POWER MANAGEMENT ALGORITHM FOR STAND –ALONE HYBRID ENERGY SYSTEM

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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ABSTRACT

In Sri Lanka grid-based electrification is possible up to maximum 95% of the population and balance 5% of the electrification has to be mainly depending on off-grid technologies such as solar PV, wind, biomass and micro hydro [2].Mostly these off grid Hybrid Energy systems are used to provide electricity in rural areas which are located far away from the grid connection.

In this research, general power management algorithm has built up for standalone hybrid energy system. It controls the sharing of generated power and optimizes the hybrid operation, maximizes the use of energy produced by renewable sources and minimizes the cost of the energy produced by the system.

The simulation model of stand-alone system is developed from mathematical models of solar photovoltaic system, wind turbines, battery and diesel generators. The model of solar photovoltaic energy conversion system is constructed with maximum power point tracking control to extract maximum power from the solar photovoltaic system.

In order to validate the proposed strategy under real situations, optimized hybrid energy system was designed for Delft Island by considering the future demand. The effect of the capital cost, operation & maintenance cost, life time of the components, load pattern, available renewable resources level has been considered in the optimization. "HOMER" optimization tool was selected for optimization and optimized capacities of each component considered for power management strategy simulation in "MATLAB" simulation tool. The developed firmware permits to determination of diesel consumption and Load Loss probability of different kind of energy systems.

Results obtained from the simulation are presented to validate the control algorithms developed in this work and in order to examine the economic viability of the proposed system, the total net present cost has been calculated for 20 years of systemic lifetime.

Keywords: Off grid Hybrid Energy system, Optimization, Power Management, Rural electrification, Wind/Solar PV/battery/diesel generator

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LIST OF ABBREVIATIONS

Abbreviation	Description
CEB	Ceylon Electricity Board
DG	Diesel Generator
HRES	Hybrid Renewable Energy system
MPPT	Maximum Power Point Tracking
NPV	Net Present Value
O&M	Operation & Maintenance
PI	Proportional Integral
PSO	Particle Swarm Optimization
P&O	Perturb and Observe
PV	Photovoltaic
SOC	State of Charge

LIST OF APPENDICES

1 INTRODUCTION

1.1 Background

Electrical energy demand is increasing day by day and conventional sources which are used for energy generation creates a lot of greenhouse gases. More than 60 % of the world's electricity is generated by means of fossil fuels and from an estimation it has been calculated that the coal will last for another 30 to 50 years[10].The main two problems of using these fossil fuels as energy sources are, they will be depleted over time and greenhouse effect caused by CO_2 emission. It can lead several problems as climate changes and melting glaciers resulting in the rise of sea-water levels. As a solution for these problems, attention to the renewable energy resources has been increased. Renewables include solar, wind, hydro and bio-energy as well as geothermal energy and tidal power. Many countries widely used solar and wind energy for electricity generation.

Developed renewable energy electricity production systems have been used 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 [1-4].Unavailability of national grid access is the major reason and it takes higher cost to extend the transmitting and distributing infrastructure to these 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. Photovoltaic (PV) systems and small wind turbines are widely used renewable energy systems and PV systems applications higher due to sunlight is sufficiently available.

The application of renewable energies in off-grid systems however is challenging due to the nature of intermittence of the sources, the dependence on geographical and weather conditions. Further the initial cost of investment in solar and wind systems is still relatively high in comparison to fossil fuel-based electricity. Integration of renewable energy sources with conventional energy sources has been identified as a solution for this and it creates more reliable and cost effective systems. Hybrid power systems combine two or more electricity generation methods, like diesel engines and solar panels into a single plant to reduce long term generation costs. 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.

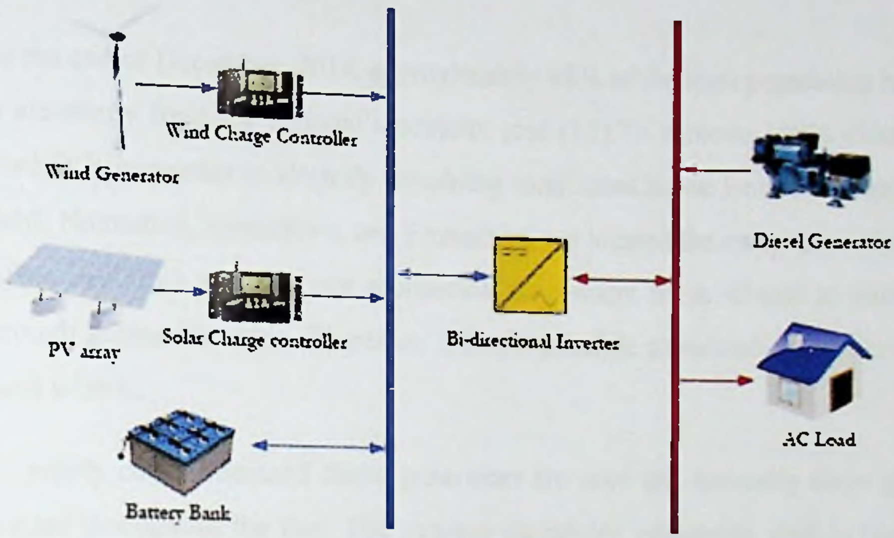

Figure 1.1: Hybrid Energy System

It is very important to select the hybrid energy system component capacities and proper power management algorithm to cater the energy demand. And also it affects to both lifetime of the system and its affordability to the end users. For this selection detailed technical and economic analysis of the possible hybrid system configurations for selected site location is required. For that availability of the renewable energy resources throughout the year is also considered.

1.3 Topic of Research

1.3.1 Research Motivation

When I was about to embark on my research for my Master's degree, I have found that there was a problem of energy dispatching of hybrid energy system which was installed at Eluvathivu island. Preliminary investigation revealed to me that the main reason for this being that the power management has not properly designed for the system at the designed stage considering the maximize use of the available renewable resources and minimizing the energy generating cost. Therefore I have interested to build a general power dispatching algorithm for standalone hybrid energy systems.

1.3.2 Problem Statement

By the end of December, 2014, approximately 98% of the total population had access to electricity from the national electricity grid [11].To achieve 100% electrification level, it is important to electrify remaining rural areas.Some Isolated Islands such as Delft, Nainathvu, Analathivu, and Erunathivu are located far away from main land in Jaffna Peninsula and it is not economical to connect these islands to national grid through submarine cable. Therefore it is not possible to extend the national grid to these islands.

To supply current demand diesel generators are used and normally these generators operate throughout the day. The average electricity generating cost is (only diesel and lub oil cost) Rs. 75.53 per kWh and the average selling price is Rs. 14.70 per kWh in these Islands [17]. Hence electricity supply to isolated locations using diesel solutions is very expensive. Further high wind potential and solar potential is available throughout the year and financial assistance from ADB is available to improve the socio economic background of the villagers.

Since high cost is bared by utility to supply electricity to above mentioned islands, it is required to supply electricity in these areas with low cost. Further these islands enrich with the renewable resources throughout the year. Therefore it is important to model, optimize a hybrid energy system and select a proper power management strategy.

1.4 Objective of the study

The main objective of this thesis is to optimize stand-alone hybrid energy system with power management strategy which can provide affordable and reliable electricity for a rural community in Sri Lanka.

The specific objectives summarized as follows,

1. Decide the optimum capacity of Solar, wind, Diesel generator & Battery by considering the demand, industrial expansion and future growth.
2. Model and Simulate Wind-Solar-Diesel Battery Hybrid system in HOMER.
3. Find out the optimum power dispatching algorithm.
4. Verify the suitability of the proposed algorithm by using simulation analysis and economic Analysis.

1.5 Contributions

Hybrid energy system is novel concept to Sri Lanka and it is a challenge to design hybrid energy system with power management strategy for a particular site location.

Therefore the results of this research will help the decision makers of the energy sector of Sri Lanka to minimize the electricity generation cost and to maximize the use of renewable energy resources. Further the developed software can be used to different kinds of hybrid energy systems to measure the load loss probability.

1.6 Organization

Rest of this dissertation is organized as follows.

- Section 2 summarizes the literature survey.
- Section 3 explains the research methodology.
- Section 4 presents the collected data and analysed results which are needed for thesis.
- Section 5 explains the hybrid energy system components and mathematical equations.
- Section 6 preparing & optimizing the hybrid model of the study.
- Section 7 gives the proposed power management algorithm.
- Section 8 verify the results
- Section 9 discusses the economic analysis

- Sections 10 presents all the assumptions made and discuss the difference & important of the research from previously completed researches.
- Sections 11 discusses on the conclusions, recommendation and future work of the research.

2 LITERATURE REVIEW

2.1 Background

An optimum power management strategy is required to improve the reliability and power quality of the standalone hybrid energy system. It has become of great importance with the increase in usage of hybrid renewable energy systems, specially in remote area electrification. There have been number of researches carried out in this regard over the last few decades.

Some significant research papers are discussed in the following section to identify research already carried out and to identify research gap.

2.2 Technical papers reviewed

H.P.Hemantha Kumara [1], in his Master of Science in Electrical Engineering dissertation in 2011 on "Analysis on Wind Solar Hybrid System for Stand-Alone power Generation in Sri Lanka" has developed a Solar Photovoltaic system combined with Wind power generation.

A case study was carried out at a place called Nikavaratiya in the Kurunagala district, Sri Lanka. Four units of 100W wind turbines have been installed in Nikavaratiya area as wind home systems. After commissioning the wind turbines, the generated power was found to be insufficient in fulfilling the electricity requirements of the houses. Therefore in this analysis, it is suggested to develop separate dynamic models for wind and photovoltaic systems with a storage battery system as a mean of enhance the system capacity.

The hybrid system used for this simulation consisted of a 100W wind turbine, 150W solar array and a 70Ah lead acid battery. A Fuzzy Logic Maximum Power Point Tracker (MPPT) controller was applied to the variable–speed, fixed–pitch small scale wind turbine while maximum power point tracking (MPPT) method based on Perturb & Observation (P&O) searching algorithm was applied to the stand–alone solar photovoltaic system.

MATLAB Simulink 7.2 / Simpower system software environment was used to carry out the simulation of individual wind and PV dynamic models of the hybrid system and HOMER software was used in optimizing the hybrid system. The simulation result shows the efficiency of 96.2% for the P & O algorithm and the proposed fuzzy controller performs better than a conventional controller and 47% more energy can be generated by the system with a Fuzzy controller.

However, his study is limited to wind solar battery energy system and mainly focus to enhance the output power from renewable energy resources by introducing Maximum Power Point Tracking control mechanism for wind turbines and photovoltaic system. Through this research dispatch concept was not considered.

Rathneswaran K.,Samarakoon [2]",in his Master of Science in in 2011 on "Hybrid Power System for Eluvaithivu Island Sri Lanka" has studied a demand side management for an isolated island power system of a small island in Sri Lanka. In this research a Wind Diesel Battery based power system was selected as more economical optimum solution by using HOMER optimization tool.

D.T.D.Dissanayake [3], in his Master of Science in Electrical Engineering dissertation in 2011 on "Wind-Solar-Diesel hybrid model for telecommunication base station" has designed a Wind Solar Diesel hybrid energy system for Telecommunication Base stations with 100% availability. In his study, he investigates the feasibility of establishing wind-solar-diesel hybrid energy system at remote telecommunication base station.

A case study was carried out for Debbokkawa site, Sri Lanka. HOMER optimization tool was selected for modeling and Probabilistic approach was taken to determine the technically and economically optimal hybrid energy system.

However, his study is limited to 200W to 250W typical energy consumption which is required for telecommunication base station. In fact HOMER optimization tool has limited dispatch strategies and battery life time calculations are not performed using detailed algorithm.

Mohan Kolhe, K.M.Iromi Udumbara Ranaweera, A. G. B. Sisara Gunawardana [4] has investigated an optimum combination of different energy systems which can supply electricity to a rural community in Sri Lanka. For that "HOMER" optimization software and Cycle charging dispatch strategy is used. HOMER simulations have done for several hybrid system configurations, which are the combination of PV/wind/Battery/Diesel Generator system with different capacities. It reveals that hybrid systems with diesel generators are more economical than the systems with only renewable energy resources or diesel powered micro grids.

Cai Guanglin, Chen Rouyi, Lin Yong, Zhang Yongjun [5] have designed and simulated operating model for Wind-Solar-Diesel-Battery system using PSCAD simulation software. The control system of micro-grid is Master Slave Control mode. Each operation mode has only one generation as the main control power, the rest are slave power supply. There are two control modes as Diesel generator control mode and Energy storage master control mode. In Diesel generator master control mode, if diesel engine is running the energy storage and wind, PV act as a slave power supply. In Energy storage master control mode, If no diesel generators are running, the centralized storage is choose as the master control power and wind, PV act as slave power supply. PSCAD simulation carried out to verify the validity of the model. The simulation analysis proved the usability of the model and the effectiveness of the control strategy.

According to the proposed strategy Diesel Generator or Battery always act as master power source and wind and PV generated power has taken for only battery charging purpose. In this study minimization of the cycles of charging and discharging of the battery and battery state of charge level are not taking in to account. Also the Wind and PV generated power not directly supply to the system.

B.Kanaga Sakthivel and Dr. D.Devaraj [6] have published a paper on hybrid energy system with variable speed wind generation, photovoltaic system with power electronic interface under stand-alone mode. The proposed hybrid energy system consists of a PV array and Induction generator-driven Wind energy conversion system meeting a common load and battery system is used to maintain the balance between the source and load.

The wind and solar systems are inter-connected with individual DC-DC converters and connected to the storage battery. The output of DC-DC converters is sent to an external H-Bridge inverter to supply ac power to load. MA TLAB/SIMULINK is used to simulate the system and to evaluate its performance of the system.

Power Control Mechanism of PV System is Maximum Power Point Tracking (MPPT).The Performance of the hybrid system is evaluated under various wind speeds and various irradiation levels. Simulated results show that DC-DC boost converter is a most efficient topology which ensures good efficiency along with low cost.

Dan Shen, Afshin Izadian, Ping Liao [7] have discussed a research paper on control strategy for standalone distributed hybrid power system which consists of solar power, wind power, battery storage and the load. Figure 2.1 depicts the proposed topology of combined power sources consisting of solar, wind and battery with two stage DC-DC converters to interface the load. There are two main branches in the system, thus two new energy sources can compensate each other to some extent under different climates. The first stage converters are controlled by MPPT controller and capture the maximum power from wind and solar respectively. The second stage converters are controlled by local controller as a constant voltage sources (CV). The control action as voltage source is determined by the supervisory controller. Each power system branch runs a maximum-power-point tracking (MPPT) algorithm and receives the voltage and current references from the supervisory controller.

Supervisory controller was built in Matlab/Simulink and control strategy was proposed to generate the maximum power from these renewable energy sources and battery. The perturb and observe (P&O) method is used on both the solar and wind power sources.

Simulation results demonstrated an accurate operation and applicability of the proposed method.

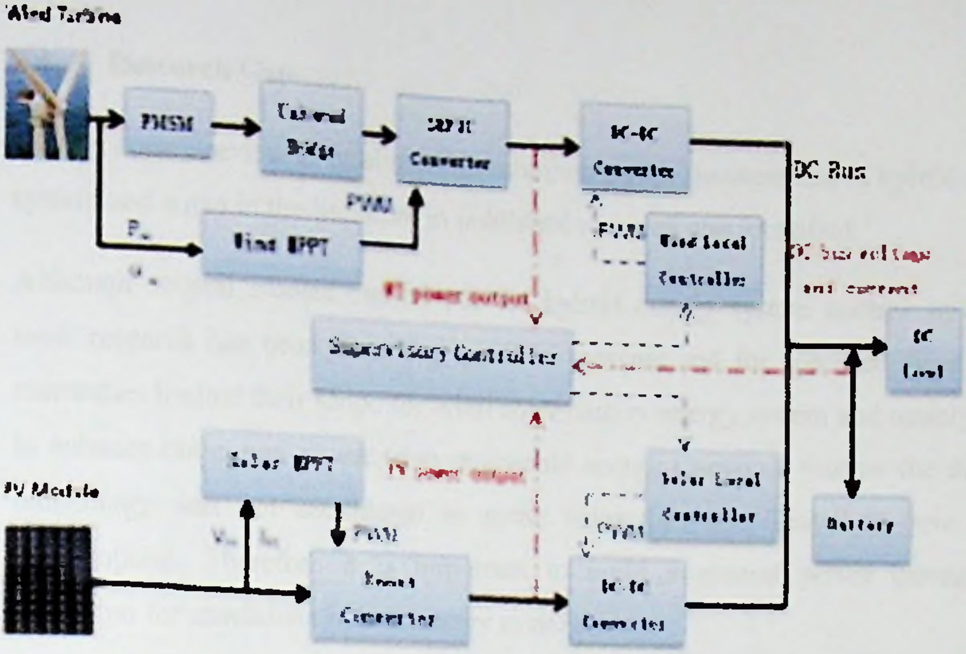

Figure 2.1: Hybrid energy generation system

S.M. Mousavi, S.H. Fathi,G.H. Riahy [8] have focused on linear short term prediction of wind and solar with energy management of wind/PV hybrid system with battery storage system. To achieve this goal first, each subsystem of this hybrid system was modeled in MATLAB-Simulink. Then system control strategy with consideration of memory effect was modeled. The recommended system in this study embraces a wind turbine, PV arrays and a backup battery which are standalone and far away from the power network. In this system Wind and Solar energy are the primary resources of producing power and battery is the backup storage system. Two quadrant chopper is used to store the extra power of Wind turbine and PV in battery and to discharge battery banks in the situation of lacking energy in producing of load power. Fast charge and discharge strategy is applied to avoid the memory effect in batteries. PSO algorithm is used for economical optimization. The results illustrated that by using proposed control strategy the reliability of system can be enhanced. However, in this research only PV and wind system is considered and no emergency power source is used and dispatch technologies were not considered.

2.3 Research Gap

Having done a review of published literature on power management of hybrid energy system and a gap in the literature in published research was identified.

Although several studies carried out for hybrid energy system control strategies, most research has been done for specified systems and for specified sites. Some researches limited their scope for wind solar battery energy system and mainly focus to enhance the output power from renewable energy resources. Further the dispatch technology was not considered in some researches and limited to low power consumption. Therefore it is important to build a general power management algorithm for standalone hybrid energy system.

The research has targeted to fill the above research gap and propose a general power management strategy which can provide affordable and reliable electricity for a rural community in Sri Lanka. Computer programme also built for proposed power management. For power management strategy, increase the battery life time, maximum energy extraction from renewable resources will be considered.

3 RESEARCH METHODOLOGY

3.1 Introduction

This research project systematically fills the research gap of build a general power management algorithm for standalone hybrid energy system. This Chapter presents the methodology used in this project to fill the research gap.

The various stages of this methodology are detailed in the following sections.

3.2 Identification of research gap

Firstly a broad topic of research was identified, namely that of develop a power management algorithm, based on the requirement of the planning division of Distribution Division 1.

A detailed literature review was carried out in order to identify a research gap and significant work has been given in the Literature Review chapter. Further, the literature survey was concentrated on finding work done on two main areas. Firstly, determination of optimized hybrid energy system for the selected location and secondly presently used power management strategies for hybrid energy system.

3.3 Current demand survey

Detail survey was carried out to Collect the data of existing power system such as Capacity, Distribution system arrangement and cost, power demand, daily load profiles & load factor of the selected community. An Excel model was used to predict the future load profile.

3.4 Demographic Data Analysis

Under the demographic data analysis population, number of families, number of consumers, Industrial growth, Population growth and Demand growth has analysed.

3.5 Data Analysis of Renewable resource

Renewable resource data such as solar radiation, temperature, sun shine hours, and wind data were collected from various sources and analyzed.

3.6 Optimum generation capacities selection

Available renewable based equipment data as specifications, prices, O&M cost and replacement cost was gathered. Technology options were analyzed using actual cost data and renewable resource data. "HOMER" hybrid power system optimization software was used for the analytical purpose to find out the optimal power system configuration.

3.7 Mathematically modeling

Find out the mathematical expressions for the generated power from each component and modeled a hybrid system in MATLAB program.

3.8 Proposed power management algorithm, simulated in MATLAB & results comparison

Power management algorithm was derived and programmed in MATLAB using commands. This proposed strategy was simulated for different scenarios and results were compared.

3.9 Economic Analysis for proposed hybrid energy system

Detail analysis was conducted to check and verify the Economic viability of the proposed system.

4 DATA COLLECTION

Load profile data of the Delft Island and available renewable resources data are required for the design and optimization of a hybrid energy system. This chapter is described the estimation of village load profile and the assessment of renewable resources.

4.1 Introduction

Delft is the largest island in Sri Lanka(see Figure 4.1)which is located 10 km away from the Jaffna Peninsula, Sri Lanka and the Coordination as WGS84, 931'0''N, 79 41'0''E. The island is approximately 11 km long with an approximate surface of 50 km^2. The population in 2015 is 4,540 inhabitants (1308 families). There is a growing tourism in the island due to different attractions such as Dutch history, its temples and wild horses.

The fishery industry is major income of the people. Unavailability of basic facilities and the low income level have badly affected on the living standards and the education of the children. Therefore, in order to improve the living standards, health, education and local economy of the people in the rural areas of islands, it is very important to provide basic facilities including electricity for them. The Average Electricity Consumptions is about 70,376 kWh /Month. During the Christmas & New Year time, expect to have a 30% of load increase [19].

Figure 4.1: Map of the Delft Island

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

4.1.1 Existing Site Condition

In Delft, the output of the diesel generators are stepped up using 400V/11kV transformers and transmitted through medium voltage lines with a total length of 7.5 km. The low voltage distribution lines are 15.6 km long in total [19].

4.1.2 Existing Gen Sets

Three diesel generators with a rated capacity of 250 kVA are currently in the island, which forces them to work at low loading levels during most of the day, thus having an overall bad efficiency [19].

4.1.3 Grid Infrastructure

Generators are connected to a 3-phase bus bar at low voltage (230/400V). Main distribution is carried out in 3-phase power lines. Measures performed on the current in each phase during one day show that the 3 phases are highly unbalanced. This is one of the causes of the very low efficiency of this electric power system.

