# PERFORMANCE ANALYSIS OF AN INSTALLED WIND, SOLAR, DIESEL AND BATTERY HYBRID POWER SYSTEM


Amukotuwe Gedara Asela Nirmala Bandara Jayasinghe

128363V


Degree of Master of Science


Department of Mechanical Engineering

University of Moratuwa
Sri Lanka


December 2017

# PERFORMANCE ANALYSIS OF AN INSTALLED WIND, SOLAR, DIESEL AND BATTERY HYBRID POWER SYSTEM

Amukotuwe Gedara Asela Nirmala Bandara Jayasinghe

128363V

Thesis/Dissertation submitted in partial fulfillment of the requirements for the degree Master

Department of Mechanical Engineering

University of Moratuwa
Sri Lanka

December 2017

# DECLARATION

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

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my thesis, in whole or part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature: .............................. Date: ..............................

A. G. A. N. B. Jayasinghe

The above candidate has carried out research for the Master's Thesis under my supervision

Signature: .............................. Date: ..............................

Prof. R. A. Attalage,
Deputy Vice Chancellor,
University of Moratuwa.

**Performance Analysis of an Installed Wind-Solar-Diesel and Battery Hybrid Power System**


## ABSTRACT:

Hybrid power system is identified as most economical solution for providing electricity to communities currently isolated from the national grid and mostly main land. Recently, first Solar wind diesel Battery Hybrid commissioned in one of the northern Island of Sri Lanka called Eluvathivu, as a pilot power plant for demonstrating the maturity and feasibility of hybridization of different power sources. One of other objective of implementing this project was train CEB staff to prepare them for implementing similar projects on the other Islands. During this study performance analysis of this power system was carried out using HOMER pro software. It was identified that initial capital cost of the hybrid system is more than 10 times higher than diesel power system. However present worth value of the hybrid system will be $ 1,152,154 and discounted payback will be less than 4 years. Sensitivity analysis was done using future load demand demonstrates that design configuration of hybrid power system can be sustained maximum average load up to 235kWh/day and when the hybrid system operates in higher load demands than design, overall efficiency of the system increases. Sensitivity analysis was done for possible expansion of the current system illustrates installed configuration is the optimum configuration to meet the site conditions. Performance of the hybrid system very much depends on wind speed of the Island. When the wind speed exceeds cut in speed of wind turbines, 1m/s of increment of wind speed will result more than 6% increment of renewable fraction of the system. 0.5 kWh/m2/day increment of solar scaled average increment will generate around 7000kWh/ year of additional electrical energy. However cost of energy and net present cost of the power system do not depend on the variation of solar radiation since almost all the additional energy generated due to increment of solar radiation is accounted as excess energy to the system. When analyzed using actual data of hybrid power system with output predicted by using HOMER Pro, it was observed that HOMER Pro under estimates total renewable energy generation and total unmet load of the hybrid system and overestimates generated energy by the diesel generator and total electricity consumption. Therefore estimated values of COE and NPC are over estimated.



Key Words; Eluvathivu Island, HOMER Pro, Hybrid Power System

# ACKNOWLEDGEMENT

I would first like to thank my thesis Supervisor Prof. R. A. Attalage, Senior Professor in Mechanical Engineering, Deputy Vice Chancellor of the University of Moratuwa and course coordinator Dr. H. K. G. Punchihewa, Senior Lecturer, Department of Mechanical Engineering, University of Moratuwa for giving me greatest support and guidance during this research. They consistently allowed this Thesis to be my own work, but steered me in the right the direction whenever they thought I needed it.

I would also like to thank the Staff DGM North, Ceylon Electricity Board and my colleagues Eng. Sharadha Premaratna and Eng. J. A. S. A. Jayasinghe for their cooperation for succeeding in my thesis. Without their passionate contribution, this thesis could not have been successfully conducted.

I would be very much grateful to Eng. V.K Jayasiri, Eng. P. Kalubovila and Eng. A. I. A. Baduge, who are former DGMs, Workshop and Ancillary Services and Eng. D. R. M. Harasgama, who is a present DGM, Workshop and Ancillary Services and Eng. P. K. S. Chandrasekara and Eng. A.P.K. Muthunayake former and current Chief Engineers of Power Plant Unit of Ceylon Electricity Board respectively for giving me utmost support and opportunity to complete this thesis. I wish to thank Mr. S.D.L. Sandanayake, Lab Attendant, Department of Mechanical Engineering, and University of Moratuwa.

Finally, I would appreciate wife, daughter and all the other members of my family without their scarification this work would not be realized and everybody, who has helped me in numerous ways at different stages of the research, which was of utmost importance in bringing out this effort a success.

