally Sizing a PV/Diesel Hybrid System," in *International Conference on Renewable Energies and Power Quality*, Granada (Spain), 2010.

[7] S. Farahat, M. A. Y. Jahromi and S. M. Barakati, "Modeling and Sizing Optimization of Stand-alone Hybrid Renewable Energy Systems," in *International Conference on Mechanical, Nanotechnology and Cryogenics Engineering (ICMNC'2012)*, Kuala Lumpur (Malaysia), 2012.

[8] R. Belfkira, C. Nichita, P. Reghem and G. Barakat, "Modeling and Optimal Sizing of Hybrid Renewable Energy System," in *International Power Electronics and Motion Control Conference (EPE-PEMC)*, Poznan, 2008.

[9] L. Zhang, R. Belfkira and G. Barakat, "Wind/PV/Diesel Energy System: Modeling and Sizing Optimization," in *Power Electronics and Applications*, Birmingham, 2011.

[10] H. Yang, W. Zhou, L. Lu and Z. Fang, "Optimal sizing method for stand-alone hybrid solar–wind system with LPSP technology by using genetic algorithm," *Solar Energy,* vol. 82, p. 354–367, 2008.

[11] M. Muralikrishna and V. Lakshminarayana, " Hybrid (solar and wind) Energy Systems for Rural Electrification," *Engineering and Applied Sciences,* vol. 3, no. 5, pp. 50-58, 2008.

[12] S. Ashok, "Optimized model for community-based hybrid energy system," *Renewable Energy,* vol. 32, pp. 1155-1164, 2007.

[13] A. Kaabeche, M. Belhamel and R. Ibtiouen, "Optimal sizing method for stand-alone hybrid PV/wind power generation system," in *Revue des Energies Renouvelables SMEE'10 Bou Ismail Tipaza*, 2010.

[14] G. Bekele and B. Palm, "Feasibility study for a stand-alone solar–wind-based hybrid energy system for application in Ethiopia," *Applied Energy,* vol. 87, p. 487–495, 2010.

[15] O. Hafez and K. Bhattacharya, "Optimal planning and design of a renewable energy based supply system for microgrids," *Renewable Energy,* vol. 45, pp. 7-15, 2012.

[16] A. Helal, R. El-Mohr and H. Eldosouki, "Optimal Design of Hybrid Renewable Energy System for Electrification of a Remote Village in Egypt," in *International Conference on Communications, Computing and Control Applications (CCCA)*, Marseilles, 2012.

[17] M. Khan and M. Iqbal, "Pre-feasibility study of stand-alone hybrid energy systems for applications in Newfoundland," *Renewable Energy,* vol. 30, p. 835–854, 2005.

[18] C. Kirubi and A. Jacobson, "Community-Based Electric Micro-Grids Can Contribute to Rural Development: Evidence from Kenya," *World Development,* 2009.

[19] N. A. A. Razak, M. M. B. Othman and I. Musirin, "Optimal Sizing and Operational Strategy of Hybrid Renewable Energy System Using HOMER," in *International Conference on Power Engineering and Optimization (PEOCO)*, Selangor, Malaysia, 2010.

[20] R. B. Roy, "Design and Cost Analysis of Hybrid Power System for Off-Grid Rural Areas of Bangladesh," *Electrical and Electronics Engineering,* vol. 3, no. 7, pp. 413-423, 2012.

[21] U. Sureshkumar, P. S. Manoharan and A. P. S. Ramalakshmi, "Economic Cost Analysis of Hybrid Renewable Energy System using HOMER," in *International Conference On Advances In Engineering, Science And Management*, Nagapattinam, Tamil Nadu, 2012.

[22] "Households in occupied housing units in districts, Divisional Secretary's Divisions and Grama Niladhari Divisions by principal type of lighting," Department of Census and Statistics, 2012.

[23] "Microgrids- Promotion of Microgrids and renewable energy sources for electrification in developing countries," Intelligent Energy, Europe, 2008.

[24] C. V. Nayar, "Diesel Generator Systems," *Electrical India,* vol. 50, no. 6, June 2010.

[25] "Surface meteorology and Solar Energy, A renewable energy resource web site (release 6.0)," Prediction of Worldwide Energy Resource Project, [Online]. Available: http://eosweb.larc.nasa.gov/cgi-bin/sse/sse.cgi?rets@nrcan.gc.ca.

