FEASIBILITY AND PERFORMANCE ANALYSIS OF AN INVERTER BASED HYBRID POWER GENERATION SYSTEM

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DECLARATION PAGE OF THE CANDIDATE & SUPERVISOR

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ABSTRACT

For rural electrification, the use of off-grid hybrid energy systems based on renewable energy has become an intelligent solution for regions where electricity from the main electricity grid is not profitable or impractical. A hybrid distribution system uses either one or more renewable power generation technologies as the main source of energy and as a backup source, the conventional diesel generator is used.

Therefore, this kind of system reduces the necessity on an energy source, causing affordable and reliable electricity for rural users. Since hybrid distribution systems use some energy technologies, selecting the appropriate technologies and optimally determining the size of the designated components is essential to lessen the total cost and increase the availability and reliability of the supply.

The aim of the study was to find the feasibility of constructing a hybrid distribution system that can provide electricity to the rural community living Eluvaithivu which is a remote island in the Jaffna District. Also, once the hybrid system is established this study will continue to analyze the output of the system to check if the quality is up to the general standards. This remote island contains about 110 houses and the daily power demand of 255 kWh and a night-time peak of 30 kW. Similar inverter based hybrid power generation system has being modeled using the load profile and renewable resource data at the site.

Simulation results shows that the grouping of PV systems, wind turbines, diesel generator and Li-ion battery bank gives a hybrid system with following rated capacities will match the load requirement of the island, Simulation results shows the optimal combination of 44.9 kW solar modules, 18kW wind turbines, 126 kWh battery bank and 32 kW diesel generator.

This study analyzes the system by measuring the voltage, current, utility frequency and power factor of the generated output of the system. And from this analysis, it was found that those parameters mentioned above were varying within acceptable tolerance levels define in engineering standards. Also, from the wind power generation analysis it was found that during April wind energy harvesting becomes comparatively low and in June it becomes comparatively high.

Due to the high rate of electrification; in future the demand may increase significantly. To face this situation provisions have been kept increasing the battery bank capacity when necessary. Otherwise the system will not capable of handling the night time load and may cause to run the generator more often during night time peak.

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TABLE OF CONTENTS

LIST OF FIGURES Page

LIST OF TABLES

Page

LIST OF ABBREVIATIONS

CEB - Ceylon Electricity Board

MCB - Miniature Circuit Breaker

RMC- Root Mean Cube

MCCB - Molded Case Circuit Breaker

NPC - Net present cost

O & M - Operation & Maintenance

PSO Particle Swarm Optimization

PV – Photo-Voltaic

PF – Power Factor

FSPC – Frequency Shift Power Control

LIST OF APPENDICES

Chapter 1

INTRODUCTION

The integration of technologies related to renewable energy sources for the supply of electricity has been growing worldwide in recent years. Still, because of the high volatility due to seasonal changes in these sources and the unusual nature of renewable energy sources, their use is somewhat uncertain; In addition, there is sometimes a requirement for durable power storage, which is very expensive. Therefore, off-grid hybrid distribution systems have stepped in to provide economical and consistent electricity for isolated areas that supply electricity is difficult.

1.1 Motivation

More than 80% of the world's electricity is generated by fossil fuels. Much of this is generated by the use of coal, while natural gas and oil also make a major contribution to the production of electricity. The two main glitches of consuming fossil fuels as energy resource are,

1) Pollutant gases have been discharged to the atmosphere when burning fossil fuels.

2) Fossil fuels are a finite resource, over time eventually will be depleted.

The pollutants NO_2, CO, NO, N_2O is harmful to plants, creatures and cause health complications in humans. In fact, CO_2 and N_2O emissions have created a "greenhouse effect" by increasing the temperature of the earth, leading to a variety of problems such as melting of glaciers that cause rising sea water levels and changes of climate and weather patterns. In the difficulty of finding an answer to these issues, the world's scientists were looking for renewable energy sources to fulfil the energy needs. Hydropower, bioenergy, geothermal, tidal, and solar and wind have been very popular renewable energy resources around the world. As an example, for electricity generation in Sri Lanka, hydropower, wind and solar power are majorly used.

The development of renewable electricity generation systems has been very useful for the electrification of small communities in remote rural areas where the main grid supply is not possible. There are many isolated societies around the globe without electricity. The main reason for not having electricity in such groups is the lack of a national network due to the expensiveness of expanding the transmission and distribution infrastructure in these remote regions. In some countries, rural residents produce their own electricity using diesel generators. However, the cost of kWh generated by such a generator is significantly greater than the cost of electricity from the public grid. Because of the high cost of expanding the national network, it is not cost-effective for electricity service firms to extend the network to such isolated areas like remote islands or villages in hill country as an example. Compared to the cost of network expansion, renewable energy systems have become an affordable solution for providing electricity to remote communities.

Commonly used renewable energy generation systems are photovoltaic (PV) solar panels and wind turbines. Also, bioenergy and mini-hydro power plants are also used. Photovoltaic systems can be fixed almost everywhere because solar energy can be used in many regions across the globe. However, other power generation technologies can only be useful where renewable sources are available. For instance, a mini hydropower plant needs a waterfall with adequate flow and a bioenergy plant needs biomass planting in sufficient quantities. For this reason, an appropriate energy system should be selected in a given geographical region, taking into account the number of events; one out of them is throughout the year these resources should be available.

Renewable energy sources which are very irregular in nature, do not provide a reliable and uninterrupted supply of electricity due to its common periodic and seasonal changes. Then again, the initial cost of investment in wind power and solar power systems are still comparatively higher than electricity based on fossil fuels. Remarkably, the use of multiple renewable energy sources makes more reliable electricity output than depending on one renewable energy resource has been recognized as one of the solutions for this issue. By combining renewable energy source with conventional energy resources, the system turns out to be more reliable and economical. Blends of such diverse but matching energy generation systems based on renewable or mixed energy (backup fossil fuel generator with renewable energy resources) are known as a hybrid renewable energy system. The network created by this system is known as the micro-off grid because of its size compared to the large-scale main electrical grid. Figure 1.1 shows a typical hybrid distribution system. It combines a photovoltaic system with a wind turbine as its main renewable energy resource and a Li-ion battery bank as an energy storing unit. In addition, a diesel generator is used as a standby energy resource.

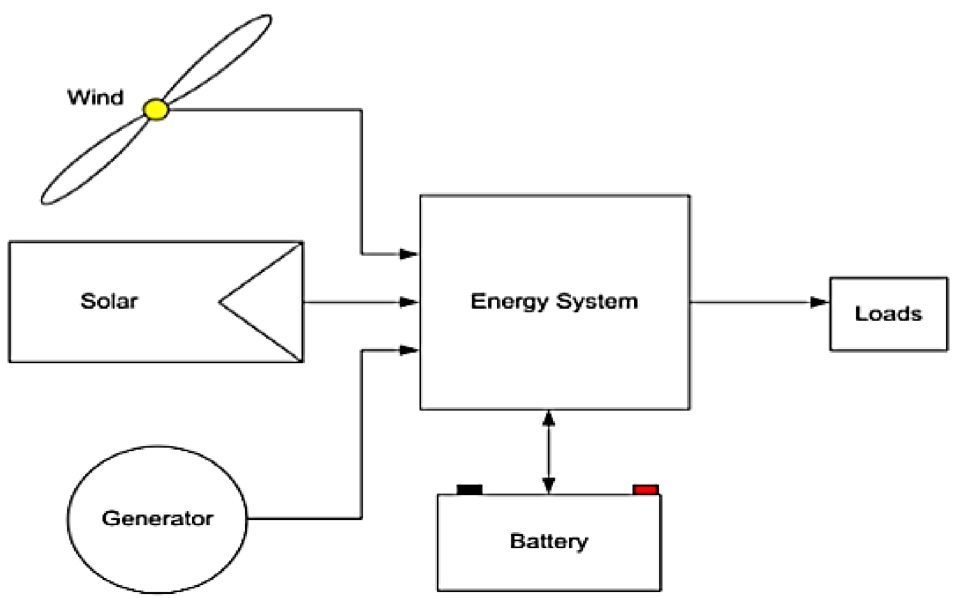


Figure 1.1: Renewable energy-based hybrid distribution system

The power generation of a hybrid distribution system has a great influence on the combination of the renewable sources and selected components. Both duration of the system and the affordability for end users depend on this. To increase the productivity of the system and make it more economical, it is very important to measure the size of the system correctly. The most significant part is identifying the suitable energy resources. As stated above, renewable power generation technologies may use in various types in a hybrid distribution system such as wind, solar, bioenergy and micro-hydro.

In a hybrid system, Battery storage systems and generators based on fossil fuel are also doing very significant job. The energy production from the renewable energy sources is high, after fulfilling the demand the excess energy needs to be stored for later use when the energy production from the renewable energy sources become lower. The fossil fuel generator is essential to guarantee service quality when the output of other renewable technologies is low, or the demand becomes high. In addition, there must be automated management technology integrated into the system to safe-guard vital modules from getting damaged, such as batteries being completely drained out during operation [1].

The overall NPC of the hybrid energy system throughout its technical lifetime fixes the energy cost. It also depends on the capacity of the production systems and the type of energy sources used. For this reason, in order to make the system, cost-effective and efficient, it is very important to select the appropriate blend of energy resources and the proper gauging of each production system according to the load profile of the site. This combination requires a thorough economic, social and technical analysis of the practical configurations of the hybrid systems that can be implemented in the site location provided in accordance with the availability of renewable energy resources during all over the year.

In the literature, a number of approaches have been discussed to find the approximately ideal configuration of hybrid systems. In addition, several organizations have developed a set of software to analyze hybrid energy systems (e.g. PVsysts and HOMER) [2]. Furthermore, business organizations related to renewable energy have developed their own technologies (ex: multi-cluster-based hybrid distribution system introduced by SMA solar technology company). At present, these tools and technologies are widely used in many countries for sizing, analyzing and implementing hybrid systems. Study of hybrid systems for rural electrification is experiencing fast evolution in Sri Lankan renewable energy sector in recent years. Therefore, as a pilot project, the first hybrid power plant has been constructed for Remote Island in Jaffna called Eluvaithiu and based on the results of this first project, the government is keen on expanding this kind of hybrid systems for other rural areas where supplying electricity is difficult from the main grid.

1.2Background

In Sri Lanka there are several isolated islands situated away from the main island, due to the sea water between two islands, constructing tower lines are not practically convenient. Each island has a considerable amount of population, inhabitants whose income mainly depends on fishery activities. There are many fishing villages in these islands without continuous electricity which are located far from town centres in the district.

Table 1: Electrification details of the sub-islands in Sri Lanka, March 2016

	Baththalangunduwa	Deilft Island	Eluvaithivu Island	Nainathivu Island
Total Population (Families)	1250	1,392	185	881
Total houses	650	1,181	110	833
Electrified houses (SHS ,genset)	152	214	73	520
Rate of electrification	72%	85%	59%	95%
Existing diesel generator system	250kVA	250kVA	100kVA	2x250kVA
Average monthly demand kWh	7,069	16,198	3,455	29,222
Average Consumption by Home kWh/Month	47	76	47	56

According to Ceylon Electricity Board, the power demand of these islands is maintained by running diesel generators 24 hours, which means the cost per generated power unit is very high compared to the generation cost per unit in main grid, since the unit rate has been fixed to the whole country CEB has to charge the same rate even though the generation cost is very high. Also transporting diesel is also not easy to these remote islands. Since these generators are not sufficient to generate power for the whole village, a significant amount of these villages remains without electricity. More threateningly, not only does kerosene fuel consume a big portion of a family's regular income, but using kerosene lamps also causes the threat of fire accidents to increase, not to mention that consuming both kerosene and diesel is risky to both the environment and people's health.

Modern days, electrical energy has turn out to be a much more necessary to mankind to continue their day to day life, and for this reason, every human being in these isolated areas must have the privilege of consuming electricity for a reasonable prize; because it helps people to improve their lives. Furthermore, in terms of improving medical care and education as well as the local economic growth of those people in rural areas majorly depends on the availability of electricity. Now, this is made possible by the implementation of the renewable energy systems. Knowledge gathered from all around the world has shown that renewable energy systems can easily provide the power needs of isolated remote societies.

Instead of supplying electricity by operating 24-hour diesel generators, it will be more cost-effective and reliable to construct a microgrid that can provide all the demand for electricity. This micro-network can be powered by a hybrid system based on sources of renewable energy, where a number of renewable energy technologies can be combined. In addition, type of dispatchable conventional electricity generation technology is possible to be selected to improve the continuous availability and quality of the generated electricity output. However, appropriate technologies should be carefully selected because the total cost of the system should be minimized as much as possible to guarantee that the system is economically feasible. In addition, the prices of system components must be measured appropriately to reduce costs. For this reason, the selection of electricity generation sources and the component measurement process require a detailed analysis of the potential of the renewable energy sources at these sites geographical locations, the daily load profile, possible technologies, as well as possible costs and operational technical features of system components.

1.3Problem Statement

In some developing countries, several rural electrification projects based on hybrid systems are being implemented. In addition, researches to study the feasibility of using off-grid hybrid distribution systems for rural electrification in various geographical regions around the world are constantly increasing; for this reason, attention has been paid to the construction of micro-grids based on hybrid systems for supply electricity to the community in isolated islands. Hence, this study addresses the availability of renewable resources and the feasibility of using an off-grid hybrid system to supply electricity to the Eluvaithivu Island in Jaffna as a pilot project.

Once completed, this study also continues to analyze the operation of this first hybrid system in Sri Lanka along with the regional weather conditions. Moreover, by collecting its' functionality data, to propose the necessary enhancements, process optimization techniques and cross-check the assumptions made during the first project which would help in designing the future hybrid distribution systems which planned to establish for electrification in other isolated islands in Sri Lanka.

1.4 Objectives and Goals

The main purpose of this study is to check the availability of renewable energy resources, study on load profile of the selected site and design an off-grid hybrid distribution system as a pilot project that can provide economical and reliable electricity for a rural community living in an isolated island in Northern Sri Lanka. Furthermore, by collecting and analyzing its' functionality data with the demand, this study would be able to check the quality of the electricity output , propose the necessary enhancements, process optimization techniques based on wind resource variations which would applicable to existing system and as well as for the future hybrid distribution system projects in the region.

The following objectives can be achieved by fulfilling these goals:

- Estimating and reviewing the village daily load profile.
- Analyzing the potential of renewable resources in the region.
- Model a mini grid system using a simulation software using the data gathered during data collection.
- Evaluating performance of the hybrid distribution system based on the output parameters.

1.5. Method of Research

The research process is basically gathering the data about renewable energy resources, estimating the load profile of the area, observing the properties and costs of the equipment, proposing the configurations of the hybrid systems, construction of the hybrid system, and analyzing the output of the system and by using the results evaluate the performance of the system. By measuring and gathering the data related to the power generated from wind recourse each month, to get an idea about the wind resource variations in the region.

In the beginning, the daily load profile of the village needs to be estimated. The average load profile and peak demand are to be considered. Estimation of the village load profile can be done by analyzing the energy production capacity of the small diesel production plant which was used to supply electricity to the village.

Before setting up a hybrid plant, it is important to identify the appropriate renewable energy resources that can be easily integrated into the site location. For that, the annual variations of renewable sources have to be collected during the past years in order to investigate the potential of each renewable resources at selected geographical locations. Renewable resource data can be obtained referring to the Internet or requesting from local weather stations. There are a variety of databases on internets, renewable sources, including meteorological data gathered from different geographical locations all around the world. Such as NASA's website for renewable energy and surface and solar meteorological resources is a great reference for this kind of work.

Using these data, a similar module has been modeled in a simulation software called Homer. By simulating this model, it can be identified the optimal combination of each power source.

After constructing the actual off-grid distribution system which combines both renewable and conventional energy sources the different types of output parameters (ex: power, voltage, utility frequency, power factor, etc.) were measured during the selected time. The amount of power generation by wind resource of each month throughout a year (2016/2017) was gathered. With this data, we can analyze the wind patterns with seasonal variations of the northern region. Since, there are several other isolated islands in the region, when implementing this hybrid system on those islands the more accurate wind resource variation data can be considered.

Furthermore, the output parameters were gathered (ex: power, voltage, utility frequency, power factor etc.) for given time we can save the data and use for analyzing. By referring to these different data collection results, it is possible to check the quality and reliability of such a hybrid system. Moreover, after referring to the data collection results, it will be possible to analyze the performance of the current system.

performance of the current system as well as propose some of the future implementation and modifications which can enhance the efficiency of the system.

1.6 Limitations and Assumptions

This study is limited to analyzing of the feasibility of renewable energy resources and determination of component capacity in a hybrid distribution system that can meet the electricity demand of a certain village in northern Sri Lanka. In addition, there will be a monitoring process of the output of this system to give a performance review on different aspects of this off-grid hybrid distribution system. The proposed arrangement has the following restrictions.

- The hybrid system formation is location-specific and will not have an ideal formation for another site where the potential for renewable energy is not the same as the chosen area, but the load profile could be very similar.
- Due to the lack of availability of other renewable source data in the nominated site, only solar and wind energy will be selected for this study. For instance, this means the number of biofuels available throughout the year that can be used to generate electricity through thermochemical conversion and tidal flow rate data of the sea waves around the island.

The study of the off-grid hybrid-distribution system was completed with the assumptions mentioned below.

- NASA meteorology and solar energy data acquired via satellite are practically precise for gauging wind systems and photovoltaic solar systems for OFF-Grid hybrid systems.
- The similar yearly variations of solar and wind resource variations happen during the lifetime of the project.
- Villagers live every day according to the daily routine that results in the same load profile.
- Homer simulation software is accurate enough for this study.

1.7. Necessities

System requirements can be separated into two; Non-functional and functional requirements. A functional requirement specifies a function that should be able to perform a system or component, but how a system behaves is mentioned under a non-functional requirement. The hybrid distribution system observed in this study has non-functional and functional requirements listed below.

Nonfunctional Requirement

1. Availability – 99.8 %

Without the breaks triggered by the system failures due to inevitable reasons (ex: natural disasters) and prearranged shutdowns essential for maintenance. There should be a minimum value for the acceptable yearly outage hours occurred due to absences in the power generation. This value must be approximately 18 hours which results in 99.8 % of the service availability, the aim is reducing the cost by letting the hybrid system to function with a minimum percentage of capacity deficiency.

2. System Operating Reserve

The increased working capacity that the system can respond to in the event of a sudden increase in electrical load or a sudden drop in renewable energy production is known as an operational reserve. In general, an energy system always has an operating reserve to answer for unexpected fluctuations in load as well as the generation of power. This is true in energy systems, where it is crucial to sustaining significant operating reserves to keep the supply to the load so that regular shutdowns due to the unpredictable behaviour of the renewable sources wouldn't occur. The following indicators are defining the terms of the essential operating reserve of a system.

- Wind energy production percentage:
  Wind turbine energy production is proportional to the cube of the wind-speed. Therefore, a sudden drop in wind-speed causes a huge drop in turbine energy production. For this reason, as generated output, we consider only 15% of the total capacity of wind turbines.
- Solar energy production Percentage:
  Approximately 16.6% is the point plant load factor for solar. It is not necessary to have a higher percentage as of wind turbines because of the probability of sudden variation of solar resource is quite low compared to wind resource.
- Future growth:
  When considering the future power demand growth of the site, the system must provide the capacity to handle an additional 15% of the load.

3. Protection

Safety features must be included to protect the installations from overcurrent caused by high energy demand and possible network errors. Current limiting devices, such as miniature circuit breakers (MCB) and fuses with appropriate ratings, must be installed on both the generation side and the consumer side to guard against overcurrent.

Also, if there are underground cabling certain safety and protection methods like usage of warning tapes and protective concrete slabs is important. The battery bank system should be maintained within given temperature ranges. Therefore, the temperature-controlled environment must provide to store batteries.

Since wind turbines are a tall metallic device which needs proper grounding and surge protection to protect this equipment from lighting. Furthermore, there should be a mechanism to protect the wind turbine and internal circuitry during heavy wind loads.

The solar panels should have mounted in a place that they wouldn't get damage from the sounding objects from the environment. (Ex: coconut trees are there in these island areas)

Also, when storing diesel for diesel generator there must be a separate storage since those fuels are highly flammable. Firefighting equipment is needed, and the staff should be trained to handle the fuel properly.

Functional Requirements

1. Estimated Demand – maximum demand 29 kW, 255 kWh/day average daily load

The system should be able to provide sufficient energy uninterruptedly according to the sudden demand within the installed availability requirement. As a result, the off-grid power station should be accurately gauged to meet the maximum possible load that rises at any time. The selected community listed in Chapter 2.2 has a derived daily profile, a maximum load of 29 kW, and a daily average demand of 255 kWh / day. The system must be able to provide this power requirement continuously.

2. Energy Management

If the gap between the maximum energy demand and average daily power demand is quite higher, the system cost will increase because the system capacity should be extended to a level which has the ability to provide the maximum load, in such scenario an energy management strategy should be deployed to reduce the maximum load. As a Microgrid is not extended to a large area, advanced energy management mechanisms will not be necessary. Even the usage of modest strategies will lessen the cost of the system.

3. Diversity Factor

The nominal capacity of a hybrid distribution system must not be calculated through simply referring the load profile since the extra capacity to answer for sudden fluctuations in the load is a constant necessity. Additionally, the renewable energy sources sometimes vary critically with time. So, accordingly, the equipment must be gauged so that the total system can fulfil the power requirement, although due to the fluctuating nature of renewable sources the energy production from some apparatuses drops. In this case, 10 % diversity factor was considered.

4. System Cost

To consumers the supplied service ought to be affordable; in the meantime, throughout the project lifetime, the system should guarantee sustainable operation. Components must be carefully chosen by considering their price, reliability and productivity. Less reliable and less efficient components will decrease the initial investment, nevertheless throughout a lifetime, choosing such equipment wouldn’t be a wise choice.

1.8. Outline of the Thesis

This thesis deals with the content related to feasibility, design, output analysis, and propose future improvements to an off-grid hybrid distribution system for supplying electricity to a remote community who lives in an isolated island in Sri Lanka. There are seven sections containing in thesis and these sections have been organized as follows.

First chapter introduces the importance and the necessity of renewable energy-based hybrid energy systems for electrification in rural areas. Moreover, chapter one also discusses the research methodology, important assumptions, system requirements and limitations related to hybrid distribution systems.

Second chapter under the literature review debates various approaches for optimizing hybrid systems. Next, in third chapter discuss the data essential for planning the off-grid hybrid distribution system. As weather data of the region, estimated village load curves, availability and data related to wind and solar resource.

The fourth chapter is to describe the key mechanisms used in the hybrid system. It defines the important features of the system components in general, such as electrical characteristics, costs, and operation and maintenance issues. Also, in this chapter, a similar system has been modeled using Homer and based on the simulation results optimal sizing of each capacities have been identified.

Existing design and components selection of the hybrid distribution system in Eluvaithivu island Sri Lanka is discussed more deeply with characteristics of selected components in the fifth chapter.

The data collected from the actual inverter-based power generation system is analyzed in the sixth chapter. The values of the output parameters like generated power, voltage, power factor, utility frequency and power generation from wind turbines have been collected for sufficient time periods for analysis. By analyzing the figures, the performance of the system has been discussed in the same chapter.

To conclude, the seventh chapter delivers the overall discussion and the conclusion including the proposed future implementation of the off-grid hybrid distribution system.

Chapter 2

Literature Review

The design of the hybrid system in terms of reliability and cost has been one of the priorities to consider, especially in the electrification of remote areas, with the increase in the use of hybrid renewable energy systems. In recent years, a series of research has been conducted in this regard.

L Reddy Lella et al [3] has stated that electric utilities makes a growing need of renewable energy and it has also laid the foundation for an increased penetration of distributed generators. The impact of penetrating Diesel, Solar and wind distributed generators has being analyzed on their study and has identified that there are improved power quality, improved power system reliability, improved fault-ride through capability, voltage support, reduced losses and transmission and distribution in such hybrid systems. DIgSILENT Power Factory software has being used for model and analyzation of the system.

Garvita Upadhyay et al [4] has stated that simple Newton Raphson method and the sizing has been attempted through Genetic Algorithm for unit sizing and cost analysis of hybrid solar, wind and solar photovoltaic independent power systems. The algorithm produces random vector component sizes. For the relevant analysis, only the scaling vectors that can compensate the load during the relevant time period are used. The optimal locations and the sizes of the capacitors in order to save the energy loss as well as the annual cost of the power generation System. This method does not consider the charging status of the battery bank, which is a crucial factor in determining the battery life. Mohsen and Javed [5] also explain the hybrid wind system with solar PV and PSO based battery optimization. They use data wind speed and solar radiation data gathered for 32 years to obtain the functions of the probability distribution. In addition, they took into account the varying nature of solar and wind energy.

Abid El-Shaify [6] has come up with a simple idea of a mathematical calculation, for a hybrid system optimal sizing with solar PV system and diesel generator. The diesel generator assumes to be run only to meet the maximum demand. Referring to the particular load profile, the size of the diesel generator is set somewhat higher than the maximum load. The total cost of the system, excluding the cost of fuel, was selected as the most reduction target since the cost of fuel for each combination of PV and battery size is fixed. Setting the generator size to a fixed value greatly simplifies calculations compared to the methods discussed in other papers, but this will not yield a correct outcome.

To optimize the wind / PV hybrid system, S. Farahat [7] have proposed a PSO-based multipurpose algorithm called MOPSO and the results were verified by the non-dominant genetic sorting algorithm (NAGA-II). The coefficient of Inequality (CI), correlation coefficient and annual capital cost (ACC) are used as objective functions for optimization. This algorithm can assess only 32 dissimilar patterns of photovoltaic and wind equipment.

Using the Homer Software Ester Hamatwi et al, [8] has simulated and optimized a hybrid solarPV and wind, with energy storage and a back-up diesel generator. Their study on economic and environmental analysis indicated that it is more advisable to electrify remote settlements using a

DC nano-grid based on hybrid systems with multiple renewable sources as they have lower operating costs and more environmental friendly due to the reduced dependence on diesel generating units. Using the DIRECT algorithm (Dividing RECTangles) was used for modelling and optimization studies by L. Zhang et al. [9] for hybrid systems with solar, wind and diesel.

H.Yang [10] suggested the best gauging based on genetic algorithm to a hybrid system. A genetic algorithm has the capability to reach spherical optimizations with a sufficient amount of computational simplicity. In their work, the photovoltaic module selects the slope angle and the height of the wind turbine as optimization variables outside the photovoltaic modules, wind turbine, and a number of bottles. [11], [12], [13] discussed similar optimization methods for hybrid systems. In all of the research studies mentioned above, the most appropriate design was found by reducing the total cost function to the lowest, meeting certain constraints such as loss of demand probability and battery status. The precision of the final optimal design and the number of possible combinations for analysis are dependent on the method used to derive the most objective function. One of the main weaknesses of these methods is that they do not take into account the effects of possible changes in future fuel prices. For this reason, sensitivity analysis is also very important for choosing the optimum design. Another thing is that none of these studies can calculate the emission of CO2 into the environment and calculate CO2 incentives and carbon tax benefits. Since hybrid systems also use diesel backup generators, the CO2 emission is also an important issue to consider.

Kolhe, Mohan, [2] has done techno-economic analysis for Hybrid distribution systems and found that, using diesel generators appear to be cost-effective in terms of initial capital investment, but due to the high cost of O & M for fuel, maintenance and replacements the lifetime cost analysis reveals generators cost more in the long run. Therefore, in long-term wise renewable energy based hybrid distribution systems are more cost-effective than fossil fuel based micro-grids due to not having any significant amount of fuel cost or regular maintenance cost.

Chapter 3

Data Collection and Analysis

The design and optimization of the hybrid system require assessment of the village's load profile and the availability of renewable sources in the area. In this section, the estimation of the village load curve and the evaluation of available renewable sources, wind and solar resources in the site will be discussed. This section also concerns the data and calculation related to solar radiation in a sloped photovoltaic panel through and the practically ideal location of the photovoltaic array in the site, horizontal radiation data, wind energy density and wind distribution curves.

3.1 Overview

Eluvaithivu, is a remote island in Jaffna District, Sri Lanka. In this research renewable hybrid energy system for supplying electricity to this island has been selected for the study. This is a small island located on the western side of the Jaffna. The island is oriented in a north-south direction and covers an area of 1.7 km2. A large part of the island is covered by dense vegetation comprising Palmyra and Coconut palm trees. Island's western side is covered with coral and limestone whereas the eastern side is sandy. Almost the entire Island is underlain with limestone. [14] The Eluvaithivu Island map is shown in Figure 2.1. As for the problem statement, on this island contains some fishing communities with an overall population of 245, which lives in 110 houses. By these entire households, only 73 families have electricity connection referred to a survey done in the village.

Majority of the villagers' main income source is based on fishing. The lack of low-income level and basic facilities have seriously affected the standards of villagers' lives and the education of kids in this remote island. For this reason, at least providing the basic facilities are very vital together with electricity, to uplift the living standards, health, local economy and education of people in Eluvaithivu. Only during the night time, the village was electrified by two sets of diesel generators. Which cost a lot of money for fuel and also the burning of fuel caused air pollution.

Figure 2.1: Location of the Eluvaithivu Island

Source: https://www.google.com/maps/@9.6929469,79.820435,6228m/data=!3m1!1e3

To design a hybrid renewable power generation plant for electricity supply, it was first necessary to determine the availability of renewable sources which can be used to harness energy in the selected region and the electricity demand of the selected village.

3.2 Load Curve

The planned hybrid distribution system is for electrifying a community with approximately 110 houses. With the intention of estimating the load profiles of people who have not previously been electrified, it is necessary to realize the living environments of the people in the selected site. Fundamentally, the earnings of a household influence the load profile of a home.