4.2 Demographic Data

4.2.1 Year Vs Population and Number of Families

The population of this island increases in exponentially growth by year to year and the population in 2016 is approximately 4750 (1500 families).By using past few years record the future population is predicted and these results has taken consideration when designing the optimum capacities of machines. The population and number of families are shown in Table 4.1 and graphically show in Figure 4.2.

Table 4.1: Number of Families & Population Vs Year

Year	Number of Families	Population
2008	944	2832
2009	992	2976
2010	1004	3012
2011	1014	3042
2012	1,033	3500
2013	1,057	3750
2014	1,086	4000
2015	1,308	4540
2016	1,500	4750
Predicted Data		
2017	1552	5095
2018	1670	5424
2019	1789	5753
2020	1907	6082

Source: Data from CEB -Jaffna Area Office

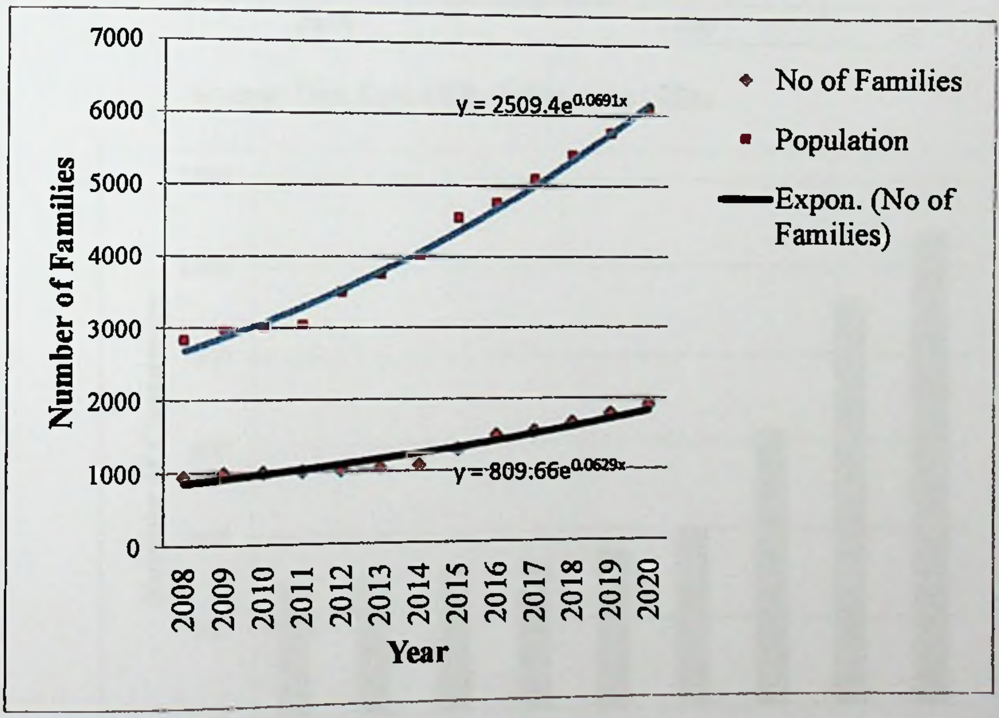

Figure 4.2: Number of Families & Population Vs Year

4.2.2 Consumer mix Vs Year, Purpose and the Connection type

Currently, the electricity is provided to 846 houses and 1080 of population in the island using a Diesel Generator set (DG set) of capacity 250 kVA. Electricity is made available from 4.30 am to 6.30 am and 6.00 pm to 10.30 pm. Number of consumers versus year is shown in Table 4.2 and graphically illustrates in Figure 4.3.

Table 4.2: Number of Consumers Vs year

Year	Number of Consumers
2008	295
2009	310
2010	324
2011	338
2012	355
2013	405
2014	630
2015	930
2016	1080

Source: Data from CEB -Jaffna Area Office

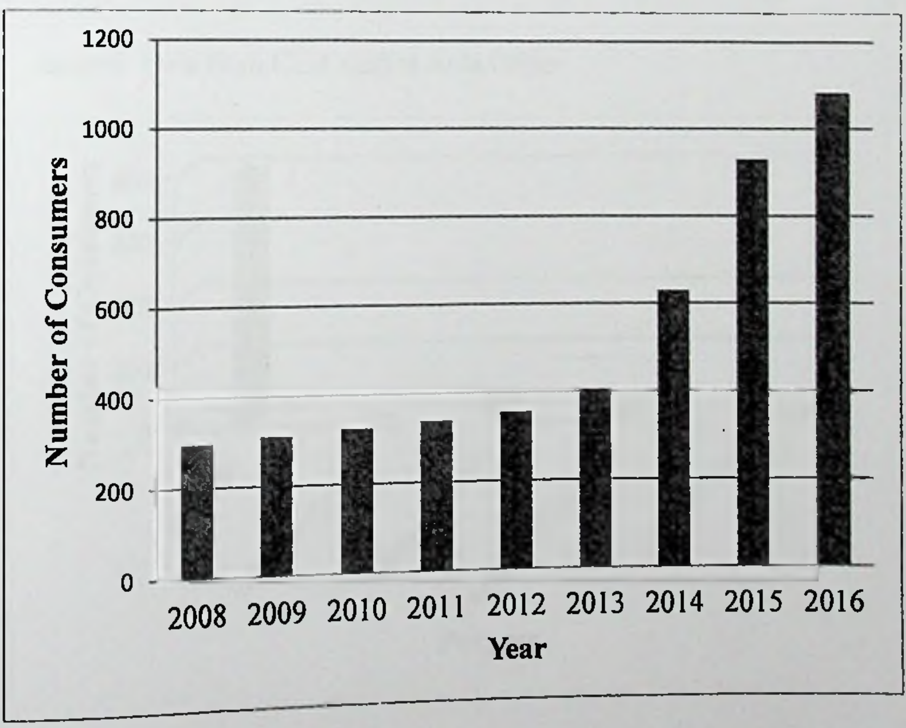

Figure 4.3: Number of Consumers Vs Year

Total energy generation in 2013 was 388,340 kWh and 427,470 kWh in 2014. This corresponds to an 8.5% increment. Annual electricity consumption in year 2015 was 719,737 kWh and it is 17% increment. Usage of electricity within this region is mostly residential. By considering past records, it has been expected that the amount of consumers will increase rapidly in this region in future. Table 4.3 and Figure 4.4 give the number of consumers according to the connection type and purpose.

Table 4.3: Number of Consumers Vs purpose

Connection Type	Purpose	No. of Consumers Year 2015
1ϕ 30 A	Domestic	845
	Industrial Purpose	3
	General Purpose	60
	Religious/Charitable	17
3ϕ 30 A	Industrial Purpose	1
	General Purpose	2
	Religious/Charitable	1
3ϕ 60 A	Domestic	1
	General Purpose	3
Total		933

Source: Data from CEB -Jaffna Area Office

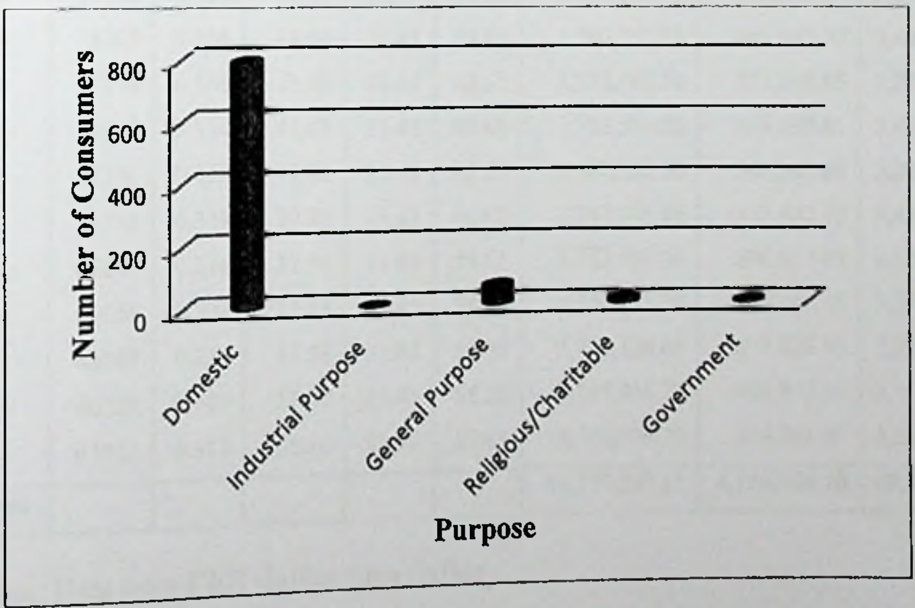

Figure 4.4: Existing Consumer Mix Vs Purpose

4.3 Energy Sales Data

The cost incurred by CEB in running the power plant is comparatively high. The old DG set operating in the power plant consumes excessive amounts of diesel and the fact that the DG set is always partly loaded also contributes to the inefficiency. As depicted in Table 4.4, the electricity generation cost in the island (on average) is above 61 Rs/kWh (US$ 0.41), while CEB charging a tariff of only US$0.038/kWh. Average Energy Delivery /month is 59,978 kWh and CEB incurs severe financial loss about Rs.3.34 million. Therefore, Hybrid energy system is needed to reduce Energy generation cost.

Table 4.4: Energy Sales Data

Month	Energy Delivery (Kwh)	Average Fuel Consumption	Fuel Cost (Rs/kWh)	O&M Cost (Rs./kWh)	Cost of Electricity (Rs/kWh)	Total Cost (Rs/kWh)	Revenue (Rs.)	Loss for the month (Rs.)
Jan	57590	0.409	47.41	21.45	68.86	3,965,647.40	302,590.20	3,663,057.20
Feb	50646	0.359	41.61	21.45	63.06	3,193,736.76	322,286.45	2,871,450.31
Mar	58207	0.376	43.60	21.45	65.05	3,786,365.35	340,043.90	3,446,321.45
Apr	57130	0.354	41.10	21.45	62.55	3,573,481.50	320,958.65	3,252,522.85
May	60540	0.354	41.03	21.45	62.48	3,782,539.20	329,597.85	3,452,941.35
Jun	57250	0.353	40.88	21.45	62.33	3,568,392.50	346,347.80	3,222,044.70
Jul	61793	0.338	39.70	21.45	60.65	3,747,745.45	313,402.10	3,434,343.35
Aug	66836	0.324	37.56	21.45	59.01	3,943,992.36	306,617.85	3,637,374.51
Sep	63658	0.323	37.43	21.45	58.88	3,748,183.04	427,680.05	3,320,502.99
Oct	63868	0.324	37.58	21.45	59.03	3,770,128.04	398,826.45	3,371,301.59
Nov	60286	0.319	37.07	21.45	58.52	3,527,936.72	408,973.50	3,118,963.22
Dec	61933	0.312	36.18	21.45	57.63	3,569,198.79	308,391.90	3,260,806.89
Total						**44,177,347.11**	**4,125,716.70**	**40,051,630.41**

Source: Data from CEB -Jaffna Area Office

Figure 4.5 graphically illustrates the monthly power generation cost, monthly income and total loss bared by supplier.

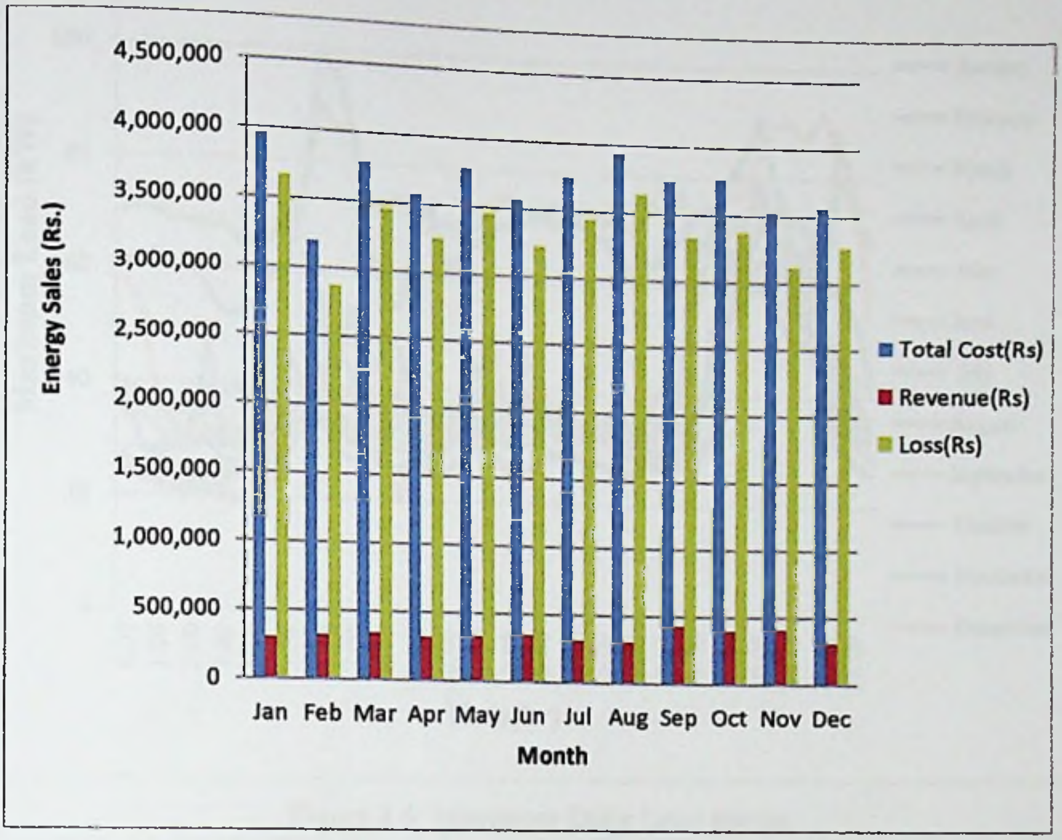

Figure 4.5: Energy Sales Data in 2015

In order to model a hybrid renewable energy system for supplying electricity, initially 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.

4.4 Power Demand

Estimation of electricity demand is very much important to design a power system to Delft Island. Probable Energy Demand can be forecast by studying the present energy supplied by Diesel Generators. Power demand was measured during the period in 30 minute intervals. The measured peak demand profiles for each month as shown in Figure 4.6.The average electricity consumption is about 70,376 kWh/ month, Maximum Daily Peak load is 100 kW and load factor is 0.75.

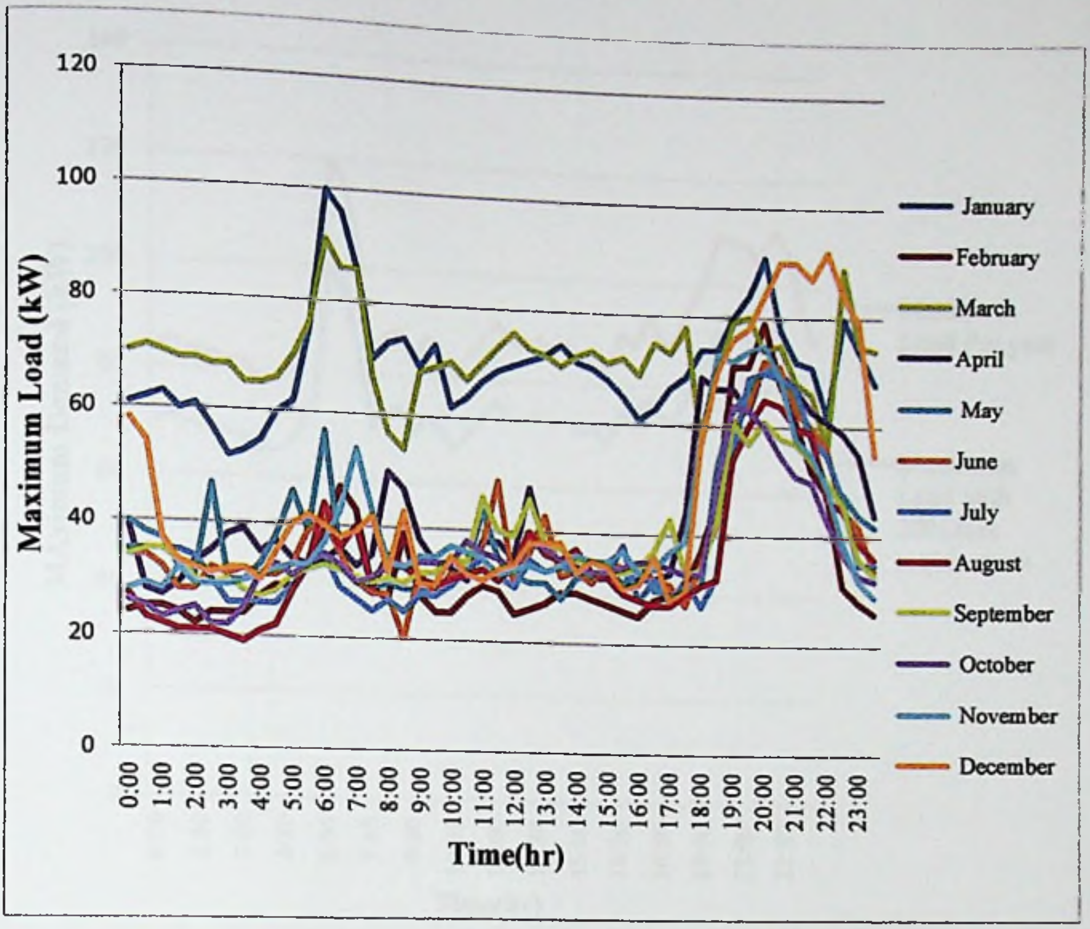

Figure 4.6: Maximum Daily Load curves

Source: Data from CEB -Jaffna Area Office

For the optimization of capacities, maximum demand is considered and according to the future growth of population it is assumed that the power demand will be increased in 20 %.

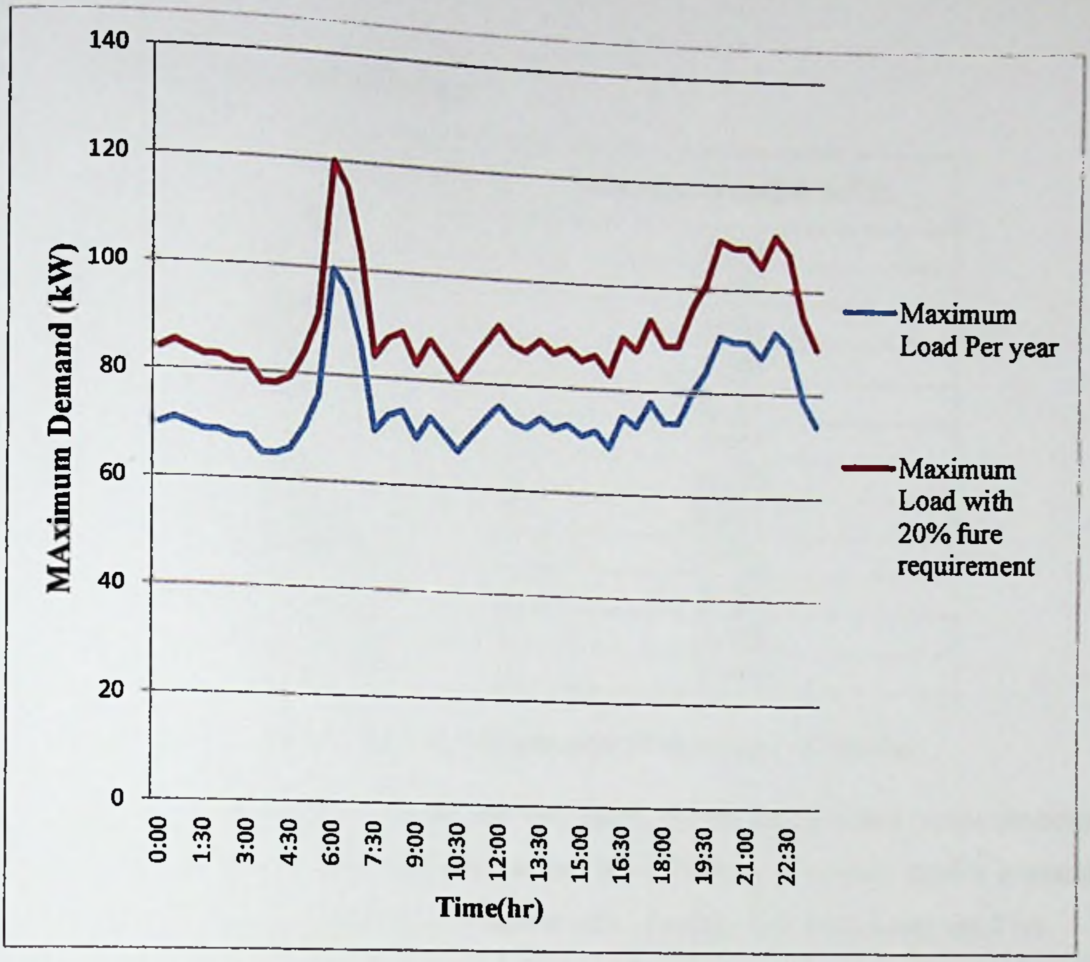

Figure 4.7: Maximum Daily Load curves

Source: Data from CEB -Jaffna Area Office

4.5 Renewable Resources Data Analysis

The general climate prevailing in the island is very much similar to the overall climatic condition of the northern part of Sri Lanka.

4.5.1 Solar radiation Data

The region receives rains mainly during the period from October to December. Rainfall during this period accounts for about 70% of the annual total. The island has an equatorial climate with high humidity and average temperatures ranging between 29° and 13° C all year. Average daily radiation value obtained is 5.681 kWh/m^2/day and solar intensity varies from 3.416 -6.646 kWh/m2/d.