[26] C. Schillings, R. Meyer and F. Trieb, "Solar and Wind Energy Resource Assessment (SWERA)," UNEP, 2004.

[27] J. A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, John Wiley & sons, inc., 1980.

[28] "HOMER User Manual," National Renewable Energy Laboratory.

[29] D. Elliott, M. Schwartz and G. Scott, "Wind Energy Resource Atlas of Sri Lanka and the

Maldives," NREL, 2003.

[30] C. G. Justus and A. Mikhail, "Height variation of wind speed and wind distribution statistics," *Geophysical Research Letters,* vol. 3, pp. 261-264, 1976.

[31] W. Tong, Wind Power Generation and Wind Turbine Design, WIT Press, 2010.

[32] S. Rolland and G. Glania, "Rural Electrification with Renewable Energy: Technologies, quality standards and business model," Alliance for Rural Electrification, Belgium, 2011.

[33] J. Manwell, J. Mcgowan and A. Rogers, Wind Energy Explained- Theory, Design and Application, John Wiley & Sons, 2002.

[34] M. Hankins, Stand-Alone Solar Electric Systems, Earthscan, 2010.

[35] N. R. E. Laboratory, "Small Wind Electric Systems," U.S. Department of Energy, 2007.

[36] A. Mcevoy, T. Markvart and L. Castaner, Solar Cells - Materials, Manufacture and Operation, Elsevier, 2013.

[37] M. Kolhe, S. Kolhe and J. Joshi, "Economic viability of stand-alone solar photovoltaic system in comparison with diesel-powered system for India," *Energy Economics,* vol. 24, pp. 155-165, 2002.

[38] T. Crompton, Battery Reference Book, Reed Educational and Professional Publishing Ltd, 1990.

[39] *Surrette Deep Cycle 6CS25PS, 6 V battery Data Sheet.* [Performance]. Surrette Battery Co. Ltd..

[40] A. Cherif, M. Jraidi and A. Dhouib, "A battery ageing model used in stand alone PV systems," *Power Sources,* vol. 112, pp. 49-53, 2002.

[41] S. Energy International, Photovoltaics design and installation manual, Canada: New Society Publishers, 2004.

[42] V. A. Graham and K. G. T. Hollands, "A method to generate synthetic hourly solar radiation globally," *Solar Energy,* vol. 44, pp. 333-341, 1990.

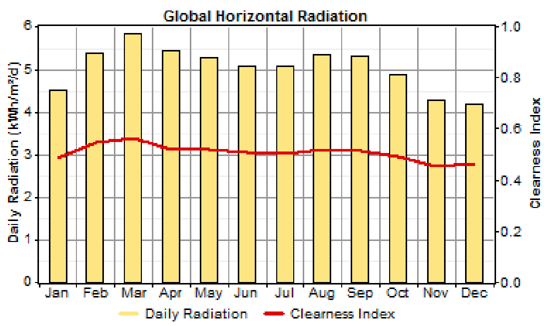
[43] D. Ranasinghe, "Climate Change Mitigation - Sri Lanka Perspective," in *International Forestry and Environment Symposium*, Sri Lanka, 2010.

Appendix A

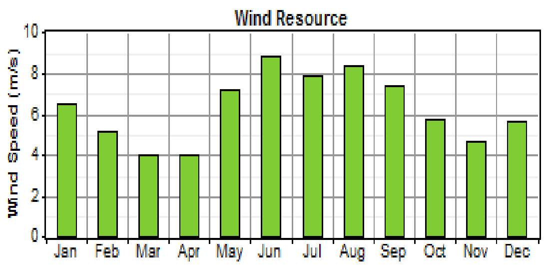
HOMER software; Input Summary

A.1. The following table gives the renewable resource inputs that have been given as inputs to the HOMER hybrid model.

Solar Resource

Monthly average solar radiation	

Wind Resource

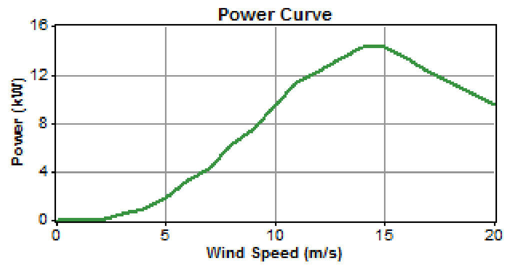
Monthly average wind speed	
Altitude	85 m
Anemometer height	50 m
Weibull k	2
Autocorrelation factor	0.94
Diurnal pattern strength	0.25
Hour of peak wind speed	20
Surface roughness length	0.001 m

A.2. The following table gives the technical specifications of the components used in the hybrid system which have been given as inputs to the HOMER hybrid model.