In addition to the income, aspects such as the daily routine of the villagers, the size of the house and the desire to buy household electrical equipment will affect the family load profile. The load demand of the village is mainly influenced by the type of public services and commercial buildings and the number of houses in the village. Also, if there is electricity, new commercial facilities that may arise in the future should be considered during the load profile estimation process. To collect all these data a proper analysis of the village will be necessary. Given the fact that there is no real survey data, the load profile of the village was derived from the following assumptions and load profiles available on the Internet for different electrification projects in rural areas in developing countries [15], [16], [17]. In general, not like in urban communities the electricity demand in remote communities is comparatively low.

- The village has a community centre, church, nursery school, small hospital, two shops, street lighting and navy base and 110 houses. From the existing diesel generator plant generation record, it was found that this village is consuming an average of approximately around 202kWh / day. The assumption was made that this will not change during the project period.

- There will be very low daily power demand needed for families with low income. These people will use electrical energy to meet their basic needs such as lighting, listen to radio, watch television, and perhaps to iron clothes and occasionally for water heating. The families have very small houses in this social class. So, the lighting loads will be very small.

- Because the village does not have many public service and trade industries that create more demand throughout the day, the village's load profile will have a low hill level in the early hours of the morning and a high night peak in the lower flat days. Summit early in the morning.

Considering the above assumptions, the typical load curve for this site shown in Figure 3.2 is derived. According to the estimated load curve, the peak demand is around 23 kW and the energy requirement is about 202 kWh daily.

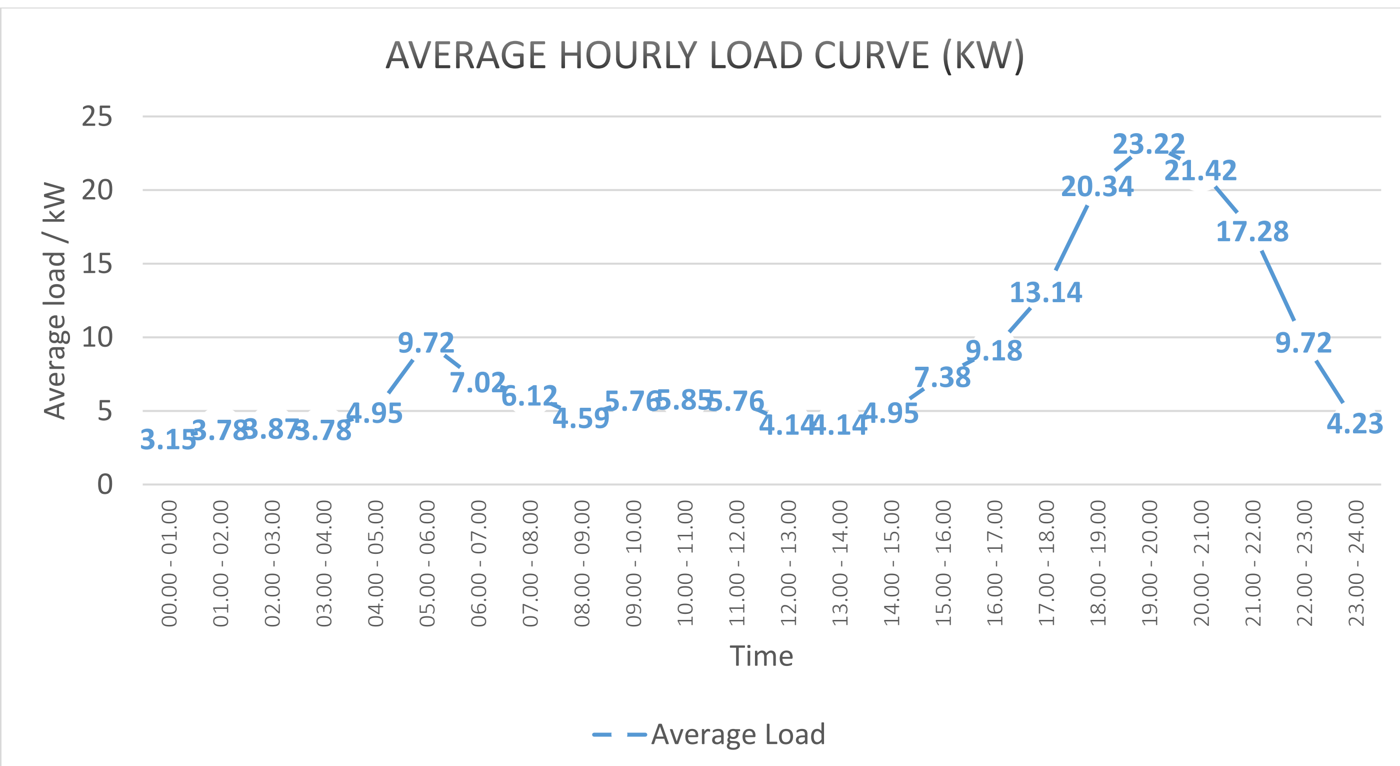


Figure 3.2: Average Village Load Profile

The average monthly temperature of this region given in Table 2.1 varies between 25.5 ° C and 27.7 ° C during the year. Temperatures may range from 4 ° C to 6 ° C day and night. For this reason, this region is not exposed to serious seasonal changes. In addition, the length of daylight in Sri Lanka does not change significantly over the year because of the geographical position close to the equator. Since during the year, there wouldn't be significant changes in the load profile. For this reason, a similar daily load profile is expected throughout the year.

Table 2: Typical weather records in the region near Eluvaithivu

Latitude 9.692	Longitude 79.811	Relative Humidity (%)	Air Temperature (°C)	Earth Temperature (°C)	Atmospheric Pressure (kPa)
Jan		72.6	25.5	26.3	100
Feb		69.9	26	27.8	100
Mar		69.3	27.1	29.5	100
Apr		78.6	27.4	29.6	100
May		79.6	27.6	29	100
Jun		74.4	27.7	28.5	100
Jul		72.5	27.6	28.4	100
Aug		72.7	27.5	28.4	100
Sep		76.1	27.1	28.3	100
Oct		79.5	26.6	27.9	100
Nov		78.6	26.3	27.1	100
Dec		75	25.9	26.3	100
Annual Average		74.9	26.9	28.1	100

Source: www.eosweb.larc.nasa.gov / cgi-bin/ sse/ sse.cgi?rets@nrcan.gc.ca.

3.3 Solar Photovoltaic Source

3.3.1 Yearly Variation of Solar Energy

Geographically Sri Lanka is located near to the equator, so there is plenty of solar radiation all over the year. There is no a significant seasonal variation of solar radiation in the over the country, but a drastic change can be detected between the lowlands and the mountain ranges of the country. It was estimated as a map of solar resources developed by the National Renewable Energy Laboratory in the USA. Much of the dry zone is getting 4 - 4.5 kWh / m^2 / day solar radiation, and mountainous areas are receiving solar radiation in the range of 2 - 3.5 kWh / m^2 / day. For this reason, there is considerable potential for the use of solar energy in the dry region of Sri Lanka. Figure 3.3 shows the average daily average radiation in kWh / m^2 / in 2004 and yearly direct annual radiation in kWh / m^2 / day for Sri Lanka is shown in Figure 3.4.

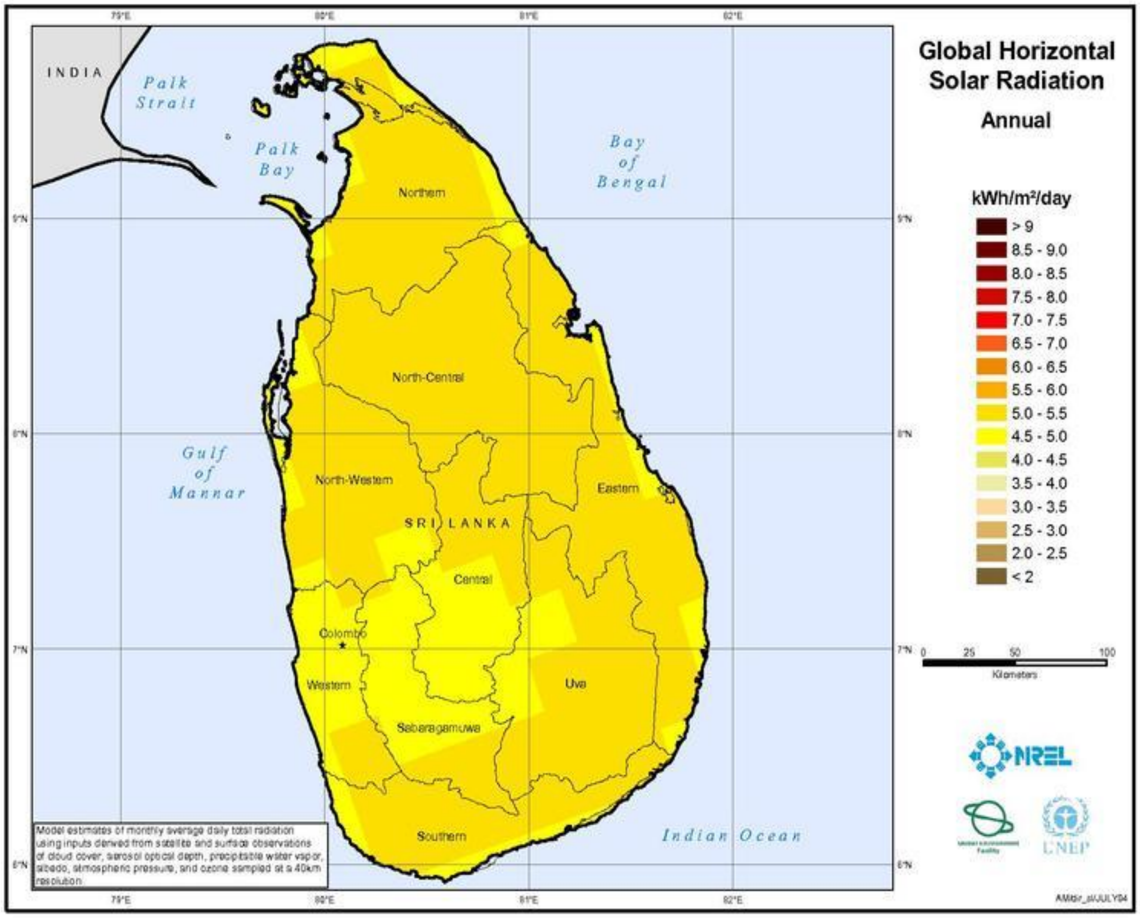


Figure 3.3: Yearly global horizontal radiation in Sri Lanka (kWh/m2/day)
Source: "Solar and Wind Energy Resource Assessment (SWERA)" UNEP, 2004

Table 3: Jaffna District Sun Shine hourly Data for year (2014/2015)

	From July to December 2014						From January to July 2015						
Date	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul
1	6.8	9.7	7.7	5.4	3.6	0.0	7.3	9.4	7.2	8.2	8.5	6.2	10.7
2	7.8	4.7	10.5	4.0	0.0	1.1	9.5	8.8	8.2	7.6	10.2	9.3	10.0
3	10.0	8.7	10.0	6.3	0.2	8.3	6.1	4.8	8.5	11.1	10.4	6.9	10.2
4	10.8	9.3	0.0	4.9	0.0	8.7	10.4	6.8	7.0	6.9	7.6	8.3	10.6
5	10.9	9.8	10.0	7.3	5.7	3.9	10.9	3.6	9.9	8.2	3.8	10.9	10.3
6	7.8	8.4	0.0	5.1	5.7	4.6	10.7	6.3	11.5	11.0	9.5	5.1	7.2
7	8.9	5.6	NA	2.3	9.4	1.6	10.1	7.2	10.6	8.6	6.4	11.1	9.1
8	4.4	5.4	NA	3.1	9.3	0.4	8.1	9.1	10.2	5.9	6.7	10.7	10.5
9	9.0	6.5	8.9	6.7	8.1	0.4	8.9	2.4	10.2	8.6	10.2	11.5	9.3
10	0.4	1.7	11.0	6.0	5.1	2.5	9.9	1.9	10.5	7.6	6.7	10.6	9.9
11	3.4	9.9	10.7	8.1	7.6	10.1	8.4	5.0	9.9	7.8	2.7	3.9	5.2
12	6.7	10.6	6.7	6.0	0.6	9.0	9.8	7.9	7.2	8.7	9.6	8.9	9.7
13	4.6	7.1	8.3	9.9	4.6	7.8	5.4	9.3	9.8	1.0	2.0	11.5	10.5
14	4.7	8.2	8.8	9.3	4.1	8.0	8.7	9.7	4.7	8.6	3.5	11.9	9.8
15	8.2	8.3	NA	6.8	10.6	6.6	8.8	10.5	7.1	4.2	1.4	11.7	8.1
16	8.2	10.1	2.3	7.3	7.8	5.5	9.2	10.2	9.2	0.6	5.6	4.4	9.6
17	10.8	5.0	7.2	1.2	6.4	4.5	8.6	10.4	9.9	8.2	0.0	1.6	10.0
18	10.4	6.5	0.6	0.0	0.0	4.3	9.6	6.9	10.3	10.0	9.4	TR	8.8
19	8.6	7.3	4.5	1.2	2.4	1.8	9.9	9.9	8.5	6.9	10.9	5.7	8.2
20	8.9	11.0	10.2	2.4	7.1	0.0	9.5	10.6	8.5	9.4	7.8	6.1	8.3
21	9.6	6.0	9.7	0.7	0.0	1.9	9.6	10.2	9.6	6.5	11.0	11.0	10.0
22	7.7	6.5	6.4	9.7	1.0	0.0	5.8	10.7	10.0	10.2	9.5	10.8	4.9
23	10.1	NA	8.2	0.0	7.1	1.8	9.5	10.9	10.1	7.4	10.0	10.9	6.4
24	10.9	8.5	8.8	6.3	0.4	2.2	8.8	7.3	9.6	10.7	10.6	10.8	8.5
25	9.4	9.2	5.8	7.4	0.0	4.8	10.6	1.6	9.6	1.7	10.6	11.3	8.8
26	10.6	7.7	7.2	7.1	0.1	0.0	8.2	6.1	9.6	7.6	8.6	6.9	7.7
27	6.7	6.9	4.8	9.1	0.4	0.0	6.9	8.3	8.6	6.6	9.1	6.6	8.4
28	7.3	6.3	6.0	10.5	0.4	0.0	5.3	8.6	3.4	10.0	9.0	3.7	5.7
29	8.8	5.1	4.4	8.3	0.0	0.0	2.0		8.4	10.8	9.0	9.6	6.2
30	9.2	9.2	4.0	1.5	0.0	1.2	9.4		10.1	10.1	7.9	10.3	7.5
31	10.9	10.5		0.0		9.3	10.4		9.3		5.0		7.3

Source: Sunshine hourly data from Jaffna metrological stations

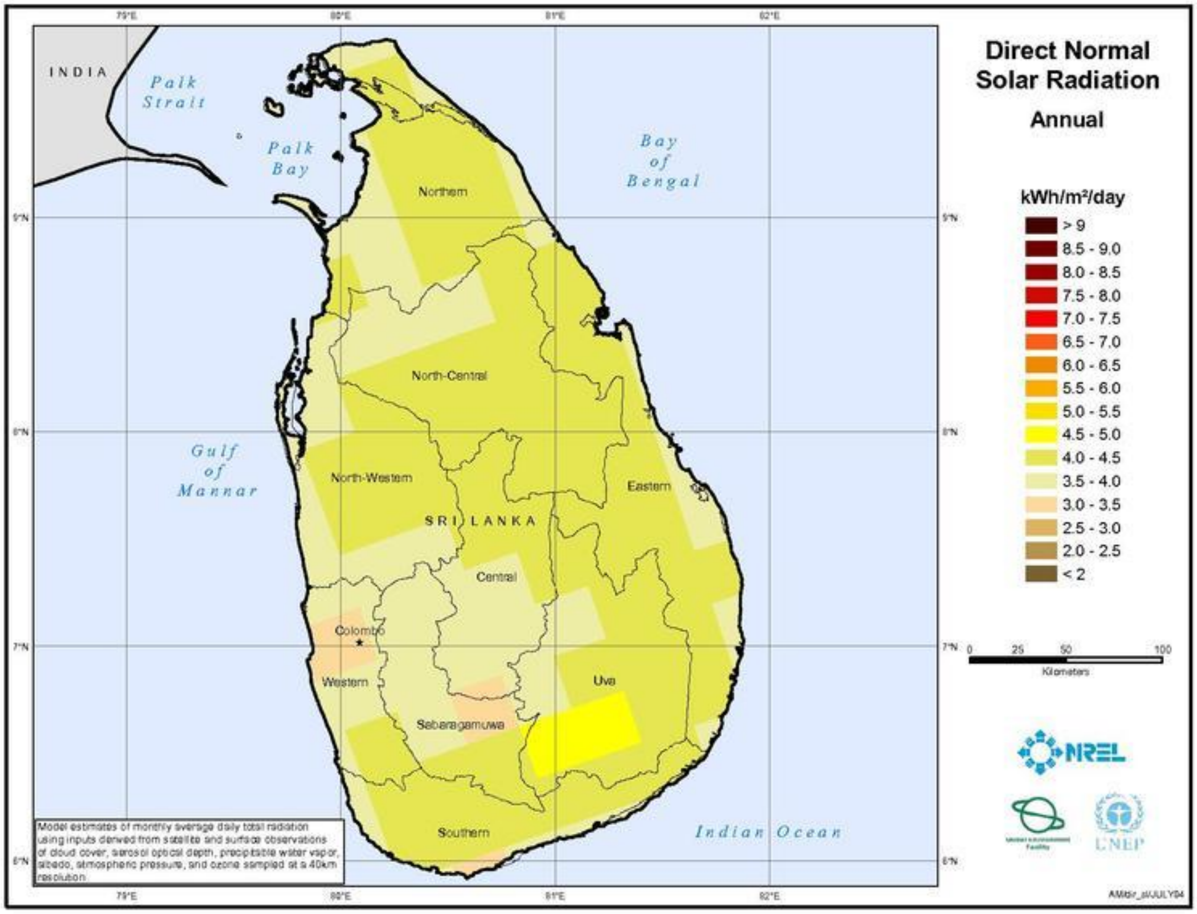


Figure 3.4: Yearly Direct Normal Solar Radiation for Sri Lanka (kWh/m2/day)

Source: "Solar and Wind Energy Resource Assessment (SWERA)" UNEP, 2004

The selected area marked in Figure 3.3 and Figure 3.4 is situated at 9,692N latitude, 79,811 E longitude. In Figures 3.3 and 2.4, it is clearly mentioned that the global annual average daily total radiation and the normal direct radiation are relatively high at the selected location. For this reason, it would be a better option to use a photovoltaic solar energy for a hybrid energy system. Still, a thorough study should be conducted to determine if photovoltaic solar energy is sufficient and, if appropriate, the capacity of the photovoltaic system must be derived. Hence, Annual solar radiation data is essential for this. According to Table 3 the average daily sunshine hours for Jaffna region is 7 and also this is identified as very good potential to harness solar energy resource.

Due to the inability to find terrestrial measurement data of the solar radiation at the selected site, NASA renewable energy resource website has been used to gather relevant data. Daily average solar energy data on a horizontal surface obtained from the NASA database are represented in Figure 2.5 for one year from January 1 to December 31. In addition, Table 4 shows the clearness index and average monthly insolation incident on a horizontal surface. The clearness index is a measure of the atmospheric transparency (i.e. the portion of solar radiation diffused through the atmosphere to Ground).

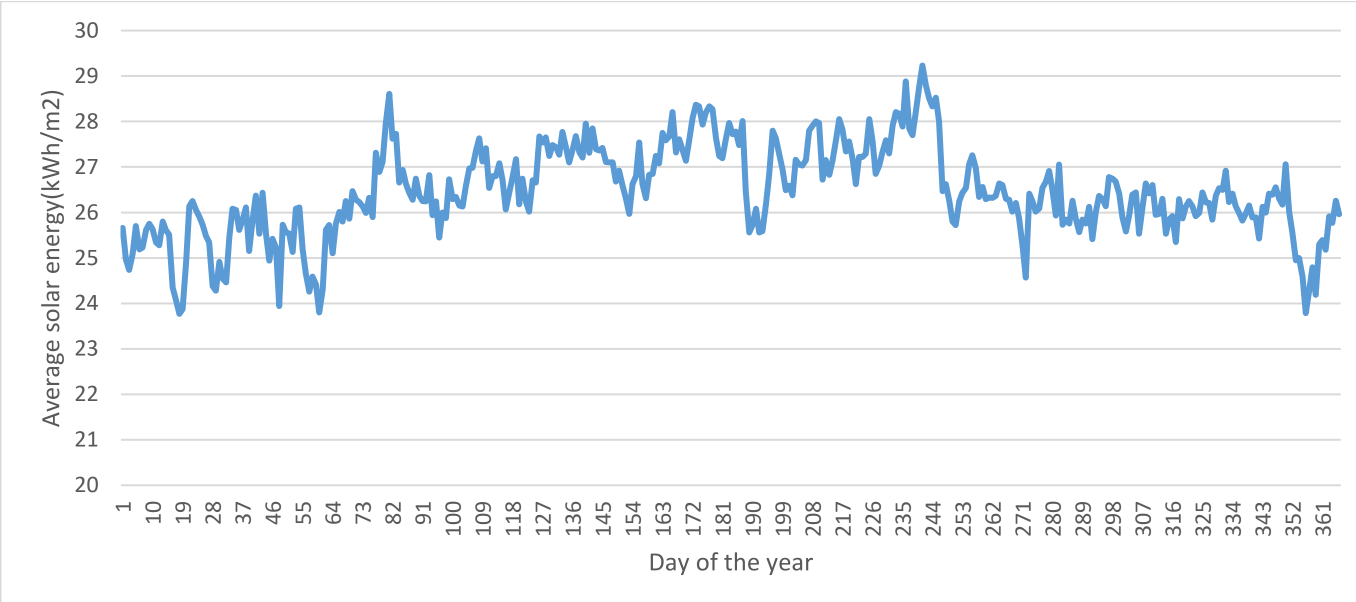


Figure 3.5: annual daily average insolation incident on a horizontal surface at site
Source: www. eosweb.larc.nasa.gov / cgi-bin/ sse/ sse.cgi?rets@nrcan.gc.ca.

Table 4: Clearness index and Monthly average direct normal radiation at site

Month	Clearness index	Monthly Averaged Direct Normal Radiation (kWh/m2/day)
Jan	0.63	5.4
Feb	0.64	6.55
Mar	0.65	7.13
Apr	0.65	5.99
May	0.63	5.61
Jun	0.62	5.16
Jul	0.62	4.88
Aug	0.62	4.88
Sep	0.63	5.06
Oct	0.62	4.12
Nov	0.63	3.72
Dec	0.62	4.41
Annual Average	0.63	5.4

Source: www. eosweb.larc.nasa.gov / cgi-bin/ sse/ sse.cgi?rets@nrcan.gc.ca.

Referring to solar radiation figures, the average solar radiation in isolated islands such as Eluvaithivu in the Jaffna district is relatively high. This will provide a relatively good chance and opportunity to include solar energy as a key component in the hybrid distribution system.

3.3.2. Ideal Placement for Photovoltaic Panels

To gather the maximum volume of solar power, the PV arrays should be located facing the sun. However, the location of the sun in the sky changes throughout the day and year. For this reason, the biaxial solar tracking device can be used to monitor both suns' paths. In general, the cost of these biaxial monitors is relatively high. For this reason, in commercial applications, it is not very popular. In general practice, the panes are fixed on base with a constant incline. The fixed inclined solar panels are typically angled in the direction of the equator and the inclination angle of the solar collector is at an angle identical to the geographical latitude. This angle is a decent estimate for the best angle to maximize annual collector performance. By setting the slope angle once-a-month or seasonally, a considerable amount of energy can be gathered than the slope is constant throughout the year. The angle setting depends on the geographical latitude and angle of declination.

The angle between the track of the sun and the equatorial plane is the declination angle (δ). It ranges from 23,450 to -23,450 in one year. The declination angle for a given day of a year can be found at an accuracy of 0.50 using the formula below, known as the Cooper equation. [20]

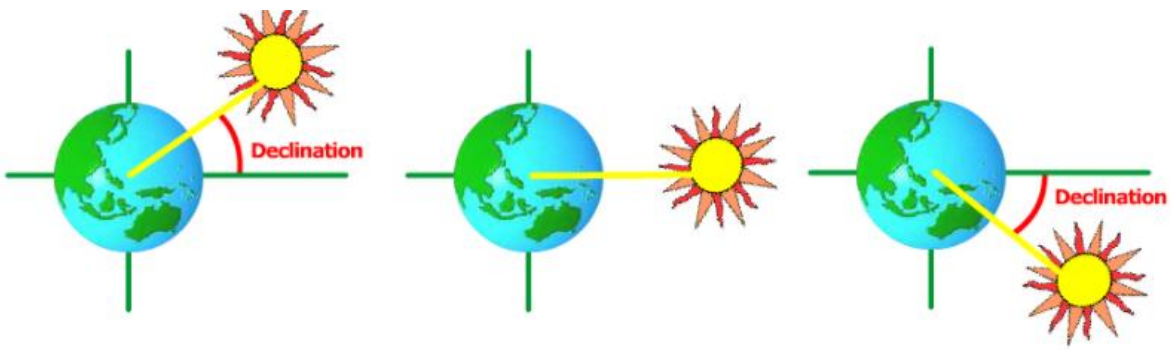


Figure 3.6: declination angle of the sun

Source: google images

$$\delta = 23.45\, Sin\left(\frac{360(284+n)}{365}\right) \quad \textbf{(1)}$$

Where,

δ - Declination angle

n - Day in the year

According to the above equation in Figure 3.7 the variation of solar declination angle is shown for a year.

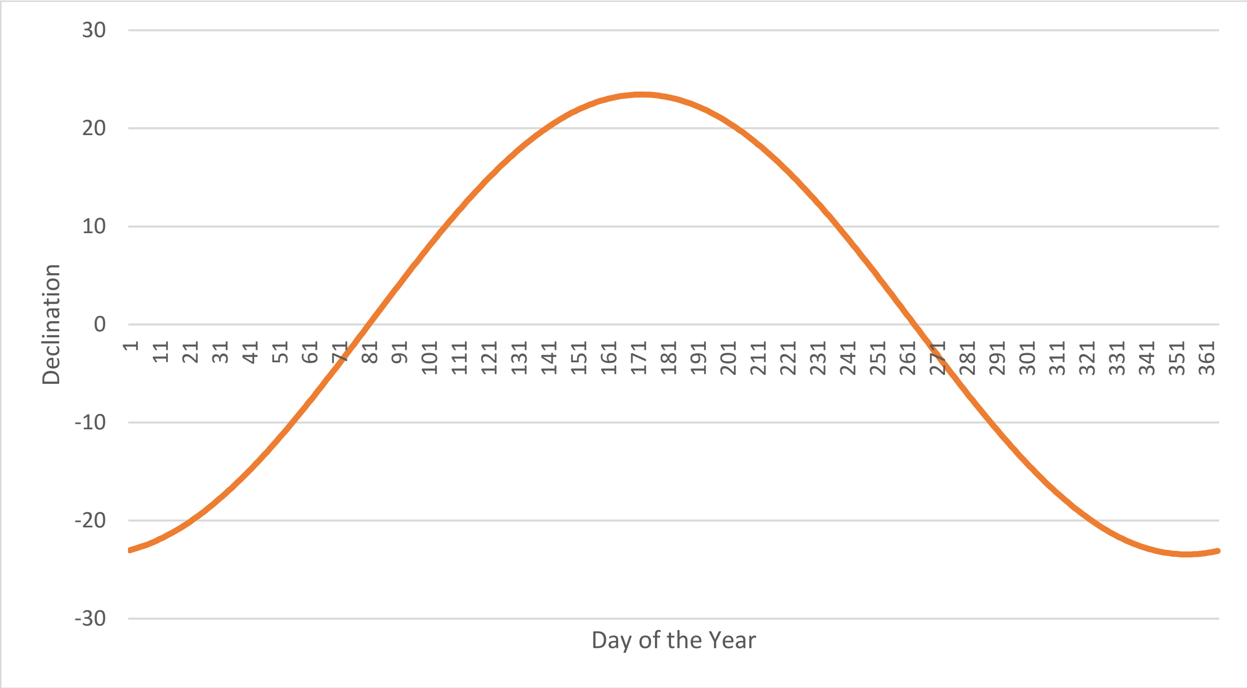


Figure 3.7: variation of the solar declination angle for a year

Ideal tilt angle for the Solar Collector

The direction of the directivity and the ideal tilt angle of a PV panel depend on the deviation angle (δ) and the latitude (Ψ). The optimum angle (Ψ + δ) for a PV panel located at the latitude of the northern hemisphere (Ψ), on the other hand (Ψ - δ) is for PV panel located in the southern hemisphere. The fronting direction varies by following ways.

• If |Ψ| > δ, at that point PV panel positioned in the southern hemisphere, must direct towards north and PV panels placed in the northern hemisphere must direct towards the south.
• PV panel in the northern hemisphere (Ψ positive), if | δ | > Ψ for negative δ, the panel must be north facing.
• An adder in the southern hemisphere (Ψ negative), if | δ | > Ψ for positive δ, the panel must be south facing.