Table 4.5: Solar Radiation Data

Month (2015)	Daily Radiation(kW/m²/d)
January	5.875
February	5.457
March	6.646
April	6.086
May	6.207
June	5.950
July	6.539
August	6.632
September	5.915
October	5.109
November	4.340
December	3.416

Source: Data from Department of Metrology –Colombo

Hours of sunlight per day do not vary much during the year due to the moderate 9° 39′ latitude in which Delft is located, the difference in average profile is mainly due to the average cloudiness in each month. Average Sun shine hours are 7 hrs.

4.5.2 Wind Speed Data

Several coastal areas in Sri Lanka, including the northern region, experience strong winds during the period of the South-West (SW) monsoon (May to October), and moderate winds during the North-East (NE) monsoon (December – February). As could be seen in Figure 4.7, this wind pattern persists along the entire northern coastal belt from Mannar to Kankesanthurai.

Since the on-site wind speed measurements in Delft were not available, wind atlas of Sri Lanka published by the National Renewable Energy Laboratory in 2003 has been considered [20]. An annual average wind speed at a 50 meters height of 7.5 m/s based on a Weibull shape factor k=2 has been considered. The map of Sri Lanka's wind speeds is shown in the Figure 4.7 and the wind resource is described as excellent.

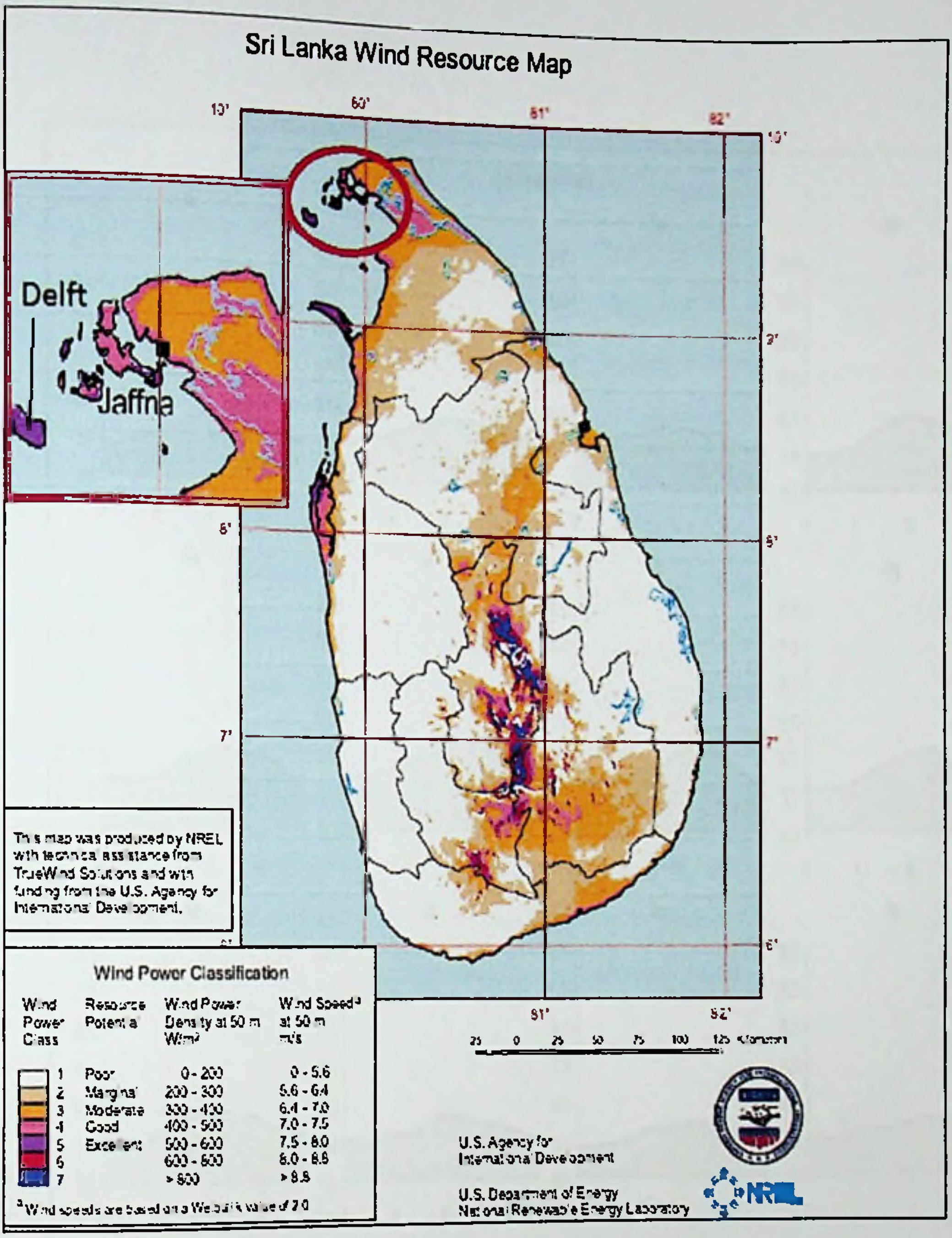

Figure 4.8: Wind resource map of Sri Lanka

Source: NREL Wind Energy Resource Atlas of Sri Lanka and the Maldives

The average monthly wind speeds are higher in May, June and July, according to NASA data available from the software HOMER pro. The Figure 4.8 shows the average daily wind speed profiles at a 50 meters height for each month that have been used in simulations.

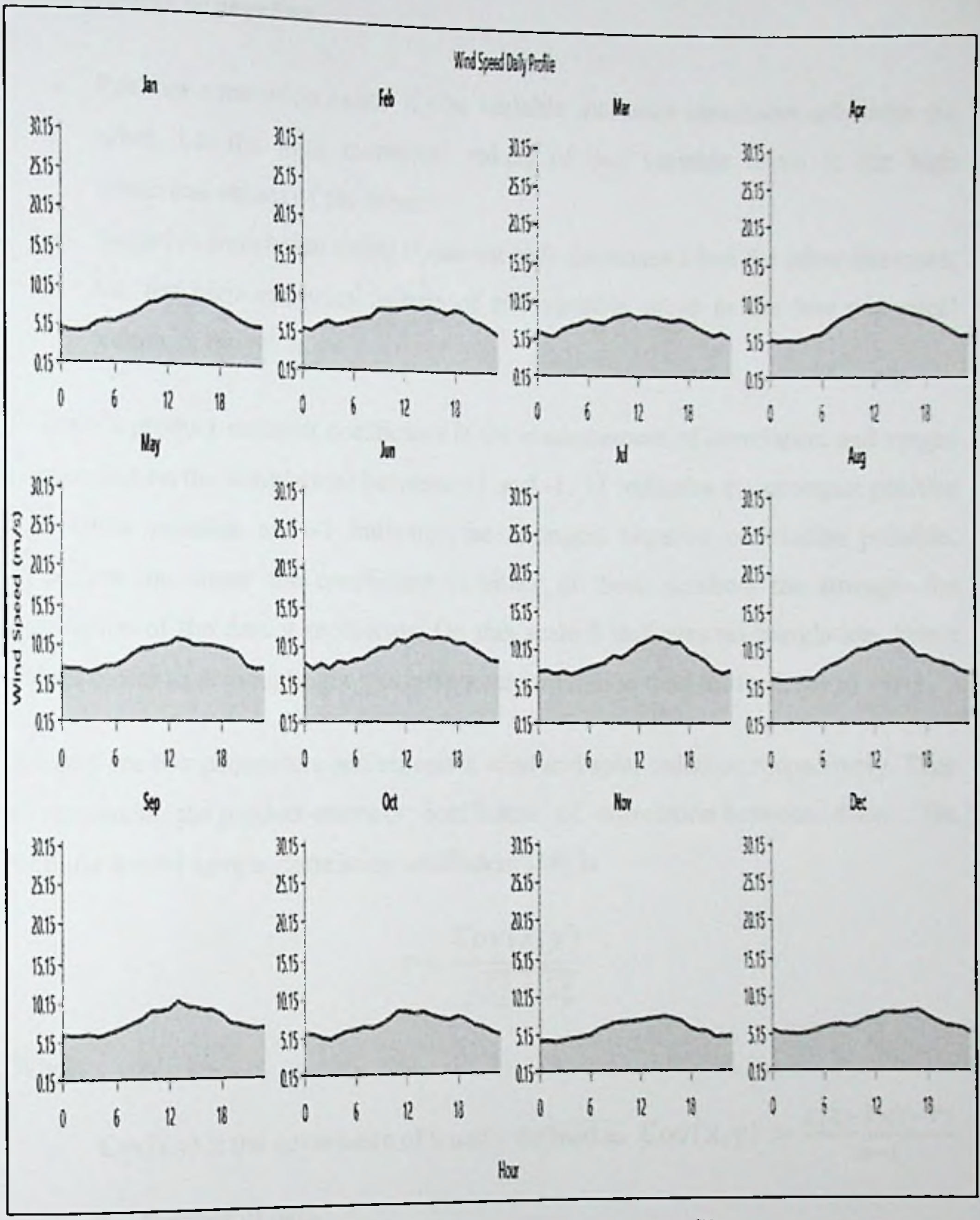

Figure 4.9: Average daily wind speed profiles

4.5.3 Correlation analysis

Correlation analysis is a method of statistical evaluation used to study the strength of a relationship between two, numerically measured, continuous variables. If there is correlation found, depending upon the numerical values measured, this can be either **positive** or **negative.**

- Positive correlation exists if one variable increases simultaneously with the other, i.e. the high numerical values of one variable relate to the high numerical values of the other.
- Negative correlation exists if one variable decreases when the other increases, i.e. the high numerical values of one variable relate to the low numerical values of the other.

Pearson's product-moment coefficient is the measurement of correlation and ranges (depending on the correlation) between +1 and -1. +1 indicates the strongest positive correlation possible and -1 indicates the strongest negative correlation possible. Therefore the closer the coefficient to either of these numbers the stronger the correlation of the data it represents. On this scale 0 indicates no correlation, hence values closer to zero highlight weaker/poorer correlation than those closer to +1/-1.

X and y are two parameters and represent wind and solar radiation respectively. Then r represents the product-moment coefficient of correlation between them. The formula for the sample correlation coefficient [18] is

$$r = \frac{Cov(x,y)}{\sqrt{S_x^2 * S_y^2}}$$

Where

Cov(x,y) is the covariance of x and y defined as $Cov(x,y) = \frac{\Sigma(X-\bar{X})(Y-\bar{Y})}{n-1}$

n – Number of data

$\bar{X}$ and $\bar{Y}$ be the arithmetic means of the elements in X and Y respectively.

s_X^2 and s_Y^2 be the standard deviations of X and Y respectively and defined as

$S_x^2 = \frac{\Sigma(X-\bar{X})^2}{n-1}$ *and* $S_y^2 = \frac{\Sigma(Y-\bar{Y})^2}{n-1}$

4.5.3.1 Correlation ship between solar and wind speed in Delft Island

$$r = \frac{Cov(x,y)}{\sqrt{S_x^2 * S_y^2}}$$

$$r = -1.89/\sqrt{347.08 * 3.55} = -0.025$$

Pearson's Correlation Coefficient (r) is Negative; Indicates that one variable increases other variable decrease

5 HYBRID SYSTEM COMPONENTS

In this chapter, we will discuss the characteristics, operation, maintenance, and the relevant costs of the hybrid system components. First the basic technological configurations of hybrid system are discussed and then the characteristic of the components as wind turbine, PV panel, Battery bank and the inverters are discussed.

5.1 Introduction

Hybrid renewable energy systems (HRES) are becoming popular as stand-alone power systems for providing electricity in remote areas due to advances in renewable energy technologies and subsequent rise in prices of petroleum products. A hybrid energy system or hybrid power, usually consists of two or more renewable energy sources used together (see figure 5.1) to provide increased system efficiency as well as greater balance in energy supply.

The potential of solar and wind resources are relatively high in Delft island, thus they can be used for developing a renewable energy based electricity supply system. In addition to these resources, a diesel generator and a battery bank have been selected for the hybrid system.

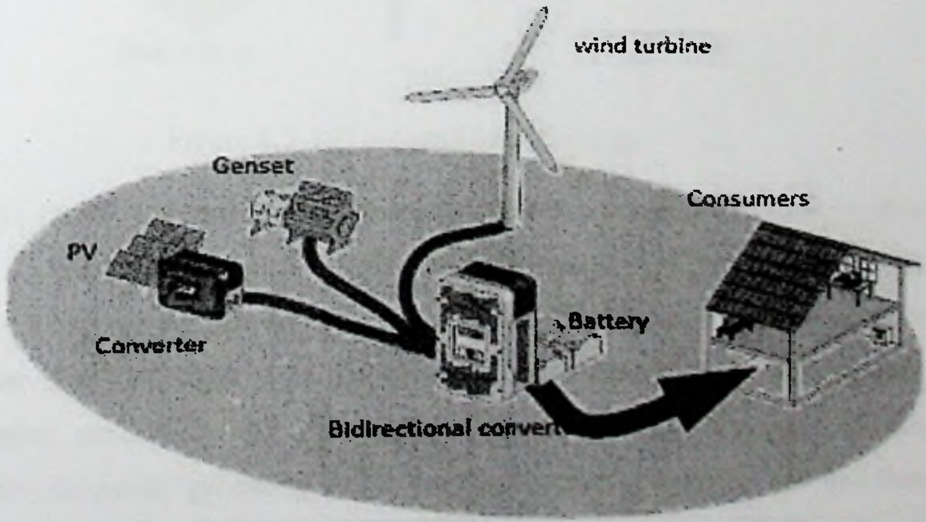

Figure 5.1: Hybrid System Configuration

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 [10].

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

5.1.1 DC coupled hybrid system

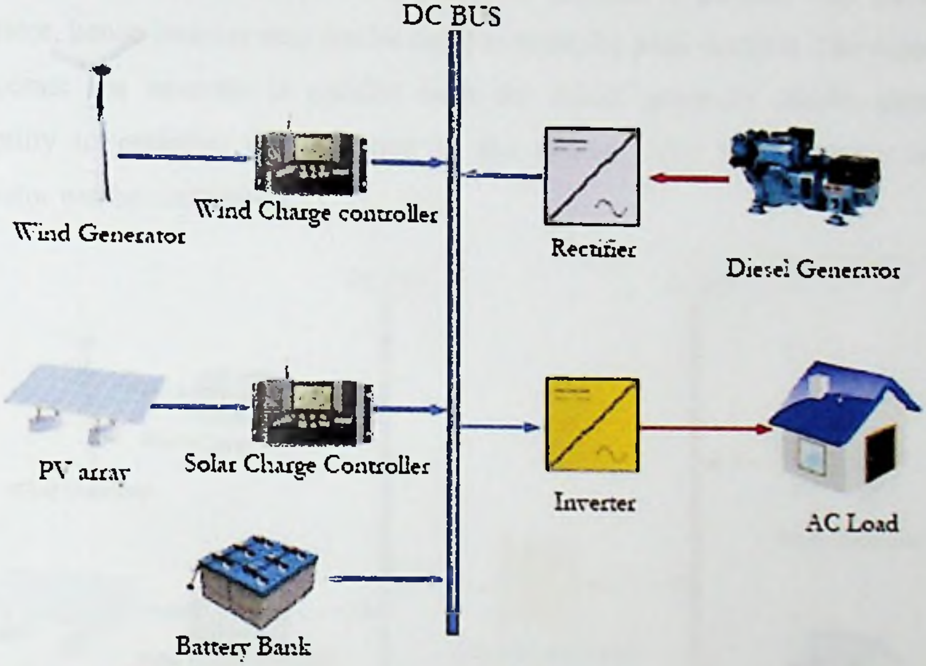

Figure 5.2: DC coupled hybrid system

In the direct current combination all the energy conversion systems are connected to the main DC bus before connected to the AC load side. All AC power sources are converted into DC power sources then connected to the AC load consumer using a relevant converter (see figure 5.2). 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.

5.1.2 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 (see figure 5.3). 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.

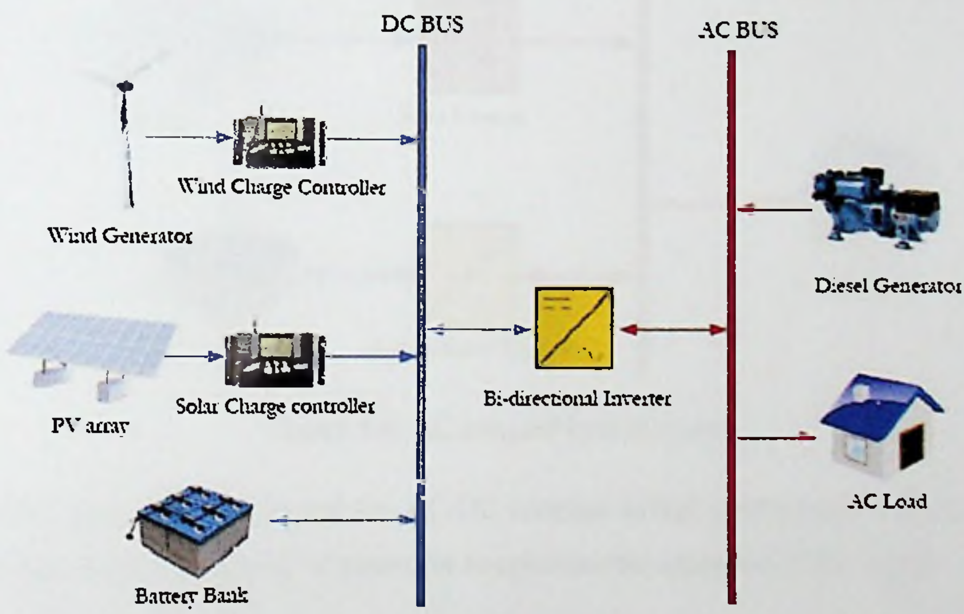

Figure 5.3: DC/AC coupled hybrid system

5.1.3 AC coupled Hybrid system

In such topology all the energy generating components or units and the energy storage technologies are connected to the AC bus in line with the load or directly to the load (see figure 5.4). 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 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.

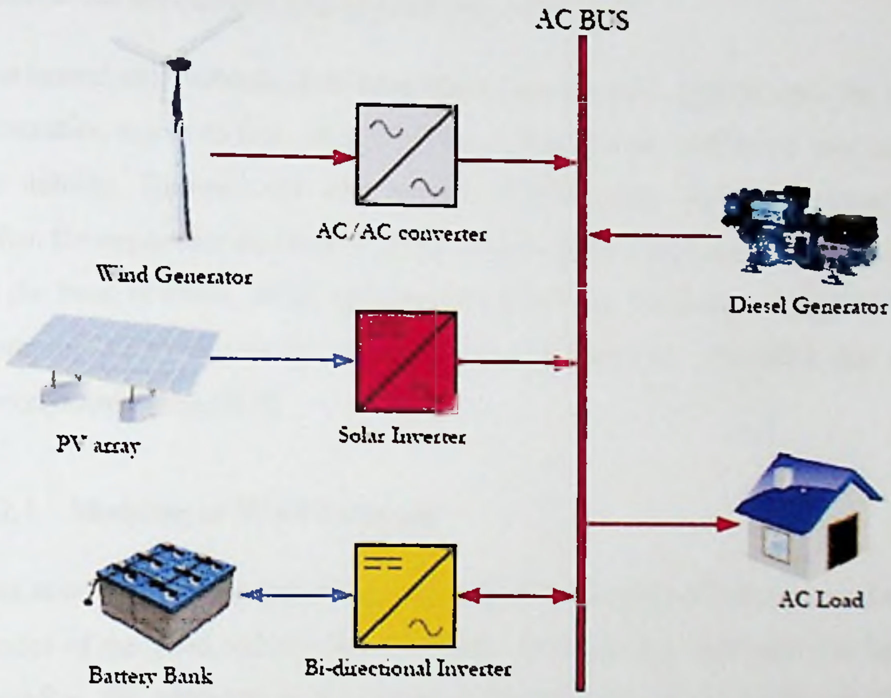

Figure 5.4: AC coupled hybrid system

In this study I have selected the AC/DC coupled hybrid configuration, because, it provides higher flexibility of generator to optimize the operation of the system.

5.2 Wind Turbine

Wind turbines are machines that generate electricity by using power from wind. The wind kinetic energy from the swept area of the turbine blades is extracted from the wind energy conversion machines. The pressure differences across the blade initiate the electrical generator to generate electricity. The wind turbine includes components like; tower, rotor, nacelle, and the turbine rotor control structure or yawing mechanism.

Wind turbines start to generate power when the wind speed flow passes the minimum wind speed (cut-in speed). The wind turbine power increases with the wind speed until it reaches the rated speed where it produces maximum power. The turbine does not produce power beyond the cut-off wind speed due to assembly of safety mechanisms that could stop turbine from producing power. The larger wind turbines used in utility scale applications and smaller wind turbines used in residential and commercial applications as grid connected or off grid.

Horizontal axis turbines with three blades are the most popular ones for electricity generation due to its low cut-in wind speed, high power coefficient, easy curling and its stability. Turbines with even number of blades have stability problems because when the uppermost blade twists back, the lowermost one passes into the wind shade at the front of tower. Wind turbines with more than 20 blades are applied for water pumping purposes and are not applicable for electricity generation due to higher aerodynamic losses [10].

5.2.1 Modeling of Wind Turbines

The wind turbine's output energy depends on the amount of wind power that hits the blades of the wind turbine. Wind is made up of moving molecules that have mass; therefore, the wind energy is in terms of the molecules kinetic energy and it is given by equation 1 [7 , pp. 3].

$$P_{wind} = \rho S V^3 \tag{1}$$

Where P_{wind} - Wind energy

P – Air density (kg/ m^3)

S – The area swept by the blades (m^2)

V – Wind speed (m/s)

However, just a part of this wind energy is captured by the wind generator and wind Energy captured by the wind generator (P_r) is expressed as equation 2.

$$P_r = \frac{1}{2} C_p(\beta,\lambda)\, \rho S V^3 \tag{2}$$

Where C_p - Performance coefficient of the turbine

β – blade pitch angle (deg)

λ – Tip speed ratio of the rotor blade tip speed to wind speed

Performance coefficient (C_p) is a non-linear function depends on pitch angle β and the speed λ. This power coefficient of the turbine is given by equation 3.

$$C_p(\beta,\lambda) = 0.5176 \left(\frac{116}{\lambda_i} - 0.4\,\beta - 5\right) 0.5\, e^{-16.5/\lambda_i} \tag{3}$$

λ_i is expressed as equation 4.