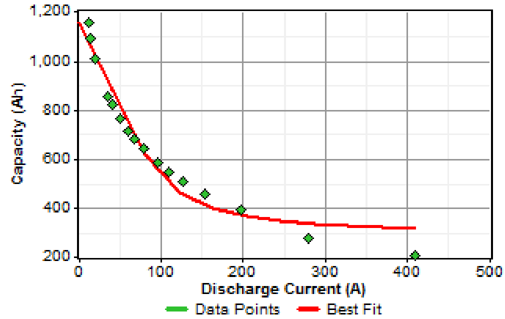
PV System

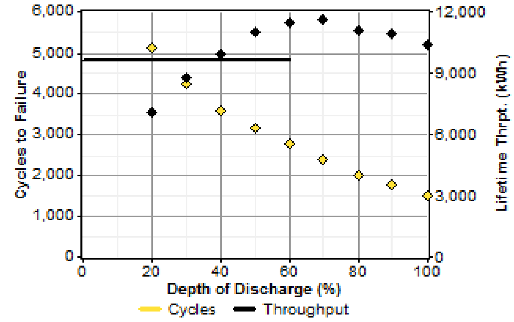
Model	Canadian Solar CS6P-240P
Peak power	240 W
Derating factor	80 %
Slope	6.8⁰
Azimuth	0⁰
Ground reflectance	20 %
Temperature coefficient	-0.43 %/⁰C
Nominal operating temperature	45 ⁰C
Efficiency at standard test conditions	14.92 %
Lifetime	20 years

Wind turbine

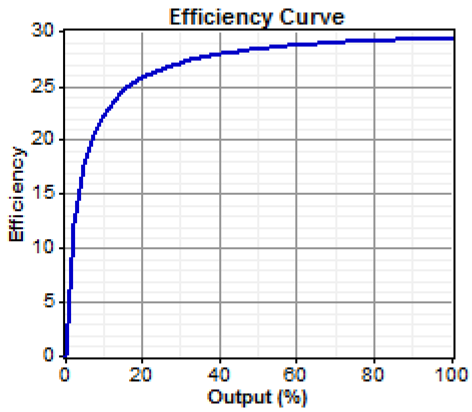
Model	Hummer H8.0-10kW
Rated power	10 kW
Power Curve	
Hub height	15 m
Lifetime	20 years

Battery

Nominal voltage	6 V
Nominal capacity	1156 Ah
Lifetime throughput	9645 kWh
Round trip efficiency	80 %
Min. state of charge	40 %
Float life	15 years
Maximum charge rate	1 A/Ah
Max. charge current	41 A
Capacity curve	

Lifetime curve	
Batteries per string	8 (48 V, DC bus)

Diesel generator

Lifetime (operating hours)	25000 hours
Minimum load ratio	50 %
Fuel	Diesel
Fuel cost ($/L)	$ 0.96
Efficiency curve	

Converter

Lifetime	20 years
Efficiency	85 % (3 inverters having individual efficiency of 95 % operates in parallel)

Economics

Annual interest rate	2 %
Project lifetime	20 years
System fixed capital cost	$ 30000
System fixed O & M cost	6000 $/year
Capacity shortage penalty	0

Appendix B

Grid Connected Analysis

The detailed calculation of the NPC of the hybrid system if the hybrid system is connected to the national grid after 10 years of off-grid operation is given in the Table A.1.