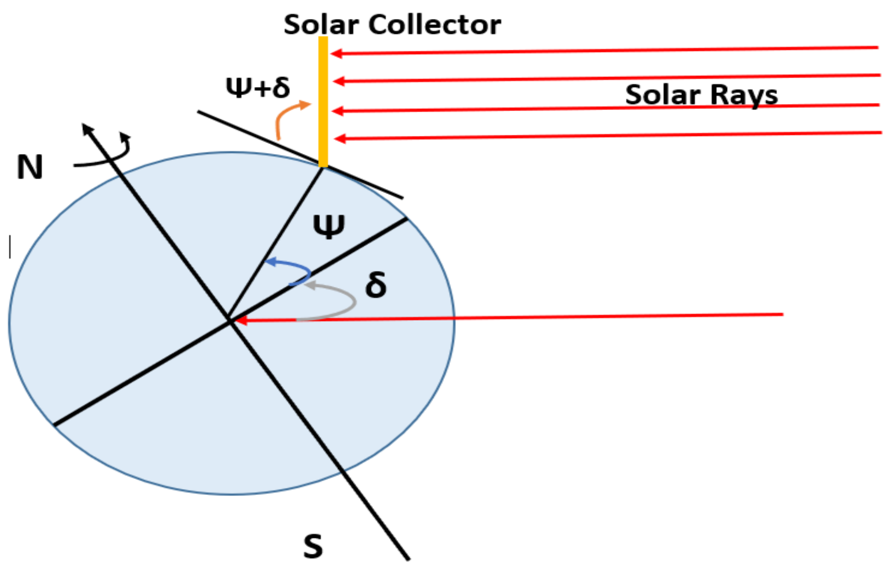


Figure 3.8: Ideal incline angle of a PV panel placed in the northern hemisphere

Referring to these points, the most appropriate monthly alteration in the slope angle to a selected site located where latitude = 9.6920 in Sri Lanka is specified in Table 4. Data in table 4 shows, the collectors should be directed south for several months and for other months it should be direct towards the north. For this reason, there is a monthly tilt angle adjustment system which is quite expensive. For practical reasons, I consider a photovoltaic system with an immovable tilt angle. For this site, the best approximate placement is when the tilt angle is 160 ° and collector facing south direction.

Table 5: Average monthly declination, ideal tilt angle and pointed direction for PV array

Month	Average Monthly declination (δ) **(NASA Surface meteorology and Solar Energy)**	Tilt Angle (Ψ+ δ)	Pointed Direction
January	-20.7	-11.008	North
February	-12.3	-2.608	North
March	-1.8	7.892	South
April	9.71	19.402	South
May	18.8	28.492	South
June	23	32.692	South
July	21.2	30.892	South
August	13.7	23.392	South
September	3.08	12.772	South
October	-8.45	1.242	South
November	-18.1	-8.408	North
December	-22.8	-13.108	North

3.3.3. Solar Ray Incident on an Inclined PV Array

The solar radiation statistics are normally accessible in terms of global horizontal radiation. Then, typically in solar energy applications, solar arrays are not positioned with parallel to the ground. For this reason, to find the energy production from solar arrays this global horizontal radiation information is essential to be converted into solar radiation on tilted surfaces. In the following, a calculating method of solar radiation on an inclined solar panel by means of global horizontal radiation data has been discussed.

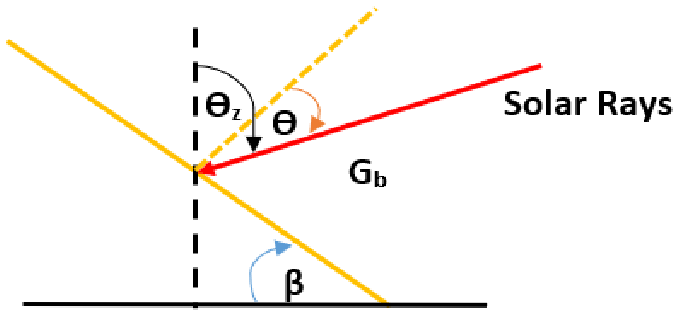


Figure 3.9: Solar energy on an inclined PV array

The angle of incidence (θ) of a direct solar radiation on an inclined PV array is shown in Figure 3.9, furthermore, by following formula (θ) can be calculated [20].

$$\cos\theta = \sin\delta \sin\varphi \cos\beta - \sin\delta \cos\varphi \sin\beta \cos\gamma + \cos\delta \cos\varphi \cos\beta \cos\omega + \cos\delta \sin\varphi \sin\beta \cos\gamma \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega \quad \textbf{(2)}$$

Where; G_b is direct radiation and β, δ and Ψ are the angle of the PV collector, declination angle and latitude respectively. Surface azimuth angle of the solar panel which is the 'deviation of the projection on a plane normal to the surface from the local meridian', is denoted by the parameter γ. Finally, angular displacement of the sun to the east or west from the local meridian known as the hour angle is denoted by ω which is occurring due to spin of the earth on its axis at 15^0 degrees per hour.

By using the following equation, the extraterrestrial radiation which is the amount of solar radiation received at the upper point of the atmosphere can be calculated;

$$Gon = Gsc\left(0.033 \cos\frac{360n}{365} + 1\right) \quad \textbf{(3)}$$

Where;

Gon : extraterrestrial normal radiation (kW/m2)

n : day of the year

Gsc : solar constant (01.367 kW/m2)

As shown below, we can calculate the extraterrestrial horizontal radiation by the extraterrestrial normal radiation.

$$\text{Go} = \text{Gon}\cos(\theta z) \quad \textbf{(4)}$$

Then, the zenith angle Θz is the angle between the line of the sun and the vertical axis or in other words angle of incidence of beam radiation on a horizontal surface, because a horizontal surface has an angle of zero, by setting β = 0° in equation 2 an equation for the zenith angle can be derived, which produces:

$$\cos\theta z = cos\ \varphi\ cos\ \delta\ cos\ \omega + sin\ \varphi\ sin\ \delta \quad \textbf{(5)}$$

Hourly average extraterrestrial horizontal radiation is given by integrating the equation 4 over a period of one hour. Which is; [21]

$$\overline{Go} = \frac{12}{\pi} Gon(cos\varphi\ cos\delta(\sin\omega 2 - sin\omega 1) + \frac{\pi(\omega 2-\omega 1)}{180}\sin\varphi\sin\delta \quad \textbf{(6)}$$

Where;

ω1: at the start of the time step, the value of hour angle

ω 2: at the end of the time step, the value of hour angle

Another vital parameter is the clearness index. The explanation of the clearness index is the average value over a time step for global horizontal radiation on the earth's surface over average value over a time step for extraterrestrial horizontal radiation.

$$K_T = \frac{\bar{G}}{\overline{G_o}} \quad \textbf{(7)}$$

Where the average value over a time step for global horizontal radiation on the earth's surface given by $\overline{G}$.

There are two types of radiations which decides the total radiation on a horizontal surface;

i. $\overline{G_d}$ - diffuse radiation
ii. $\overline{G_b}$ - direct radiation

$$\overline{G} = \overline{G_d} + \overline{G_b} \quad \textbf{(8)}$$

If solar radiation emitted from the sun haven't been filtered by the atmosphere, then it is known to be direct radiation, and diffuse radiation is the solar radiation when it scattered by the atmosphere and its radiation path has been altered due to that. The diffuse radiation component has the following relationship with the clearness index and the global horizontal radiation. [21].

$$\frac{\overline{G_d}}{\overline{G}} = \begin{cases} 1 - 0.09\,K_T & for\ K_T \leq 0.22 \\ 0.9511 - 0.16\,K_T + 4.388K_T^2 - 16.638K_T^3 + 12.336K_T^4 & for\ 0.22 < K_T \leq 0.8 \\ 0.165 & for\ K_T > 0.8 \end{cases} \quad \textbf{(9)}$$

The rays of the sun striking the angled surface of the solar panel ($\overline{G_T}$) contains of 3 types of radiations which are direct radiation ($\overline{G_{t,b}}$), diffuse radiation ($\overline{G_{t,d}}$) and ground reflected radiation ($\overline{G_{t,r}}$). Further, the ground reflectance (ρ_g). by using the following formula ($\overline{G_T}$) can be calculated [21].

$$\overline{G_T} = \overline{G_{t,b}} + \overline{G_{t,d}} + \overline{G_{t,r}} \quad \textbf{(10)}$$

$$\overline{G_T} = \overline{G_b}\frac{\cos\theta}{\cos\theta_z}\left(1 + \frac{\overline{G_d}}{\overline{\overline{G_o}}}\right) + \overline{G_d}\left(1 - \frac{\overline{G_d}}{\overline{\overline{G_o}}}\right)\left(1 + \sqrt{\frac{\overline{G_d}}{\overline{G}}}\sin^3\left(\frac{\beta}{2}\right)\right)\frac{1+\cos\beta}{2} + \overline{G}\,\rho_g\left(\frac{1-\cos\beta}{2}\right)$$

3.4. Wind Energy Source

3.4.1. Variation of Annual Wind Speed

In South Asia, Sri Lankan islands located with significant wind energy sources. The windy climate is mostly governed by two Asian monsoons, which are southwest and northeast monsoons. The southwestern monsoon continues from May until the beginning October, while the north monsoon continues from December to February. The southwest is the stronger of the two monsoons and was felt on the western coast of Sri Lanka, in the inner regions and some mountainous regions. Although the winds in mountainous regions are highly region-specific, stormy and confined to the southwest monsoons. During both monsoons, the winds on the flat land in the southeastern and northwest coastal waters are more steady and visible. [22]

The Sri Lankan wind source map and the wind energy classification table are shown in Figure 3.10 for large-scale wind power projects, wind source zones of class 4 and above are known as appropriate. Class 2 and above wind resources might be sufficient for feasible wind power expansion in off-grid renewable applications as it needs less wind source for a system to be viable. For this kind of projects, [23]. According to the map, this site location has good wind resources-class 4. Therefore, for an off-grid hybrid system in this location adding wind turbines are a good selection.

For this location at the site, there is not any available ground wind speed data. For this reason, wind speed data is taken from the website of NASA renewable energy sources. In Table 5 the data gathered by the NASA website is tabularized.

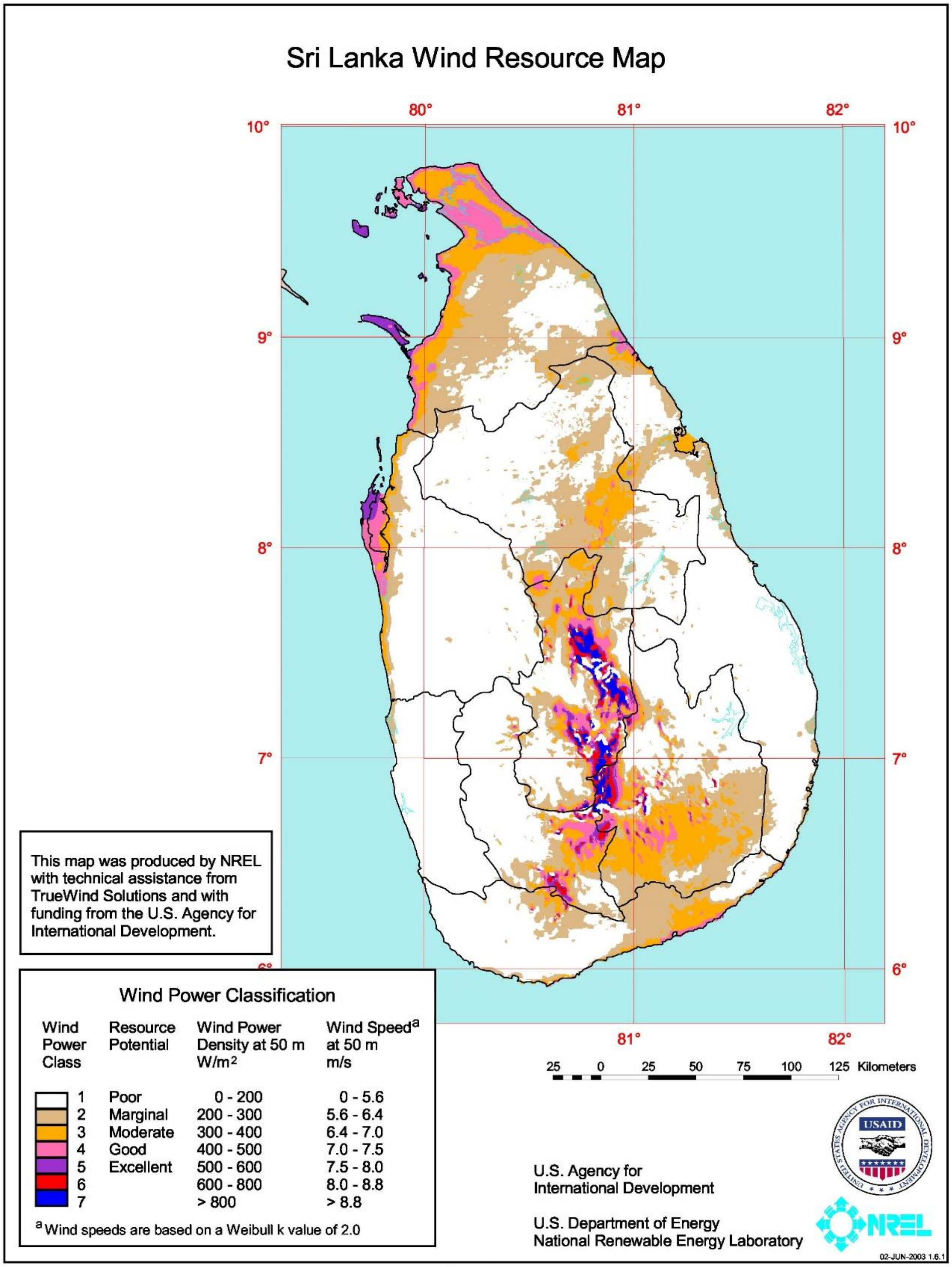


Figure 3.10: Sri Lankan Wind resource map

Source: "Wind Energy Resource Atlas of Sri Lanka and the Maldives," NREL, 2003

Table 6: 15m and 50m above from ground level average monthly wind speed data

Month	Monthly Averaged Wind Speed (m/s) at 15m Open water	Monthly Averaged Wind Speed At 50 m
Jan	5.5	6.5
Feb	4.4	5.2
Mar	3.5	3.94
Apr	3.1	3.71
May	6.6	6.57
Jun	7.6	8.55
Jul	6.1	7.63
Aug	7.2	8.49
Sep	6.3	7.01
Oct	4.8	5.66
Nov	4.4	5.54
Dec	4.9	5.43
Annual Average	5.39	6.20

Source: www. eosweb.larc.nasa.gov / cgi-bin/ sse/ sse.cgi?rets@nrcan.gc.ca.

3.4.2. The Wind Speed Variation with Distance from Ground Level

Table 5 shows the wind speed fluctuates with the elevation. Mostly, because of the irregularity of the earth's surface, there is an effect on the wind speed from the height above the ground level. Following equation can be used to define this relationship [24].

$$u(h) = u(h_1)\frac{\ln\left(\frac{h}{z}\right)}{\ln\left(\frac{h_1}{z}\right)} \qquad \textbf{(11)}$$

Wherever;

h - Distance from ground level where the winds speed to be measured

h_1 - Height of Anemometer

z - Surface-roughness

$u(h_1)$ – Wind speed in anemometer reading

$u(h)$ – Wind speed to be measured

By equation 11, if the wind measurements at a different height and surface roughness are known, then the wind speed at any given tower height can be calculated. Therefore, when wind speeds at two dissimilar levels are available. By these values, the surface roughness (z) of the selected location can be calculated. To calculate the roughness value (z), MATLAB has been used, as equation 11 has nonlinear characteristics. Then it was found that z = 0.001. This data has been used to represent the variation of average annual wind speed with different heights above the ground level at the site in Figure 2.11.

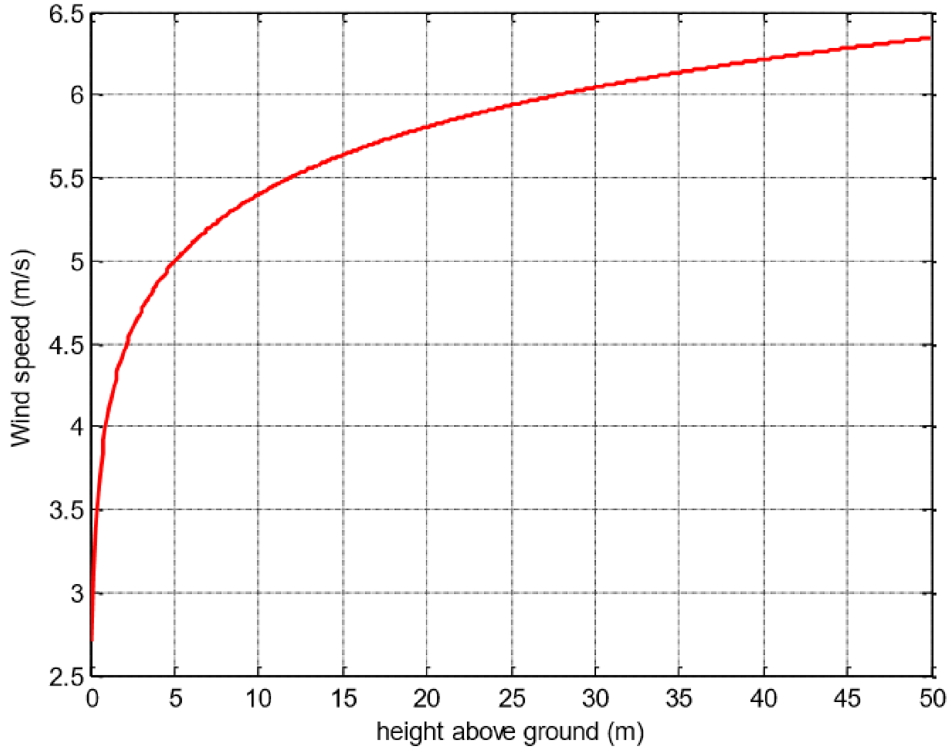


Figure 3.11: variation of averaged wind-speed with elevation

3.4.3. Distribution of Wind-Speed

By using the Weibull distribution function, the fluctuation of wind speed can be defined at a selected location. During a period, the likelihood of diverse mean wind speeds taking place at the site is illustrated in Weibull distribution. Following calculation illustrates the probability density function [25].

$$f(u) = \frac{k}{\lambda}\left(\frac{u}{\lambda}\right)^{k-1} exp\left(-\left(\frac{u}{\lambda}\right)^{k}\right) \quad \textbf{(12)}$$

K – Weibull shape factor (unitless)

λ - Weibull scale parameter (ms^{-1})

U – Wind speed (ms^{-1})

k is a size of the width of the distribution and scale factor (λ) is correlated to the mean wind speed. Between 1.5 to 2.5 is the normal range for Weibull k value. When (Γ) is representing gamma function. Then, the average wind speed and Two Weibull parameters are related to the following equation. [25].

$$\bar{u} = \lambda\Gamma\left[\frac{1}{k} + 1\right] \quad \textbf{(13)}$$

The Weibull k value together with an average wind speed can describe the Weibull distribution. Four different Weibull distributions have listed down in the following graph, each with different Weibull k value but all got the same 6 ms-1 average wind speed. The broader distributions are generated to lower values of k according to the graph.

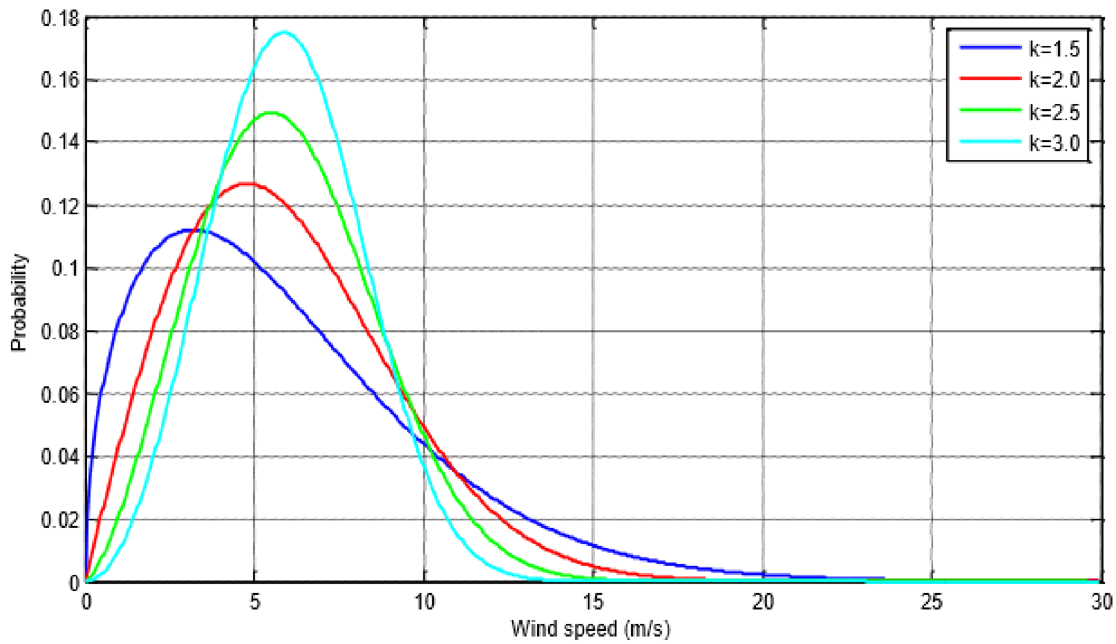


Figure 3.12: wind speed probability distribution for dissimilar Weibull parameter k values

By the statistical study of gathered wind resource data at the location, The Weibull parameter k can be calculated. To get an accurate result large collection of hourly wind speed averages are required for this. In this study, it was assumed that the value of 2 for Weibull k since there was no sufficient amount of data available to discover the precise value of Weibull k and in general practice also for island sites k=2 is more common.

3.4.4. Site Wind Power Density

Wind power potential of a selected location can be identified by referring to its wind power density. It gives the value of the average wind power per square meter (W/m2). As shown in the following equation the cube of the wind speed is proportional to wind power density at the site,

$$WPD = \frac{1}{2}\rho u^3 \quad \textbf{(14)}$$

u - Uninterrupted wind speed (m/s)

ρ - Density of air (kg/m3)

WPD - wind power density (W/m2)

By following formula, we can find the density of the air.

$$\rho = \frac{P}{RT} \tag{15}$$

P – Pressure of the air (N/m2)

T - Temperature (K)

R - Specific gas constant (287.0 Jkg-1K-1)

In formula 14 for wind power potential, the assumption was made that the wind speed u is constant throughout the time. But practically it is fluctuating. To get a precise approximation, as in the equation 16, the total average of wind speed values over time should be measured for the wind power density calculation.

$$WPD = \frac{1}{2n}\sum_{j=1}^{n} P_j u_j^3 \tag{16}$$

Wherever,

P_j - j^{th} readings of the air density

u_j - j^{th} readings of wind speed.

n - The number of wind speed readings

On the other hand, to calculate the wind power density following formula can be applied if the wind speed frequency distribution is known at the site location.

$$WPD = \frac{1}{2}\sum_{j=1}^{n} P_j u_j^3 f(u_j) \tag{17}$$

To describe the probability of different wind speeds occurring at the site, Weibull distribution can be applied, therefore, equation 17 has been derived as;

$$WPD = \frac{1}{2} \sum_{j=1}^{n} P_j u_j^3 \; \frac{k}{\lambda} \left(\frac{u}{\lambda}\right)^{k-1} exp\left(-\left(\frac{u}{\lambda}\right)^{k}\right) \qquad \textbf{(18)}$$

Where,

$f(u_j)$ - wind speed frequency rate through a certain time duration

u_j - wind speed

Another popular parameter for reviewing the wind resource potential at a site location is the Root Mean Cube (RMC) of wind speed (V_{rmc}). The equation below can be applied for calculation of V_{rmc}.

$$V_{rmc} = \sqrt[3]{\sum_{i=1}^{n} f(u_j)}\, u_j^3 \qquad \textbf{(19)}$$

For the fast approximation of the wind power density at a selected location, following equation which derived by (V_{rmc}) can be used.

$$WPD = \frac{1}{2} \rho V_{rmc}^3 \qquad \textbf{(20)}$$

Wind Power Density and RMC wind speed variation with Elevation

As mentioned in Chapter 2.4.2, the wind speed changes with elevation. For this reason, wind power density and RMC wind speed also change with the elevation levels. If the average annual wind speed is identified for a given height (h1), the average annual wind speed at any elevation can be calculated by equation 11 and each average wind speed can be calculated by assigning respective lambda (λ) values to equation 13. By replacing λ values for dissimilar elevations which obtained by calculations, the wind power density and RMC wind speed variations with the height can be found.

The average annual wind speed of the area is assumed to be 5.4 m / s at an elevation of 10 m from the ground, 0.001 is considered as surface roughness and k is equal to 2 as discussed in **3.4.3**. Substituting these values, the power density and RMC wind speed variation curve with the elevation has been obtained for the given location. The Figure 2.13 and Figure 2.14 shows the obtained graphs.

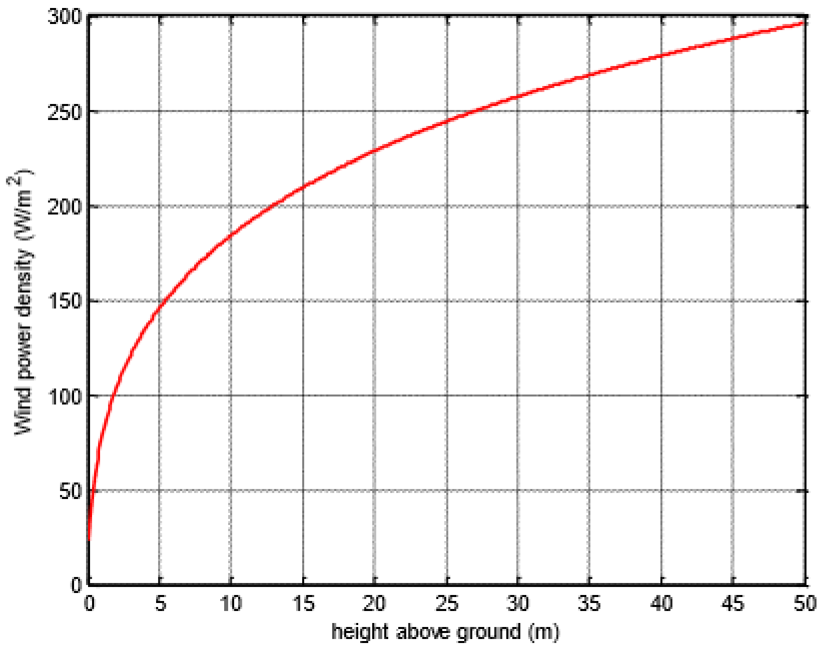


Figure 3.13: wind power density variation at the site, with elevation

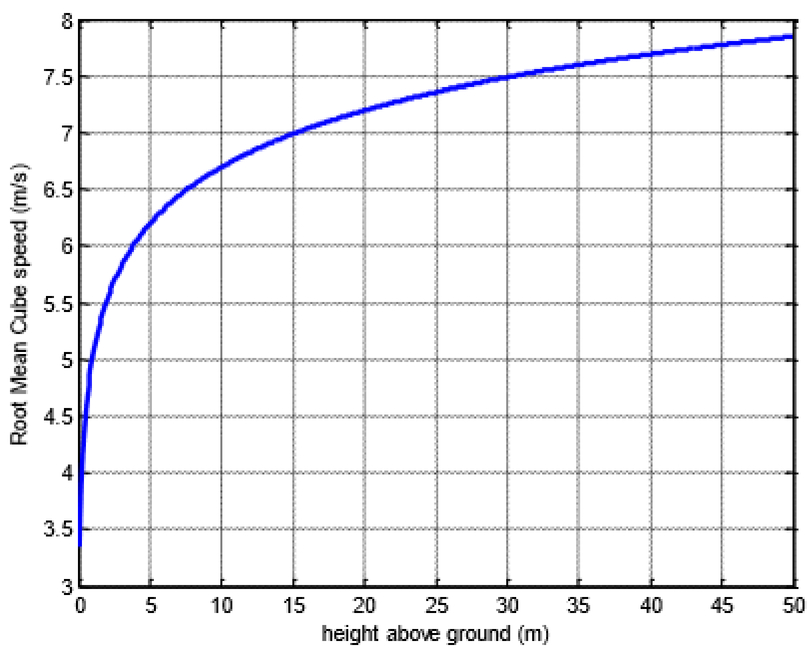


Figure 3.14: the RMC wind speed variation at the site, with elevation

Chapter 4

Technologies and Modeling of Hybrid Distribution Systems

Throughout this chapter, we will be discussing the current technologies related to hybrid distribution systems which used globally. Deferent technical arrangements and their pros and cons will be reviewed. Furthermore, using Homer software similar mini - grid will be modeled by inputting the actual renewable and load data at site location. By simulating the model the optimal combination of each component will be analyzed.

4.1. Background

By combining different renewable energy sources, hybrid power system produces AC electricity output through an inverter, also conventional fossil fuel generator can be combined in parallel or alternatively to this system. As discussed in Chapter 2, wind and solar sources potential are comparatively higher in the Northern region, therefore for establishing a renewable power supply system for the selected site, both wind and solar resource can be used. Moreover, for the hybrid system, instead of these renewable sources, a storage battery bank and diesel generator set have been included. Hybrid plants can be classified as follows based on the bus type that will connect dissimilar modules together and the type voltage which the system operates [26].

Hybrid systems with,

- AC coupled
- DC\AC coupled
- DC coupled

4.2 Hybrid systems with DC coupled technology

In a hybrid system which uses DC coupled technology, all components that produce electricity are connected to the DC bus bar. For this reason, DC generation components with control devices to control charging and with rectifiers there are AC generation systems as well. According to this arrangement, the energy produced by the diesel generator is first rectified before transformed back to AC, because of these several steps of the energy conversion procedures the efficiency will reduce due to power loss. In addition, the diesel generator and inverter cannot function at the same time. For this reason, the inverter must be large enough to meet the maximum demand. Then again, the breakdown of an inverter may result in a power cut, if the load cannot be provided directly from the diesel generator during emergency situations.