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.089\beta} - \frac{0.035}{\beta^3 + 1} \tag{4}$$

$$\lambda = \frac{\omega R}{V}$$

Where λ -Tip speed ratio

ω -The frequency of distribution

R -Rotor radius [m]

V -wind speed [m/s]

5.3 Photovoltaic System

The Photovoltaic system converts radiant energy of the sun to the direct electrical current using semiconductor cells. The complex physics of a PV cell can be represented by the equivalent electrical circuit as shown in Figure 5.5 [3].

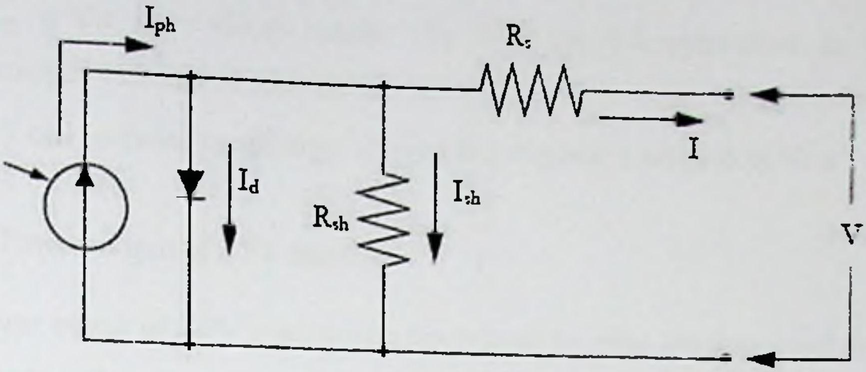

Figure 5.5: Equivalent circuit of a PV module

The current generated by a photovoltaic cell is described in equation 5.

$$I= I_{ph} - I_0\{exp\frac{q(\frac{V_{cell}+IR_S}{Rsh})}{AkT} - 1\} - \frac{V_{cell}+IR_s}{Rsh} \quad (5)$$

Where	I	:	Load Current (A)
	V_{cell}	:	Cell Output Voltage (V)
	I_{ph}	:	Photo Current (A)
	T	:	PV cell operating temperature (*K*)
	k	:	Boltzmann's constant (1.38*10-23 j/K)
	q	:	Electron charge (1.66 x10-16)
	A	:	Ideality factor of the n-p junction
	R_s	:	PV cell intrinsic series resistance (Ω)
	I_0	:	Diode reverse Saturation current (A)

The behaviour of solar PV cell directly depends on these parameters. Output of a PV module varies as a function of solar irradiance which can be obtained from the equation 6.

$$I_{ph} = [I_{sc} + K_i (T - T_{ref})]\frac{B}{1000} \quad (6)$$

Here I_{sc} is the short circuit current (A), T is the cell temperature, k_i is the temperature co-efficient of short circuit current,T_{ref} is the reference temperature, T is the PV cell operating temperature (K) and B is the solar irradiation in W/m^2.

5.3.1 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 equation 7[9, pp.5].

$$P_{pv} = Y_{pv}f_{pv}(\frac{G_T}{G_{T,stc}}[1 + \alpha_p(T_c - T_{c,STC})] \tag{7}$$

Where

P_{pv}	:	Power output of the PV module
Y_{pv}	:	Rated capacity of the PV module
f_{pv}	:	PV derating factor
G_T	:	Solar radiation striking the PV array (kW/m^2)
$G_{T,STC}$	:	Incident Radiation at standard test condition
Y_{pv}	:	PV cell Temperature (C)
T_C	:	Temperature Coefficient (%/^{0}C)
$T_{C,STC}$	:	Cell temperature under standard test conditions (25^{0}C)

5.3.2 Perturb and Observe method

In this study Perturb &Observe (P&O) algorithm is used as Maximum Power Point Tracking (MPPT) mechanism. It is very popular and is the most frequently used algorithm in practice due to its simplicity and the ease of implementation [11, pp.8].

If the ΔP value is positive, then it is considered that it has moved the operating point closer to the MPP. Thus, further module voltage perturbations in the same direction should move the operating point towards the MPP. If the ΔP value is negative, the operating point has moved away from the MPP and the direction of perturbation should be reversed to come back towards the MPP.

5.4 Diesel Generator

Diesel generators are used as a backup energy source in hybrid power systems. When there is no output power from the PV panel, wind turbine and the battery bank has discharged all the stored energy within its allowable depth, the diesel generator will start working.

The hourly energy generated (E_{DEG}) by a diesel generator with rated power output (P_{DEG}) is defined by equation 8[9].

$$E_{DEG}(t) = P_{DEG}(t) \times \eta_{DEG} \tag{8}$$

Where E_{DEG} (t) - Hourly Energy Generated

P_{DEG}(t) - Rated Power Output

η_{DEG} - Diesel Generator Efficiency

5.5 Storage Battery

If the applied voltage is greater than the battery's voltage, V_{bat}, the current, I_{bat}, will flow in the battery as a charging current. Meanwhile, if the applied voltage is less than the battery's voltage battery, the current will flow out from the battery as a discharging current. Physical model of the charging mode is as Figure 5.6.

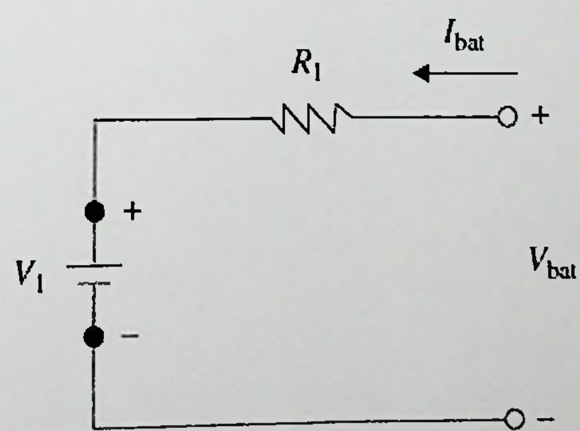

Figure 5.6: Physical model of the battery in charging mode

Normally, the battery capacity changes can be expressed by using the temperature coefficient δ_c as equation 9 [1, pp.9].

$$C_{bat} = C_{bat}'(1+\delta_c(T_{bat} - 298.15)) \tag{9}$$

Where δ_c - Temperature Co-efficient (0.006)

C_{bat}' - Rated capacity of the battery (Ah)

State of Charge is the percentage from the maximum possible charge that is present inside the battery. The state of charge of the battery depends on energy production by the solar photovoltaic, wind speed, and the required load. SOC at any hour t is depending on the battery current, the charge or discharge time and the previous SOC. In hybrid system Battery State of Charge level maintain between its minimum and maximum values. ($SOC_{min} \leq SOC \leq SOC_{max}$)

6 OPTIMIZATION

In this chapter we will discuss about the modelling 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 modelling the system in HOMER.

6.1 Optimization Software Comparison

A hybrid renewable energy system incorporates two or more electricity generation options based on renewable energy or fossil fuel unit. Due to multiple generation systems, hybrid system analysis is quite complex and requires to be analysed thoroughly. This requires software tools for the design, analysis, optimization, and economic viability of the systems. There are several optimization tools as HOMER, Hybrid2, RETScreen, HOGA, INSEL, TRNSYS, RAPSIM, SOMES, SOLSTOR, HySim, HybSim, IPSYS, HySys, Dymola/Modelica, ARES, SOLSIM. Before choosing the one among those I have analyzed most commonly used software as HOGA, RET Screen, HOMER, Hybrid2 and TRNSYS and comparison as below.

Table 6.1: Optimization Tool comparison

HES Software	Manufacturer	Availability	Accuracy	Economic Analysis	optimization
HOGA	University of Zaragoza	Free	Low	Yes	Yes
RET screen	Natural Resources Canada	Free	Low	Yes	No
HOMER	NREL, USA	Some free and some commercial	High	Yes	Yes
Hybrid2	RERL, University of Massachusetts	Free	High	Yes	Yes
TRASYS	University of Wisconsin, Madison, US	Commercial	High	Yes	No

By considering the availability, high Accuracy HOMER optimization tool is used for the model the hybrid energy system.

6.1 Input Data

Input data for power demand and solar resource has been introduced in HOMER from the available sources trying to be as close to reality as possible given the available sources.

6.1.1 Power Demand

For an effective design of an electrical system, it is desirable to perform an accurate analysis of the electricity demand to be covered. The energy demand characteristics play a decisive role in the definition of the technology to be used and in the final power generation and storage system size needed to meet the demand.

To characterize Delft's electrical demand, the data provided on energy consumption described in the "Power Demand" section has been used. Available demand measurements correspond to the each month. Due to the regular climate of Delft, no significant seasonal variations have been considered.

The Figure 6.1 shows a map of the baseline power demand time series used in simulations. The vertical axis represents the hour of the day while the days of the year are represented in the horizontal axis.

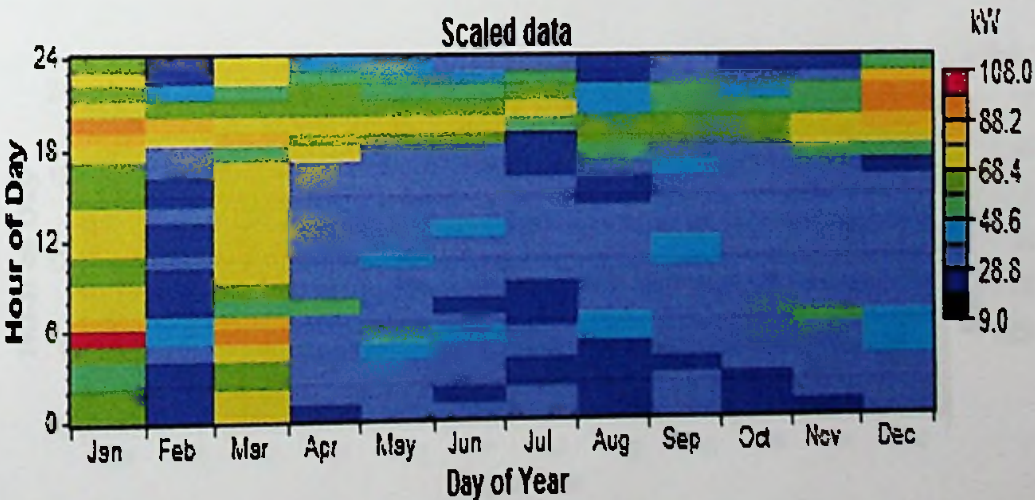

Figure 6.1: Daily and hourly demand map

The diurnal variation of the primary load profile of the community is depicted in Figure 6.2 generated by HOMER after inserting the 24 hour load data.

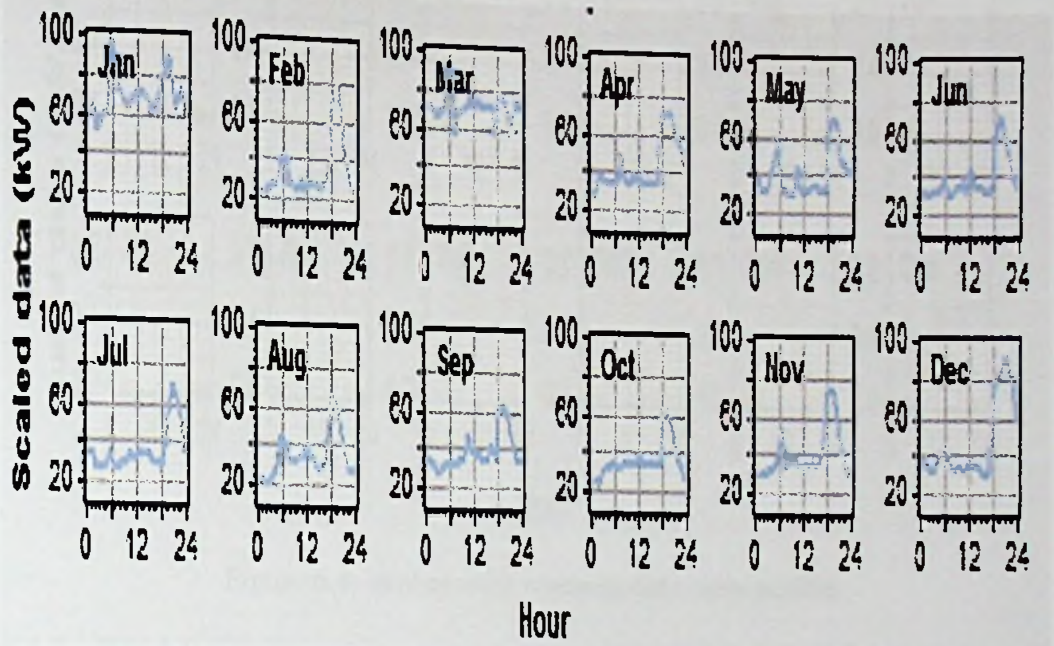

Figure 6.2: Scaled Daily Profile

6.1.2 Solar Resource

Solar radiation data from Metrological department is considered for the analysis. A map with the solar radiation value in kW/m^2 for each hour of the year used for simulations is shown in the Figure 6.3.

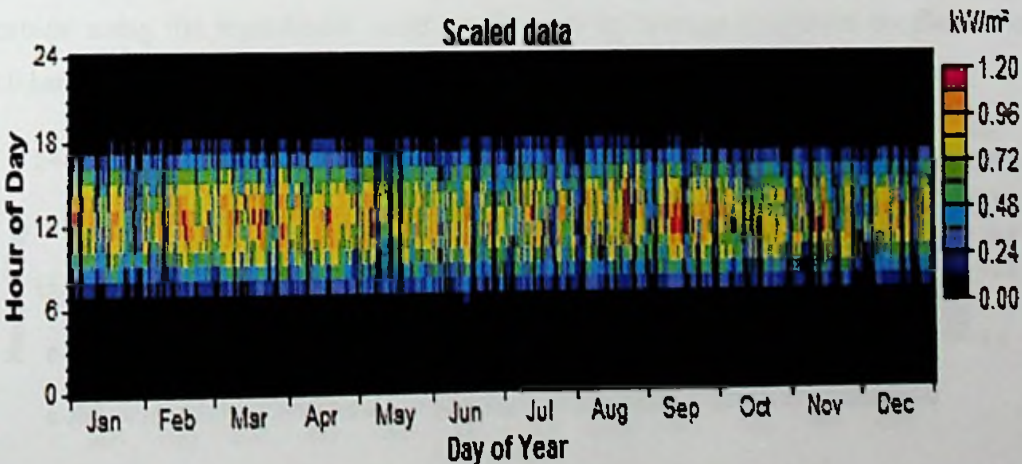

Figure 6.3: Monthly and hourly solar resource

Figure 6.4 generated by HOMER after inserting the 24 hour solar radiation data.

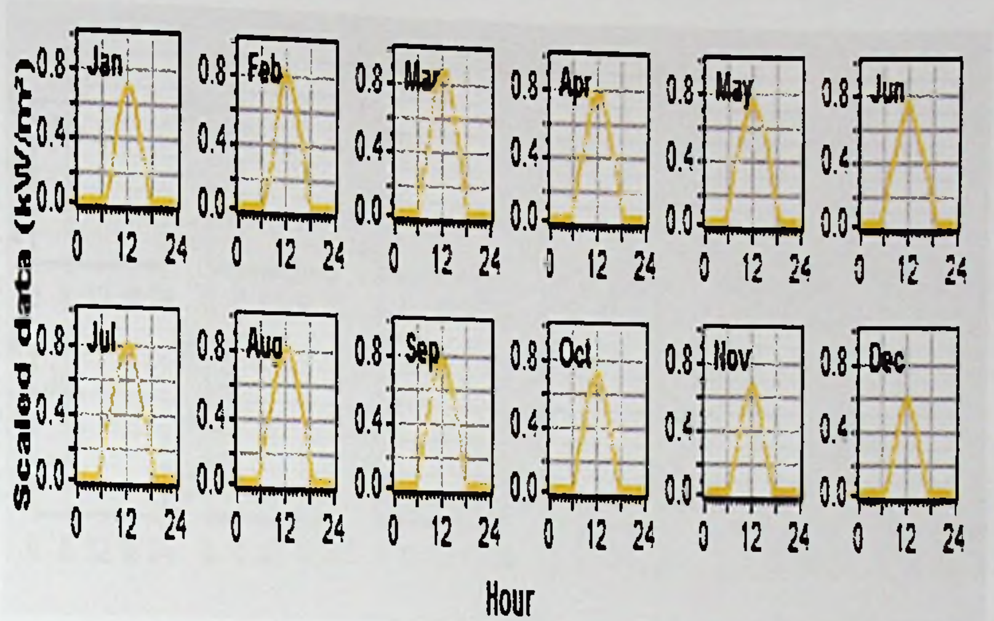

Figure 6.4: Scaled solar resource data daily profile

6.1.3 Wind Resource

Hourly values of wind speed for every hour of the day are generated by the software HOMER pro from the data described in the Meteorology point of this document. A map with the wind speed at a 50m height for each hour of the year used for simulations is shown in the Figure 6.5. Each pixel shows the average wind speed for each hour of the year varying from 30 m/s (red) to 0 m/s (black). To compute the power generated by wind turbines, this wind speed is adapted to the height of the turbine using the logarithmic wind profile with an average roughness coefficient of 0.01m, which corresponds to terrains with few trees and other obstacles around.

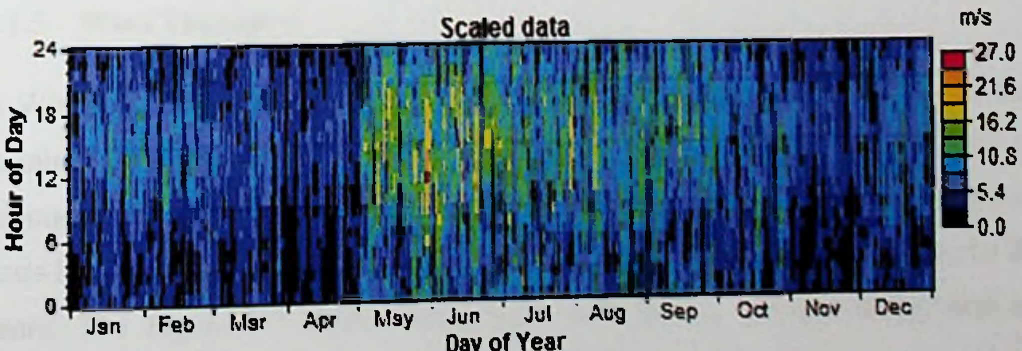

Figure 6.5: Hourly Wind speed

Figure 6.6 generated by HOMER after inserting the 24 hour wind speed data.

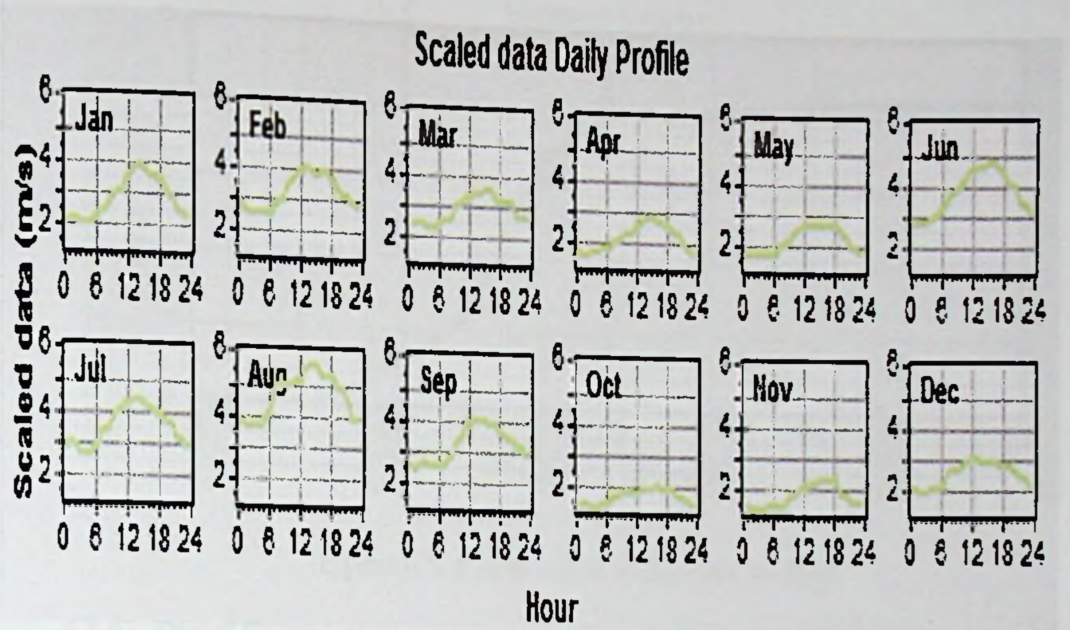

Figure 6.6: Scaled wind speed daily profile

6.1.4 Solar Photovoltaic Technology

Based on recent similar projects, the cost of kWp of PV panels (including the necessary structures) is estimated at $1,000/kWp while the cost of the necessary inverters, wirings and protections for these panels is estimated at $250/kW. Operation and maintenance costs are estimated to be $10/kWp. PV modules are expected to last for 25 years, although it can be longer with proper maintenance. The average de-rating factor of PV installation used for simulations is 80% which accounts for losses in conversion, dust and temperature effect.

6.1.5 Wind Turbine

A Windspot 3.5 kW wind turbine has been used for simulations. The height of the turbine's hub is assumed to be 20 meters. The cost of each 3.5 kW turbine is estimated at $35,000 and replacement cost $15,000. Operation and Maintenance costs have been estimated at $500 per turbine and year. Lifetime is assumed to be 20 years. The Figure 6.7 shows the power curve of the generic model used in simulations.