Table B.1 : Calculation of the otal NPC of the project

	Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	Total
PV	Capital	-87,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-87000
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Operating	0	-29	-29	-28	-28	-27	-27	-26	-26	-25	-25	-24	-24	-23	-23	-22	-22	-21	-21	-21	-20	-491
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	-87,000	-29	-29	-28	-28	-27	-27	-26	-26	-25	-25	-24	-24	-23	-23	-22	-22	-21	-21	-21	-20	-87491
Wind turbine	Capital	-100,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-100000
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Operating	0	-1,961	-1,922	-1,885	-1,848	-1,811	-1,776	-1,741	-1,707	-1,674	-1,641	-1,609	-1,577	-1,546	-1,516	-1,486	-1,457	-1,428	-1,400	-1,373	-1,346	-32704
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	-100,000	-1,961	-1,922	-1,885	-1,848	-1,811	-1,776	-1,741	-1,707	-1,674	-1,641	-1,609	-1,577	-1,546	-1,516	-1,486	-1,457	-1,428	-1,400	-1,373	-1,346	-132704
Generator	Capital	-14,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-14000
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	7073	0	0	0	0	0	0	0	0	0	7073
	Operating	0	-970	-951	-933	-914	-896	-879	-862	-845	-828	-812	0	0	0	0	0	0	0	0	0	0	-8890
	Fuel	0	-5,462	-5,355	-5,250	-5,147	-5,046	-4,947	-4,850	-4,755	-4,662	-4,570	0	0	0	0	0	0	0	0	0	0	-50044
	Total	-14,000	-6,432	-6,306	-6,183	-6,061	-5,942	-5,826	-5,712	-5,600	-5,490	-5,382	7,073	0	0	0	0	0	0	0	0	0	-65861
Battery	Capital	-44,800	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-44800
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	14933	0	0	0	0	0	0	0	0	0	14933
	Operating	0	-314	-308	-302	-296	-290	-284	-279	-273	-268	-263	0	0	0	0	0	0	0	0	0	0	-2877
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	-44,800	-314	-308	-302	-296	-290	-284	-279	-273	-268	-263	14,933	0	0	0	0	0	0	0	0	0	-32744
Converter	Capital	-20,400	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-20400
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	10200	0	0	0	0	0	0	0	0	0	10200
	Operating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	-20,400	0	0	0	0	0	0	0	0	0	0	10,200	0	0	0	0	0	0	0	0	0	-10200
Other	Capital	-12,000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-12000
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Operating	0	-5,882	-5,767	-5,654	-5,543	-5,434	-5,328	-5,223	-5,121	-5,021	-4,922	-4,826	-4,731	-4,638	-4,547	-4,458	-4,371	-4,285	-4,201	-4,119	-4,038	-98109
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	-12,000	-5,882	-5,767	-5,654	-5,543	-5,434	-5,328	-5,223	-5,121	-5,021	-4,922	-4,826	-4,731	-4,638	-4,547	-4,458	-4,371	-4,285	-4,201	-4,119	-4,038	-110109
Grid sales	Capital	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Operating	0	0	0	0	0	0	0	0	0	0	0	20480	20098	19722	19353	18992	18637	18288	17946	17611	17282	188409
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	0	0	0	0	0	0	0	0	0	0	0	20480	20098	19722	19353	18992	18637	18288	17946	17611	17282	188409
Distribution lines	Capital	-18000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-18000
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	14400	0	0	0	0	0	0	0	0	0	14400
	Operating	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Fuel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	-18000	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-3600
Entire system	Capital	-296,200	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-296200
	Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Salvage	0	0	0	0	0	0	0	0	0	0	0	32,206	0	0	0	0	0	0	0	0	0	32206
	Operating	0	-9,156	-8,977	-8,802	-8,629	-8,458	-8,294	-8,131	-7,972	-7,816	-7,663	14,021	13,766	13,515	13,267	13,026	12,787	12,554	12,324	12,098	11,878	45338
	Fuel	0	-5,462	-5,355	-5,250	-5,147	-5,046	-4,947	-4,850	-4,755	-4,662	-4,570	0	0	0	0	0	0	0	0	0	0	-50044
	Total	-296,200	-14,618	-14,332	-14,052	-13,776	-13,504	-13,241	-12,981	-12,727	-12,478	-12,233	46,228	13,766	13,515	13,267	13,026	12,787	12,554	12,324	12,098	11,878	**-268700**

The followings calculate the salvage values of the components that is required when calculating the NPC of the project in the Table B.1 and the LCOE.

Connection to the grid after	10	years
Grid electricity price	0.08	$/kWh
Electricity selling price to the grid	0.16	$/kWh
Annual generation	157528	kWh/yr
Annual load served in the micro grid	100729	kWh/yr
Inflation rate	0.05	
Interest rate	0.07	
Real interest rate	0.02	