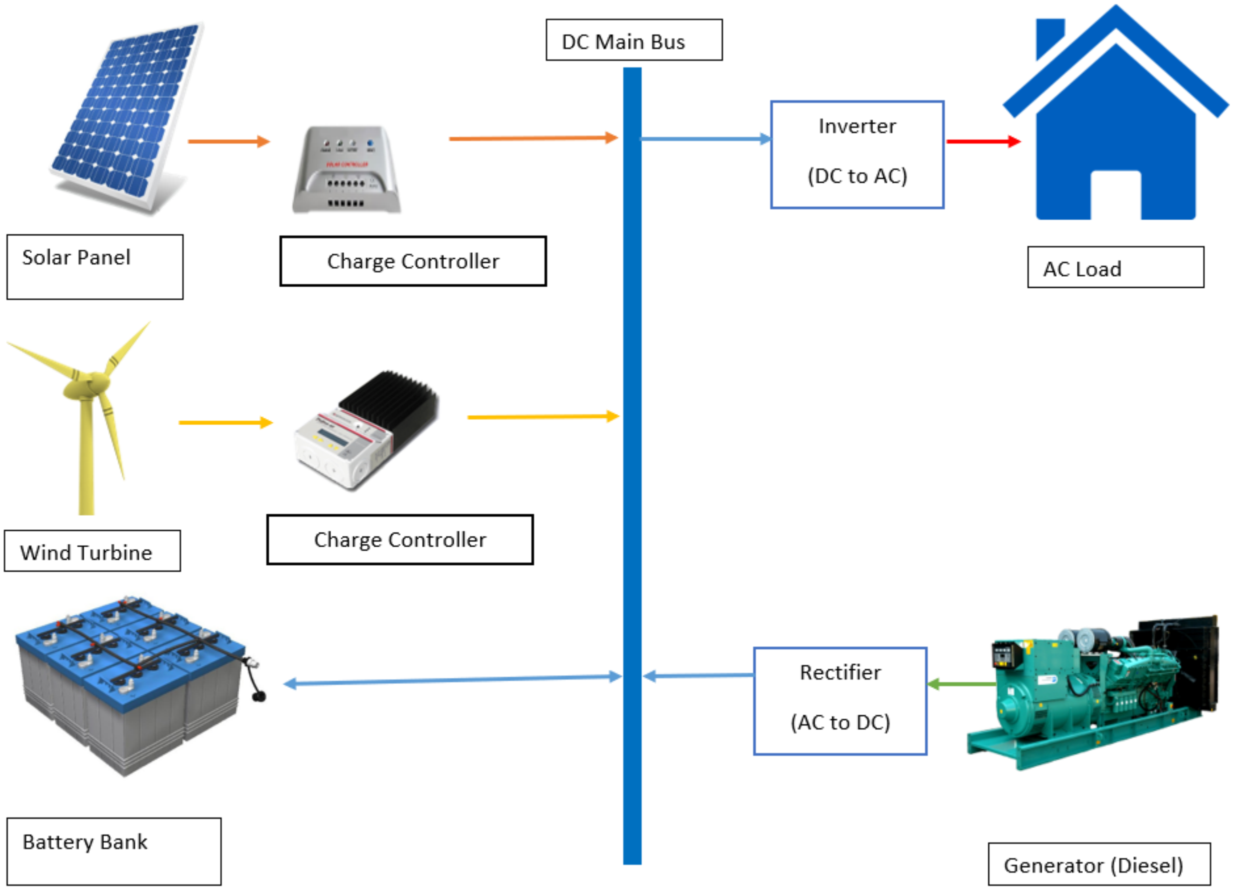


Figure 4.1: Block Diagram of Hybrid System Which Uses DC Coupled Technology

4.3 Hybrid systems with AC coupled technology

In the hybrid system with AC coupled technology, AC bus is linked to all the power generation components in the hybrid system. The AC generation apparatuses can be linked directly to the AC bus bar or may need an additional AC to AC converter to allow a steady coupling. Further, the DC generation systems are connected to the AC bus through inverters. In this arrangement, the bi-directional inverter has been used to control the power supply for the battery bank. AC coupled hybrid systems are more popular because it is also expandable and provides the benefits of DC/AC coupling hybrid system, which will discuss later.

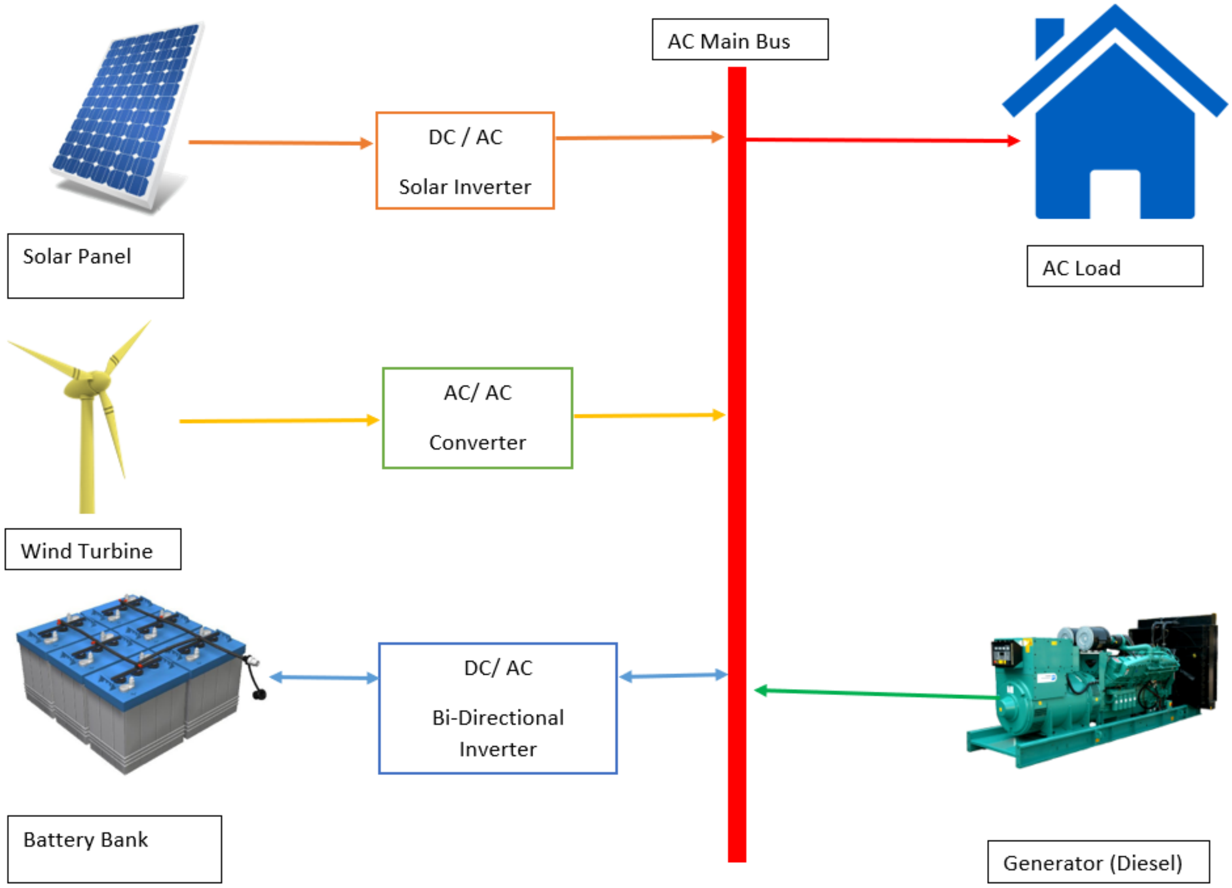


Figure 4.2: Block Diagram of Hybrid System Which Uses AC Coupled Technology

4.4 Hybrid systems with DC\AC coupled technology

In a hybrid DC \ AC connected system, the apparatuses that generate electricity can be linked to the either DC or AC bus, based on their type of production voltage. This arrangement uses a bi-directional inverter to connect the AC bus and the DC bus. In this arrangement, the diesel generator and inverter can be functioned at the same time, so the inverter may not be gauged to fulfil the maximum demand. The ability to function the inverter and the diesel generator at the same time ensures the flexibility of the generator to optimize the process of the hybrid system. In addition, this would let the system to maximize the generator efficiency.

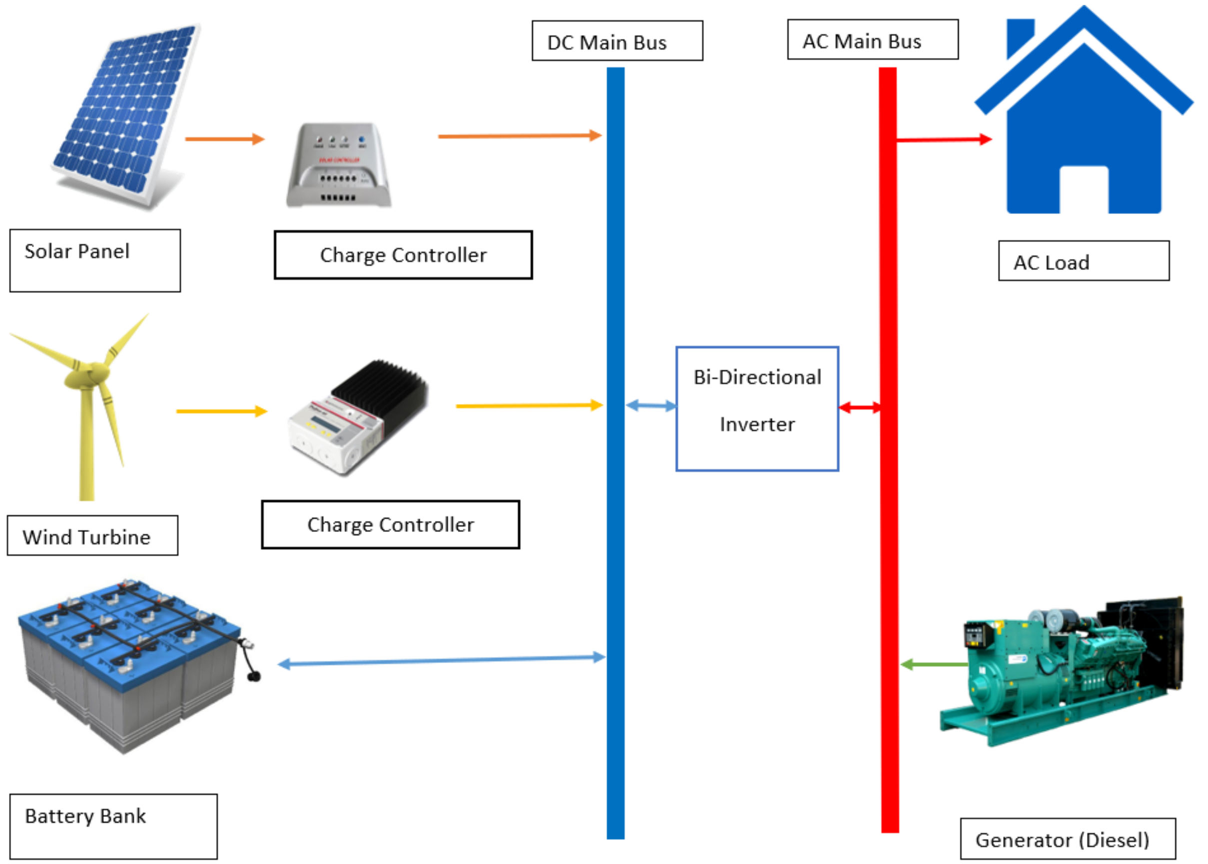


Figure 4.3: Block Diagram of Hybrid System Which Uses DC\AC Coupled Technology

The hybrid system which deploys AC coupled technology has been chosen for this study, since not only because of the benefits argued above, it offers more freedom to choose the voltage of the DC bus, and so the hybrid system apparatuses. But then again in a DC-coupled system, the voltage of the DC bus depends on a number of components. In this system, wind turbines, photovoltaic panels, storage battery banks and bi-directional inverters. Each of the component voltage range which decides the voltage of DC bus must be identical. For that reason, we have less sensitivity range in the market when buying components for the configuration of this system. Similarly, in the AC-coupling, the production resources can be linked to practically any point in the grid. Furthermore, connecting this system to the network is a very covenant, deprived of extra costs if the network can be expanded in future.

In this study, as for the AC coupled off-grid hybrid distribution system, the key apparatuses which essential are; photovoltaic panels, wind turbines, storage batteries, inverters and a diesel generator. For the proposed arrangement, three inverters, basically a wind inverter, solar inverter and a bi-directional inverter for battery, are required. SMA multicluster technology is also based on AC coupled systems and the following sections discuss special features of this multicluster technology.

4.5Multi Cluster Technology

Off-grid AC-based systems open new opportunities to provide a stable and prevailing power supply, while maintaining overall supply quality associated with power distribution networks, regardless of the large-scale electrical distribution grid. The modular structure provides simple installation and easy expansion. Renewable energy sources usually have no fuel costs and are therefore increasingly economically viable and are now much more profitable than conventional systems operating on diesel generators. [27]

Terms Used in SMA Multicluster Technology

Cluster

Three Sunny Island inverters and one battery will form a cluster. One Sunny Island inverter per line conductor, and therefore a total of three Sunny Island inverters, is connected to form a three-phase stand-alone grid. Within the cluster, one Sunny Island is the master, while the other two are slaves.

Multicluster System

Several clusters connected in parallel will create a multi-cluster system. With the number of clusters, the performance will increase of the multi-cluster system. The clusters are linked in parallel through a Multicluster Box. Based on the energy requirement, the capacity of the Multicluster Box will select during the design time of the system.

Multicluster Box

The Multicluster Box acts as the main AC distribution board in the multi-cluster system and a module of the SMA multicluster technology. The Multicluster Box joins the Sunny Island clusters with the loads and the power generators within a stand-alone grid.

Master

Master is the centre of control and communication in a cluster. Perform the following tasks:

- Slave connection and disconnection
- Observing and control of slaves, ex: voltage and frequency regulation
- Check battery charge and discharge
- Monitoring of battery capacity and SOC
- Save cluster data and battery to SD card
- Diesel generator controlling
- Exchange of data with maters of other extension clusters
- Updating both slaves after firmware updates
- Show system values and system states
- Central registration of user inputs

Slave

A slave is a functional unit inferior to the master. A slave gets its current firmware updates, configuration settings and start\stop instructions from its master. It sends its operational information to its master and completes instructions issued by the master.

Main Cluster

The main cluster is the prominent cluster within a multi-cluster system. The master of the main cluster is the central user interface for the main cluster and all extension clusters of a stand-alone grid. The master of the main cluster is superior to the masters of the other extension clusters. The following are some of the responsibilities done by the master of the main cluster:

- Starting and stopping the multicluster system
- Controlling and monitoring the masters of the extension cluster
- Communicating with the multicluster Box

If the master of the main cluster stops operation, the entire multicluster system shuts down. If a diesel generator is integrated into the stand-alone grid, it will take over the power supply to the loads in this case.

Extension Cluster

An extension set is a cluster that is bound to the master cluster in the Multicluster system. The master of the extension cluster follows the instructions given by the master of the master cluster. The extension cluster master sends the operational data of the cluster to the master of the master cluster. If the master of an extension cluster stops the operation, only that cluster will shut down. Yet, the multi-cluster system continues to operate with reduced power. [31]

4.6 Modeling and simulating mini grid using Homer

Homer software can be used in modelling mini-grids worldwide. Selection of the geographical location can be entered to the software; so that it can identify the renewable energy resources at the selected site location.

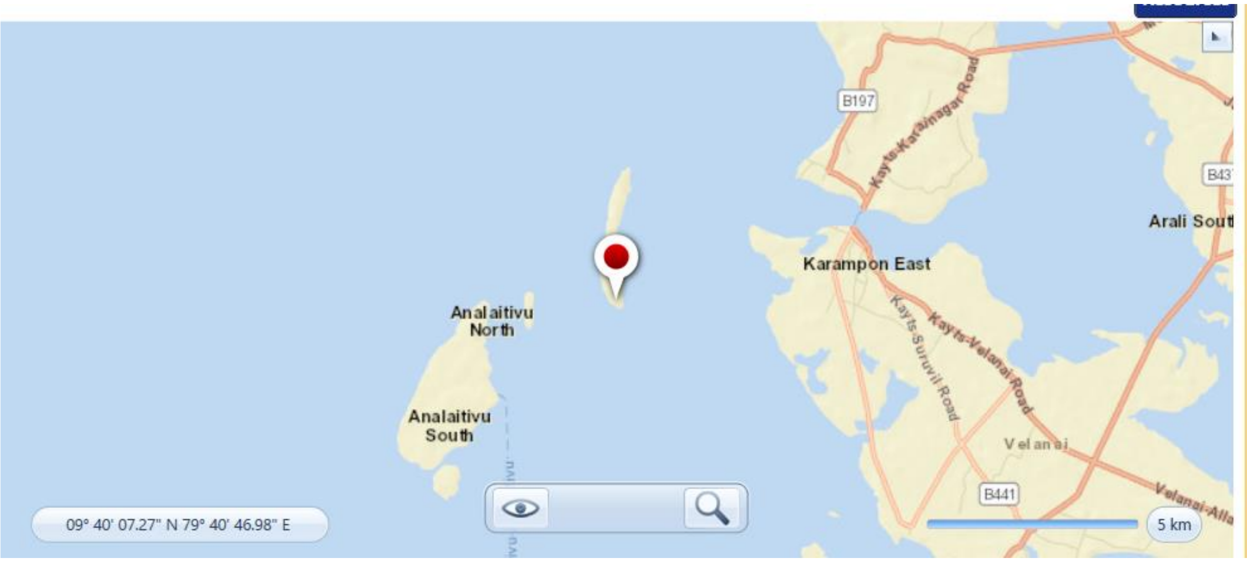


Figure 4.4: input the geographical location of the site to Homer software.

There are inbuilt sample electrical load profiles built in which user can select and there is a facility of entering the actual data and generate specific electrical load profile at the site. During the data collection stage, the average daily load profile of the village was obtained, and that data set was entered to Homer and it has generated an electrical load throughout the year after processing with scaled data algorithm.

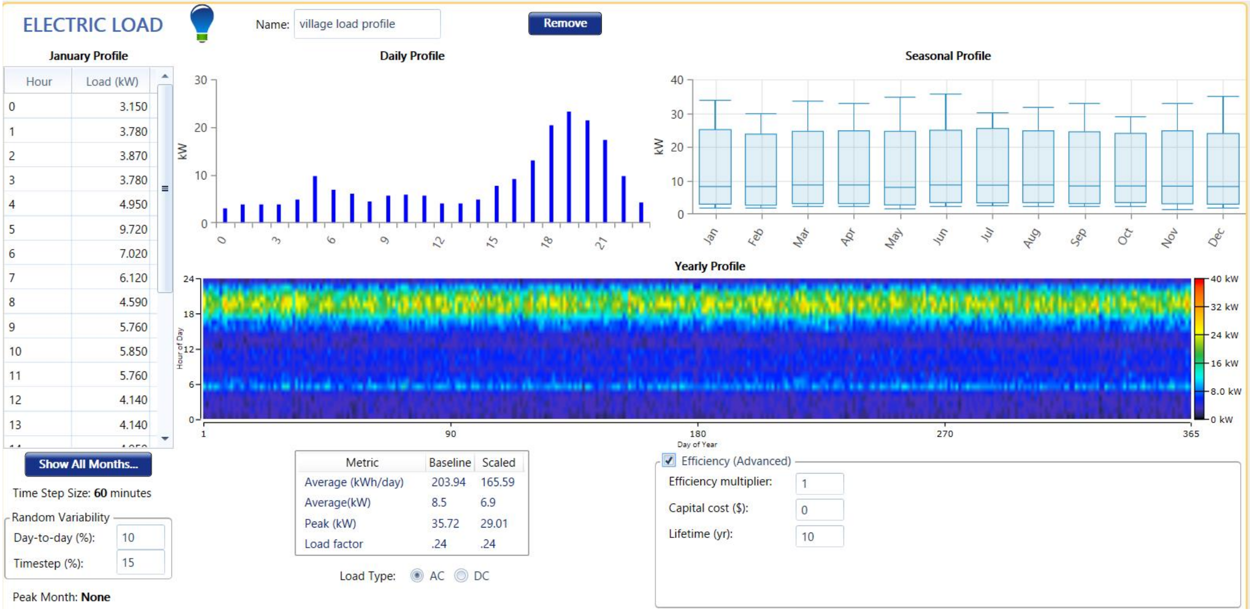


Figure 4.5 : Model of the village load profile in Homer Software

After inserting the average load data into the software; random variability of 25% was considered. ultimately the scaled peak voltage is 29.01kW and average daily demand is 165.59kW/day.

Based on the average load profile entered the scaled yearly electrical load profile has been generated. This load profile will be considered in designing the optimized mini-grid solution to the given location.

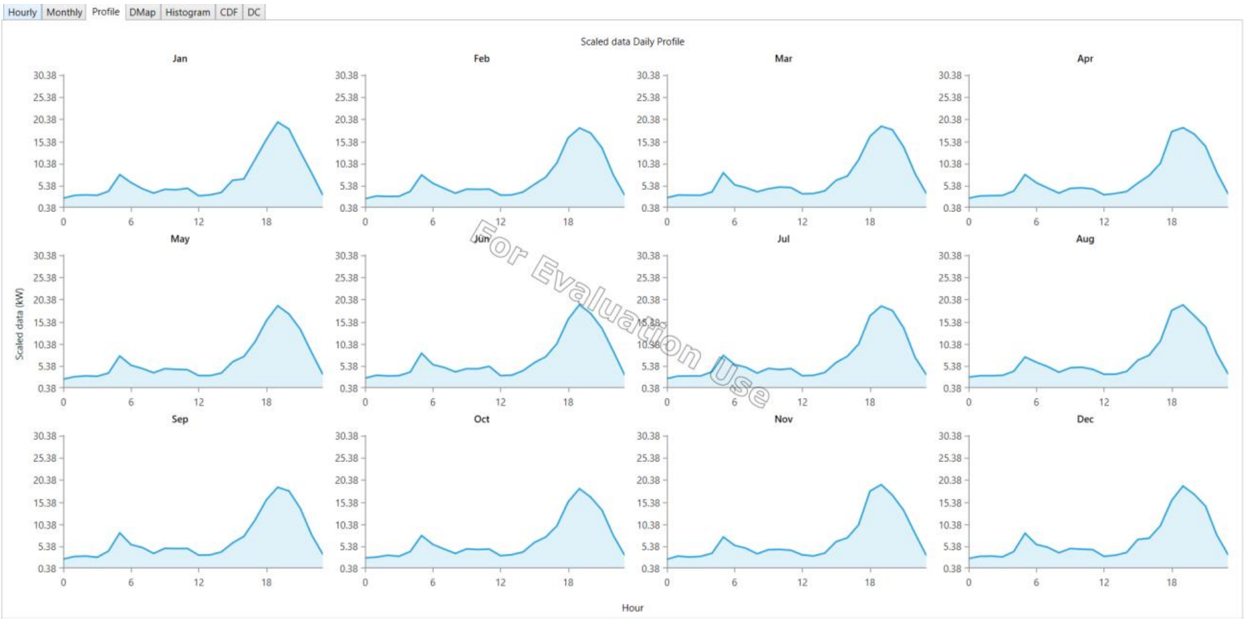


Figure 4.6 : Scaled data variation plots generated by the homer software.

By accessing the NASA surface meteorology and solar energy database; monthly averaged clearness index and daily radiation data was imported based on the site location identified in the beginning. According to this data in March, there is the highest daily radiation of 6.69 kWh/m^2/day. The annual average daily radiation in the selected geographical location is 5.48kwh/m^2/day.

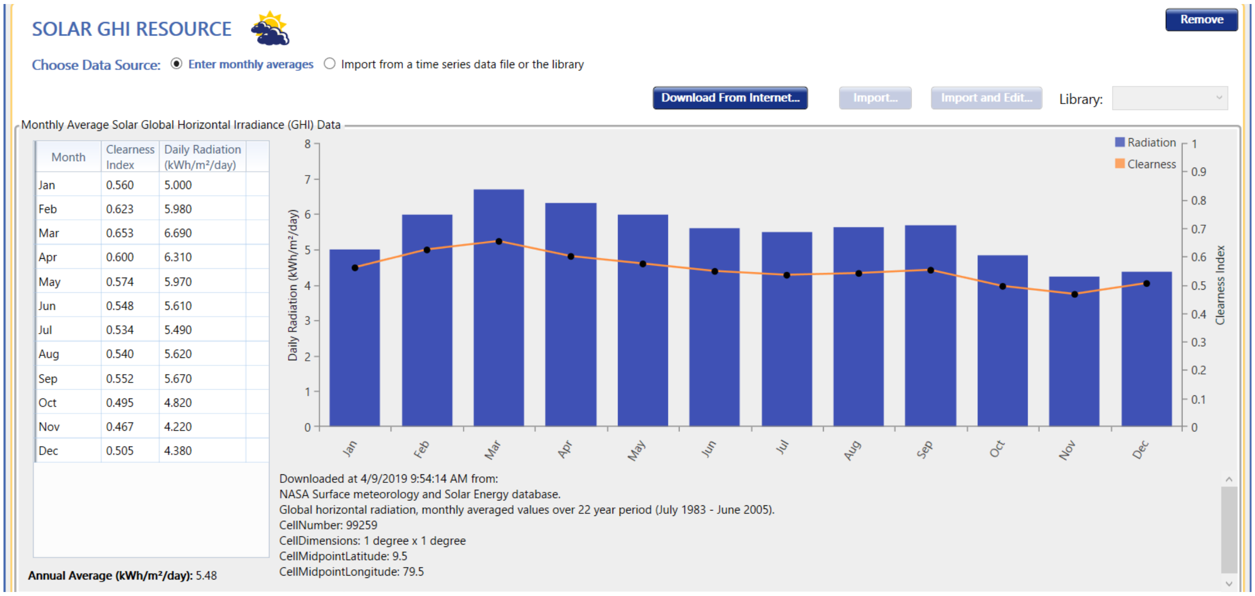


Figure 4.7 : Solar Data at site location loaded to the homer software

By accessing the NASA surface meteorology and solar energy database; monthly averaged wind speed data was imported based on the site location identified in the beginning. According to these data, in June there is the highest average wind speed of 7.6 m/s. The annual average wind speed in the selected geographical location is 5.37m/s.

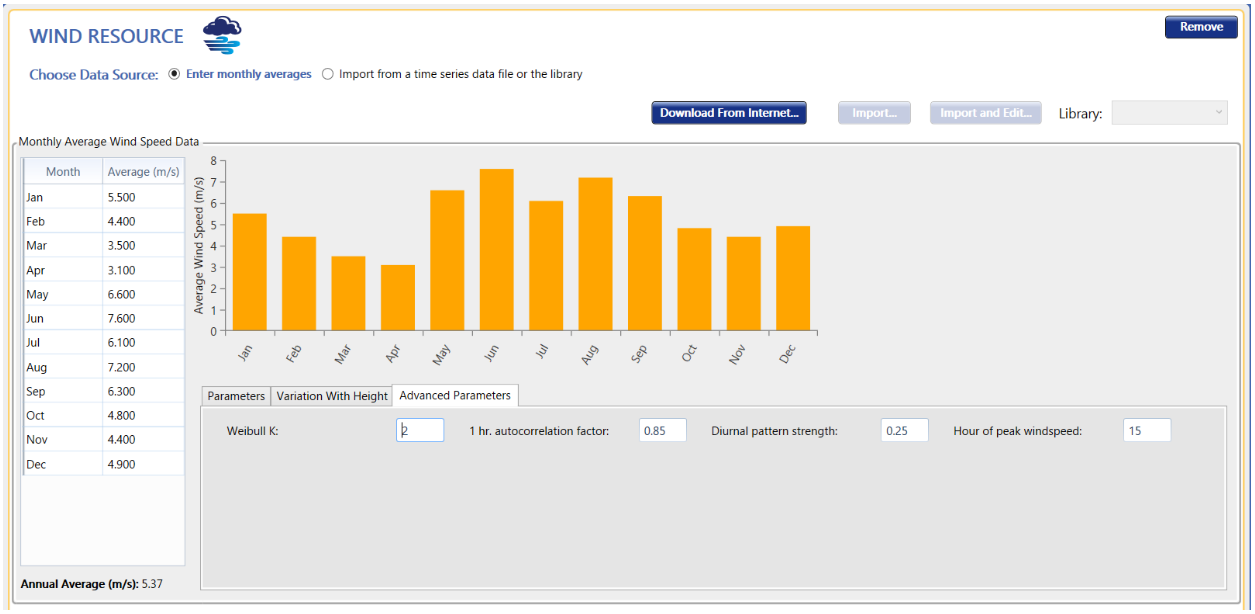


Figure 4.8 : Wind resource data at site location loaded to the homer software

Once after feeding the load data and the renewable energy resource data, next in Homer the necessary components can be selected for the mini-grid. Since in this study, the focus is to a hybrid generation system; the diesel generator has also combined with the solar panels, wind turbines and the battery bank.

The "load following strategy" has been selected in this model. Load following strategy is a dispatch strategy in homer, hence whenever the generator take-charge, it generates only sufficient power to fulfil the main load. Lower priority objectives such as charging the battery bank will be left to renewable power sources.