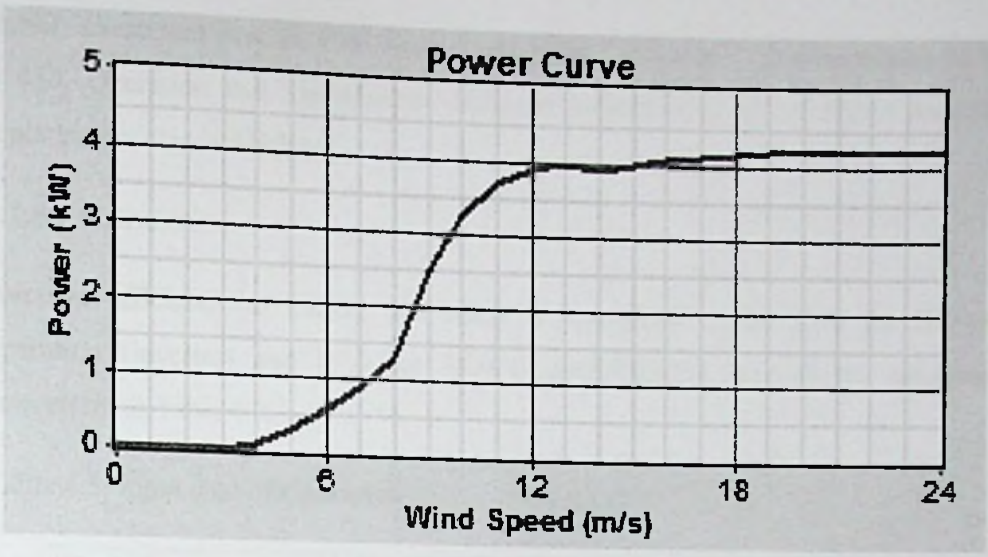

Figure 6.7: Power curve of the wind turbine

6.1.6 Diesel Generator

The generators should operate in parallel with the PV, wind turbines, and battery inverters. For new generators the capital cost, Operation and maintenance cost & Replacement cost as follows. These data (see Table 6.2) has taken from Hayleys Industry. The average price of diesel used in simulations is $0.9/liter.

Table 6.2: Input data of Diesel Generator

Size/kW	Generator Cost($)	Replacement Cost($)	O& M Cost ($/hr)
16	8,965	8,275	0.16
48	14,483	13,241	0.48

6.1.7 Battery Storage system

The size of the storage system is a key parameter for the operation of the electrical system. It will set the capacity to provide management support to the diesel generator sets and regulate variation ramps of photovoltaic and wind turbine generation. It is important to emphasize the need to provide a storage system large enough for the primary control system. Li-ion type batteries are used due to its efficiency and life span.

Initial investment cost of 100kWhr Li–ion battery alone has been estimated to be $ 450. Operation and Maintenance costs are estimated to be 10 $/year and the replacement cost is 440$[14].

6.1.8 Converter

Average efficiency of battery converters is considered to be 85% for DC/AC operation (inverter) and 90% for AC/DC (rectifier).The cost of the necessary converters as Table 6.3.

Table 6.3: Input data of Converter

Size/kW	Capital ($)	Replacement($)	O&M Cost($/yr)
6.4	3,600	3,600	108
30	8,037	6,818	241
200	40,000	30,000	1,200

6.2 Search Space

Several combinations of different capacities of hybrid system components have been considered to find the optimal system. Table 6.4 specifies the capacities of the system components that I have chosen for the simulation.

Table 6.4: HOMER Search Space

PV array (kW)	Wind Turbine 3.5kW (Quantity)	Generator (kW)	Battery	Converter (kW)
0	0	40	0	30
16	1	60	4	
40	10	80	5	
60	12		10	
80	15			
120				

7 POWER MANAGEMENT

7.1 Introduction

The distributed power generation system based on renewable energy sources such as solar PV, wind turbines is experiencing a rapid growth around the world. Since the availability of wind and solar depends on geographic location and meteorological conditions, the hybrid operation of stand-alone system can improves the reliability and power quality in remote locations.

In this chapter the Power Management Algorithm is derived for proposed system which aims to satisfy the load demand regardless the variation in the production of renewable energy and load. In order to increase the system lifetime, the management algorithm must optimally use the renewable generators and the batteries and the diesel generator which must be solicited as little as possible.

7.2 Power Management Algorithm

The main objectives of Power Management Strategy are

- Maximize use of the energy produced by renewable sources
- Minimize the cost of the energy produced by the system
- Meet the energy needs of the load
- Minimize the cycles of charging and discharging of the battery
- Avoid excessive charges or discharges of the battery

The strategy of the management algorithm is summarized in the diagram illustrated in the Figure 7.1. In this strategy, the photovoltaic system and wind turbines are considered as the principle sources. Whenever the principle sources can't satisfy load demand and the battery state of charge (SOC) is in the minimum level, the conventional source (diesel engine) will be enabled to meet load demand.

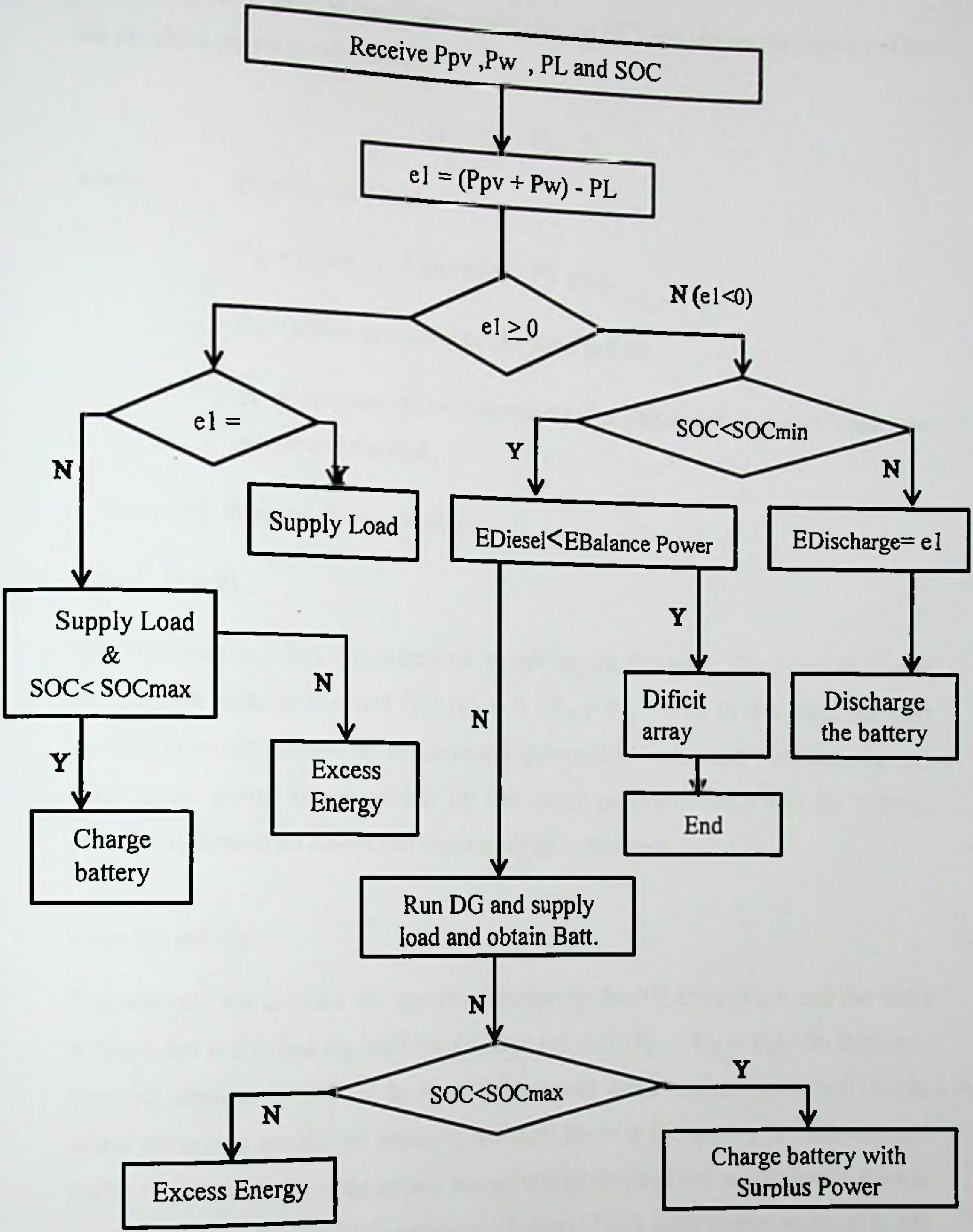

Figure 7.1: Power Management Algorithm

Firstly received power level of Solar and wind energy sources have taken into consideration and calculate the power produced by the PV array (P_{pv}) and Wind turbine (P_w).The power is generated by the wind turbine and the PV array in parallel, and this power is used to supply the loads (AC or DC) and charge the battery. Then the resultant power is calculated as

$$e1 = (P_{pv} + P_{w}) - P_L$$

where P_L = required load

P_{pv} = power produced by the PV array

P_w = power generated by the wind turbine

e1 = resulted power represents the difference between generated power and the load.

At this point, there are three scenarios:

Case I (e1=0)

The first case is when the generated power by the PV array (P_{PV}) and the wind turbines are equal to the load (P_L) (e1 = 0, ($P_{pv} + P_{w}) = P_L$). In this case, the load demand is totally fulfilled by the generated power of PV array and wind turbines and there is no power drawn neither by the diesel generator (DG) nor the battery. Moreover, there is no deficit and excess energy in this case.

Case II (e1>0)

The second case is when the generated power by the PV array (P_{PV}) and the wind turbines are more than the load requirement (e1 > 0, ($P_{pv} + P_{w}) > P_L$). In this case, the load demand is fulfilled by the PV array and wind turbines generated power, while an excess amount of power is resulted. Here, if the battery is fully charged (SOC > SOCmax), all of the excess energy will be dumped and consequently there is no current drawn by Diesel Generator and battery. There is no energy shortage in this case. Otherwise, if the battery is not fully charged (SOC < SOCmax), the battery will be charged and the new battery SOC is calculated.

Case III (e1<0)

The final case is when the generated power by the PV array (P_{PV}) and the wind turbines are less than the load requirement (e1 < 0, (P_{pv} + P_{w}) < P_L). In this case, there are two main subcases:

1. If the SOC is higher than the minimum SOC (SOC > SOC min), then the battery will provide the required power together with Wind & PV generation to full fill the load requirement.

2. If the battery SOC is less than the minimum SOC (SOC < SOC min), In this case the Diesel Generator must provide power and there are two scenarios.

(i) The first scenario is when the balance required power demand is less than the maximum Diesel Generator generated power. In this scenario, the Diesel Generator will run, supply the load demand, & charge battery with surplus power until the battery SOC is equal or less than the SOC max.

(ii) The second scenario is when the maximum Diesel Generator generated power is less than the required balance load demand. Here, the Diesel Generator is not able to cover the load demand and it is not able to charge the battery.

7.3 Simulation

A simulation is performed to study the behavior of the power management for solar wind-diesel stand-alone hybrid energy model. Simulation results were compared by using MATLAB program. For the simulation we used the profiles of irradiation, temperature and wind speed data which are taken from the metrological department and optimized system specification from the HOMER optimization tool. Simulation is carried out for different scenarios.

Scenario I

The hybrid energy system is simulated for 24 hours using the previous profiles. By using these previous profiles average values for load demand, wind speed and solar radiation and average temperature variation are calculated.

Simulation carried out for Standalone Wind PV Diesel System, Standalone PV System, Standalone Wind System and Diesel System and final results will be compared.

Scenario II

Simulated for different scenarios for a Cloudy day and Rainy day.

8 RESULTS

8.1 HOMER Implementation

The optimum hybrid system components capacities can be determined by using HOMER implementation. 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. Above mentioned data were provided to the HOMER software (see Figure 8.1) and obtained the optimized solution for hybrid energy system.

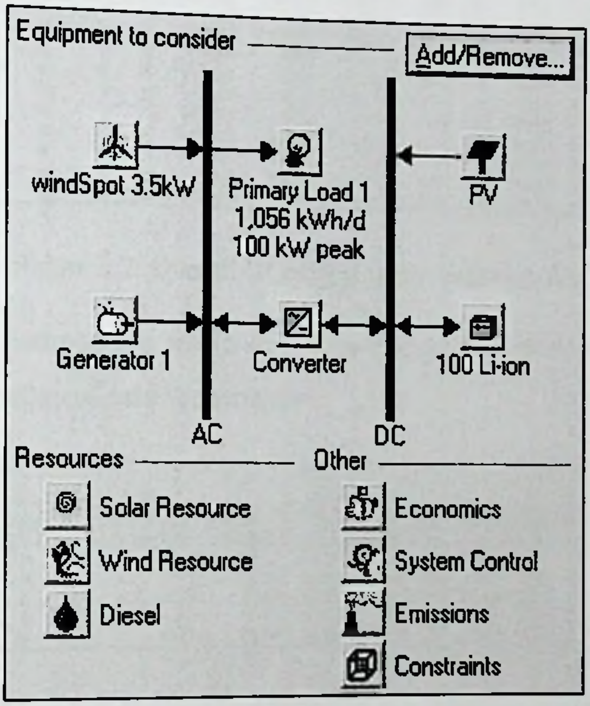

Figure 8.1: Graphical Interface of Hybrid Power system

8.2 Optimization Results for the Present Demand

Part of the overall optimization results are as shown below. According to the increasing Net Present Cost of the project, it displays the list of system configurations.

The Categorized optimization results as shown Figure 8.2 and it displays most cost effective configuration of each system type.

Sensitivity Results | Optimization Results

Double click on a system below for simulation results

○ Categorized ● Overall

PV (kW)	Winds	Label (kW)	100 Li-ion	Conv (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
40	10	80	4	30	$ 427,887	105,607	$ 1,777,994	0.361	0.36	100,577	6,152
40	10	80	5	30	$ 428,337	105,596	$ 1,778,203	0.361	0.36	100,577	5,152
40	10	80	10	30	$ 430,587	105,541	$ 1,779,752	0.361	0.35	100,577	5,152
40		80	4	30	$ 77,887	133,629	$ 1,785,111	0.362	0.09	142,827	8,623
40		80	5	30	$ 78,337	133,618	$ 1,786,423	0.363	0.09	142,827	8,623
60	10	80	4	30	$ 452,887	104,337	$ 1,786,569	0.363	0.38	99,210	5,113
60	10	80	5	30	$ 453,337	104,326	$ 1,786,979	0.363	0.38	99,210	5,113
40		80	10	30	$ 80,587	133,565	$ 1,787,997	0.363	0.09	142,827	8,623
60	10	80	10	30	$ 455,587	104,272	$ 1,788,536	0.363	0.33	99,210	6,113
16	10	80	4	30	$ 397,887	109,012	$ 1,791,424	0.364	0.33	104,254	5,272
16	10	80	5	30	$ 393,337	109,001	$ 1,791,732	0.364	0.33	104,254	5,272
16	10	80	10	30	$ 400,587	108,946	$ 1,793,285	0.364	0.33	104,254	6,272
60		80	4	30	$ 102,887	132,239	$ 1,793,342	0.364	0.11	141,094	5,604
60		80	5	30	$ 103,337	132,228	$ 1,793,553	0.364	0.11	141,094	8,604
60		80	10	30	$ 105,587	132,175	$ 1,795,225	0.364	0.11	141,094	8,604
80	10	80	4	30	$ 477,887	103,635	$ 1,802,685	0.366	0.38	99,395	6,093
80	10	80	5	30	$ 478,337	103,624	$ 1,802,996	0.366	0.38	99,395	6,093
16		30	4	30	$ 47,887	137,363	$ 1,803,841	0.366	0.05	147,802	8,740
16		80	5	30	$ 43,337	137,352	$ 1,804,152	0.366	0.05	147,802	8,740
80	10	80	10	30	$ 480,587	103,569	$ 1,804,551	0.365	0.38	99,395	6,093
40	1	80	4	30	$ 112,887	132,342	$ 1,804,656	0.366	0.12	140,009	8,553
40	1	80	5	30	$ 113,337	132,331	$ 1,804,965	0.366	0.12	140,009	8,553
16		80	10	30	$ 50,587	137,300	$ 1,805,741	0.366	0.05	147,802	8,740
40	1	80	10	30	$ 115,587	132,277	$ 1,806,529	0.367	0.12	140,009	8,553
80		80	4	30	$ 127,887	131,438	$ 1,808,741	0.367	0.12	139,914	8,575
80		80	5	30	$ 128,337	131,477	$ 1,809,056	0.367	0.12	139,914	8,575

Figure 8.2: Overall HOMER optimization results

The Categorized optimization results as shown Figure 8.3 and it displays most cost effective configuration of each system type.

Sensitivity Results | Optimization Results

Double click on a system below for simulation results.

● Categorized ○ Overall Export...

PV (kW)	Winds	Label (kW)	100 Li-ion	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)	Label (hrs)
40	10	80	4	30	$ 427,887	105,607	$ 1,777,994	0.361	0.36	100,577	6,152
40		80	4	30	$ 77,887	133,629	$ 1,786,111	0.362	0.09	142,827	8,623
	10	80	4	30	$ 377,887	112,610	$ 1,817,415	0.369	0.30	108,725	6,459
		80	4	30	$ 27,887	141,213	$ 1,833,057	0.372	0.00	152,537	8,760
		120		30	$ 31,775	173,719	$ 2,252,493	0.457	0.00	189,580	8,760

Figure 8.3: Categorized HOMER optimization results

According to the HOMER simulation results, the optimum system type is PV/wind/diesel generator/battery system and this system can supply the electricity at 0.361 $/kWh.

The system configuration is given in Table 8.1.

Table 8.1: Optimum Hybrid system configuration

PV system capacity	40 kW
Number of 3.5 kW Wind turbines	10 Nos.
Generator capacity	80 kW
Battery bank	140 kWh
Converter capacity	30 kW

8.2.1 Monthly Average Electric Production

Monthly average electric power production from each of the system components in the hybrid system is shown in Figure 8.4.

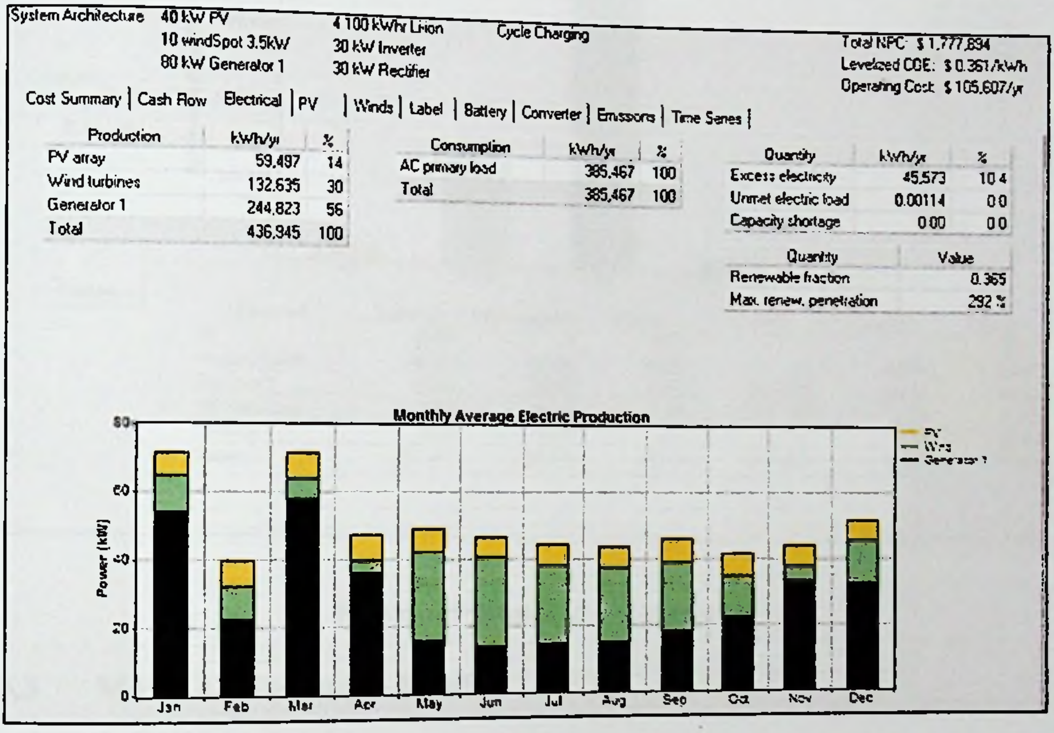

Figure 8.4: Monthly Average Electric Production

According to that the largest percentage of the power is generated by the wind turbines. From May to September the generated power from the wind turbines is considerably higher. On the other hand the average power generated from the wind turbines and the PV system 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 8.4, 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.

8.2.2 Cash Flow summary

According to the cash flow summary (see Figure 8.5) Levelized Cost of Energy is 0.361 $/kWh and it costs less than the diesel only system.