Salvage values

Generator		
Generator operating hours per year	1237	hr/yr
Generator operating hours during 10 years	12370	hr/yr
Generator lifetime operating hours	25000	hr
Generator remaining operating hours	12630	hr
Generator replacement cost	-14,000	$
Salvage value	7072	$
Battery		
Battery lifetime	15	yr
The remaining life of the batteries	5	yr
Replacement cost	-44,800	$
Salvage value	14933	$
Bi-directional Converter		
Converter lifetime	20	yr
The remaining life of the converter	10	yr
Replacement cost	-20,400	$
Salvage value	10200	$
Distribution lines		
Lifetime of the distribution lines	50	yr
Remaining life of the distribution lines	40	yr
Capital cost of distribution lines	-18000	$
Salvage values	14400	$

Total NPC	268,700	$
Total NPC recovery years	10	years
CPF (Capital recovery factor)	0.11	
Total annualized costs	29913	$/year
LCOE	**0.30**	**$/kWh**

Appendix C

Hourly Variations of Solar Radiation and Wind Speed

HOMER can calculate the hourly solar radiation and wind speed data using the monthly average solar radiation and wind speed data. Figure C.1 and Figure C.2 gives the hourly variation of solar radiation and wind speed for different months in a year that has been calculated by the HOMER.

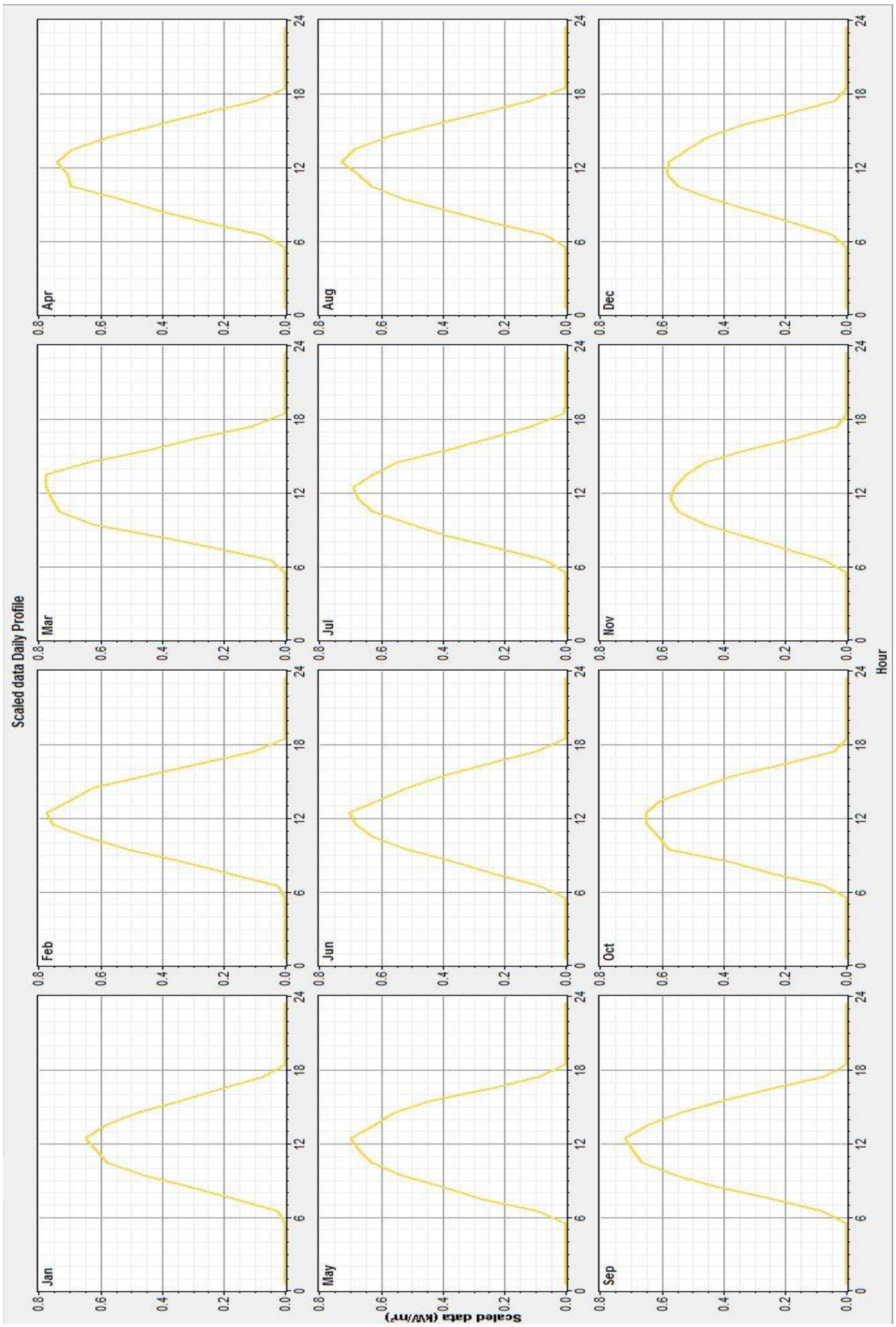


Figure C.1 : Hourly variation of solar radiation during different months in the year