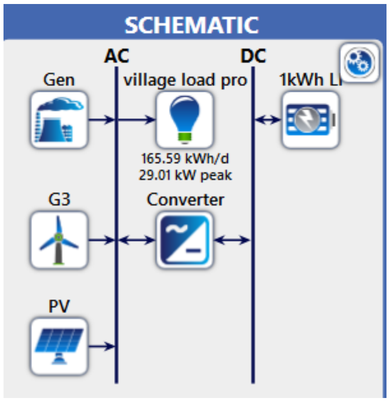
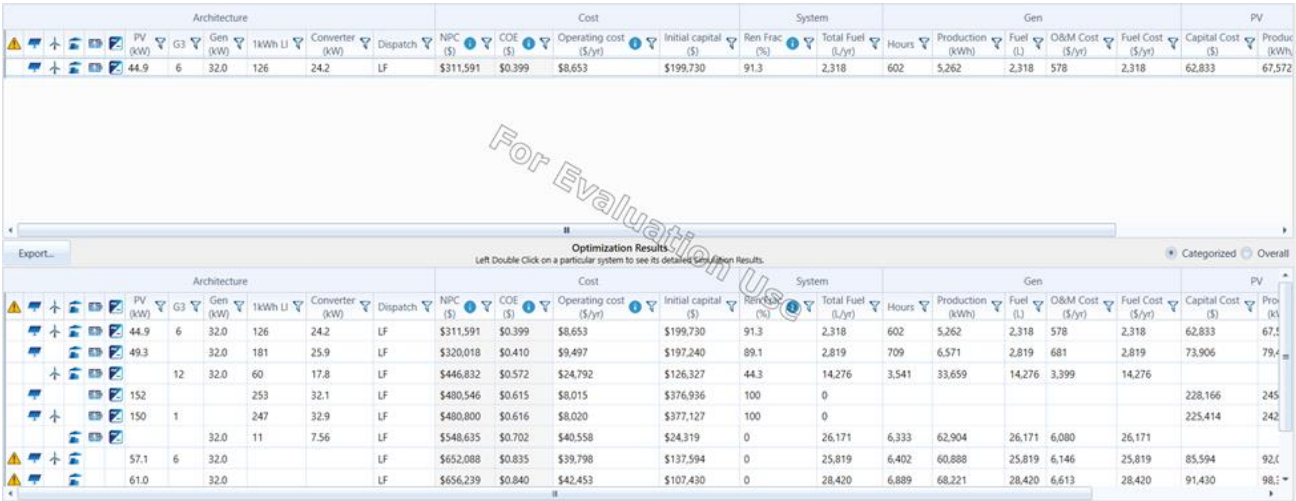


Figure 4.9 : Schematic diagram of the Homer model

After finalizing the components, the simulation can be done and based on the simulation results the optimal capacities of each component can be identified. This optimal solution is given after analyzing a number of different combination patterns.



PV (kW)	G3	Gen (kW)	1kWh LI	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)	Capital Cost ($)	Produc (kWh)
44.9	6	32.0	126	24.2	LF	$311,591	$0.399	$8,653	$199,730	91.3	2,318	602	5,262	2,318	578	2,318	62,833	67,572

Optimization Results

Left Double Click on a particular system to see its detailed Simulation Results.

Export... Categorized Overall

PV (kW)	G3	Gen (kW)	1kWh LI	Converter (kW)	Dispatch	NPC ($)	COE ($)	Operating cost ($/yr)	Initial capital ($)	Ren Frac (%)	Total Fuel (L/yr)	Hours	Production (kWh)	Fuel (L)	O&M Cost ($/yr)	Fuel Cost ($/yr)	Capital Cost ($)	Pro (kW
44.9	6	32.0	126	24.2	LF	$311,591	$0.399	$8,653	$199,730	91.3	2,318	602	5,262	2,318	578	2,318	62,833	67,5
49.3		32.0	181	25.9	LF	$320,018	$0.410	$9,497	$197,240	89.1	2,819	709	6,571	2,819	681	2,819	73,906	79,4
	12	32.0	60	17.8	LF	$446,832	$0.572	$24,792	$126,327	44.3	14,276	3,541	33,659	14,276	3,399	14,276		
152			253	32.1	LF	$480,546	$0.615	$8,015	$376,936	100	0						228,166	245
150	1		247	32.9	LF	$480,800	$0.616	$8,020	$377,127	100	0						225,414	242
		32.0	11	7.56	LF	$548,635	$0.702	$40,558	$24,319	0	26,171	6,333	62,904	26,171	6,080	26,171		
57.1	6	32.0			LF	$652,088	$0.835	$39,798	$137,594	0	25,819	6,402	60,888	25,819	6,146	25,819	85,594	92,(
61.0		32.0			LF	$656,239	$0.840	$42,453	$107,430	0	28,420	6,889	68,221	28,420	6,613	28,420	91,430	98,:

Figure 4.10: simulation test results in Homer

According to the simulation results in Homer software; the following capacities of each component has been identified as the optimal solution.

module	Capacity
Solar panel	44.9 kW
Wind Turbine	18 kW
Battery storage	126 kWh
Diesel generator	32kW

Table: optimal capacities of each component according to simulation results in Homer

Chapter 5

Design of the Hybrid Distribution System

Former units describe the availability of renewable energy resources and current technological trends related to hybrid distribution systems, model of a similar system and simulation of it. In this Chapter, we will focus on the existing design of the hybrid distribution system. Also, it will discuss the planning and design of the existing hybrid system. Furthermore, it also explains about the selected components and their characteristics; solar panel, storage battery bank, wind turbine, diesel generator and the inverters.

5.1. PRELIMINARY CALCULATION

According to the average load cure which we discussed in Figure 2.2 in chapter 2, the average maximum peak load was 23.2kW. Also, the average monthly demand was identified as 6086kWh. When designing an additional 10% tolerance factor was added in case of practical variations of the load during operation. Also, for the future growth additional 15% margin considered. Ultimately 25% margin was considered during the design stage for the average load curve. The final load curve used for the design is shown in Figure 4.1.

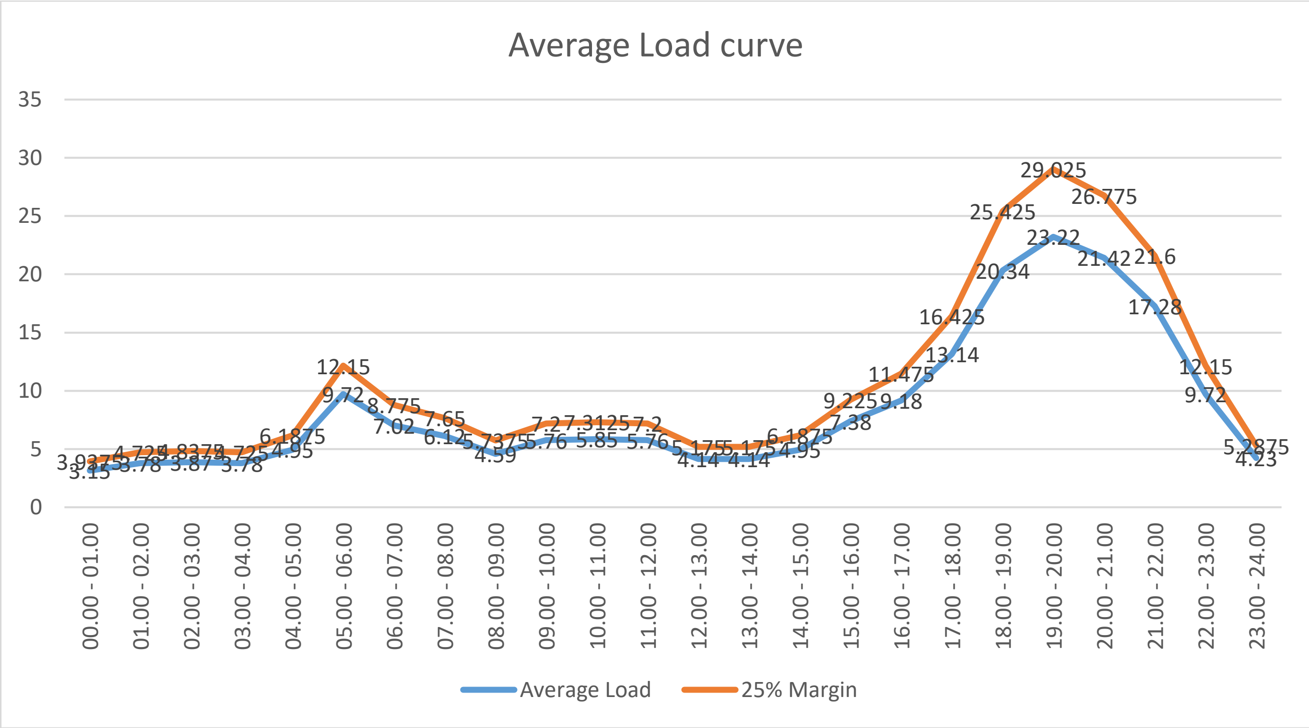


Figure 5.1: Average Estimated Village Load Profile Used for Planning

For the uninterrupted power supply, a backup generator is also very important. From the load curve with 25% margin shows the maximum peak is around 29kW during night time. If the battery storage is not sufficient to supply the demand the backup generator will take over the load from the battery bank. Since wind power is continuously feeding the grid the generator should supply the balance demand. The simulation results also show the generator capacity as 32kW but practically 30kW generator was selected as it is available in the market.

5.2Wind Generation

In the simulation result, there were 6 number of 3kW wind turbines. In the windspot turbines comes as two products 3.5kW and 1.5kW turbines.

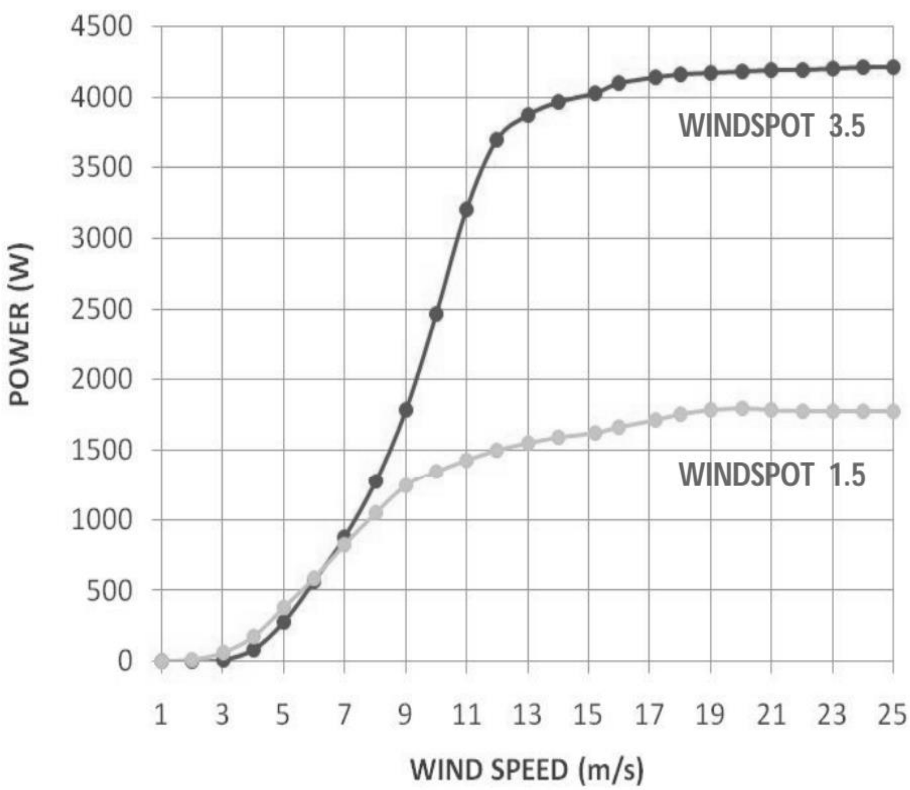


Figure 5.2: power curve comparison for windspot 1.5 and windspot 3.5

Source: windspot owner's manual

Form these two products, windspot 3.5kW was selected since there is an only a slight price difference of $ 850 (approximately). To meet the power requirement of only 6 units (3.5*6 = 21kW) were sufficient. Since there are 6 units available 2 units were combined and connected to each phase of the three-phase system.

POWER	1.5KW @ 250rpm	3.5KW @ 250rpm
ROTOR DIAMETER	4.05 m	4.05 m
ROTOR SWEPT AREA	12.88 m^2	12.88 m^2
CUT IN SPEED	3 m/s	3 m/s
RATED SPEED	12 m/s	11,5 m/s
WEIGHT	165 kg	185 kg
TOTAL LENGTH	3.17 m	3.2 m
ESTIMATED ANNUAL ENERGY OUTPUT	3.945 – 6.622 kWh (5-7 m/s)	4.802 – 10.839kWh (5-7 m/s)
CO2 SAVED	2.621 – 4.966 kg (5-7 m/s)	3.610 – 7.350 kg (5-7 m/s)
GENERATOR	Synchronous, permanent magnets; 3 phases, 24-48-110-220 V, 50/60 Hz	Synchronous, permanent magnets, 3 phases, 48-110-220 V, 50/60 Hz
TYPE	Up-wind horizontal rotor	
YAW CONTROL	Passive system: yaw tail	
POWER CONTROL	Passive variable pitch system, centrifugal and absorbed (patented design)	
TRANSMISSION	Direct	
BRAKE	Electric	
CONTROLLER	On-grid or off-grid connection option	
BLADES	Polyurethane core + polyester resin +fiber glass	
INVERTER	Efificiency ≈ 95% ; Algorithm MPPT	
NOISE	37 dB (A) from 60 m (65 yd) with a wind speed of 8 m/s	
ANTI-CORROSION PROTECTION	Sealed design + e-coat + galvanizing + anodizing + UV resistant paint	
TOWER	12, 14 and 18 m (39, 46 and 59 ft); hydraulic or mechanical lay down system	
DESIGN	According to IEC61400-2	
SURVIVAL WIND SPEED	60 m/s (class 1 according to IEC 61400-2)	
TEMPERATURE RANGE	-20 C / 50 C (extreme conditions according to IEC 61400-2)	

Figure 5.3: technical specification for windspot 1.5 and windspot 3.5

Source: windspot owner’s manual

As shown in figure 4.3 the size and the weight of the wind turbine are comparatively low to other large-scale wind turbines. Since the turbine weight is 185 Kg, and the size is 3.2m the turbine system is transportable to the islands using ferries.

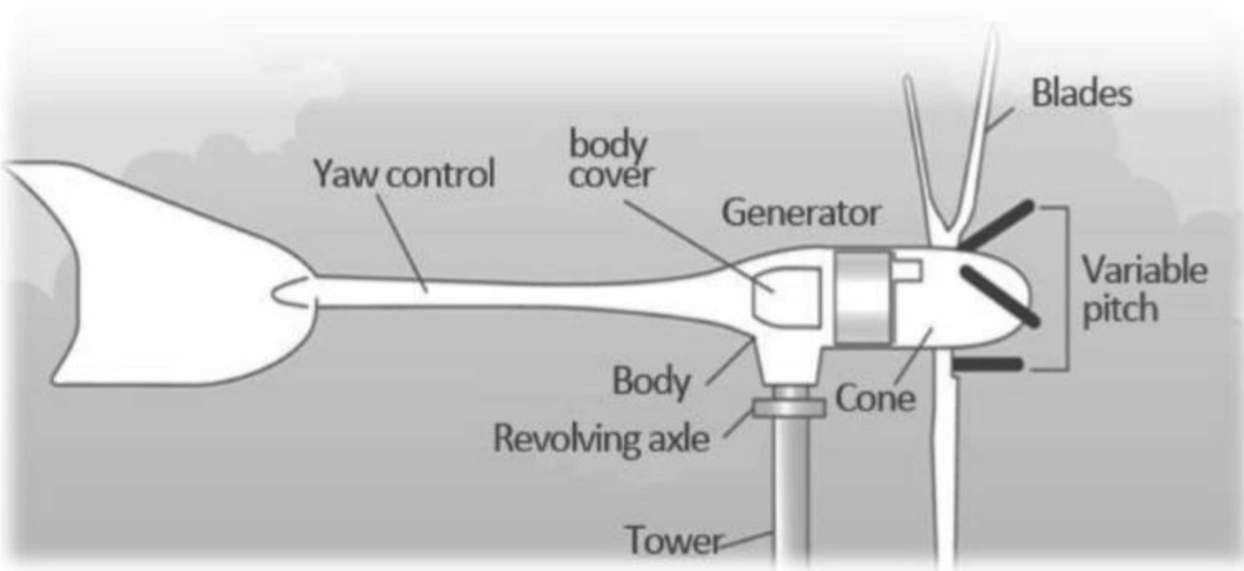


Figure 5.4: Body part list for windspot wind turbine

Source: windspot owner's manual

Not like most wind turbines; because of the yaw bearing, there is an ability to harvest maximum power by permitting the turbine to rotate to face the wind.

The variable pitch system (governor) limits the rotor rpm as well as generator output to protect the turbine from high winds. The variable pitch system is protected by a cone. Variable pitch system which prevents, in the event of heavy winds, any surges that may damage both the generator and the electronics. The system uses the centrifugal force created by the spinning of the wind turbine to change the angle of attack of the blades.

These windspot turbines are specially designed for coastal and offshore applications. All metal parts have been coated with marine grade powder coat for ensuring superior protection from the environment. [28]

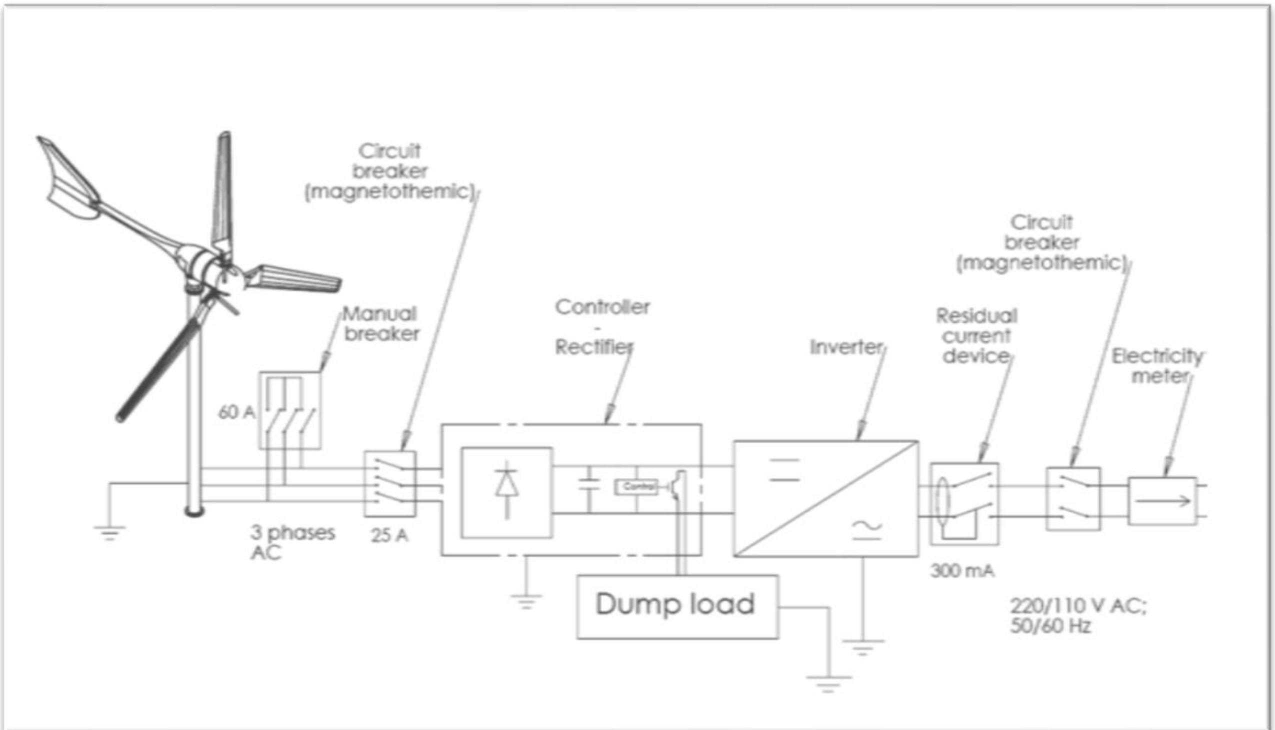


Figure 5.5: general on grid connection electrical diagram for windspot wind turbine.

Source: windspot owner's manual

As shown in figure 4.5 the wind turbines generate 3 phase electrical supply which can be unsteady and fluctuating with wind speed and this output cannot be directly connected with a load. To produce much reliable electricity output there are an internal circuitry and other components in-between the load and wind turbines. Its internal electrical circuitry contains protective breakers, controller unit with a rectifier to convert AC into DC and a dump load to release excessive power which generated.

Then, the DC output of the controller circuit is connected to an inverter so that it will generate 220V/50Hz AC output which can be directly connected to the load. Furthermore, for protection RCB and MCB can be used in between to get overload and short circuit protection. Finally, in figure 4.6, there is a flowchart which illustrates the process of the wind turbine.

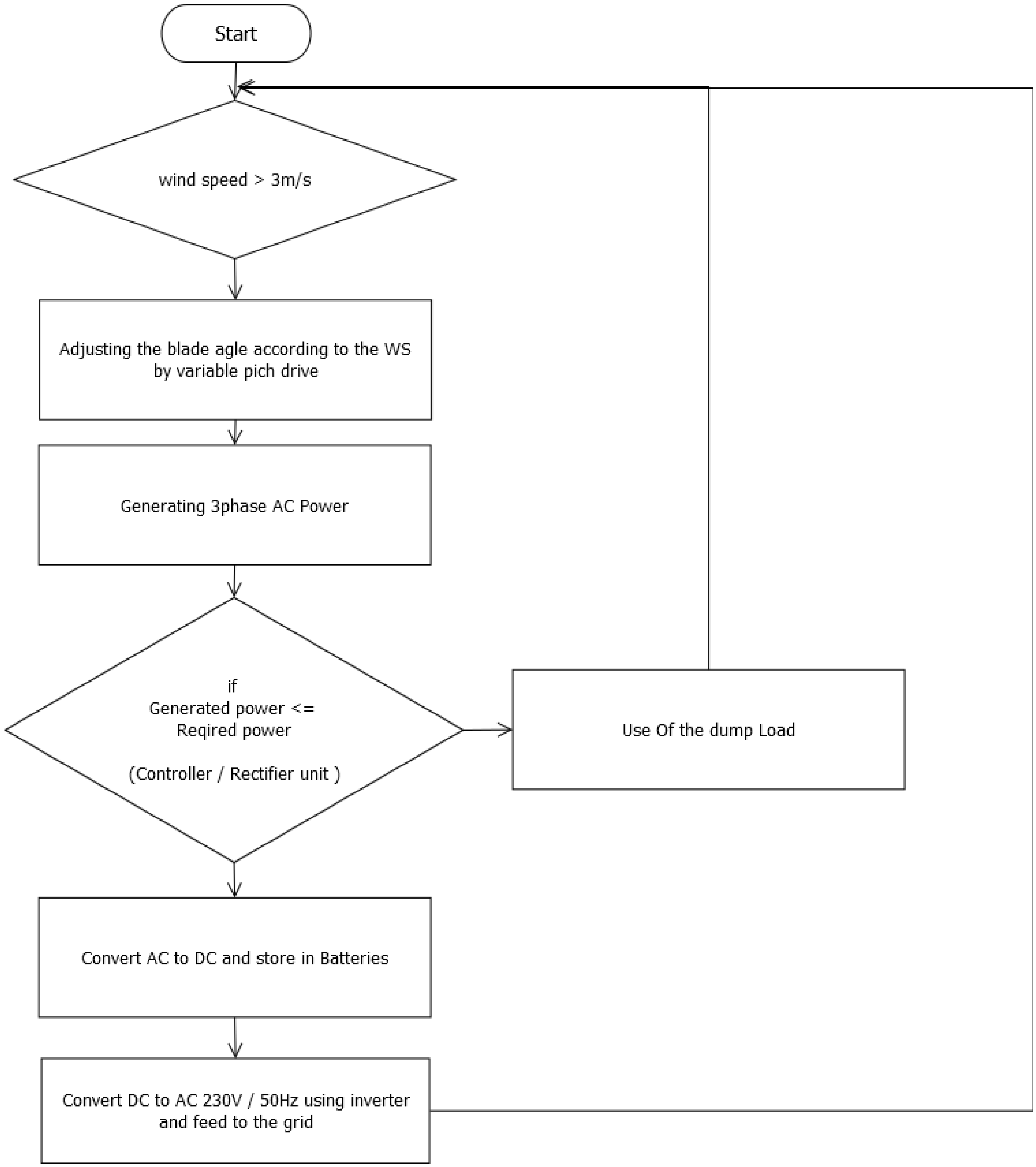


Figure 5.6: Flowchart of the operation of the wind turbine in the Hybrid system.

Figure 5.7: Base of a wind turbine and two wind turbines operating at the site.

5.3Solar Generation

The simulation gives 44.9kW as the solar panel capacity. The solar module which was selected was 260W each. Since the system is near to the coastal area there is a risk of getting metal parts to corrode. Because of that in the supporting structures, fewer metal frames should be used.

Dual glass solar module type is used due to less metallic structures and this type of solar modules are having following advantages compared to conventional solar modules.

- No need for grounding
- Electrical current leak (no metal-frame)
- More efficient.
- Stronger fire safety rating (no back sheet)

ELECTRICAL PARAMETERS

TYPE		HR-240W	HR-245W	HR-250W	HR-255W	**HR-260W**	HR-265W	HR-270W
STC AM 1.5, 1000W/m², Module Temperature 25°C	Rated Max. Power at STC (W)	240	245	250	255	260	265	270
	Max. Power Voltage / Vmp (V)	29.67	29.88	30.02	30.26	30.55	30.93	31.29
	Max. Power Current / Imp (A)	8.09	8.20	8.33	8.43	8.52	8.57	8.63
	Open Circuit Voltage / Voc (V)	37.65	37.80	37.94	38.13	38.20	38.41	38.72
	Short Circuit Current / Isc (A)	8.48	8.61	8.72	8.84	9.00	9.12	9.21
	Module Efficiency (%)	14.46	14.76	15.06	15.36	15.66	15.96	16.26
NOCT AM 1.5, 800W/m², Ambient Temperature 20°C, Wind Speed 1m/s	Rated Max. Power at NOCT (W)	179.20	182.90	186.60	190.70	194.00	197.30	200.40
	Max. Power Voltage / Vmp (V)	28.40	28.50	28.70	28.90	29.00	29.10	29.40
	Max. Power Current / Imp (A)	6.32	6.41	6.50	6.59	6.70	6.79	6.82
	Open Circuit Voltage / Voc (V)	35.10	35.20	35.40	35.60	35.70	35.90	36.20
	Short Circuit Current / Isc (A)	6.87	6.97	7.06	7.16	7.29	7.39	7.46
	Module Efficiency (%)	13.49	13.77	14.05	14.36	14.61	14.85	15.09
Temperature Coefficient of Pm		-0.42%/°C						
Temperature Coefficient of Voc		-0.34%/°C						
Temperature Coefficient of Isc		+0.071%/°C						
Nominal Operating Cell Temperature		42.6°C±3°C						
Output Tolerance		0~5W						

260W CURVES

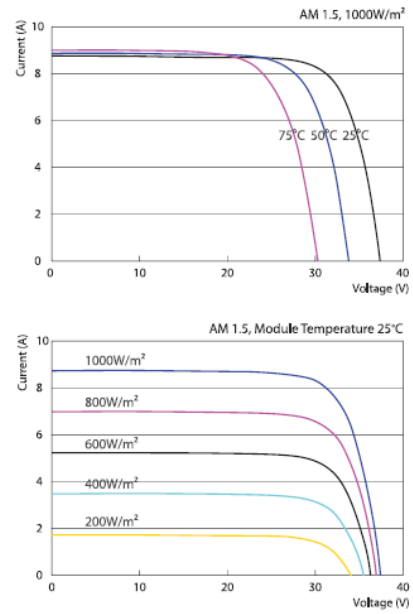


Figure 5.8: Specification for Hareon Solar 4BBHR-240P dual glass solar module

Source: Hareon Solar brochure

Duel glass 260W solar module was selected. So, the number of solar modules needed is equal to;

- 44900/260 ≈ 178

Figure 5.9: fixing solar modules on top of the powerhouse operating at the site.

Since the solar modules are mounted on the roof of the control building the roof angles were made between 12 degrees – 15 degrees to get the maximum solar radiation during the daytime. A maximum number of solar modules were placed facing south-east to harness higher amount of solar energy through the day. During the operation of this system, the battery bank is charged by solar for night time operation, in case if the battery drained out during the morning time the system needs more energy. Hence, the majority of solar modules were facing south-east as shown in figure 5.9.

Figure 5.10: solar module arrangement in powerhouse and storage shed at the site.

5.4 Solar Inverter

Instead of converting DC to AC, Solar inverters offer a number of extra facilities to guarantee that the inverter can function at the best performance level, such as data monitoring and advanced utility controls. In our study, we have selected SMA Sunny Boy solar inverters.