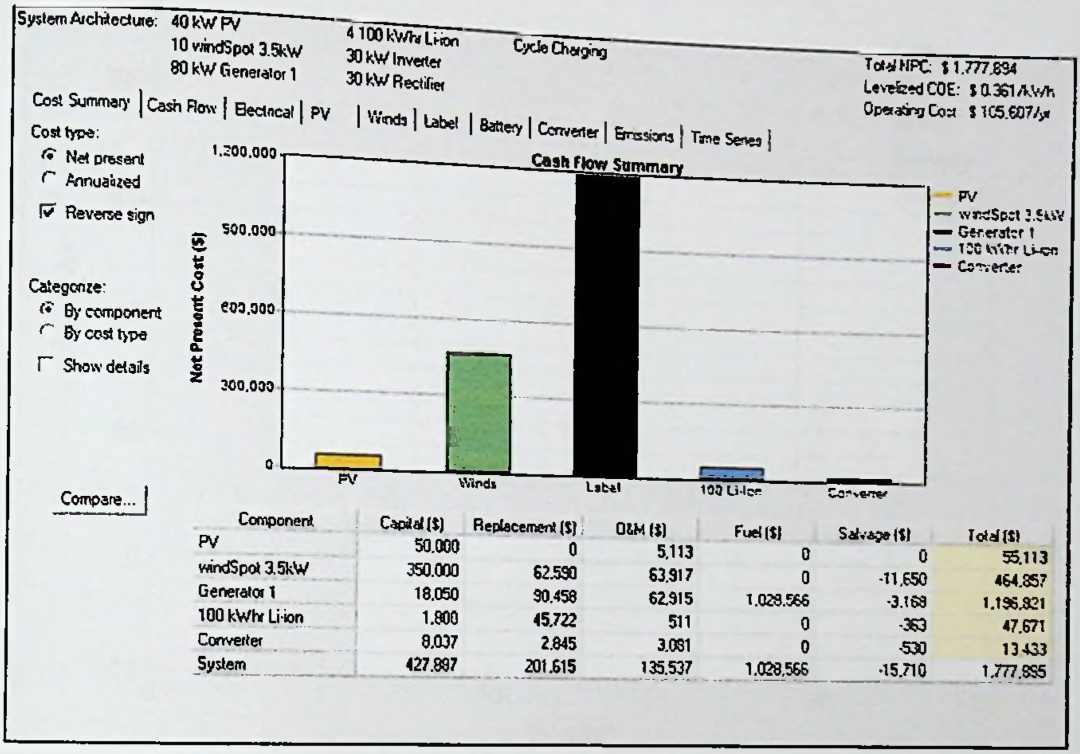

Figure 8.5: Cash Flow Summary

8.3 MATLAB Simulation Results

8.3.1 MATLAB Simulation Results– scenario 1

Simulation carried out for Standalone Wind PV Diesel System, Standalone PV System, Standalone Wind System and Diesel System and final results will be compared.

8.3.1.1 Standalone Wind PV Battery Diesel System

In standalone Wind PV Diesel System, the load demand is supplied by both wind & PV renewable sources. If these renewable energies are insufficient Diesel Generator will operate. Load demand, Generated power from wind & PV system, Diesel Generator generated power and Battery discharge power illustrated in Figure 8.6.

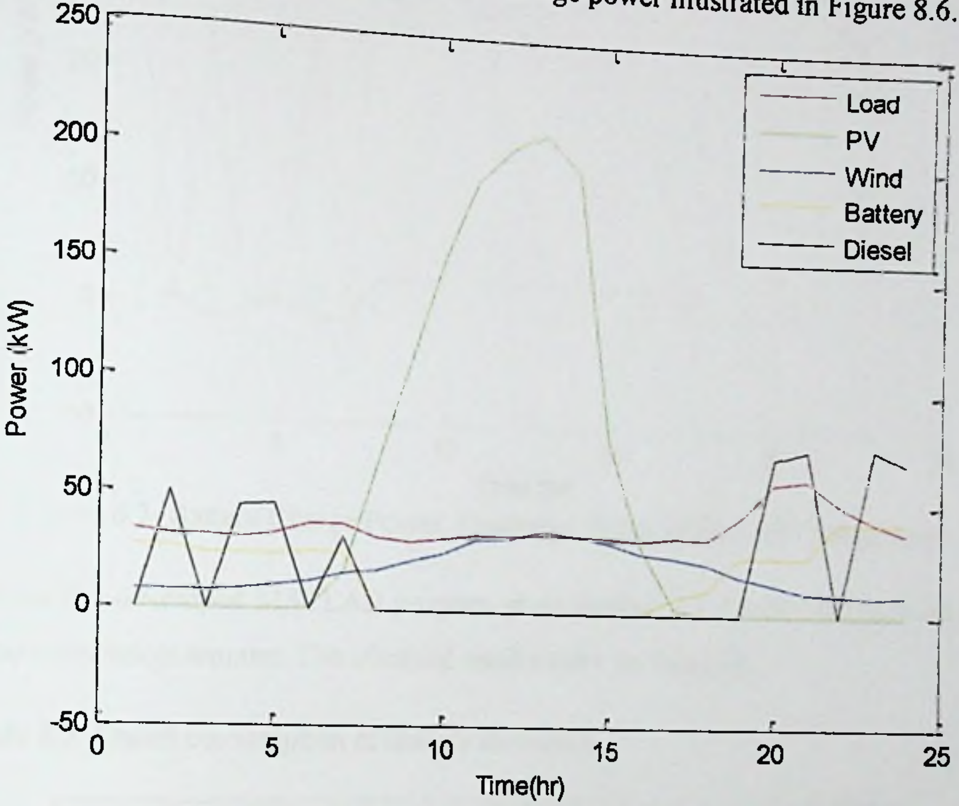

Figure 8.6: Results of standalone Wind PV Battery Diesel system

Battery power, Battery discharge power, Battery charge power and Battery state of charge level as Figure 8.7.

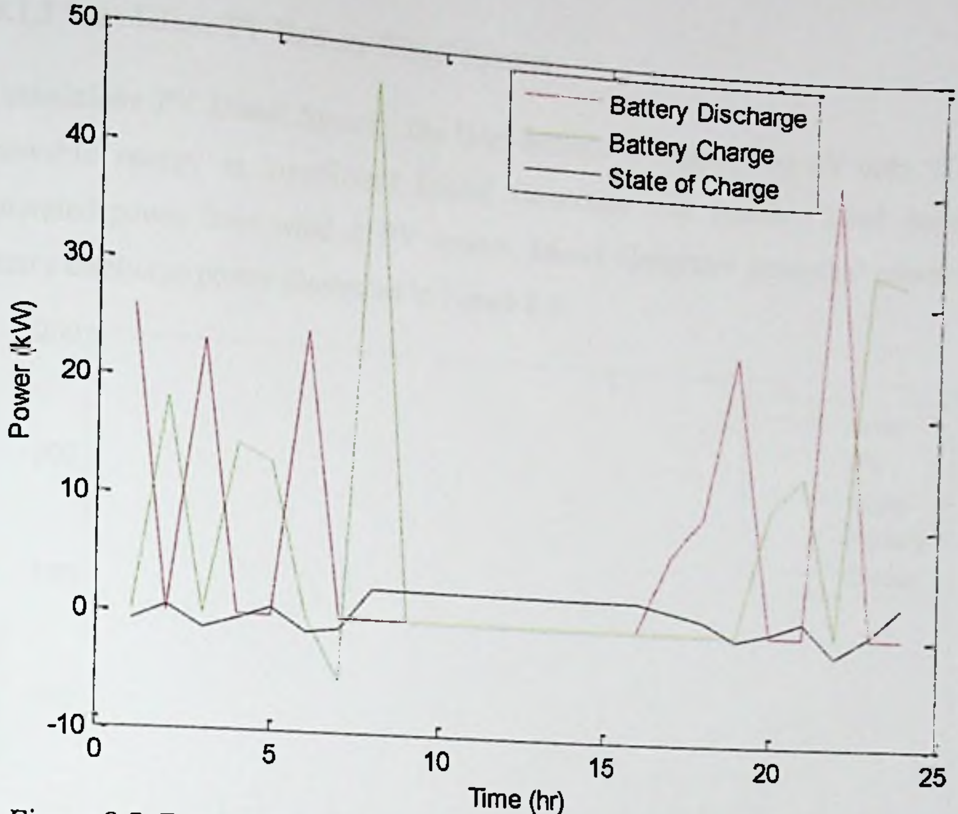

Figure 8.7: Battery Charge Power, Discharge Power & State of Charge level

Further the developed MATLAB program gives outputs for diesel consumption and battery discharge amount. The obtained results show in Table 8.2.

Table 8.2: Diesel consumption & Battery discharge

Diesel_consumption	239.378 Litres
Battery_Discharge	732.460 kWh

According to the output graph the average power generated by solar PV is approximately 310 kW. Wind energy generates up to 40 kW depending on load demand. Diesel consumption to run this system for 24 hrs is 239.378 Litres and battery discharge amount is 732.460 kWh.

8.3.1.2 Standalone PV Battery Diesel System

In standalone PV Diesel System, the load demand is supplied by PV only. If this renewable energy is insufficient Diesel Generator will operate. Load demand, Generated power from wind & PV system, Diesel Generator generated power and Battery discharge power illustrated in Figure 8.8.

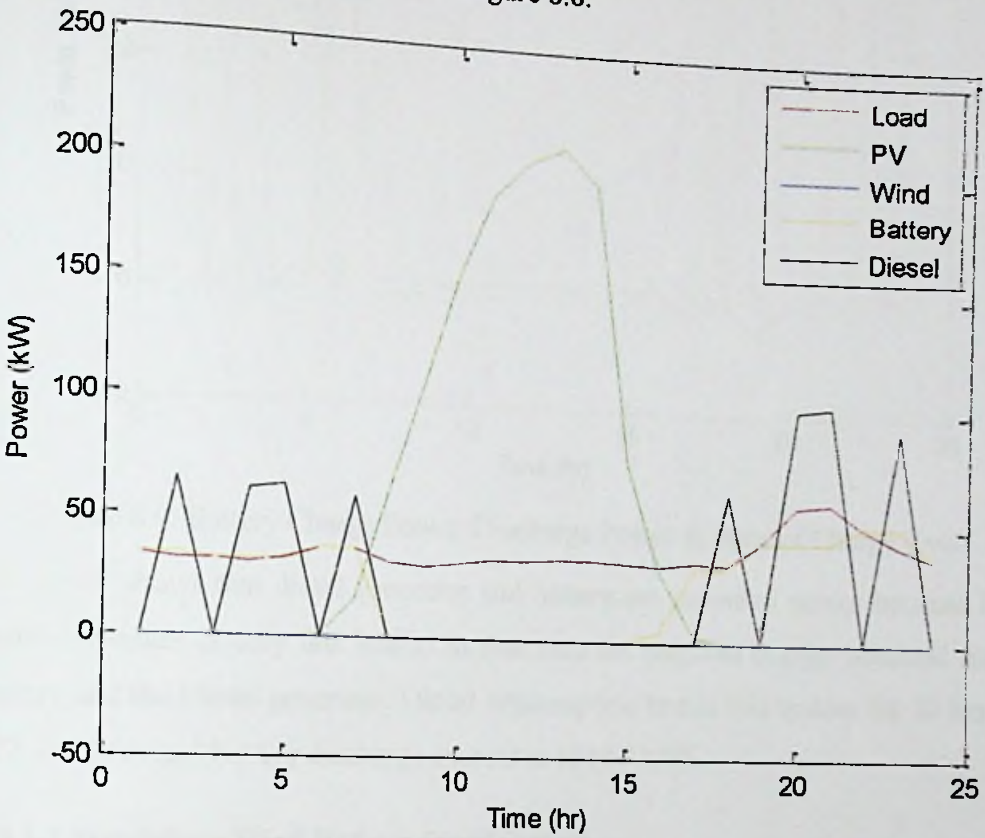

Figure 8.8: Results of standalone PV Battery Diesel system

Diesel consumption, battery discharge amount and excess energy amount as Figure 8.9.

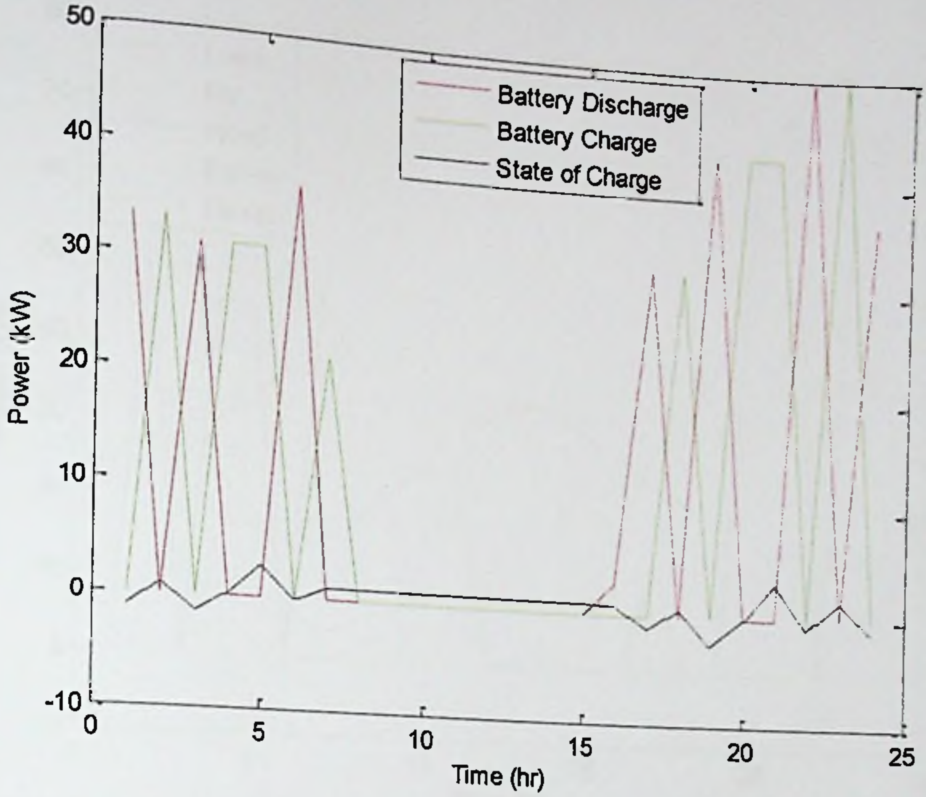

Figure 8.9: Battery Charge Power, Discharge Power & State of Charge level

The result shows that diesel generator and battery are provided power because PV system operates in only few hours. At that time the required energy obtained from battery and the Diesel generator. Diesel consumption to run this system for 24 hrs is 322.76 Litres and Battery discharge amount is 1018.7 kWh.

8.3.1.3 Standalone Wind Battery Diesel System

The proposed algorithm has simulated for standalone wind diesel system also. Generated Power from wind system, Load Demand and Diesel Power and as Figure 8.10.Further Diesel consumption, battery discharge amount and excess energy amount are shown in Figure 8.11.

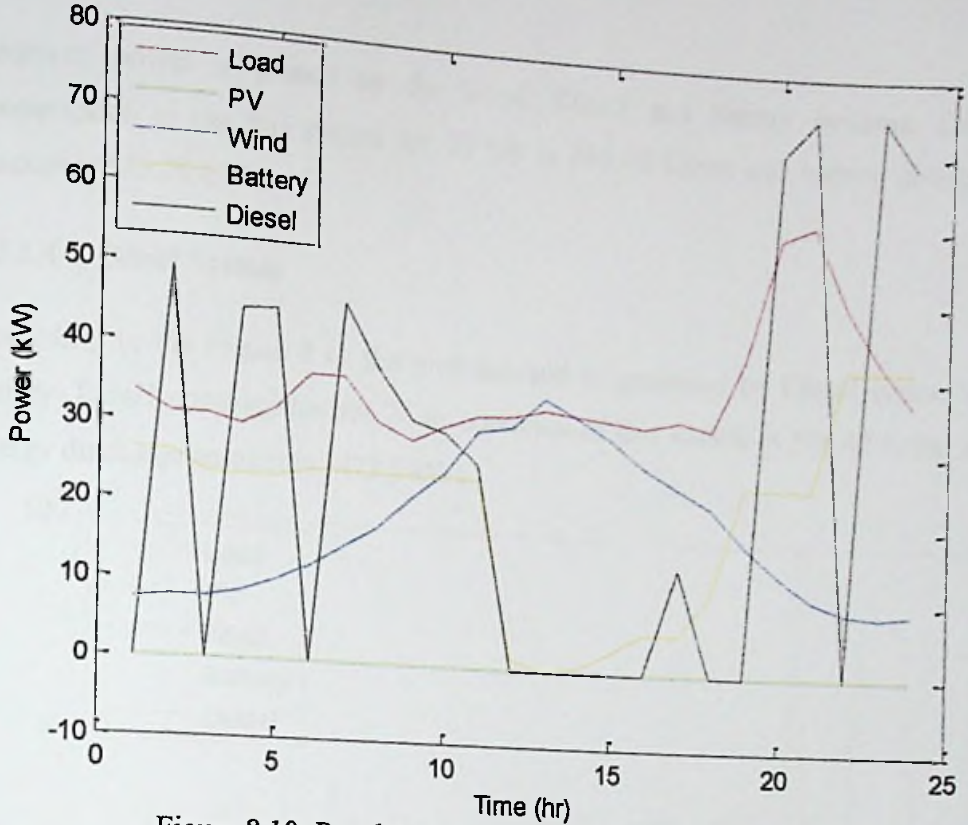

Figure 8.10: Results of standalone Wind Diesel system

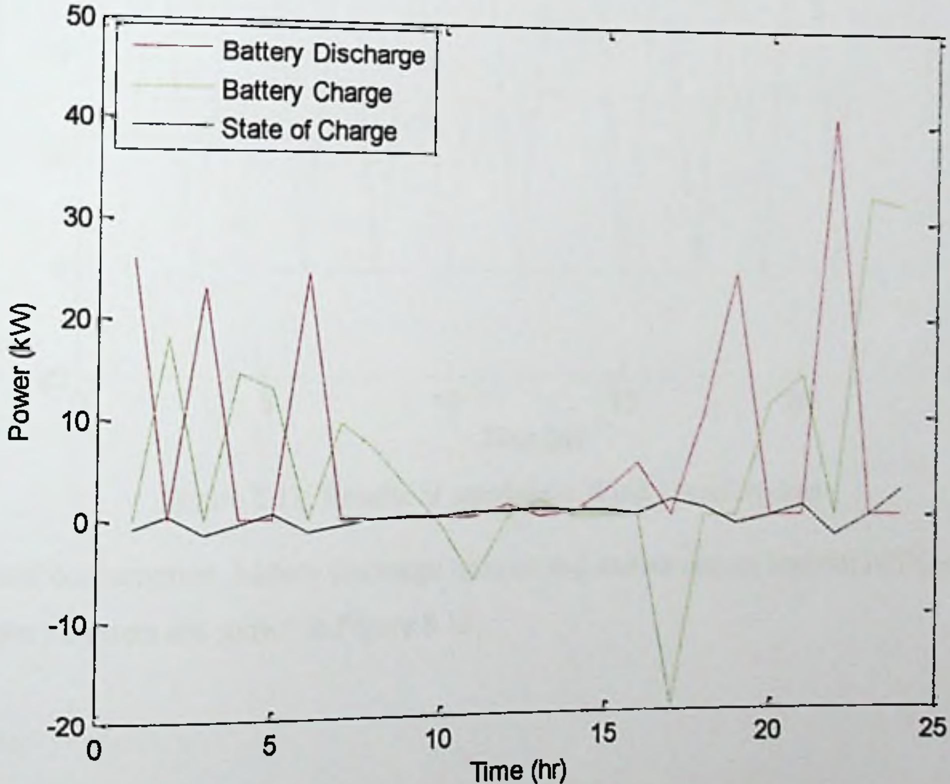

Figure 8.11: Battery Charge Power, Discharge Power & State of Charge level

Required power is gained by the Wind, Diesel and battery systems. Diesel consumption to run this system for 24 hrs is 439.90 Litres and battery discharge amount is 581.76 kWh.

8.3.1.4 Diesel System

According to the Figure 8.12 the total demand is generated by Diesel system and battery. Diesel consumption for 24 hr operation of this system is 576.42 Litres and energy discharge amount is 1472.3 kWh.

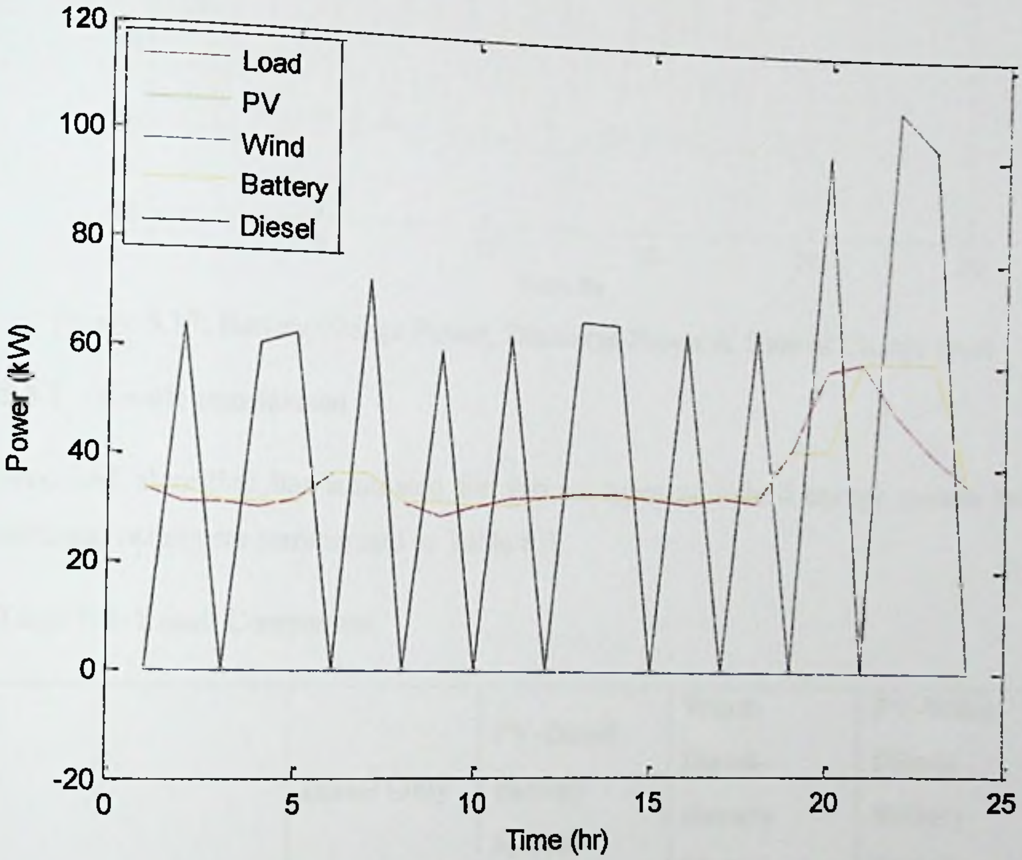

Figure 8.12: Results of standalone Wind Diesel system

Diesel consumption, battery discharge amount and excess energy amount of Diesel Battery System are shown in Figure 8.13.