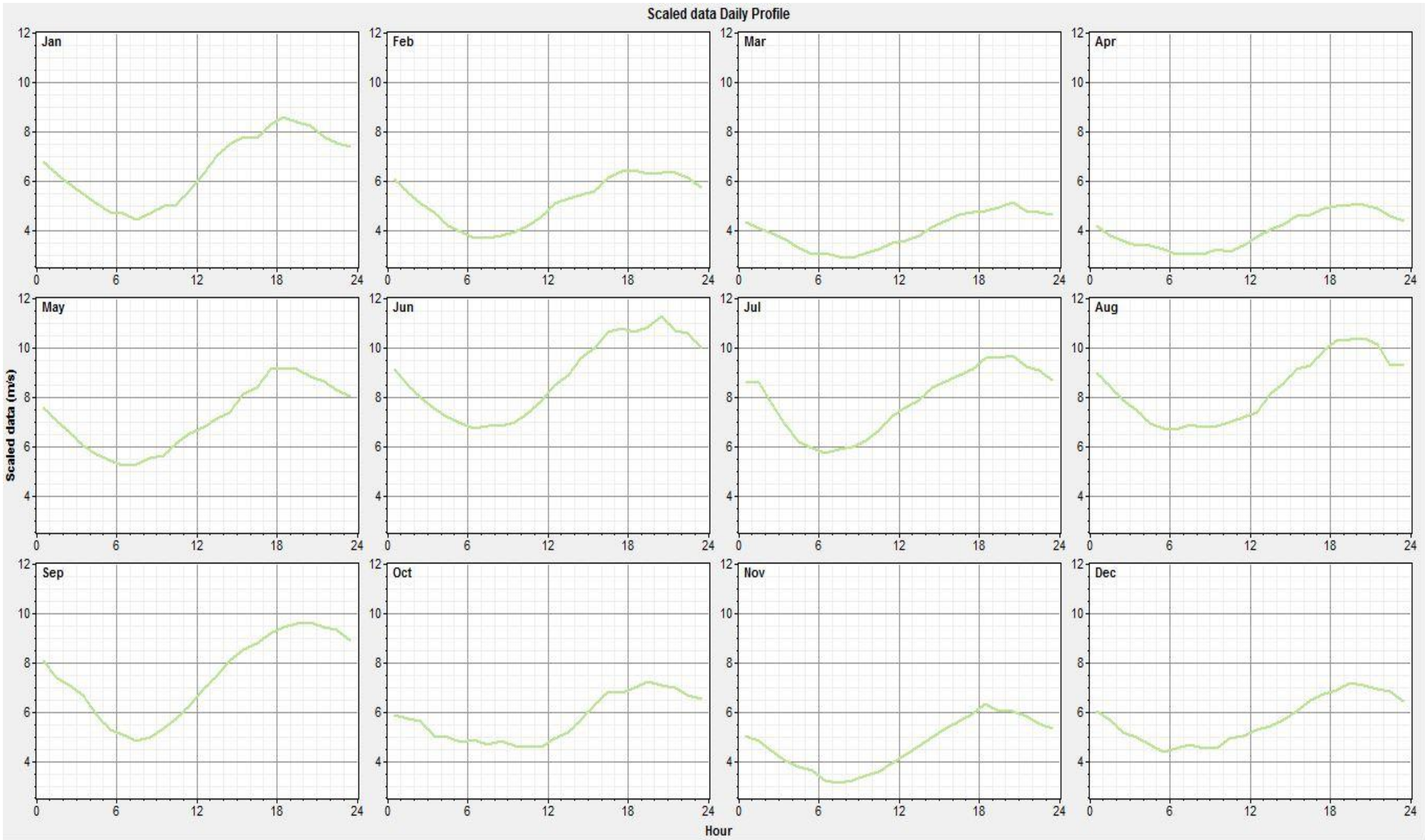


Figure C.2 : Hourly variation of wind speed during different months in the year