Technical data	Sunny Tripower 10000TL	Sunny Tripower 12000TL	Sunny Tripower 15000TL
Input (DC)			
Max. DC power (@ cos φ = 1)	10200 W	12250 W	15340 W
Max. DC voltage	1000 V	1000 V	1000 V
MPP voltage range	320 V – 800 V	380 V – 800 V	360 V – 800 V
DC nominal voltage	600 V	600 V	600 V
Min. DC voltage / start voltage	150 V / 188 V	150 V / 188 V	150 V / 188 V
Max. input current / per string	A: 22 A, B: 11 A / 33 A	A: 22 A, B: 11 A / 33 A	A: 33 A, B: 11 A / 33 A
Number of MPP trackers / strings per MPP tracker	2 / A: 4, B: 1	2 / A: 4, B: 1	2 / A: 5, B: 1
Output (AC)			
AC nominal power (@ 230 V, 50 Hz)	10000 W	12000 W	15000 W
Max. AC apparent power	10000 VA	12000 VA	15000 VA
Nominal AC voltage; range		3 / N / PE, 230 V / 400 V; 160 V – 280 V	
AC grid frequency; range	50, 60 Hz; –6 Hz, +5 Hz	50, 60 Hz; –6 Hz, +5 Hz	50, 60 Hz; –6 Hz, +5 Hz
Max. output current	16 A	19.2 A	24 A
Power factor (cos φ)		0.8 leading ... 0.8 lagging	
Phase conductors / connection phases / power balancing	3 / 3 /–	3 / 3 /–	3 / 3 /–
Efficiency			
Max. efficiency / Euro-eta	98.1 % / 97.7 %	98.1 % / 97.7 %	98.1 % / 97.7 %
Protection devices			
DC reverse-polarity protection / reverse current protection	●/electronic	●/electronic	●/electronic
ESS switch-disconnector	●	●	●
AC short circuit protection	●	●	●
Ground fault monitoring	●	●	●
Grid monitoring (SMA Grid Guard)	●	●	●
Galvanically isolated / all-pole sensitive fault current monitoring unit	–/●	–/●	–/●
DC overvoltage protector type II	○	○	○
String failure detection	●	●	●
Protection class / overvoltage category	I / III	I / III	I / III
General data			
Dimensions (W / H / D) in mm	665 / 690 / 265	665 / 690 / 265	665 / 690 / 265
Weight	65 kg	65 kg	65 kg
Operating temperature range	–25 °C ... +60 °C	–25 °C ... +60 °C	–25 °C ... +60 °C
Noise emission (typical)	www.SMA-Solar.com	www.SMA-Solar.com	www.SMA-Solar.com
Internal consumption: (night)	1 W	1 W	1 W
Topology	transformerless	transformerless	transformerless
Cooling concept	OptiCool	OptiCool	OptiCool
Electronics protection rating / connection area (as per IEC 60529)	IP65 / IP54	IP65 / IP54	IP65 / IP54
Climatic category (per IEC 60721-3-4)	4K4H	4K4H	4K4H

Figure 5.11: Technical specification of SMA Sunny Boy solar inverters

Source: SMA solar inverter Catalogue

For the hybrid system with 46kW solar generation, four solar inverters were selected as follows,

- SMA STP12000TL Sunny Boy solar inverters = 3
- SMA STP15000TL Sunny Boy solar inverters = 1

Then the Total combination is equal to 51kW (12kWx3 + 15kWx1) which will be greater than to 46kW. The maximum 260W solar modules which can connect to each solar inverter will be as follows;

- SMA STP12000TL = 12250 W / 260W ≈ 47
- SMA STP15000TL = 15340 W / 260W ≈ 59

In the design, each SMA STP12000TL inverter connected to 42 solar modules and SMA STP15000TL inverter connected to 52 solar modules. Hence, if needed in future, can add another 22 units of 260W solar modules to the existing system.

Figure 5.12: Solar inverters operating at the site

In this off-grid distribution system, design PV inverters are coupled on the AC side. Hence, the Master inverters must be capable to control their output power. This situation occurs when, for instance, the battery of the system is fully charged and the PV power available from the PV system surpasses the power demand of the associated loads. To avoid the extra energy damaging the batteries from overcharging, these solar inverters have a method called Frequency-Shift Power Control (FSPC).

When there is excess energy the Master inverter identifies this state and changes the frequency at the AC output. PV inverter is monitoring this frequency change. The instant the power frequency rises beyond the value specified in F_{AC} Start Delta, the solar inverters control their output energy accordingly.

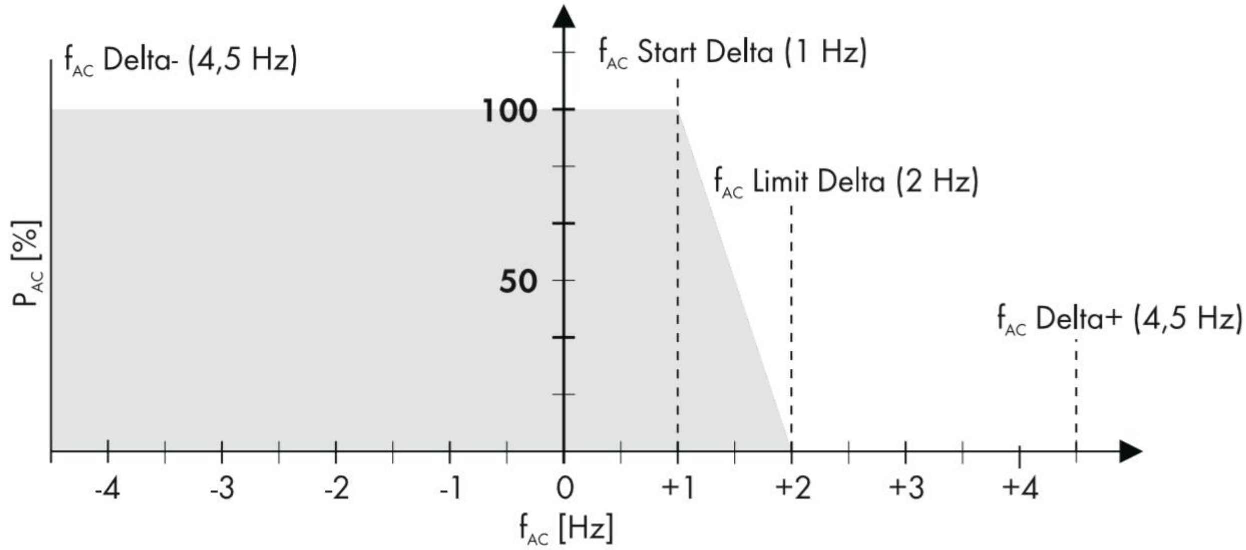


Figure 5.13: Operating principle of the FSPC

Source: SMA solar inverter Catalogue

The terms used have the following meanings:

- f_{AC} - base frequency of the stand-alone grid (here 50 Hz).
- f_{AC} Delta (–)and f_{AC} Delta(+) - the maximum range relative to f_{AC} in which the PV inverter is active.
- f_{AC} Start Delta is the frequency increase relative to f_{AC}, at which the frequency-based power control starts.
- f_{AC} Limit Delta is the frequency increase relative to f_{AC}, at which the frequency-based power control ends. The output power of the PV inverter at this point is 0W.

If the value is below the fAC Delta limit or above the fAC Delta + limit, the PV inverters are separated from the grid. If the diesel generator operates, the diesel generator sets the frequency and the photovoltaic inverters react to certain changes in the frequency of the diesel generator. Due to diesel generators, the output voltage frequency under load is 50 Hz. Therefore, in most cases, PV inverters will provide full power to the independent network even during the operation of the diesel generator.

If the existing battery voltage is larger than the rated battery voltage and is also to be synchronized with a diesel generator, the Sunny-Island inverter will momentarily escalate the frequency and the Solar inverters will cut off from the grid through frequency shutdown (over frequency). Later, the Sunny-Island inverter synchronizes with the diesel generator. [31]

5.5 Multicluster Box

Multicluster Box as an AC distribution centre for connecting generators and to supply loads up to 300 kW especially for these systems. The Multicluster Box is the main AC distribution board in the multicluster based off-grid distribution system and a component of the multicluster technology. The Multicluster Box connects the Sunny Island clusters with the loads and the power generators within a stand-alone grid. To simplify installation, all Multicluster Boxes are compound with the main connector for PV and wind generators.

Technical data	Multicluster-Box 6	Multicluster-Box 12	Multicluster-Box 36
General			
Number of phases	3-phase	3-phase	3-phase
Nominal AC voltage	230 V (L,N), 400 V (L1, L2)	230 V (L,N), 400 V (L1, L2)	230 V (L,N), 400 V (L1, L2)
AC voltage range	172.5 V – 265 V, 300 V – 433 V	172.5 V – 265 V, 300 V – 433 V	172.5 V – 250 V, 300 V – 433 V
Nominal AC frequency (range)	50 Hz (40 Hz – 70 Hz)	50 Hz (40 Hz – 70 Hz)	50 Hz (40 Hz – 70 Hz)
Permitted grid structure	TN	TN	TN
Dimensions (W / H / D) in mm	760 / 760 / 210	1000 / 1400 / 300	1200 / 2000 / 850
Mounting type	suspended	standing on a plinth	standing on a plinth
Weight	60 kg	140 kg	300 kg
Connections for Sunny Island			
Number of devices max.	6	12	36
Continuous AC power / AC current at 25 °C	30 kW / 3 x 44 A	60 kW / 3 x 87 A	180 kW / 3 x 260 A
Continuous AC power / AC current at 45 °C	24 kW / 3 x 35 A	48 kW / 3 x 70 A	144 kW / 3 x 209 A
AC power / AC current for 30 min.	40 kW	80 kW	234 kW / 3 x 340 A
AC power / AC current for 1 min.	50 kW	100 kW	300 kW / 3 x 440 A
Fuses	circuit breaker C32A	circuit breaker C32A	circuit breaker C32A
PV system connection			
Quantity	1 (three-phase)	1 (three-phase)	1 (three-phase)
Continuous AC power PV / continuous AC current PV at 25 °C	55 kW / 3 x 80A	110 kW / 3 x 160 A	300 kW / 3 x 435 A (AC1)
Fuses	–	–	–
Load connection			
Quantity	1 (three-phase)	1 (three-phase)	1 (three-phase)
Nominal power / current at 25 °C	55 kW / 3 x 80A	110 kW / 3 x 160 A	300 kW / 3 x 435 A (AC1)
Fuses	NH00	NH00	NH03
Generator connection			
Quantity	1 (three-phase)	1 (three-phase)	1 (three-phase)
Nominal generator power / current at 25 °C	55 kW / 3 x 80A	110 kW / 3 x 160 A	300 kW / 3 x 435 A (AC1)
Fuses	NH00	NH00	NH03
Features / function			
Warranty (5 / 10 / 15 / 20 / 25 years)	●/○/○/○/○	●/○/○/○/○	●/○/○/○/○
Certificates and permits	CE	CE	CE
Ambient Conditions			
Ambient temperature	–25 °C ... +50 °C	–25 °C ... +50 °C	–25 °C ... +60 °C
Protection class (according IEC 60529)	IP65	IP65	IP55
Air humidity	0 % ... 100 %	0 % ... 100 %	0 % ... 100 %

Figure 5.14: Technical specification of multicluster Box

Source: SMA multi-cluster box 6,12,36 Catalogue

Since there is extra capacity for future expansions, Multicluster Box 36 was selected from the available options.

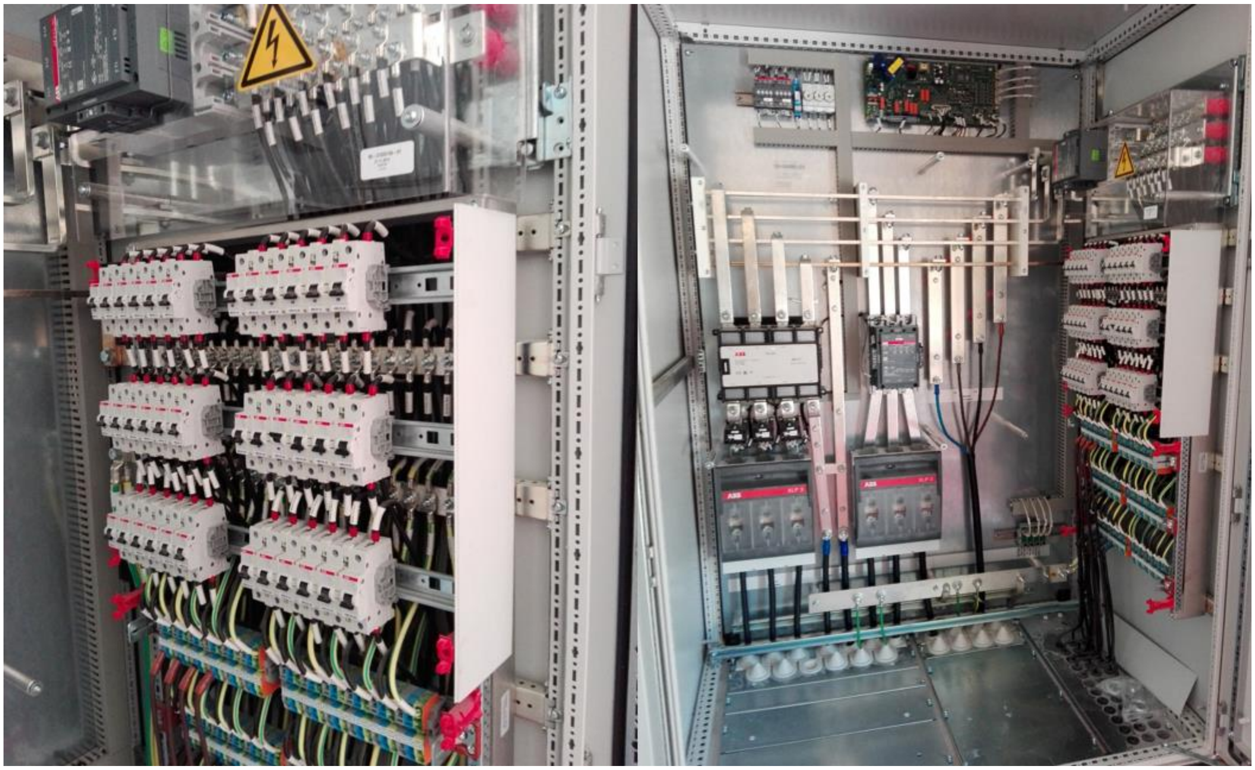


Figure 5.15: Inside the Multicluster Box36 operating at the site

5.6 Sunny Island Inverter

Figure 5.16: Sunny Island inverters operating at the site

Sunny island inverter is the main component of the multi-cluster based hybrid distribution system. It will act as the main controlling unit which automates the off-grid distribution system. Due to high AC power and high battery charging current Sunny island 8.0H was selected.

Technical data	Sunny Island 6.0H	Sunny Island 8.0H
AC output (loads / stand-alone grid)		
Rated grid voltage / AC voltage range	230 V / 202 V ... 253 V	230 V / 202 V ... 253 V
Rated frequency / frequency range (adjustable)	50 Hz / 45 Hz ... 65 Hz	50 Hz / 45 Hz ... 65 Hz
Rated power (for Unom / fnom / 25 °C / cos φ = 1)	4600 W	6 000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	6 000 W / 6 800 W / 11 000 W	8 000 W / 9 100 W / 11 000 W
Rated current / maximum output current (peak)	20 A / 120 A	26 A / 120 A
Total harmonic factor output voltage / power factor with rated power	< 4 % / -1 ... +1	< 4 % / -1 ... +1
AC input (PV array, grid or MC box)		
Rated input voltage / AC input voltage range	230 V / 172.5 V ... 264.5 V	230 V / 172.5 V ... 264.5 V
Rated input frequency / allowable input frequency range	50 Hz / 40 Hz ... 70 Hz	50 Hz / 40 Hz ... 70 Hz
Maximum AC input current	50 A	50 A
Maximum AC input power	11 500 W	11 500 W
Battery DC input		
Rated input voltage / DC voltage range	48 V / 41 V ... 63 V	48 V / 41 V ... 63 V
Maximum battery charging current	110 A	140 A
Rated DC charging current / DC discharging current	90 A / 103 A	115 A / 136 A
Battery type / battery capacity (range)	FLA, VRLA / 100 Ah ... 10 000 Ah	FLA, VRLA / 100 Ah ... 10 000 Ah
Charge control	IUoU charge procedure with automatic full charge and equalization charge.	IUoU charge procedure with automatic full charge and equalization charge
Efficiency / self-consumption		
Maximum efficiency	95 %	95 %
Self-consumption without load / standby	< 26 W / < 4 W	< 26 W / < 4 W
Protective devices (equipment)		
AC short-circuit / AC overload	● / ●	● / ●
DC reverse polarity protection / DC fuse	- / -	- / -
Overtemperature / battery deep discharge	● / ●	● / ●
Overvoltage category as per IEC 60664-1	III	III
General data		
Dimensions (width x height x depth)	467 mm x 612 mm x 242 mm	467 mm x 612 mm x 242 mm
Priority	63 kg	63 kg
Operating temperature range	-25 °C ... +60 °C	-25 °C ... +60 °C
Protection class (according to IEC 62103)	I	I
Climatic category according to IEC 60721	3K6	3K6
Degree of protection according to IEC 60529	IP54	IP54
Features / function		
Operation and display / multifunction relay	External via SRC-20 / 2	External via SRC-20 / 2
Three-phase systems / parallel connection	● / ●	● / ●
Integrated bypass / multicluster operation	- / ●	- / ●
State of charge calculation / full charge / equalization charge	● / ● / ●	● / ● / ●
Integrated soft start / generator support	● / ●	● / ●
Battery temperature sensor / data cables	● / ●	● / ●
Certificates and approvals	www.SMA-Solar.com	www.SMA-Solar.com
Warranty: 5 years	●	●
Accessory		
Battery cable / battery fuse	○ / ○	○ / ○
Interface SI-COMSMA (RS485) / SI-SYSCAN (Multicluster)	○ / ○	○ / ○
Extended generator start "GenMan"	○	○
Load-shedding contactor / battery current measurement	○ / ○	○ / ○
Type designation	SI6.0H-11	SI8.0H-11

Figure 5.17: Technical specification of sunny island inverters

Source: SMA sunny island inverter Catalogue

According to the following figure to match the power requirement 12 number of sunny Island inverters were used and each cluster is connected with 5 lithium-ion batteries in this multi-cluster system to match the requirement.

Power*	Number of Sunny Island inverters			Number of batteries**
	SI 8.0H	SI 6.0H	SI 5048	
102 kW	6	9	-	
108 kW	9	6	-	5
114 kW	12	-	-	
120 kW	15	-	-	
126 kW	9	9	-	
132 kW	12	6	-	6
138 kW	15	3	-	
144 kW	18	-	-	
150 kW	12	9	-	
156 kW	15	6	-	7
162 kW	18	3	-	
...	...	...	...	...
222 kW	21	9	-	
228 kW	24	6	-	10
234 kW	27	3	-	
240 kW	30	-	-	
246 kW	24	9	-	
252 kW	27	6	-	11
258 kW	30	3	-	
264 kW	33	-	-	
270 kW	27	9	-	
276 kW	30	6	-	12
282 kW	33	3	-	
288 kW	36	-	-	
98 kW***	-	-	15	5
114 kW***	-	6	12	6
144 kW***	3	6	12	7

* Power of the Sunny Island inverters for 30 minutes at 25°C
** 1 battery per cluster
*** Power of the SI5048 for 30 minutes at 25°C: 6,500 W

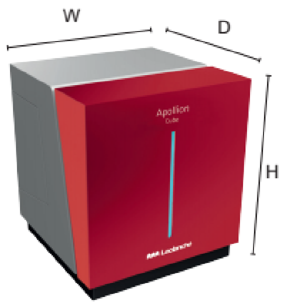
Figure 5.18: Technical Specification for Multicluster System

Source: SMA Multicluster System Design Guide

Figure 5.19: Operation of Multicluster System configured as master and three slaves

4.7Battery Storage

Battery storage is the main power source during the night time. During the daytime, batteries are charged from solar energy. Apollion cube Li-Ion battery was selected. 20 number of batteries required for the multi cluster-based hybrid distribution system. So, the battery storage capacity is 126 kWh. This result also matches with the simulation results.



Apollion Cube specifications

Cell technoloy	Li-Ion (NMC)
Nominal energy	6.3 kWh
Nominal voltage	54.7 V
Charge end voltage	61.5 V
Discharge end voltage	41.0 V
Max. discharge current	80 A
Max. discharge power	300 A (3 sec.)
Max. discharge performance	6,500 W
Efficiency	97%
Depth of discharge	80%
Expected cycles	5,000
Dimension Width Depth Height	 620 mm 620 mm 677 mm
Weight	120 kg
Charge temperature (max.)	+0°C - +45°C
Discharge temperature (max.)	+0°C - +45°C
Optimal storage temperature	+10°C - +25°C
Scalability	Max. 12 Systems parallel (with optional master unit)
Communication	CAN/SMA ready
Protection class	IP21
Warranty	7 years fair value warranty

Standards: VDE-ST-Li-ESS-001:2013/03, IEC62897Ed1, DIN EN 50272-1, DIN EN 50272-2, DIN EN 61427-1, DIN EN 61427-2, DIN EN 61508, DIN EN 62281, DIN EN 60950-1, DIN EN 62619 (Norm Entwurf). DIN EN 62620. UN 38.3

Figure 5.20: technical specification for storage DC battery

Source: Apollion cube Li-Ion battery technical Brochure

During the operation of these Li-ion batteries, the temperature control is very important. In the site location, the temperature rises more than 25 ^{0}C so the battery room had to design especially with air conditioner units to maintain the given temperature.

Figure 5.21: Battery backup system connected to the multi-cluster system.

5.8Remote monitoring software

The “AllSolus” Energy Monitoring System, the range of devices has been specifically designed to provide wireless monitoring and energy management solution. The system can be utilised to monitor and manage power consumption or producing devices, environmental conditions both internally and externally as well as provide a multitude of visualisation methods and access to reporting and the provision for alarms for improved site control. In this system, Allsolus is mainly used for wind energy generation monitoring.

Also “Epro” monitoring system is also used to monitor the microgrid. From that, we can online monitor the parameters like total power output, the voltage of each phase, a current of each phase, power factor and frequency.

5.9Diesel Generator

In a hybrid renewable energy generation system, the fossil fuel generator is doing the significant job to improve the convenience and quality of uninterruptible power supply. Subsequently, the diesel generator can be used to feed the load when the power generation of renewable resources is low or when the status of the battery charge is not enough to feed the load.

When establishing a conventional fuel generator, the initial cost is relatively small compared to the initial investment of the photovoltaic or wind power systems. Yet, there is a relatively high cost related to O&M, constant fuel supply for operation and regular maintenance during its mechanical lifetime. Since the fuel needs to be transported from the city to the main island to the isolated remote island, the transportation cost must also be considered.

So according to above facts, the diesel generator should be a backup source which is capable to handle even the peak demand and the system should design in a way that will minimize the usage of the diesel generator. In this study, according to the load curve, the 30kW generator was selected. Also, to minimize the sound pollution, the generator was placed inside a soundproof container.

5.10Distribution Grid

The electrical distribution network is what transmits electrical energy from the power plant to the end user. In general, Sri Lanka uses all aluminium conductors, which laid underground or supported by wooden, steel and concrete poles for the transmission of electricity to customers. Electricity can be conveyed via three-phase or single-phase lines. Not like the three-phase system, Single-phase transmission needs conductors with the high current rating and generates additional heat loss. The three-phase arrangement allows for larger loads to be connected, but not like in single-phase system, in three-phase the system designing is very complex and hard since load balancing is necessary to achieve better power system performance and efficiency.

In the selected site, there was an existing distribution grid which used earlier to distribute power generated by conventional generators. After the construction of the hybrid distribution system old diesel generator plant was demolished. So, the existing network was used for the power transmission of the hybrid system.

5.11The final design

The following block diagram will represent how all these modules have been connected together to perform the hybrid distribution system. There are six wind turbines and they are connected in pairs which feed each phase of the three-phase system if there is additional power generation the multi-cluster system will use that to increase the SOC of batteries. Also, there are one hundred and seventy-eight solar modules connected to Multicluster Box through solar inverters. The main purpose of solar energy is to supply the demand as well as charging the batteries and get ready the system for the night shift. There are for clusters in this multicluster system. And beck up 30kW diesel generator. All these modules are connected via the Multicluster Box.

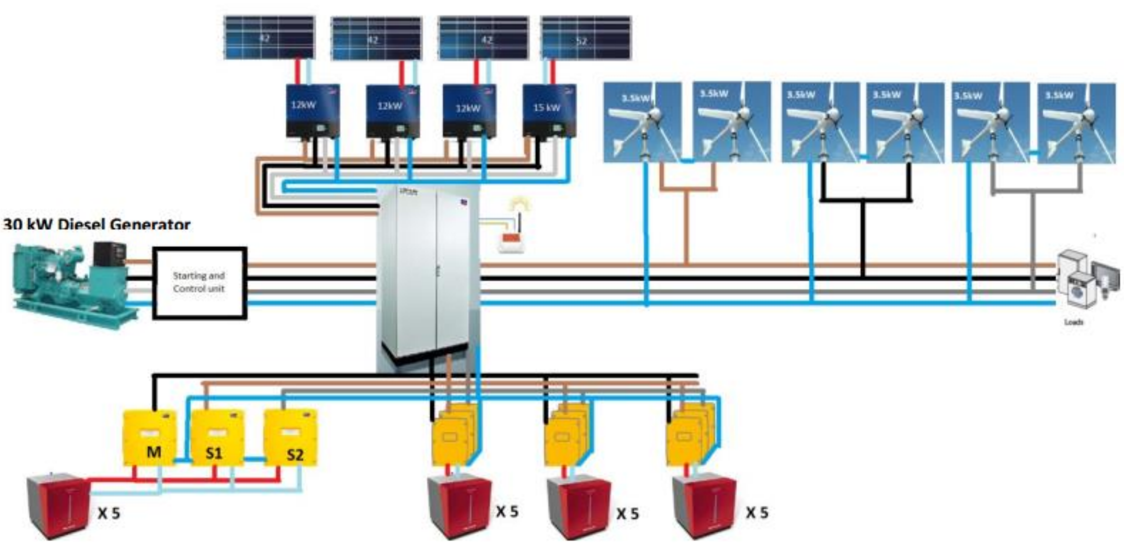


Figure 5.22: block diagram showing how components are arranged in Hybrid System

Chapter 6

Results

This chapter discusses the best location of the site where we can practically implement the Hybrid power plant. Also, once constructed there will be data collection and analyzing process to assess the level of the output of the system which is generated. The daily load variation and how system response to the load in different time of the day was also analyzed.

6.1 location of constructing the powerhouse

From the solar tilt angle analyzation result from chapter 2, the best practical direction of the powerhouse double-sided roof which solar panels are mounted was facing south-east and North West. The angel of the roof was designed approximately to 16 degrees as for the average tilt angle for both south and north sides.

Since the roof space was not sufficient to accommodate all solar modules another shed with the single-sided roof was constructed facing south-east to harness maximum solar energy throughout the year. The angel of the roof was designed approximately to 20 degrees as for the average tilt angle only for the south.

Figure 6.1: the powerhouse of the Hybrid distribution system at the site

As for the location the southern tip of the island (indicated by red rectangle of the figure) was selected for allocation of wind turbines and the powerhouse due to good wind flow because there were fewer obstacles like houses, buildings and Palmira trees in that region compared to other parts of the island and that side opens for both south-east and north-west directions, therefore, this location is getting good solar radiation throughout the day. Not only that, the main jetty (indicated by yellow circled of the figure) used to transport is very near to this location. Hence, this location was very convenient for transporting heavy equipment easily due to less transportation distance.