# TABLE OF CONTENTS

# LIST OF FIGURES

## LIST OF TABLES

# ABBREVIATIONS

| | |
|---|---|
| HOMER | Hybrid Optimization of Multiple Electric Renewables |
| NREL | National Renewable Energy Laboratory |
| COE | Cost of Energy |
| NPC | Net Present Cost |
| STP | Standard Temperature and Pressure |
| ADB | Asian Development Bank |
| PV | Photo Voltaic |
| NCRE | Non-conventional Renewable Energy |
| CEB | Ceylon Electricity Board |
| DGM | Deputy General Manager |

# 1 INTRODUCTION

## 1.1 Background

Role of renewable energy has become more significant in the current world since most of the countries in the world are increasingly concerned on their energy security and sustainable development. Promoting electricity generation based on non- conventional renewable energy sources is a vision of most of the countries and policy makers develop new policies to increase percentage of electricity generation based on renewable energy sources. 147 countries who participated for 21$^{st}$ conference of the parties of United National Framework Convention on Climate Change (UNFCCC) in Paris agreed to limit global warming to well below 2 $^{0}$C by scaling up their renewable energy [1]. Total global investment for renewable energy capacity in 2015 was $ 285.9 billion, which was recorded as highest investment for renewable up to 2015. $ 199 billion out of total investment was for utility scale wind farms and solar parks [2].

Biomass, Petroleum, coal, Hydro and non-conventional renewable energy are the primary contributors of the energy sector of the Sri Lanka. They contribute 43%, 37%, 4%, 13% and 3% to total energy respectively. Total grid connectivity of the country is around 98% and level of electrification is almost 100%. Installed capacity is approximately 4,050 MW, consisting of 900 MW of coal power, 1,335 MW of oil burning thermal power, 1,375 MW of hydro power and 442 MW of non- conventional renewable energy sources such as wind, mini hydro, bio-mass and solar power plants. The annual total electricity is about 10,500 GWh. The annual rate of rise of electricity demand is expected as 4 - 6%.

After commissioning Chunnakam and Kilinochchi Grid Sub Stations and Uthuru Janani Power Station in Chunnakam, all most all the parts other than few geographically isolated areas like northern islands, top of the mountains and few small villages which are not having proper access, of the country is connected through the national grid. There are 4 small inhabitants islands called Eluvaithivu, Analaithivu, Nainathivu and Delft (***Figure 1.1***), which are located northern part of the country [3] geographically isolated from the main land satisfied their electrical needs using diesel generators due to impossibility of construction of high voltage overhead distribution lines through deep sea and costly installation of submarine cables. Those Northern Inhabitants Island's Electrification Status is tabulated in ***Table 1.1***.

Providing uninterrupted power to these inhabitants is a great challenge due to problems in fuel transportation to produce electrical power. Therefore there are power cuts during day time. Also unit cost of generated electricity is high due to high diesel prices and cost of transportation of diesel. Renewable energy based mini grid system was identified as a solution to overcome this problem since geographical location of these islands is ideal to produce electrical energy using renewable energy. However with the seasonal variation of the solar and wind resources, power generation is limited. This issue can be avoided by coupling renewable based power generation technology with a diesel generator and forming hybrid power system. When it compares with diesel generator along with hybrid power system, hybrid power systems have significantly higher investment cost and lower operational and maintenance cost.