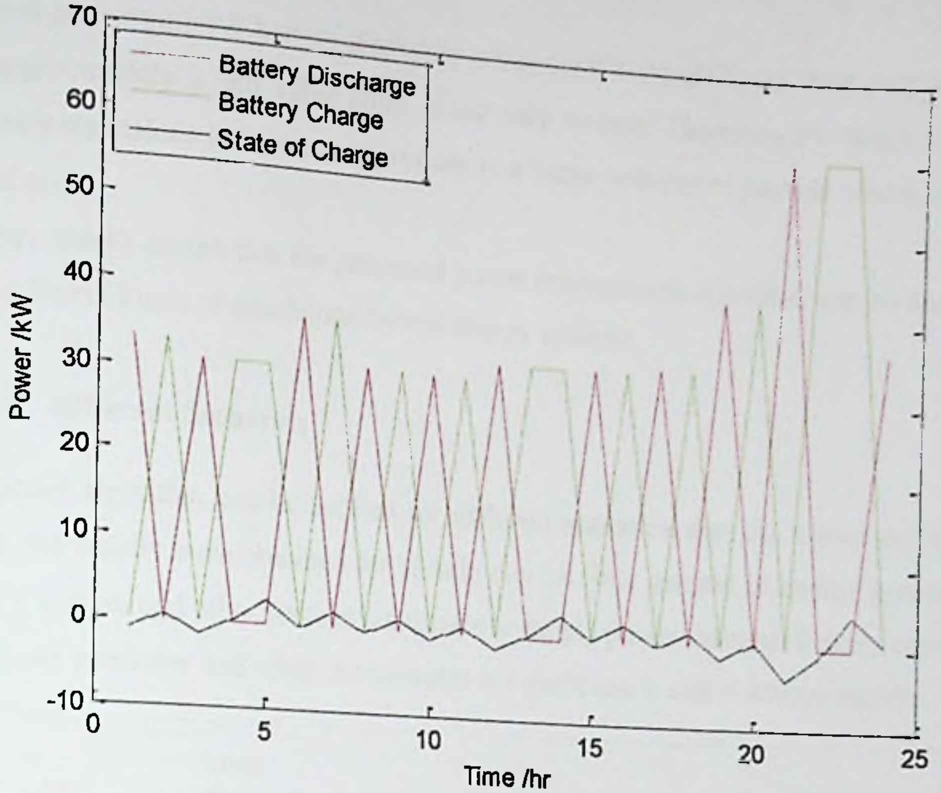

Figure 8.13: Battery Charge Power, Discharge Power & State of Charge level

8.3.2 Result comparison

Proposed algorithm has simulated for various types of hybrid energy system and obtained results are summarized as Table 8.3.

Table 8.3: Result Comparison

	Diesel Only	PV-Diesel-Battery System	Wind-Diesel-Battery System	PV-Wind-Diesel-Battery System
Diesel_consumption (Litres)	576.42	322.76	439.90	239.37
Battery_Discharge (kWh)	1472.3	1108.7	581.76	732.46

Diesel consumption for a Diesel generating system is 576.42 litres battery discharge is nearly 812 kWh and for a PV Wind Diesel Battery system diesel consumption is calculated as 239.37 ltrs and battery discharge is 732.46.According to the results

Diesel consumption & battery discharge is less for PV-Wind Diesel –Battery System. It approximately a half value from diesel only system. Therefore PV Wind Diesel Battery standalone hybrid energy system is a better solution to provide electricity to rural areas.

Above results ensure that the proposed power management algorithm can be applied for different kinds of standalone hybrid energy systems.

8.3.3 Different Scenarios

Proposed algorithm can be applied for different scenarios also. As shown in Figure 8.14, the results were obtained for cloudy day. A little amount of energy generated by PV system and other sources contribute to supply power demand. Battery charged by diesel generator and when the power is not sufficient it will discharge rapidly.

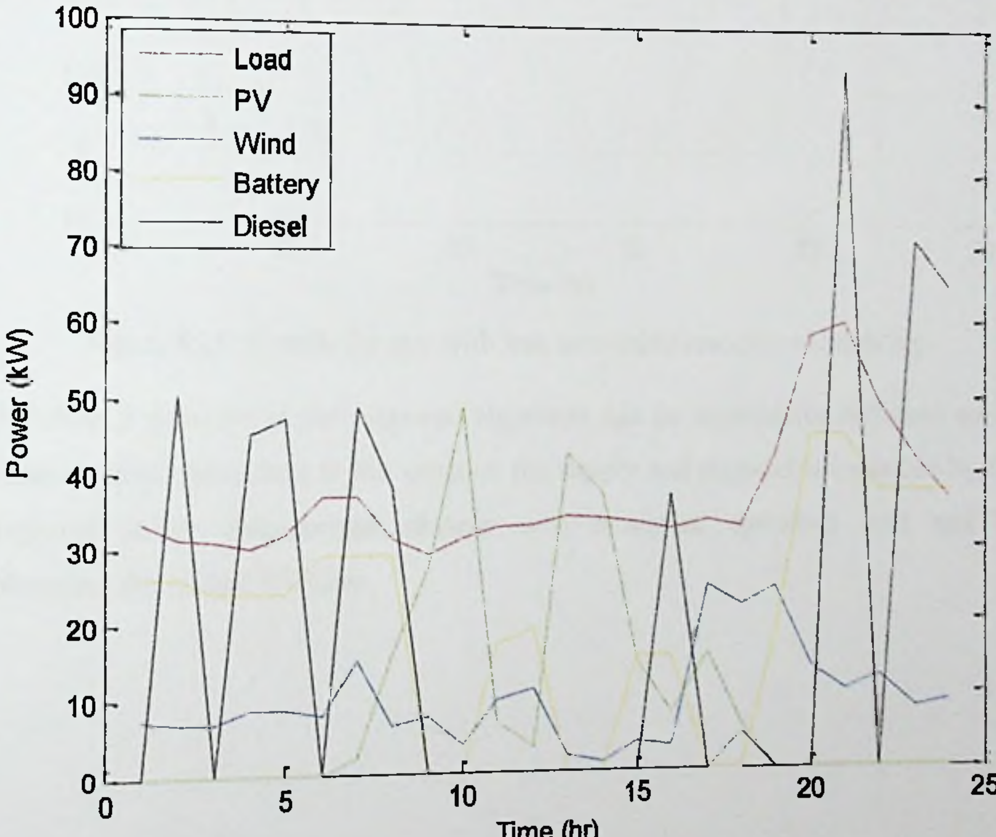

Figure 8.14: Results for Cloudy climate condition

This proposed power management algorithm is applied for a day which has poor renewable energy levels. As previous case the demand is catered by the diesel generator and battery as Figure 8.15.

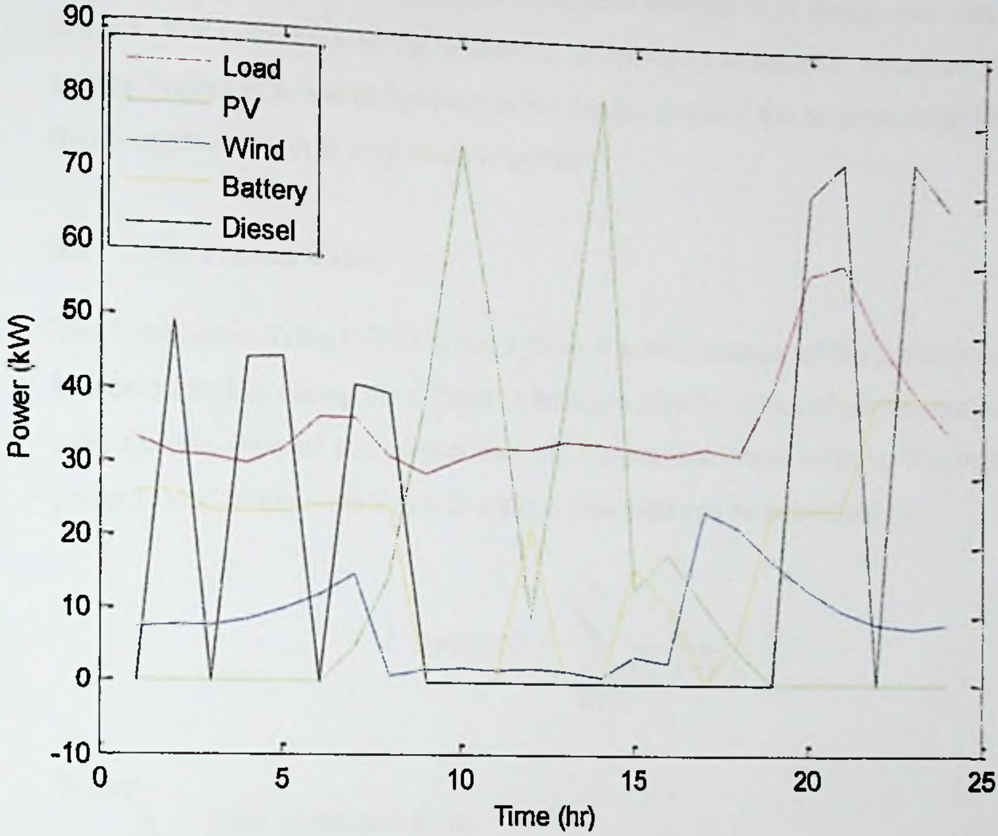

Figure 8.15: Results for day with less renewable resource availability

Therefore it proves that the proposed algorithm can be applied for different actual scenarios also. According to the situation the supply and demand is balanced by the proposed power management strategy with minimize operation cost and by enhancing the system life time.

9 ECONOMIC ANALYSIS

The main role of conducting project economic analysis is to design and select the projects that contribute to the welfare of a region or a country. Since the Hybrid energy system is a new technology to Sri Lanka, evaluate the economic viability for this proposed system is very much important.

9.1 Net Present Value

The Net Present Value (NPV) of the system is a measurement of the profitability and it is calculated by taking the difference between present values of all the costs occurs over the life time of the project and all the revenue earns over its lifetime. The present value of the costs that will make n year later can be calculated by

$$\mathrm{NPV}(i, N) = \sum_{t=0}^{N} \frac{R_t}{(1+i)^t}$$

Where

t – Time of the cash flow

i – The discount rate

R_t- The net cash flow (Cash inflow – Cash out flow, at time t)

NPV > 0; Project is economical viable

NPV < 0; Project is economically not viable

9.2 Economic Viability

Development of a rural electrification scheme based on renewable hybrid power system in Delft Island entails an initial investment of approximately $ 342000. Presently bigger amount of money spend for money. By using this kind of renewable energy system, the fuel saving per year is approximately $199,000.Operating and Maintenance cost per year is approximately $10,000.As per the analysis after the four year time from the starting of the project CEB can make profit.

10 DISCUSSION

There is a challenge to supply electricity to the rural population due to their geographical locations and economic constraints. Electrifying these remote areas by extending transmission lines from the utility grid is very labour and time intensive. Hybrid renewable energy systems are the possible means of electricity generating for rural remote areas. Due to intermittent nature of renewable energy resources and large fluctuations, using them alone is unreliable and expensive. Therefore, hybrid systems have considered as best solution for providing electricity with reliability, sustainability and environment protections.

An optimal combination of renewable energy system and optimum power management is also needed to improve the reliability and power quality of the standalone hybrid energy system.

The main objective of this thesis is to model and optimize stand-alone hybrid energy system with power management strategy which can provide affordable and reliable electricity for a rural community in Sri Lanka. The work was started by studying the daily load profiles of the selected community and at the same time potential of renewable energy resources in the selected area has been identified by analyzing past data on the annual variations of solar radiation and wind speed. Due to intermittent nature of the renewable resources, a battery bank has been added to the hybrid system and a diesel generator has also been included in order to ensure the continuity of the supply.

Further, while various component configurations for the hybrid system have been studied, AC/DC coupled hybrid configuration has been selected mainly due to maximized efficiency of the diesel generator. After selecting the appropriate components and studying their characteristics, the optimum capacity of Solar, wind & Diesel generator, Battery has been decided by considering the demand, industrial expansion and future growth. Further Wind-Solar-Diesel Battery Hybrid system has been modelled and simulated in HOMER. Finally general power dispatching algorithm for hybrid systems has been built and simulated in MATLAB. Developed

MATLAB program has been applied for different cases and results were compared. Finally economic analysis carried out to check the viability of the system.

As selected area Delft Island was taken because nowadays CEB has focused to provide electricity for these islands by using standalone hybrid energy system. Approximately 4750 population (1500 families) was comprised in year 2016.Usage of electricity within this region is mostly residential and in 2015 the 1ϕ 30 A consumed number of consumers amount was approximately 845. Further 8 consumers used 3ϕ 30 A and 3ϕ 60 A. The average electricity consumption is 70,376 kWh/ month, Daily Peak load is 100 kW and load factor is 0.75.This region receives an abundance of solar radiation with an annual average of 5.681 kWh/m2/day and the annual average wind speed of this region is 8.6 km/h.

However, the demographic data analysis has also been performed by assuming that the demand, population of this island has exponentially growth.Probable energy demand was forecasted by studying the present energy supplied by CEB's diesel generators and it has been assumed that the total energy requirement of this selected area is fulfilled by CEB's diesel generators. And also the peak load profile for each month was assumed by considering the past records and the general climate prevailing in the island is assumed as very much similar to the overall climatic condition of the northern part of Sri Lanka. The seasonal variations and the day length does not considered because Sri Lanka is located close to the equator. On-site wind speed measurements in Delft were not available. Therefore NASA data available from the software HOMER pro is used.In economic analysis it has been assumed that the interest rate as 15% and the tax as 38%.

Based on initial capital investment it seems diesel generated system is more economical than the renewable energy based hybrid systems because diesel generated system require a very small capital investment when compared to renewable energy based hybrid systems. But diesel generated system has the higher 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.

The decision concerning the final selection of the optimum configuration has been made 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 system capacity	40 kW
Number of 3.5 kW Wind turbines	10 Nos.
Generator capacity	60 kW
Battery bank	140 kWh
Converter capacity	30 kW

All the equations which are used for the mathematical modeling in this thesis is standard equations and they are taken from the books and previous researches.There are many researches have been carried out to find an optimal combination of renewable energy resources in rural electrification and most of them are only for Solar wind Battery hybrid power system. And also power management of the system does not considered. In some researches minimization of the cycles of charging and discharging of the battery is not considered and battery state of charge level is also not taking in to account for the power management. In addition to that some researches develop power management algorithm only for a specify system and not a generalized one.

In this research develop a general power management strategy has been considered as the main objective. The proposed algorithm is targeted to maximize use of the energy produced by renewable sources, minimize the cost of the energy produced by the system and minimize the cycles of charging and discharging of the battery. In shortly it helps to enhance the performance and lifetime of the system. Proposed power management strategy is a generalized one and it can be applied for different types of standalone power systems.

MATLAB program was coded for proposed management system and it was simulated for different scenarios.Simulation results clearly shown that proposed power management strategy can be used for different standalone energy systems and it minimize the fuel consumption cost by enhancing the renewable energy production whenever the renewable resources are available. By using such power management strategy the renewable energy contribution for standalone hybrid energy system can be increased by minimize the energy generated cost. Further it maintains the high power reliability throughout the day by using battery storage system.

11 CONCLUSIONS AND RECOMMENDATIONS

11.1 Conclusions

The Wind PV Diesel Battery hybrid energy systems have identified as the most economical solution to provide electricity in rural areas which cannot access the national grid. Delft Island has been considered as the sample area for the research and it has been found that the cost of energy can be significantly reduced by using hybrid energy system.

Having identified that there is a considerable effect of power management to the hybrid energy system, a general power management algorithm has been developed to maximize the use of renewable energy resources, minimize the cost of the energy produced by the system and minimize the rate battery discharging. Further it helps to enhance the performance and lifetime of the system.Software has been also developed for derived power management algorithm and it can be used to calculate the diesel consumption and battery discharge amount for a given demand, renewable energy levels. This software has been validated by applying for different hybrid energy systems and for a different climate conditions. Results show that the Diesel consumption and energy discharge amount is lower in Wind PV Diesel Battery system than the others while enhancing the availability of supply. And also results prove that the proposed algorithm is a general one.

From economic analysis, it reveals that by implementing this kind of rural electrification projects CEB can make profit after 3 or 4 year time. Further as a solution of inaccessibility of national grid, standalone hybrid energy systems can be used.

11.2 Recommendations

Renewable energy systems are environment friendly solution for rural electrification since it does not release any pollutant gas in to the environment. It is more advantage to interconnect renewable energy system with diesel and battery system due to it enhances the system reliability.

Further hybrid power system is more economically attractive than diesel system for electrifying the selected rural community in Sri Lanka under the condition that the power management of the system is properly conFigured in accordance with the renewable resource potential and load condition in the village.

11.3 Future Work

There are several possible directions for further improvements as

- 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.

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APPENDIX A

MATLAB Program

PV Module Configurations

```
function Ia = PVmodule(Va,S,TaC)
S= xlsread('inputdata.xlsx', 'sheet7', 'B3:B50');       % Solar
radiation data
TaC=42.6;
Va = 31;                        % PV voltage
k  = 1.38e-23;                  % Boltzmann's const
q  = 1.60e-19;                  % charge on an electron
A  = 2;                         % "diode quality" factor, =2 for
crystalline, <2 for amorphous
Vg = 1.12;                      % band gap voltage, 1.12eV for xtal Si,
?1.75 for amorphous Si.
Ns = 3;                         % number of series connected cells (diodes)
T1 = 273 + 25;
Voc_T1 = 38.2 /Ns;              % open cct voltage per cell at temperature
T1
Isc_T1 = 9.00;                  % short cct current per cell at temp T1
T2 = 273 + 20;
Voc_T2 = 35.7 /Ns;              % open cct voltage per cell at temperature
T2
Isc_T2 = 7.29;                  % short cct current per cell at temp T2
TaK = 273 + TaC;                % array working temp
TrK = 273 + 25;                 % reference temp
                                % when Va = 0, light generated current
Iph_T1 = array short cct current
                                % constant "a" can be determined from Isc
vs T
Iph_T1 = Isc_T1 * S;
a = (Isc_T2 - Isc_T1)/Isc_T1 * 1/(T2 - T1);      %temperature
coefficient calculation
Iph = Iph_T1 * (1 + a*(TaK - T1));
Vt_T1 = k * T1 / q;                              % = A * kT/q
Ir_T1 = Isc_T1 / (exp(Voc_T1/(A*Vt_T1))-1);      %reverse saturation
current
Ir_T2 = Isc_T2 / (exp(Voc_T2/(A*Vt_T1))-1);
b = Vg * q/(A*k);
Ir = Ir_T1 * (TaK/T1).^(3/A) .* exp(-b.*(1./TaK - 1/T1)); %diode
saturationn current
X2v = Ir_T1/(A*Vt_T1) * exp(Voc_T1/(A*Vt_T1));
dVdI_Voc = - 1.15/Ns / 2;                  % dV/dI at Voc per cell from
manufacturers graph
                                           % series resistance per cell
Rs = - dVdI_Voc - 1/X2v;
Vt_Ta = A * 1.38e-23 * TaK / 1.60e-19;  % = A * kT/q
Vc = Va/Ns
```

Perturb & Observe method for PV panels

```
function E_PV = pertubetest(T,S,TaC)

%define constants
S= xlsread('inputdata.xlsx', 'sheet2', 'B3:B50');
T1= xlsread('inputdata.xlsx', 'sheet2', 'A3:A50');
TaC =    25;         %cell temperature
C   =    0.5;        %step size
Va  =    31;         %PV voltage
Ia  =    PVmodule(Va,S,TaC);
Pa  =    Ia.*Va;          % PV output power
Vref_new     = Va+C; %new reference voltage
Va_array     =[];
E_PV         =[];
Ia= PVmodule(Va,S,TaC);
xi  =        1:200;                          % set points for interpolation
yi  =        interp1(T1,S,xi,'cubic');%Do cubic interpolation
for i=1                                      %read solar radiation value
S=yi(i);                                     %take new measurement
Va_new=Vref_new;
Ia_new= PVmodule(Va,S,TaC);
Pa_new=Va_new*Ia_new;
deltaPa=Pa_new-Pa;
if deltaPa>0;
if Va_new>Va;
Vref_new     =Va_new+C;                          %increase ref
else
Vref_new     =Va_new-C;                          %decrease ref
end
elseif deltaPa<0
if Va_new>Va
Vref_new     =Va_new-C;
else
Vref_new     =Va_new+C;
end
else
V_ref        = Va_new;
end
Va           =Va_new;
Pa           =Pa_new;
Va_array     = [Va_array Va]
E_PV         = [E_PV Pa]
end
end
```