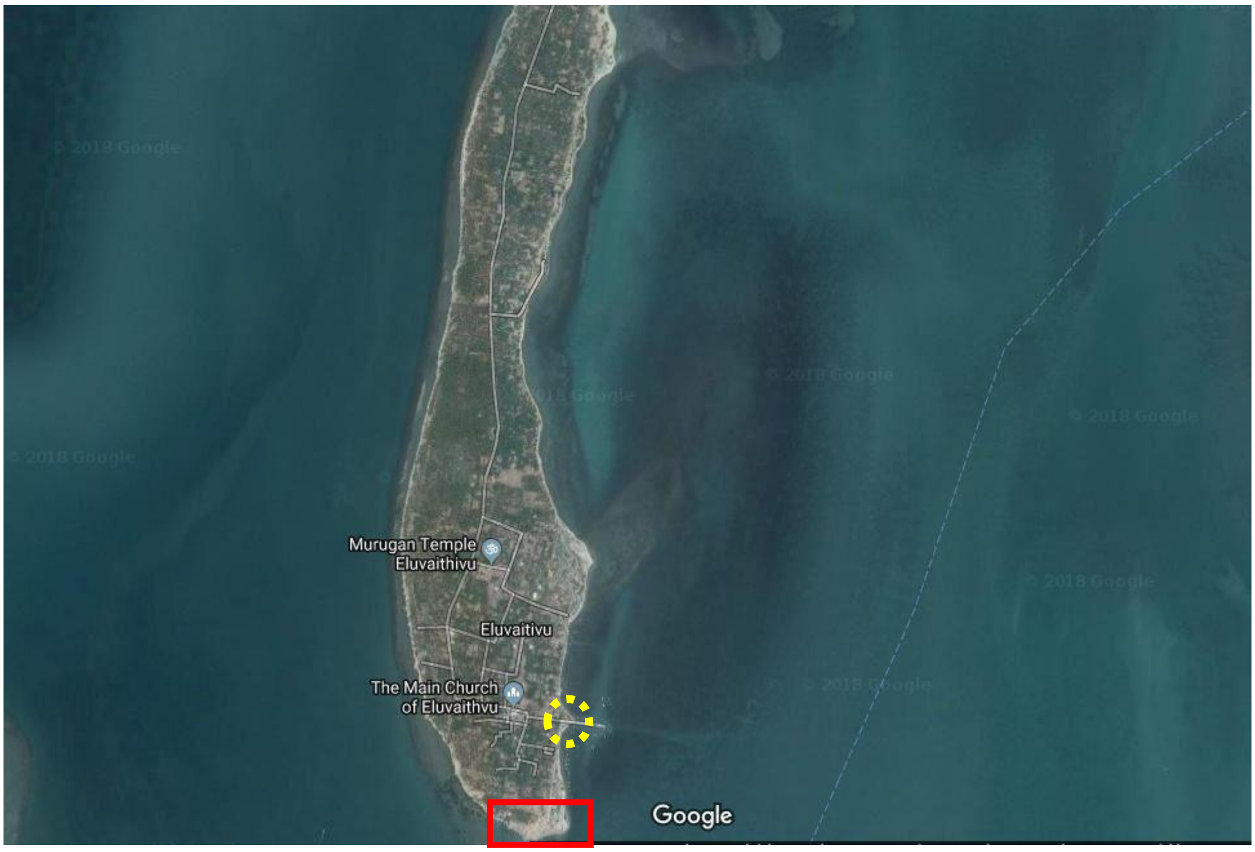


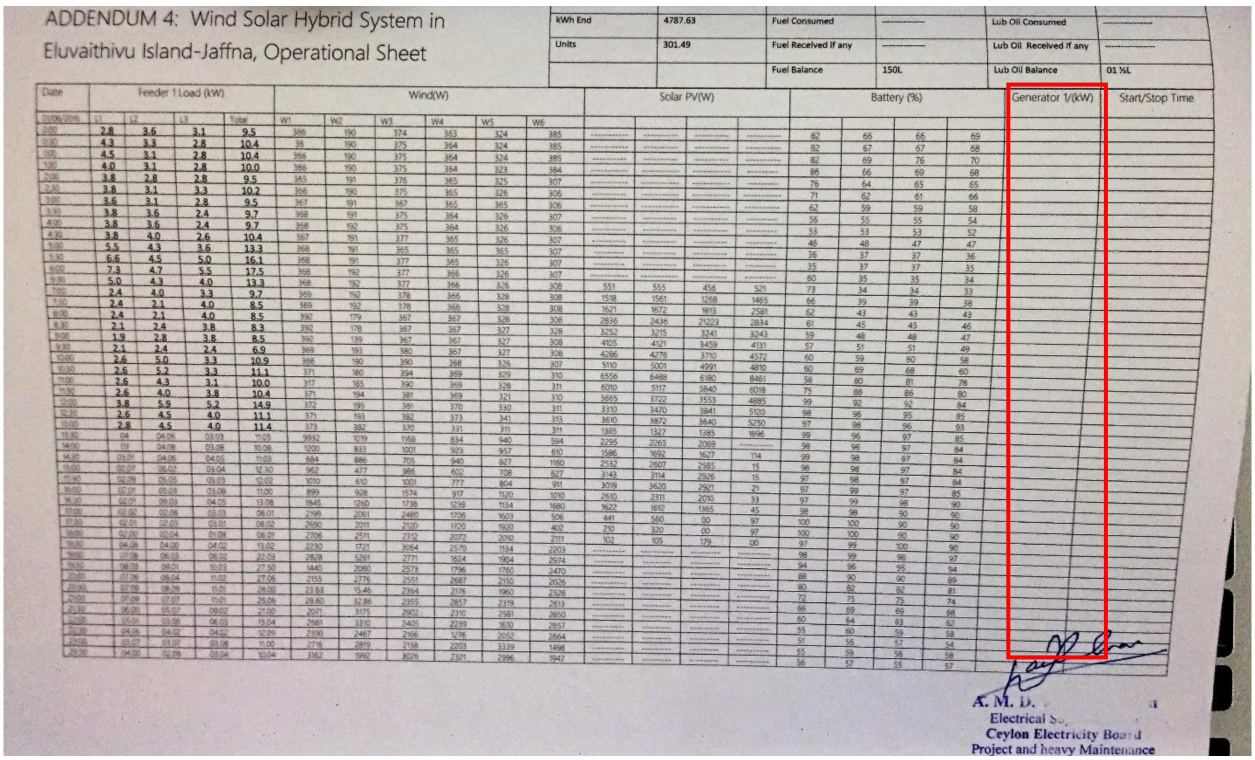
Figure 6.2: Geographical location of the proposed powerhouse

Source: Google maps

6.2 Performance of the Hybrid System

6.2.1 Operational overall Test Results

From the figure 5.3 shows the operational sheet data. This test was done on 20/06/2016 and all the data was taken by intervals of 0.5 hours. During the test, the Generator did not contribute power because the renewable energy resources were sufficient enough to fulfil the energy need of the village. According to the figure the solar power governs the majority power supply during daytime (06.30h – 17.30h) supplying the energy requirement in the village while charging the battery system. The wind resource was available throughout the day. During the night time peak hours, the battery bank was sufficient to supply the demand with the wind power generation, because of this the generator didn't need to take over.



ADDENDUM 4: Wind Solar Hybrid System in Eluvaithivu Island-Jaffna, Operational Sheet

kWh End	4787.63	Fuel Consumed	----------	Lub Oil Consumed	----------
Units	301.49	Fuel Received if any	----------	Lub Oil Received if any	----------
		Fuel Balance	150L	Lub Oil Balance	01 ½L

Date	Feeder 1 Load (kW)				Wind(W)						Solar PV(W)				Battery (%)				Generator 1/(kW)	Start/Stop Time
20/06/2016	L1	L2	L3	Total	W1	W2	W3	W4	W5	W6										
0:00	2.8	3.6	3.1	9.5	366	190	374	363	324	385	----------	----------	----------	----------	82	66	66	69		
0:30	4.3	3.3	2.8	10.4	36	190	375	364	324	385	----------	----------	----------	----------	82	67	67	68		
1:00	4.5	3.1	2.8	10.4	366	190	375	364	324	385	----------	----------	----------	----------	82	69	76	70		
1:30	4.0	3.1	2.8	10.0	366	190	375	364	323	384	----------	----------	----------	----------	86	66	69	68		
2:00	3.8	2.8	2.8	9.5	365	191	376	365	325	307	----------	----------	----------	----------	76	64	65	65		
2:30	3.8	3.1	3.3	10.2	366	190	375	365	326	306	----------	----------	----------	----------	71	62	61	66		
3:00	3.6	3.1	2.8	9.5	367	191	367	365	365	306	----------	----------	----------	----------	62	59	59	58		
3:30	3.8	3.6	2.4	9.7	368	191	375	364	326	307	----------	----------	----------	----------	56	55	55	54		
4:00	3.8	3.6	2.4	9.7	368	192	375	364	326	306	----------	----------	----------	----------	53	53	53	52		
4:30	3.8	4.0	2.6	10.4	367	191	377	365	326	307	----------	----------	----------	----------	46	48	47	47		
5:00	5.5	4.3	3.6	13.3	368	191	365	365	365	307	----------	----------	----------	----------	36	37	37	36		
5:30	6.6	4.5	5.0	16.1	368	191	377	365	326	307	----------	----------	----------	----------	35	37	37	35		
6:00	7.3	4.7	5.5	17.5	368	192	377	366	326	307	----------	----------	----------	----------	60	35	35	34		
6:30	5.0	4.3	4.0	13.3	368	192	377	366	326	308	551	555	456	521	73	34	34	33		
7:00	2.4	4.0	3.3	9.7	369	192	378	366	328	308	1518	1561	1268	1465	66	39	39	38		
7:30	2.4	2.1	4.0	8.5	369	192	378	366	328	308	1621	1672	1813	2581	62	43	43	43		
8:00	2.4	2.1	4.0	8.5	392	179	367	367	328	308	2836	2436	21223	2834	61	45	45	46		
8:30	2.1	2.4	3.8	8.3	392	178	367	367	327	328	3252	3215	3241	3243	59	48	48	47		
9:00	1.9	2.8	3.8	8.5	392	139	367	367	327	308	4105	4121	3459	4131	57	51	51	49		
9:30	2.1	2.4	2.4	6.9	369	193	380	367	327	308	4286	4276	3710	4572	60	59	60	58		
10:00	2.6	5.0	3.3	10.9	368	190	390	368	326	307	5110	5001	4991	4810	60	69	68	60		
10:30	2.6	5.2	3.3	11.1	371	180	394	369	329	310	6556	6488	6180	8461	58	80	81	78		
11:00	2.6	4.3	3.1	10.0	317	185	390	369	328	311	6010	5117	5840	6018	75	88	86	80		
11:30	2.6	4.0	3.8	10.4	371	194	381	369	321	310	3665	3722	3553	4885	99	92	92	84		
12:00	3.8	5.9	5.2	14.9	372	195	381	370	330	311	3310	3470	3841	5120	98	96	95	85		
12:30	2.6	4.5	4.0	11.1	371	193	382	373	341	313	3610	3872	3640	5250	97	98	96	93		
13:00	2.8	4.5	4.0	11.4	373	382	370	331	311	311	1385	1327	1385	1896	99	96	97	85		
13:30	04	04.06	03.03	11.05	9932	1019	1168	834	940	594	2295	2265	2069	----------	98	96	97	84		
14:00	03	04.08	03.08	10.08	1200	833	1001	923	957	610	1586	1692	1627	114	99	98	97	84		
14:30	03.01	04.06	04.05	11.03	684	886	705	940	827	1160	2532	2607	2585	15	98	98	97	84		
15:00	02.07	06.02	03.04	12.30	962	477	986	602	708	827	3143	3114	2926	15	97	98	97	84		
15:30	02.09	05.05	03.03	12.02	1010	610	1001	777	804	911	3019	3620	2921	21	97	99	97	85		
16:00	02.01	05.03	03.08	11.00	899	928	1574	917	1120	1010	2610	2311	2010	33	97	99	98	90		
16:30	02.01	09.03	04.05	13.08	1845	1260	1738	1238	1134	1680	1622	1612	1365	45	98	98	90	90		
17:00	02.02	02.06	03.03	08.01	2199	2061	2480	1706	1603	506	441	560	00	97	100	100	90	90		
17:30	02.01	02.03	03.01	08.02	2690	2011	2120	1720	1920	402	210	320	00	97	100	100	90	90		
18:00	02.00	02.04	01.08	06.01	2706	2511	2312	2072	2010	2111	102	105	179	00	97	99	100	90		
18:30	04.08	04.00	04.02	13.02	2230	1721	3064	2570	1134	2203	----------	----------	----------	----------	98	99	98	97		
19:00	07.08	06.03	08.02	22.03	2828	5261	2771	1624	1904	2974	----------	----------	----------	----------	94	96	95	94		
19:30	08.03	09.01	10.03	27.50	1440	2060	2573	1796	1760	2470	----------	----------	----------	----------	88	90	90	89		
20:00	07.09	08.04	11.02	27.06	2155	2776	2551	2687	2150	2026	----------	----------	----------	----------	80	82	82	81		
20:30	07.09	08.09	11.01	28.00	23.63	15.46	2364	2176	1960	2326	----------	----------	----------	----------	72	75	75	74		
21:00	07.09	07.07	11.01	26.06	28.60	32.86	2355	2857	2319	2613	----------	----------	----------	----------	66	69	69	68		
21:30	06.00	05.07	09.02	21.00	2071	3175	2902	2310	2581	2850	----------	----------	----------	----------	60	64	63	62		
22:00	05.01	03.08	06.05	15.04	2681	3310	2405	2239	1610	2857	----------	----------	----------	----------	55	60	59	58		
22:30	04.06	04.02	04.02	12.09	2390	2467	2166	1276	2052	2664	----------	----------	----------	----------	51	56	57	54		
23:00	03.07	03.07	03.08	11.00	2716	2819	2158	2203	3339	1498	----------	----------	----------	----------	55	59	58	58		
23:30	04.00	02.09	03.04	10.04	3162	1992	3026	2321	2996	1947	----------	----------	----------	----------	56	57	55	57		

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Ceylon Electricity Board
Project and heavy Maintenance

Figure 6.3: functional test results of the Hybrid distribution system at the site

6.2.2 Generation of the Energy requirement

Using the data gathered from the online monitoring system Epro we can analyze different features of the hybrid distribution system. The following figure is showing the energy consumption of the village throughout the year 2016-09-01 to 2017–09-01. By analyzing this we can see in moth April there is the lowest energy consumption. The reason for this is the Hindu New year season most of the villages will move to the main island for celebrations. In other months the average energy demand is approximately in between 7500 – 10000 kWh.

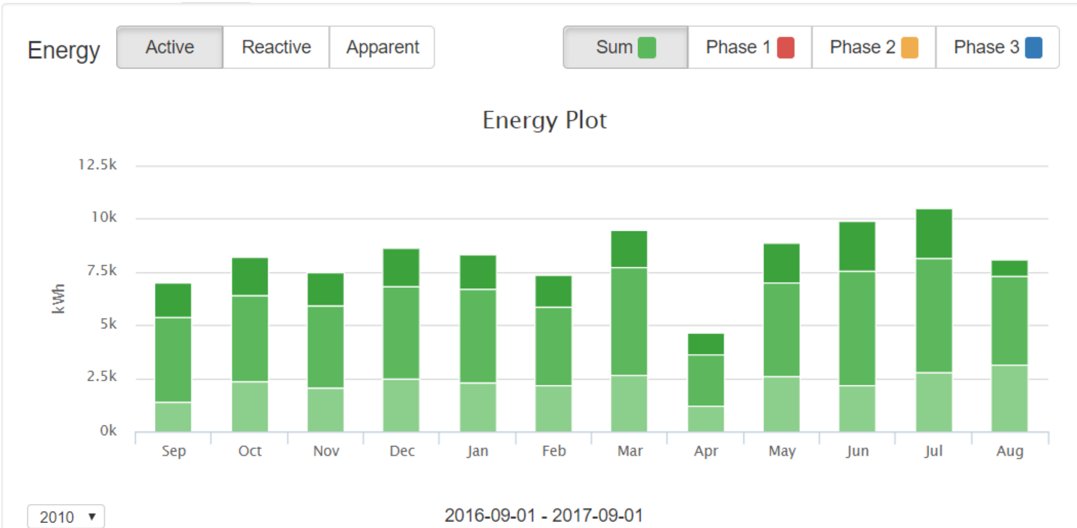

Figure 6.4: power generation summary for year 09/2016 to 09/2017

The following figure 6.5 gives more details of energy supplied by each phase of the three-phase hybrid distribution system. According to the obtained results, phase 2 is consuming more energy compared to the other two phases. At the beginning of the year there is no significant difference between each phase but with electrification rate increase we can assume that new supplies were given by this phase 2. During March 2017 – June 2017 this difference is significant but later on, this difference becomes less, analyzing this data we can assume that during that period the other phases were also used for electrification.

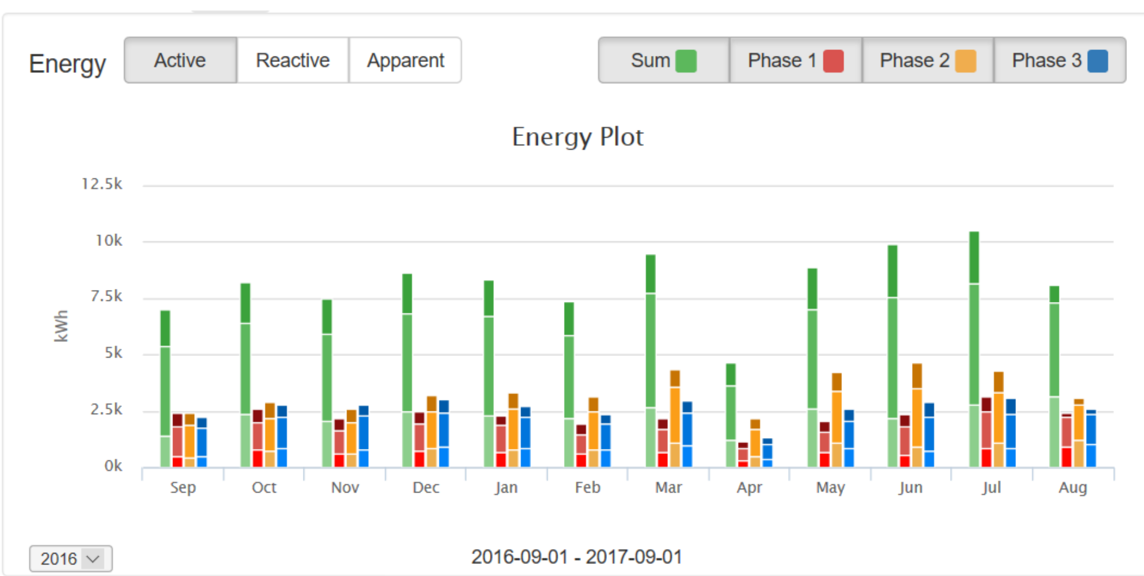

Figure 6.5: Energy generation summary for year 09/2016 to 09/2017

6.2.3 Single phase voltage variation of the system

In Sri Lanka the supply voltage is 230V. Almost all the domestic electrical equipment is rated to this voltage. Over voltage and under voltage will affect these devices and sometimes even damage them so maintaining the output supply voltage of the microgrid is very important. Maintaining the desired voltage is one component of measuring the stability of the system. When we look at the average voltage of three phase it is varying in between 229V – 233V. So the variation is -0.43 % / +1.3%, according to British standard tolerance range of 230 V +6%/−10% [113] is acceptable for public electrical supply system.

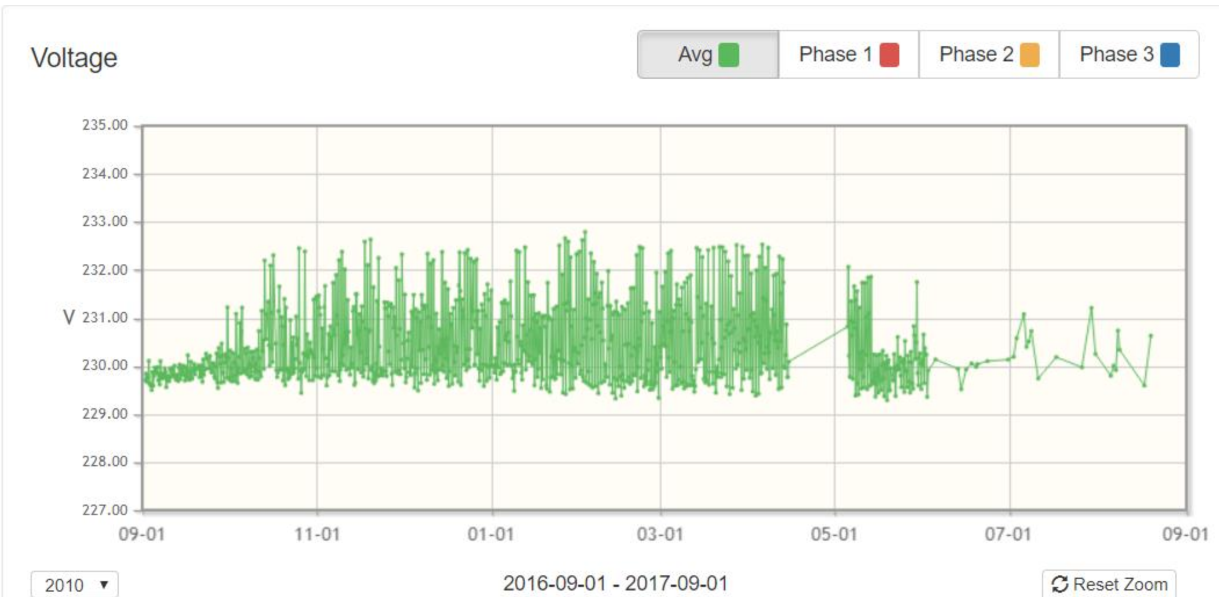

Figure 6.6: Average of the three-phase Voltage generation for year 09/2016 to 09/2017

According to the figure 5.7, figure 5.8 and figure 6.9, the voltage variation of each individual phase of the three-phase system has shown throughout the year from 2016 – 09 -01 to 2017 – 09 -01. In phase one shown in figure 6.7, the range is approximately between 228 V and 232 V. the lower range variation is -0.86% and the upper range variation is +0.86 %. therefor the stability of the voltage is in an acceptable range according to BS standards.

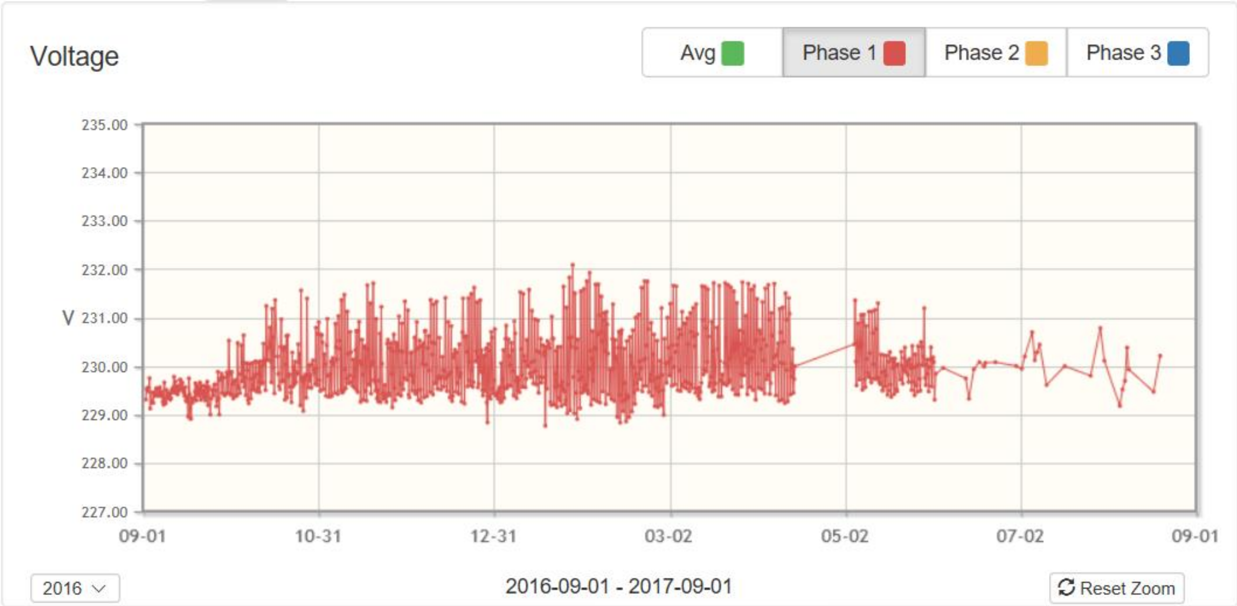

Figure 6.7: Phase 1 Voltage generation summary for year 09/2016 to 09/2017

As shown in figure 6.8, phase two has the range approximately in between 228 V and 233 V. the lower range variation is -0.86% and the upper range variation is +1.3 %. Therefore, the stability of the voltage is in an acceptable range according to BS standards.

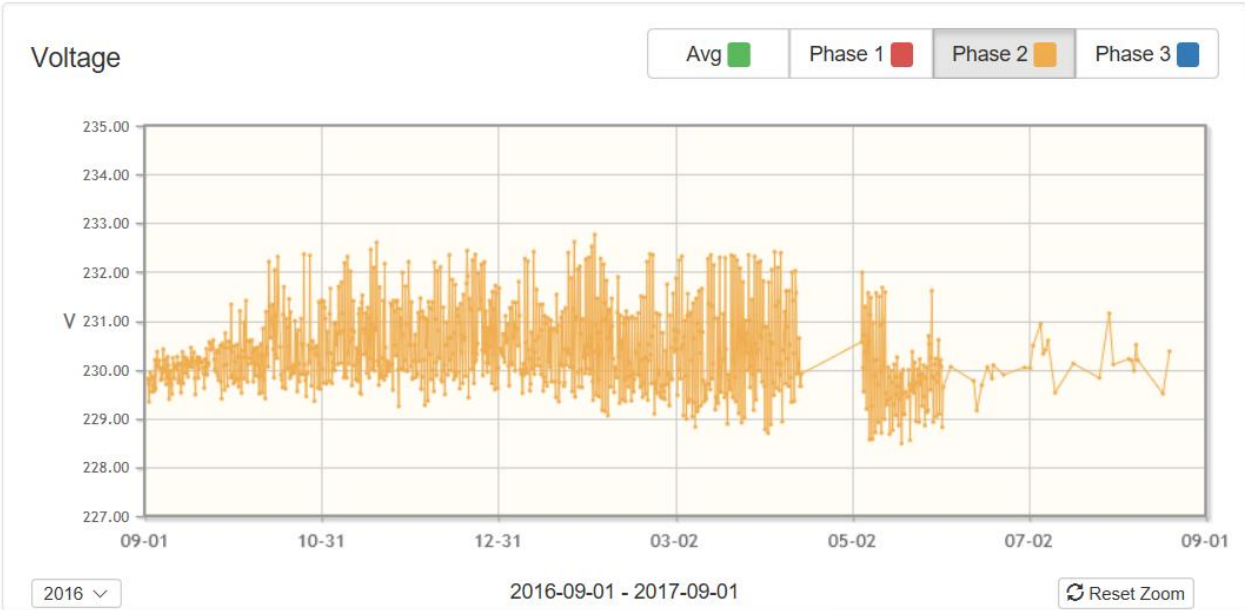

Figure 6.8: Phase 2 Voltage generation summary for year 09/2016 to 09/2017

As shown in figure 6.8, phase three has the range approximately in between 229 V and 234 V. the lower range variation is -0.43% and the upper range variation is +1.73 %. therefor the stability of the voltage is in an acceptable range according to BS standards. Compared to other two phases phase three has slightly higher value for upper range variation and slightly lower value for lower range variation.

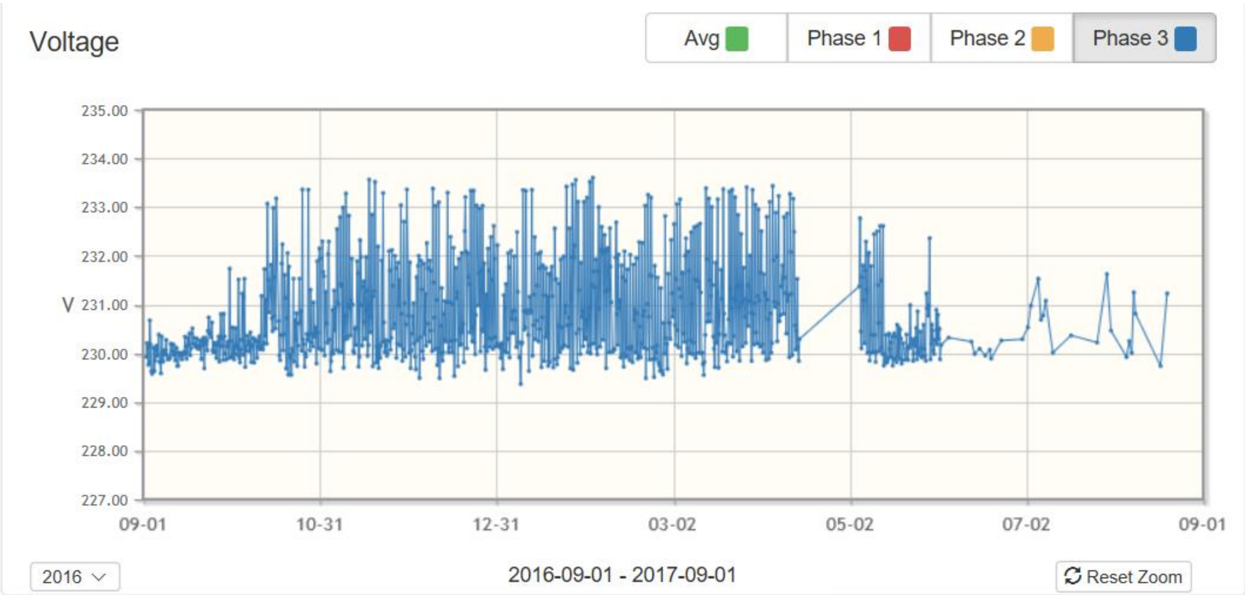

Figure 6.9: Phase 3 - Voltage generation summary for year 09/2016 to 09/2017

6.2.4 Utility Frequency variation range of the system

In Sri Lanka, 50Hz utility frequency is maintained in the national grid. Maintaining Utility frequency is a necessary parameter for load control in interconnected systems with multiple generators. But this hybrid distribution system is not connected with national grid therefore small deviation are acceptable because typical loads are insensitive to small frequency variations. in large power systems +0.5Hz or -0.5Hz will result in automatic load shedding or other system control actions to restore utility frequency but in small standalone systems like this will not tightly regulate utility frequency during heavy load periods and allow utility frequency to rise during periods of light loads, therefore to maintain a daily average frequency of acceptable accuracy.

The following figure shows the frequency variation of the system from 2017-07-19 to 2017 -08-04 and according to the figure 6.10, the frequency of the system has maintained approximately 50Hz with small variation.

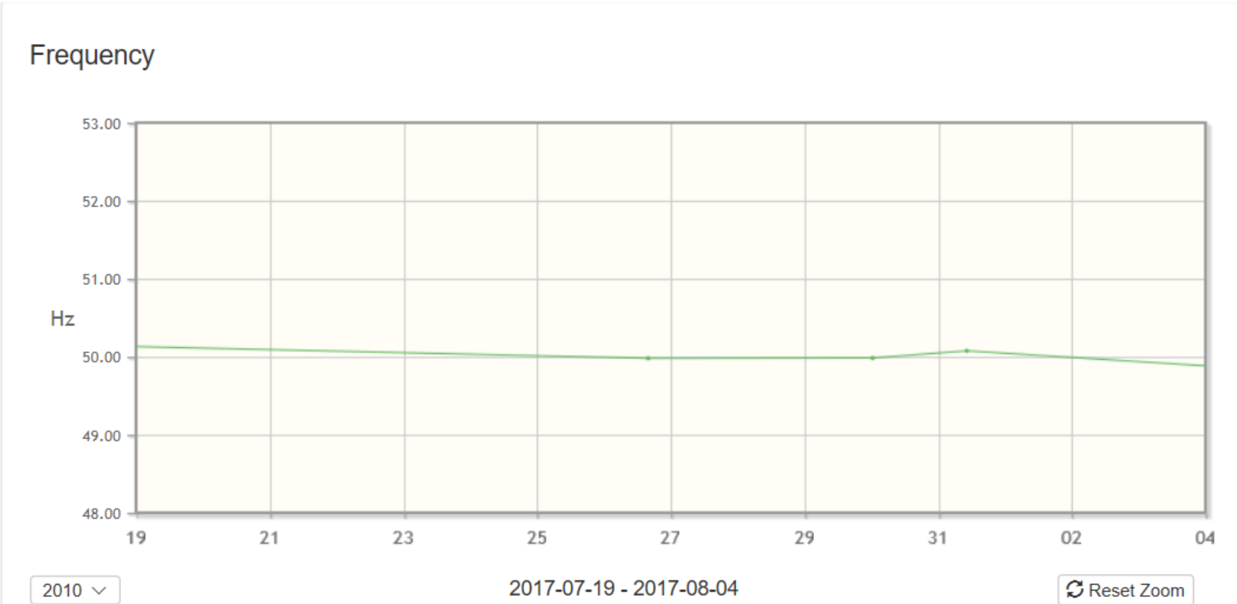

Figure 6.10: utility frequency variation for 19/07/2016 to 04/08/2017

The following figure shows the frequency variation during 14.00h – 04.00h in 2017-03-04 to 2017-03-05. As for this figure 6.11, there are some spikes in the graph causing variation of the utility frequency. The response of the inverter system is faster than the generator system in a normal grid because the inverters are not consisting of rotating mass. Also, during this selected random time where the demand is at maximum according to our load profile of the village the frequency variation is in between 5.2 Hz to 4.7Hz. which is acceptable for grid operation.