Main Program

```
clear all;
clc
close all
%%Data sources
    S  = xlsread('inputdata.xlsx', 'sheet7', 'B3:B50');          % Solar
radiation data
    T  = xlsread('inputdata.xlsx', 'sheet7', 'C3:C50');          %
Ambient Temperature
    L  = xlsread('inputdata.xlsx', 'sheet7', 'D3:D50');          % Load
    WS = xlsread('inputdata.xlsx', 'sheet7', 'E3:E50');          % Wind
Speed data

%% Simulation of the PV system
%% Specification
    Pv_eff=0.16;                                   % Efficiency of the PV
module
    PV_Wp=40;                                      % The capacity of the PV
array(kWatt)
    Alpha=0.055;                                   % Temperature
coefficient of the PV module power
    Wire_eff=0.98;                                 % Wire Efficiency
    Inv_eff=0.85;                                  % Inverter Efficiency
    NOCT=43.6;                                     % Nominal Operating Cell
Temperature
    D1 = 0.6;                                      % Derating factor
    T2=0.081451;                                   % Coeficient of the fuel
consumption curve
    TaC=25; %cell temperature

    E_PV = pertubetest(T,S,TaC)
%%Simulation of the Wind Turbine
%%Specification
    R=2.025;                                       % Radius of the blades
    Air_Density=1.22521;
    gen_eff=0.96;
    E_w= ((Air_Density*3.14*(R.^2)*0.5*0.59*(WS.^3))*0.85)*10/1000
%10 no of wind turbines are used

%%Simulation of the Diesel gen
%%Specification
  E_Diesel=120;                                    % Diesel Generator rated
power kW
  A=0.2461;                                        % co-efficient of the
fuel consumption curve in (l/kwh)
  D=1e-5;

%%Simulation of Battery
%%Specification                                    % battery capacity
    SOCmax=140;
kWh/day                                            % Voltage of the used
    V_B=400;
battery                                            % allowed depth of
    DOD=0.8;
discharge
```

```
    charge_eff=0.8;
    %SOCmin=SOCmax*(1-DOD);                          % charging eff
    t=1;
    SOCi=SOCmax;
    SOC1=1;
    SOC2=SOC1;
    ns=6;
    K=0.8;
    SOC3=0.3;
battery                                              % minimum SOC of the
    n=0;
    W=0;

%Define Metrices
    SOCf        =[];                  %Battery state of Charge
    E_Loadf     =[];                  %Load
    E_chargef   =[];                  %Battery Charging Power
    E_Dampf     =[];                  %Damped power
    E_Dischargef =[];                 %Discharged Power
    E_Batteryf  =[];                  %Battery Power
    E_Deficitf  =[];                  %Deficit
    E_Dieself   =[];                  %Diesel
    F_Cf        =[];                  %Fuel Consumption Cost

%Algorithm build process
    % E_net=(E_PV+E_w)-L
   k=length(L);                                       % For the length of the
matrix
    for i=1:1:k
        E_net(i)=(E_PV(i)+E_w(i))-L(i);        % represent the
difference between the PV,Wind power and Load

    %%%% Case of (E_PV+E_w = L) %%%%
    if E_net(i)==0                                    % Case of the PV,Wind
generated power equal to Load
        if n==0;
   E_Load(i)=E_PV(i)+E_w(i) % Supply the load
   E_Dampi=0;
   E_Batteryi=0;               % Power taken from battery.
   E_Chargei=0;
   E_Deficiti=0;
   E_Dieseli=0;
   E_Dischargei=0;
   F_Ci=0;
     if i ==1                  % This for the case of the first loop is
: (E_PV+E_w =L) then the SOC is equal to SOC maximum.
       SOCi=SOC1;
        elseif W==0            % Case the battery is not discharged at
any previous step, the SOCi is equal to the SOCm
       SOCi=SOC1;
        elseif W==1            % Case when the battery has discharged
in the one of any previous step, the SOCi=SOC(i-1);
       SOCi=SOCf(i-1);
      end
       end

    %%% Case of (E_PV+E_W >L) %%%
```

```
    elseif E_net(i)>0 && n==0                    % Case of the generated current
from PV and wind is higher than the Load current AND for
            E_Loadi=L(i);                      % the next condition which
    if i==1                                    % Supply the load
      SOCi=SOC1;
      E_Dampi=E_net(i);    % The damp power is equal to
E_net=(E_PV+E_w -L)
      E_Chargei=0;
      E_Dischargei=0;
      E_Batteryi=0;
      E_Deficiti=0;
      E_Dieseli=0;
      F_Ci=0;
   elseif i>1
                              if W==0
                                SOCi=SOC1;
                                E_Dampi=E_net(i);        % The damp Power
is equal to E_net=(E_PV+E_w-L)
                                   else W==1
                                     if SOCf(i-1)>=SOC1     %  SOC>SOCmax
                                        E_Dampi=E_net(i);
                                        SOCi=SOCf(i-1);
                                        E_Dischargei=0;
                                        E_Batteryi=0;
                                        E_Deficiti=0;
                                        E_Dieseli=0;
                                        E_Chargei=0;
                                        F_Ci=0;
                        elseif SOCf(i-1)<SOC1                  %  SOC<SOCmax
                                        E_Chargei=E_net(i);     % Charge
the battery by E_net=(E_PV+E_w - L)
                                        E_Dischargei=0;
                                        E_Batteryi=0;
                                        E_Deficiti=0;
                                        E_Dieseli=0;
                                        E_Dampi=0;
                                        F_Ci=0
                        for t=1;                              % Check the SOC
of the battery by using the following equations (charge mode)
                                        B=SOC2;
                                               V1= (2+.148*B)*ns;
                                               R1=(.758+.1309/(1.06-
B))*ns/SOCmax;
                                               R1=double(R1);
                                               syms v;
                                               ee=
double(int((K*V1*E_net(i)-D*SOC2*SOCmax),v,0,t));
                                               SOC=SOC1+SOCmax^-1*ee;
                                               SOC2=SOC;
                                     end
                                               SOC2=double(SOC);
                                               SOC(i)=SOCf(i-1)+
abs((SOC1-SOC2)); %The instantaneous SOC of the battery
                                               SOCi=SOC(i);
                                      end
                                    end
                         end
```

```
        %%% Case of (E_PV +E_w <L) %%%%
                    elseif E_net(i)<0 || E_net(i)>0 & n>=0        % Case
of the generated power from PV and wind is less than the Load power
                                                                    % and
for the next condition which
                            if W==0
                            if n==0
                               E_Dischargei=L(i)-E_PV(i)-E_w(i);
% Discharging the battery to met the load
                               E_Loadi=E_PV(i)+E_w(i)+E_Dischargei;
% Supply the load from the PV & the battery
                               E_Batteryi=E_Dischargei;
% Power taken from battery.
                               E_Chargei=0;
                               E_Deficiti=0;
                               E_Dampi=0;
                               E_Dieseli=0;
                               F_Ci=0;
                                  for t=1;
%Check the SOC of the battery by using the following
equations(dis.mode)
                                     B=SOC2;
                                     V1=(1.926+.124*B)*ns;
                                     R1=(.19+.1037/(B-
.14))*ns/SOCmax;
                                  syms v;
                                     ee=
double(int((K*V1*E_net(i)-D*SOC2*SOCmax),v,0,t));
                                     SOC=SOC1+SOCmax^-1*ee;
                                     SOC2=SOC;
                                  end
                               SOC2=double(SOC);
                               SOC(i)=SOC2;
                               SOCi=SOC(i);
                               W=W+1;
                            end
                                elseif W==1
                        if SOCf(i-1)>SOC3 && n==0
                           E_Dischargei= L(i)-E_PV(i)-E_w(i);        %
Discharging the battery to met the load.
                           E_Loadi=E_PV(i)+E_w(i)+E_Dischargei;      %
Supply the load from the PV,wind & the battery.
                           E_Batteryi=E_Dischargei;                  %
Power taken from battery.
                           E_Chargei=0;
                           E_Deficiti=0;
                           E_Dampi=0;
                           E_Dieseli=0;
                           F_Ci=0;
                        for t=1;                                 %Check
the SOC of the battery by using the following equations:
(((Discharging mode)))
                           B=SOC2;
                           V1=(1.926+.124*B)*ns;
                           R1=(.19+.1037/(B-.14))*ns/SOCmax;
                           syms v;
                           ee= double(int((K*V1*E_net(i)-
D*SOC2*SOCmax),v,0,t));
```

```
                        SOC=SOC1+SOCmax^-1*ee;
                        SOC2=SOC;
                     end
               SOC2=double(SOC);
               SOC(i)=SOCf(i-1)-abs((SOC1-SOC2));
               SOCi=SOC(i);

               elseif SOCf(i-1)<=SOC3 || n>=0
                   if  E_Diesel>=L(i)-E_PV(i)-E_w(i)
                       E_Loadi=L(i);                % Supply the load
from the diesel

                       E_Dieseli=L(i)-E_PV(i)-E_w(i)+E_Batteryi;
% power from diesel

                       E_Dischargei=0;
                       E_Deficiti=0;
                         if  SOCf(i-1)<SOC1
                             E_Chargei=E_Dieseli-L(i);
                             E_Dampi=0;

                    for t=1;                                     %
Check the SOC of the battery by using the following equations:
                       B=SOC2;
                       V1= (2+.148*B)*ns;
                       R1=(.758+.1309/(1.06-B))*ns/SOCmax;
                       R1=double(R1);
                       syms v;
                       ee= double(int((K*V1*E_Chargei-
D*SOC2*SOCmax),v,0,t));
                       SOC=SOC1+SOCmax^-1*ee;
                       SOC2=SOC;
                    end
                     SOC2=double(SOC);
                     SOC(i)=SOCf(i-1)+ abs((SOC1-SOC2));      %The
instantaneous SOC of the battery.
                     SOCi=SOC(i)
                    else
                       E_Chargei=0;
                       E_Dampi=E_PV(i)+E_w(i)+E_Dieseli-L(i);
                       SOCi=SOC1;
                    end
               F_C
=(A*(95*(E_Dieseli/60)))+(T2*(95*(E_Diesel/60)))
               F_Ci=F_C
               n=n+1;
               n=0;
                    end
                    end
                    end
          end


    SOCf(i)=SOCi;
    E_Loadf(i)=E_Loadi;
    E_Chargef(i)=E_Chargei;
    E_Dischargef(i)=E_Dischargei;
    E_Batteryf(i)=E_Batteryi;
    E_Deficitf(i)=E_Deficiti;
```

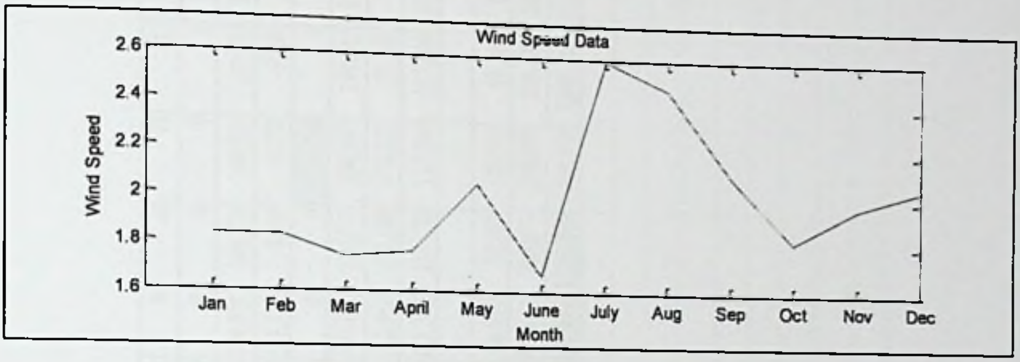
```
        E_Dampf(i)=E_Dampi;
        E_Dieself(i)=E_Dieseli;
        F_Cf(i)=F_Ci;
    end


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%% %%%

    DD=SOCf;
    SSS=0;
    DD=SOCf;
        [row,col] = size(DD)
        for i = 1:1:row
            for j = 1:1:col
                SOC = DD(i,j);
                    if (SOC <0.3)
                        SSS=SSS+1;
                    end
            end
        end
        LL=SSS     %% Number of how many time the SOC reach to
SOCmin.


Excess_energy=(((sum(E_Dampf)/60)*220))
Diesel_consumption=(sum(F_Cf))                          % Litters
Enrgy_Deficit= ((sum(E_Deficitf)/60)*220)               % kWh
Enrgy_Discharge= ((sum(E_Dischargef)/60)*220)           %kWh

Figure
plot(E_Loadf, 'red');
hold on
plot(E_PV,'green');
hold on
plot(E_w,'Blue');
hold on
plot(E_Batteryf, 'Yellow')
hold on
plot(E_Dieself, 'black')
hold on


Figure
plot(E_Dischargef, 'red');
hold on
plot(E_Chargef, 'green')
hold on
plot(SOCf,'black');

Figure
plot(E_Deficitf,'r')
hold on
plot(E_Dampf,'B')
```

APPENDIX B

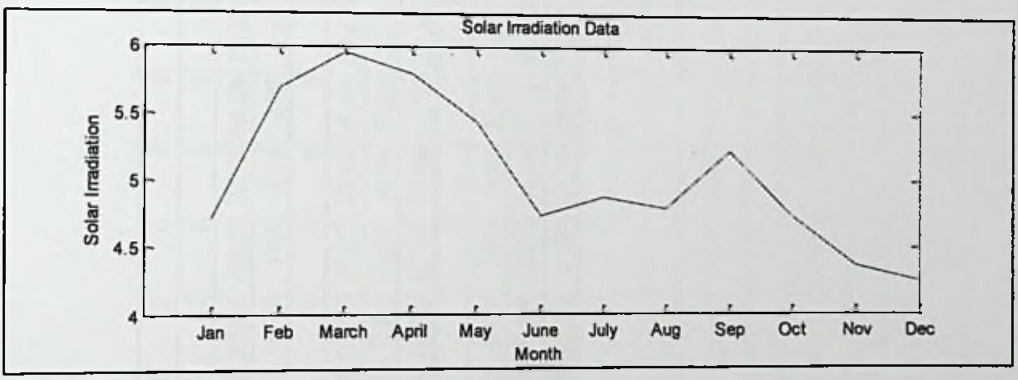
Input data for MATLAB Program

For the simulation we used the profiles of irradiation, temperature and wind speed as given in the following Figure:

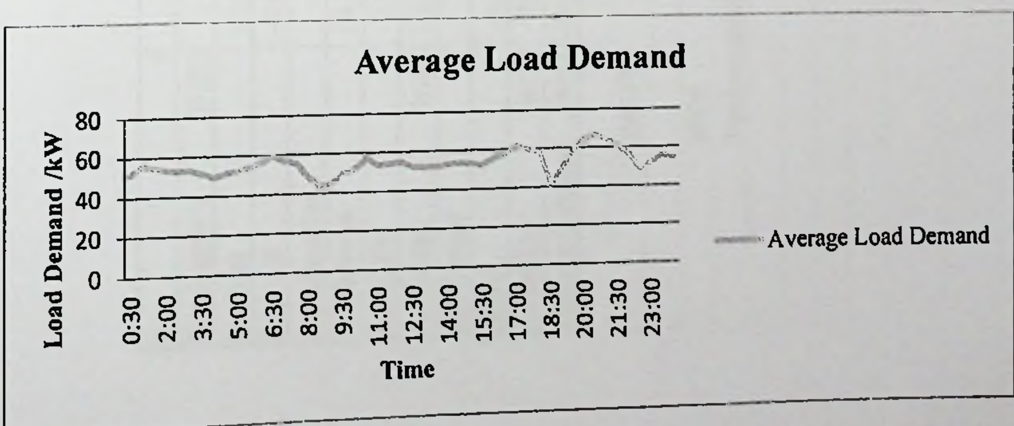
Wind Speed Data



Solar Radiation Data



Temperature



APPENDIX C

Economic Analysis

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Cost of Equipment	-341,937	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel Saving		199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024	199.024
O&M Cost		-10.014	-9.899	-9.786	-9.675	-9.565	-9.460	-9.355	-9.253	-9.153	-9.054	-8.958	-8.863	-8.770	-8.679	-8.590
Replacement Cost		0	0	0	0	0	0	0	0	0	0	0	0	0	0	-6.818
Profit Before tax		189.011	189.126	189.239	189.350	189.459	189.565	189.670	189.772	189.872	189.971	190.067	190.162	190.255	190.346	190.435
Tax @ 38%		-71.824	-71.868	-71.911	-71.953	-71.994	-72.035	-72.074	-72.113	-72.151	-72.189	-72.225	-72.261	-72.297	-72.331	-72.365
Net CashFlow before Interest	-341,937	117.187	117.258	117.328	117.397	117.464	117.530	117.595	117.658	117.720	117.782	117.841	117.900	117.958	118.014	118.069
Interest		-51.291	-33.713	-16.124	1.475	19.085	87.995	88.046	88.097	88.147	88.195	88.243	88.290	88.335	88.380	88.424
Net cash Flow	-341,937	65.896	83.545	101.204	118.872	136.549	205.525	205.642	205.755	205.867	205.977	206.084	206.199	206.293	206.394	206.494
Cumulative Cash Flows	-341,937	-276.041	-192.496	-91.292	27.580	164.129	369.654	575.296	781.051	986.918	1,192.895	1,398.979	1,605.169	1,811.452	2,017.856	2,224.350

$3,463,973.18

NPV>0

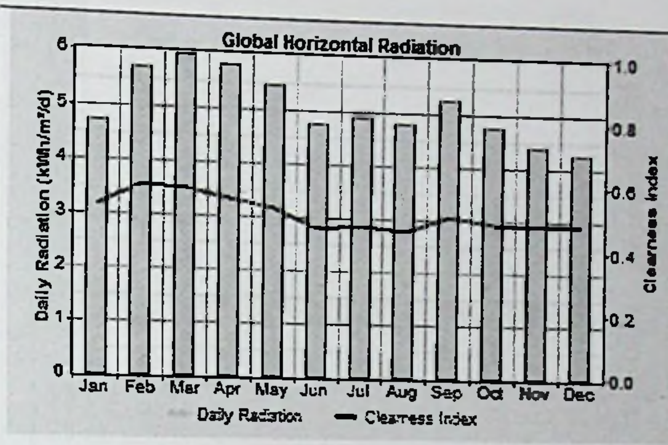
Project is economical viable

APPENDIX D

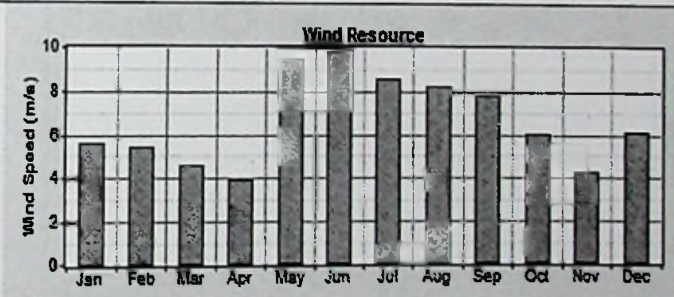
HOMER software; Input Summary

D.1 The renewable resources inputs that have given the HOMER optimization tool as follows.

Solar Resource

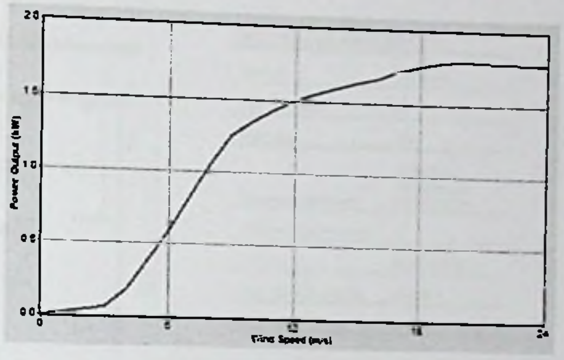
Monthly avareage solar radiation (kWh/m2/d)	

Wind Resource

Monthly avareage wind speed (m/s)	
Weibull k 1 hr autocorrelation factor Diurnal pattern strength Hour of peak wind speed	2 0.85 0.25 15

D.2.The technical specifications of the components which have given as inputs to the HOMER optimization tool as follows.

Wind Turbine

Model	WindSpot 1.5 kW
Rated Power	1.5 kW AC
Power Output curve	
Life Time	15 yrs
Hub Height	25 m

PV system

Model	4BB – HR-240 P -18Bbd-HR-270P-18Bbd
Derating Factor(%)	80
Slope (degrees)	9.52
Azimuth	0
Ground Reflectance	20%
Lifetime	25
Nominal operating temperature	43.6 °C

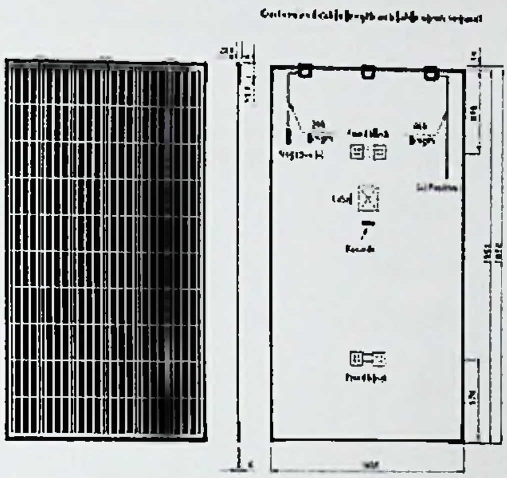
4BB – HR-240 P -18Bbd-HR-270P-18Bbd Data sheet

Hareonsolar

Hareon Solar Technology Co., Ltd.

4BB HR-240P-18/Bbd—HR-270P-18/Bbd

Dual Glass Module



MECHANICAL PARAMETERS

[illegible]

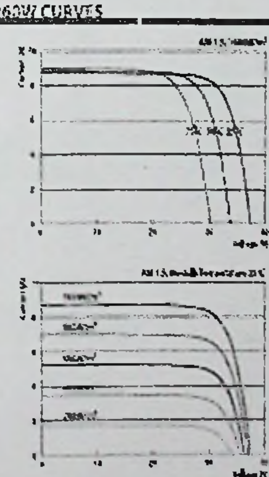
QUALIFICATION

[illegible]

ELECTRICAL PARAMETERS

[illegible]

260W CURVES



PACKING CONFIGURATION

[illegible]

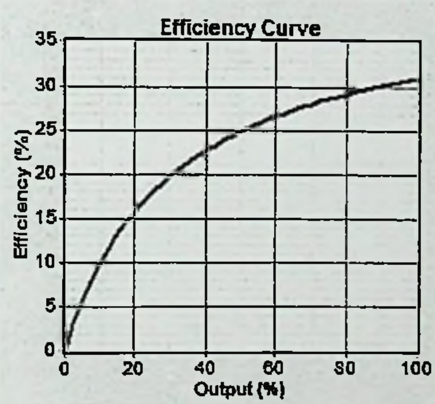
LINEAR WARRANTY

[illegible]

Battery

Nominal Capacity	350 Ah
Nominal Voltage	400 V
Lifetime Throughput	1,000 kWh
Round trip efficiency	80%
Min. state of charge	40%
Max. charge rate	3501 A/Ah

Diesel Generator

Life time (Operating Hours)	25,000 hr
Minimum load raio	50%
Fuel	Diesel
Fuel Price($/L)	$ 0.8
Efficiency Curve	

Converter

Life time	15
Efficiency	90%