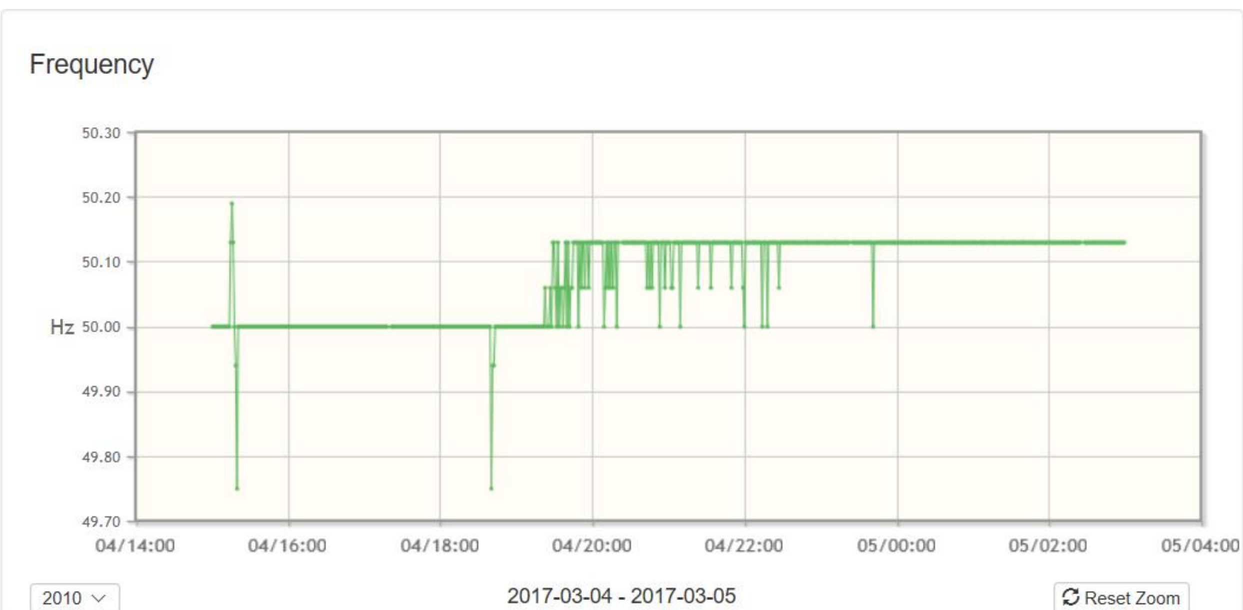

Figure 6.11: utility frequency variation results in a random day

6.2.5 Power factor variation of the system

The definition for the power factor in electrical engineering of an AC electrical power system is the ratio of the real power to the load to the apparent power in the circuit. A power factor of < 1 means that the current and voltage waveforms are not in phase, dropping the instantaneous product of the both waveforms (I x V). Real power is the volume of the circuit for carrying out the job in a time. Apparent power is the product of the voltage and current of the circuit. Due to power deposited in the load and resend back to the source, or due to a non-linear load that changes the of the current wave shape strained from the source, the apparent power > real power. When the device (generally the load) generates energy, which then currents back to the source, which is generally considered the generator, a negative power factor will occur. [29]

$$\cos\theta\ (Power\ factor) = \frac{P(real\ power)}{|S|(active\ power)}$$

A load with a high power factor in an electric power system needs less current than a load with a low power factor for the equal amount of useful power delivered. The higher currents increase the transmission cost and energy loss. Because of the wasted energy and high cost of larger wires and other gear, electrical utilities will generally issue a higher invoice to consumers where there is a low power factor.

Power factors below 1.0 require a utility to produce more than the minimum volt-amperes necessary to supply the real power (watts). This increases generation and transmission costs. [30] In normal design practices in Sri Lanka the power factor is considered as 0.8.

In this study we have gathered power factor variation data from 2017-06-08 to 2017 – 08 – 24 and it is in between 1 to 0.9. From this result, we can assume that there is no considerable amount of impact from non-leaner loads to this power system.

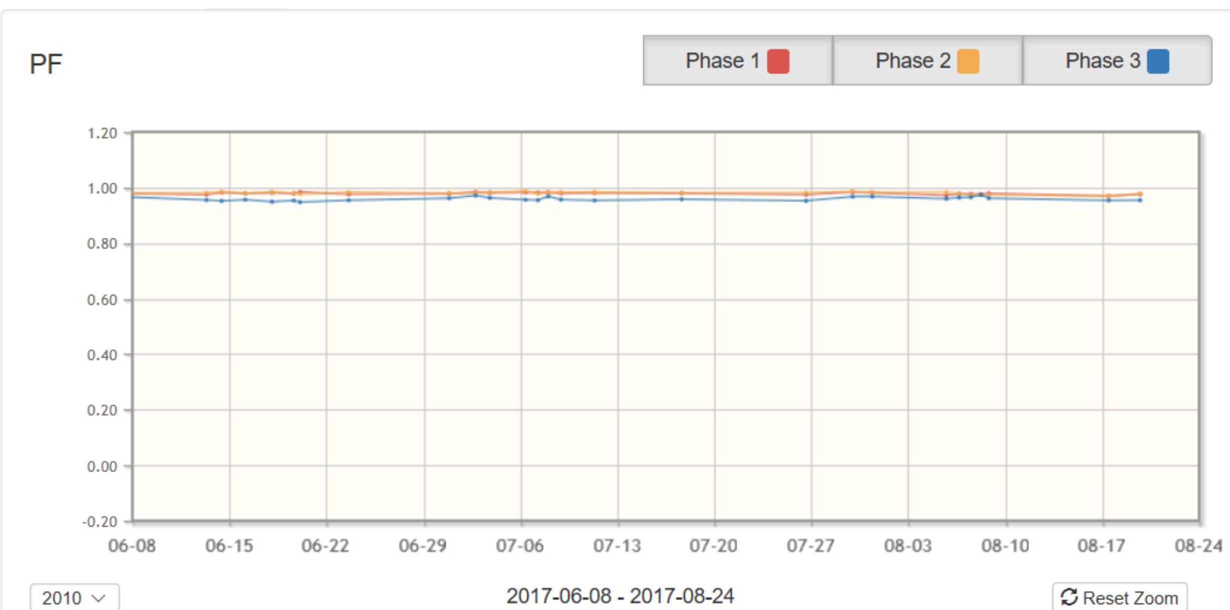

Figure 6.12: power factor variation of the Hybrid System

6.3Analysis of generation parameter variations during a day

This analysis was done starting from 2017-08-07 at 20.00h to 2017-08-08 at 20.00h. following parameters were recorded during that time.

1. Power Variation
    a. Active
    b. Reactive
    c. Apparent
2. Voltage Variation
3. Current Variation
4. Power factor variation

From these data, we can study how a load of the island varies throughout a randomly selected day.

By analyzing the following figure 6.13 the maximum power demand occurred during 18.00h – 22.00h of the day. According to figure 6.14 during the peak hour, their load has drained approximately more than 60 A and the other time of the day the current of each phase was below 40 A. during this peak hours the average voltage fluxgate around 232 V which shown in figure 6.15. and according to figure 6.16, the power factor value is also getting lower up to 0.92 during this high demand period.

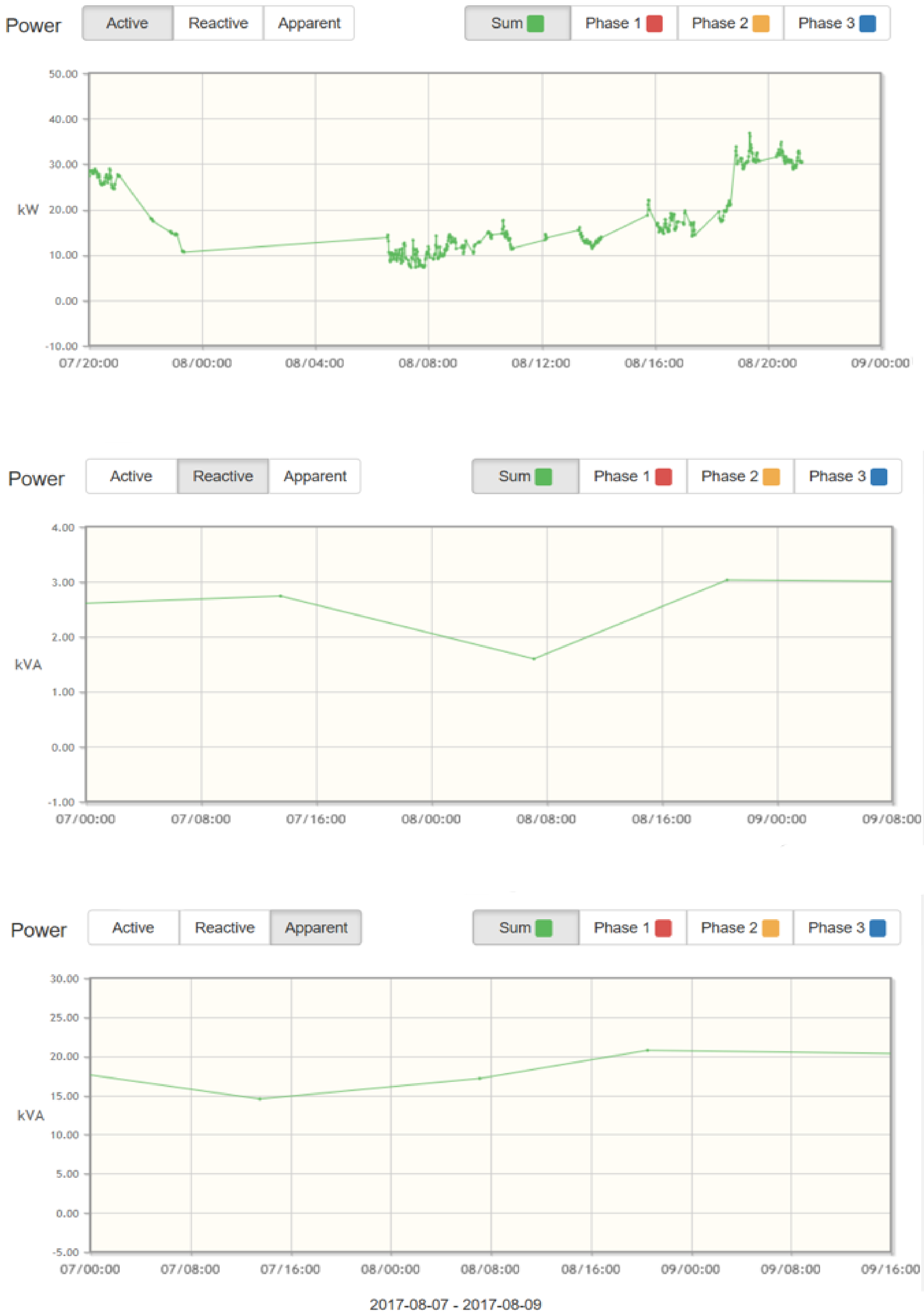

Figure 6.13: Active, reactive and apparent power variations during the random day

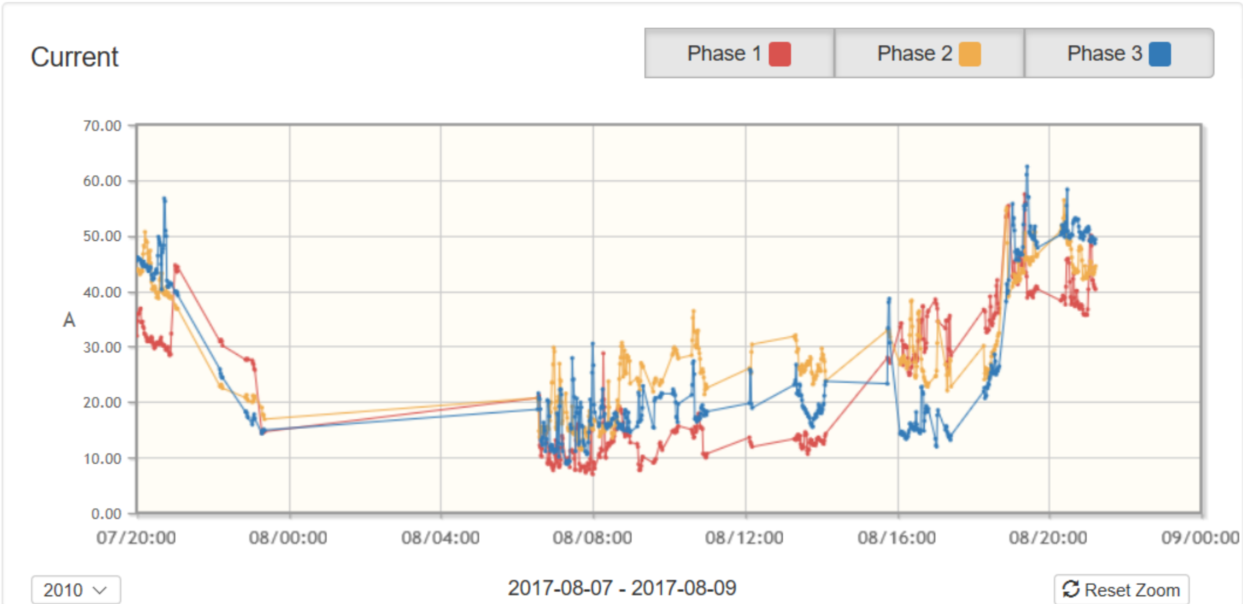

Figure 6.14: Current variation of the Hybrid System during a random day

Figure 6.15: Voltage variation of the Hybrid System during a random day

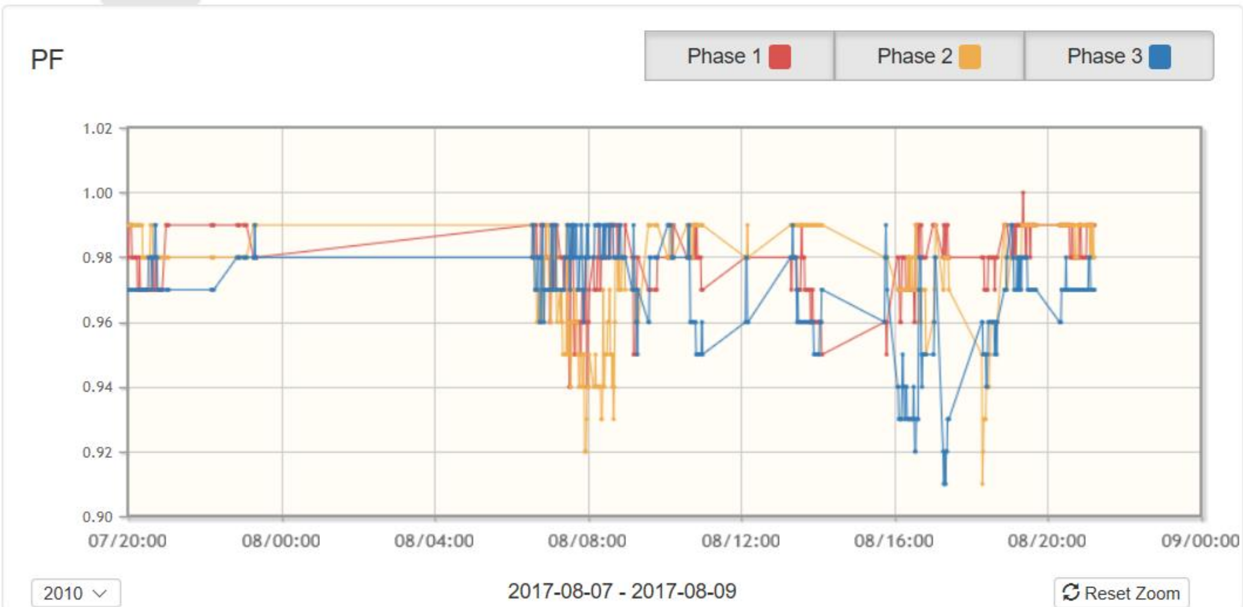

Figure 6.16: Power Factor variation of the Hybrid System during a random day

The data shown in figure 6.17 was obtained for functional test report during a day of 2016/05/24 to 2016/05/25. According to this test results, we can see that the maximum energy demand of that day was 26kW. Also, the most important observation is that the storage battery bank and wind turbines were capable enough to handle the nighttime demand and nighttime peak without requesting the diesel generator to take over.

Further, by this figure, we can understand how SOC of a battery works during the different time periods of the day. Also, these results show how excess power is used to charge the batteries. During the night time when the power demand is low, the excess wind power is used to increase the battery charge level.

Functional Tests: Battery Bank / SI Inverters

Charge/Discharge

Date	Time	Supply Method	SOC Main	SOC Ext 1	SOC Ext 2	SOC Ext 3	Energy Demand
5/25	0:00	Mini Grid /~~DG~~	67%	73%	72%	73%	9.1kW
5/25	1:00	Mini Grid /~~DG~~	67%	75%	74%	74%	8.4kW
5/25	2:00	Mini Grid /~~DG~~	64%	77%	78%	77 %	8.4kW
5/25	3:00	Mini Grid /~~DG~~	63%	80%	80 %	81%	7.8 kW
5/25	4:00	Mini Grid /~~DG~~	62%	81%	82%	82%	8.7 kW
5/25	5:00	Mini Grid /~~DG~~	59%	83%	83%	84 %	10.1 kW
5/25	6:00	Mini Grid /~~DG~~	58%	69%	68%	69%	13.3 kW
5/25	7:00	Mini Grid /~~DG~~	55%	69%	69%	69%	10.8 kW
5/25	8:00	Mini Grid /~~DG~~	52%	80%	80%	78%	6.8 kW
5/25	9:00	Mini Grid /~~DG~~	98%	94%	95%	100%	8.7 kW
5/25	10:00	Mini Grid /~~DG~~	98%	96%	95%	98%	9.6 kW
5/24	11:00	Mini Grid /~~DG~~	86%	98%	100%	98%	8.4 kW
5/24	12:00	Mini Grid /~~DG~~	82%	98%	99%	97%	10.2kW
5/24	13:00	Mini Grid /~~DG~~	97%	97%	98%	97%	9.3 kW
5/24	14:00	Mini Grid /~~DG~~	98%	99%	99%	99%	10.2 kW
5/24	15:00	Mini Grid /~~DG~~	98%	99%	98%	98%	8.9 kW
5/24	16:00	Mini Grid /~~DG~~	98%	98%	98%	99%	5.2 kW
5/24	17:00	Mini Grid /~~DG~~	97%	97%	97%	98%	14.1 kW
5/24	18:00	Mini Grid /~~DG~~	96%	97%	97%	97%	7.7 kW
5/24	19:00	Mini Grid /~~DG~~	92%	92%	93%	92%	26.0 kW
5/24	20:00	Mini Grid /~~DG~~	81%	83%	83%	83%	26.0 kW
5/24	21:00	Mini Grid /~~DG~~	70%	73%	73%	72%	25.1 kW
5/24	22:00	Mini Grid /~~DG~~	65%	69%	68%	68%	15.1 kW
5/24	23:00	Mini Grid /~~DG~~	65%	70%	70%	69%	10.1 kW

Figure 6.17: functional test results of the Hybrid distribution system at the site

6.4 Analysis of annual wind resource of the area

From the Allsouls monitoring system, the wind power generation has been recorded in three wind turbines. The following figure5.18 shows the availability of the wind resource throughout the year for our given locations for each turbine. By referring to these data it is observable that during March and April Months the wind resource becomes less compared to other months of the year. In June, the highest wind energy harvesting has done.

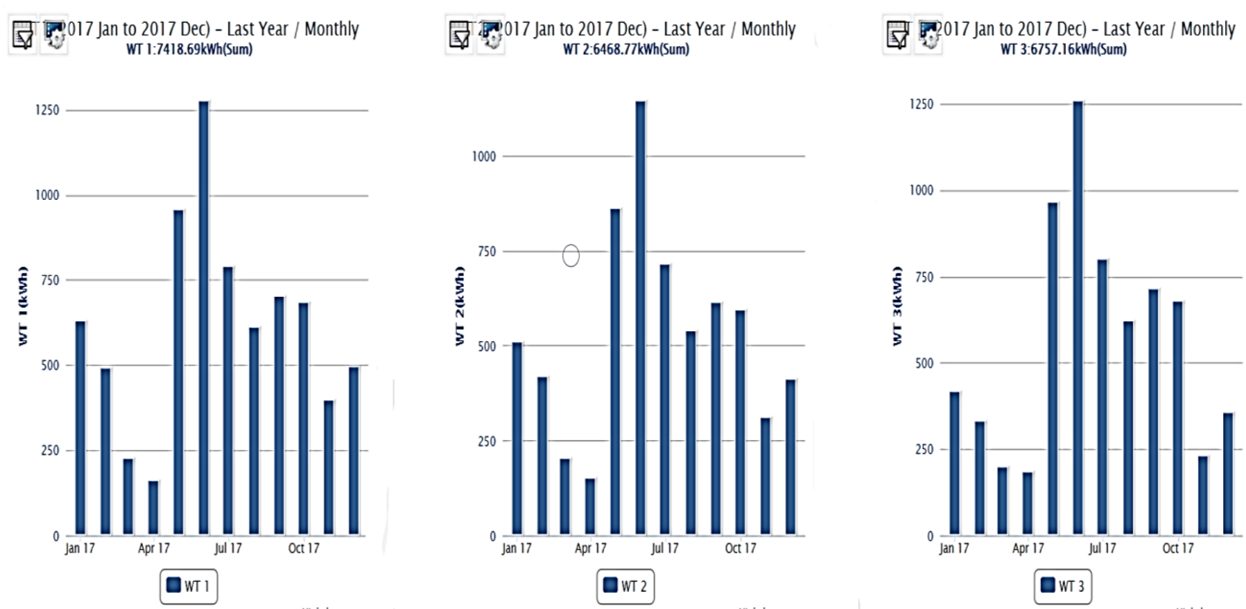

Figure 6.18 Average monthly generation results obtained for wind turbines for 2017

Chapter 7

Conclusions and Discussion

The aim of this study was to examine the ideal gauge of a hybrid energy system based on renewable energy capable of supplying electrical energy to an isolated remote island in Sri Lanka. For analysis, a small rural fishing village was selected on a remote island in the northern part of Sri Lanka, which included about 110 households, including several small businesses and public services. The estimated average of daily energy consumption in this site was 255 kWh and approximately a peak of 29 kW was observed between 7:00 and 8:00 in the afternoon. As the region is not affected by seasonal changes, for this study constant load profile throughout the year was assumed.

The northern region receives abundant solar radiation with a yearly PV energy of 5kWh / m2 / day. Furthermore, the yearly average speed of the wind flow in the area is 7.6 ms-1, resulting in a 300 W / m2 wind power density at an elevation of 50 m. Hence, wind and solar energy resources have been major sources of electricity production in the off-grid hybrid distribution, as diesel generator has become a backup power generation option which will operate only during in critical times.

Using diesel generators to supply power to small communities appear to be cost-effective in terms of initial capital investment since they don’t need a huge capital investment as needed for hybrid systems based on renewable energy. But due to the high cost of O & M for fuel, maintenance and replacements the lifetime cost analysis reveal generators cost more in long run. On the contrary, off-grid hybrid distribution systems require a huge capital investment, on the other hand, it has lower operating costs and maintenance costs. Therefore, in long-term wise renewable energy-based hybrid distribution systems are more cost-effective than fossil fuel based micro-grids.

Simulation software has been used to model similar system using the load profile and the renewable energy data. By simulating the model, the optimal capacities of each power source have been identified.

Since this was the first hybrid system in the country some parts of the design were done with certain assumptions and general thumb rules with the help of satellite-based weather reports. But the output results of different parameters such as energy, power and voltage which gathered during the period of 2016-09-01 to 2017-09-01 show that this system is operating up to expected levels. Also, throughout the year there is good solar and wind resource was available which is sufficient to handle the load of the village. The study shows from May to October there is a good potential for wind resource, which is much valuable fact when designing other hybrid systems in the area.

Even though this microgrid operates separately from the main grid, the results gathered after the construction of this hybrid microgrid shows that it is capable to supply energy demand up to the level of any other power supply from the main grid. The power, voltage and frequency results show that these parameters are varying within the acceptable standard ranges. This pilot project is a key example in establishing these kinds of systems for other remote islands in the region.

Furthermore, due to the high rate of electrification; in future the demand may increase significantly. To face this situation the battery bank capacity should increase over time. Otherwise the system will not capable of handling the night time load and may cause to run the generator more often during night time. If the nighttime peak increase with the growth of population the generator also needs to replace or coupled to a generator with higher capacity.

While this work has addressed the feasibility, modeling and operation results of the off-grid hybrid distribution system for supplying electricity, the proposed the future implementations are;

- Increase the number of clusters and battery storage capacity for the existing system to meet the future demand and minimizing the usage of the backup generator.
- Connect another high-power generator to meet the peak demand which can occur in future (the existing generator in old power house can be utilized)
- Implement an adequate financial and commercial model by analyzing the economic situation in Sri Lanka.
- Adding more wind turbines due to high availability.
- Implementing a system for energy management.
- Suggest an adequate operation and maintenance plan to guarantee the sustainable operation of the system.
- Consider the possibility of replacing diesel generators with locally produced biofuels in the hybrid system.
- Feasibility study and research conduct on the possibility of including tidal waves as a renewable energy resource to the system.

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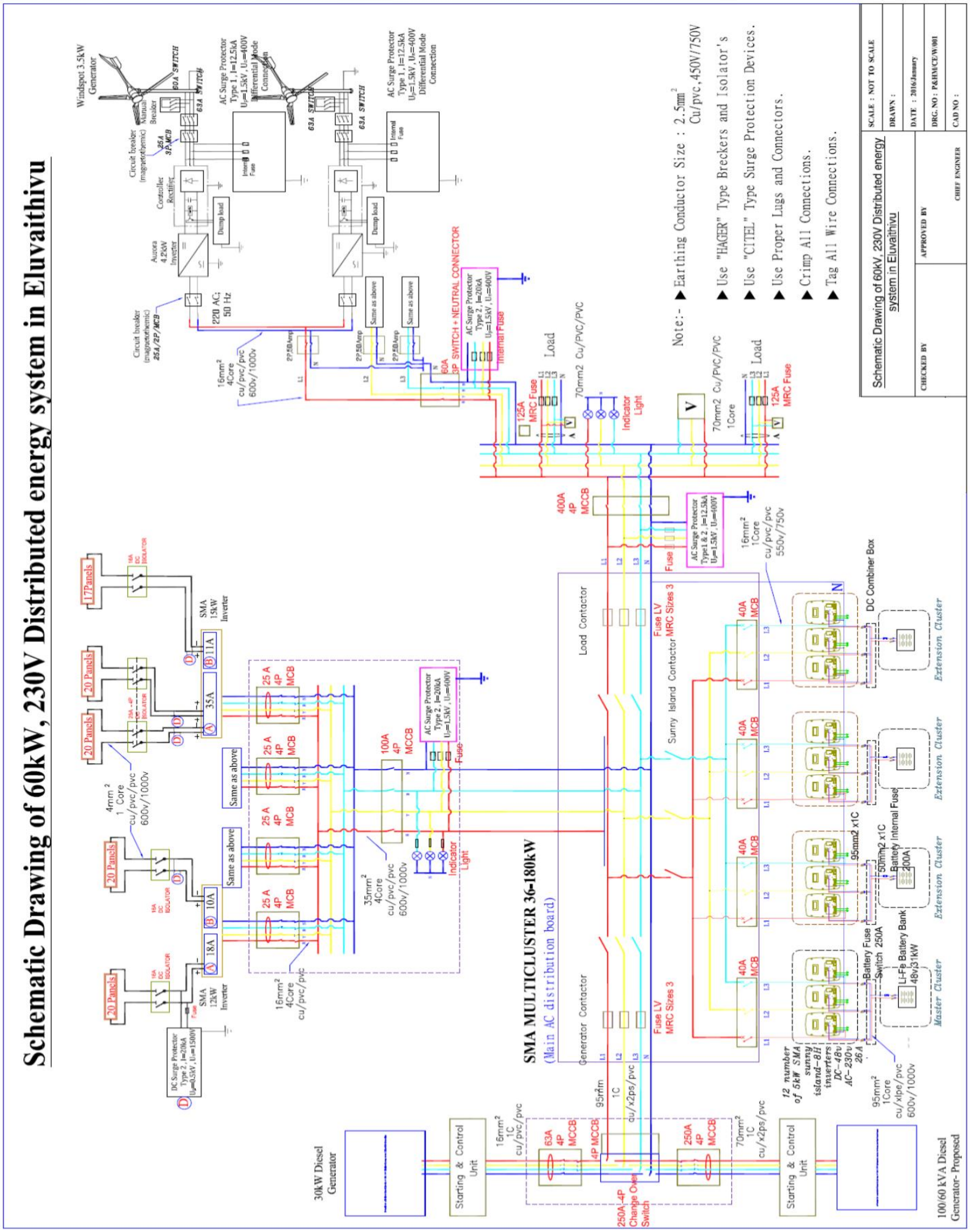
APPENDICES



Schematic drawing