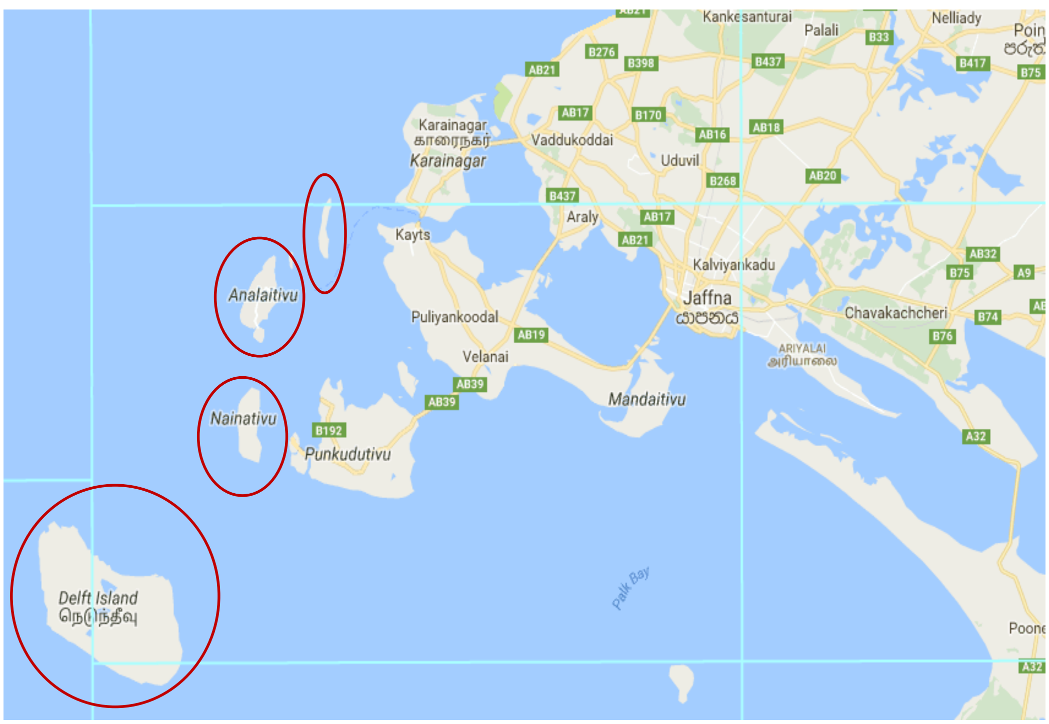



***Figure 1-1  Northern Region of Sri Lanka***

*Table 1.1 Northern Inhabitants Island's Electrification Status*

| No | Description | Population | No. of Houses | No. of Electrified houses | Level of Electrification |
|---|---|---|---|---|---|
| 1 | Eluvaithivu | 787 | 110 | 73 | 66% |
| 2 | Analaithivu | 2,324 | 452 | 152 | 34% |
| 3 | Nainathivu | 3,030 | 833 | 520 | 62% |
| 4 | Delft | 4,540 | 1,181 | 214 | 18% |

## 1.2 Renewables in Sri Lanka

When consider the history, until early 1990s large-scale commercial hydropower projects were the primary source of power generation in Sri Lanka. However, droughts in 1992, 1996, 2001 and 2002 have led the Ceylon Electricity Board (CEB) and other major Sri Lankan power producers to shift to thermal power. In 2012, "oil-fired thermal power provided nearly 60% of generation" in Sri Lanka, while hydropower accounted for around 23% of the total [4].

Currently Sri Lanka is in a key turning point of a move towards non-conventional renewable energy (NCRE) technologies, including mini hydro projects, solar projects, wind projects and formal biomass projects. Biomass is already estimated to be a leading source of energy supply in Sri Lanka, but market has not well formalized yet. By agreeing to buy power at set prices, the state effectively encouraged long-term planning and investment in this segment among private sector as well, thus facilitating the growth of the NCRE market [4].

As of January 2015 connected capacity of solar and wind Power connected to the national grid were 1.4MW and 124MW respectively. As per the government policies, CEB plans [5], [6] to increase NCRE capacity to 972MW by 2020, which will contribute 20% of the total power generation of the country. This percentage will reach its maximum (21.4%) in 2025, when installed capacity will reach 1367MW. It is expected to reach installed capacity to 1897MW in 2034. Wind power will be the major contributor of NCRE in 2034. Installed capacity of Wind and Solar Power will be 719MW and 226MW respectively.

## 1.3 Aim & Objectives of the Thesis

The aim of the research is to analyse performance of installed Wind, Solar, and Diesel Battery Hybrid Power System. Objectives are set as follows to achieve this aim.
The objectives are:

- Compare the performance of design configuration of the hybrid system with the base case diesel generator in view of identifying the feasibility of the project.
- Analyse the performance of the system with possible expansions to the current system
- Analyse the unit Cost of Energy for different input conditions and identify best operating point of the hybrid power system.
- Compare the  computer based simulated results with actual data for validation

## 1.4 Methodology

Following methodology was used to achieve the above objectives of the research. Initially, a literature review was carried out to get a better understanding about similar type of early research done for Si Lanka context as well as other part of the world. At the same time the design data of the hybrid power system was also collected from staff of Deputy General Manager (Northern Province). This data includes system configuration of the installed power system, hourly electricity variation before installed the hybrid system, electricity generation data of wind, solar and diesel generator system of current system and historical power generation data of previously installed stand along diesel generator system.

A model was developed using ‘HOMER Pro’ software by including cost and lifetime data of each component of the system, monthly average solar radiation, monthly average wind speed and predicted load demand. Optimized system configuration performances obtained from the software was compared with Old generator system to check feasibility of the project.

Sensitivity analysis was carried out to identify the system performance by varying scale average load to the system, monthly average wind speed and monthly average solar radiation and compare results to identify possible operating condition of the power system.

Another sensitivity analysis was carried out to identify possible future expansion of the system. Capacity of solar panels, angle of solar panels, number of wind turbine and capacity of generator were considered as sensitivity inputs. An analysis was done to analyse feasibility of each system configuration.

## 1.5 Outline of the Thesis

This thesis is organized in 6 Chapters. The general introduction about Renewable Energy resources in Sri Lanka and Research Methodology for “Performance Analysis of Installed Wind, Solar, Diesel, Battery Hybrid Power System” are illustrated in Chapter 1. Available technologies of Wind, Solar, Diesel Battery Hybrid Power System and developments that have been carried out by various researchers were also studied and discussed in the Chapter 2. Chapter 3, is illustrated introduction about HOMER Pro software, which is used for optimizing simulation and sensitivity analysis. Over view of Eluvathivu Island and installed hybrid system are described in Chapter 4. Chapter 5 presents the Results and discussion. Final Conclusion is given in the Chapter 6.

# 2 LITERATURE REVIEW

According to the United Nations Energy Security, Drinking water, climate change and poverty are the four main priorities of the world [7] . There are many papers published about hybrid power generating systems. Most of them are about feasibility analysis of hybrid energy system for different location of the world. Majority of these papers are about feasibility analysis of Electrification of by using off grid hybrid power plants. And very few papers have used optimization technique to model how hybrid systems could reduce electricity generation cost over conventional fossil fuel systems.

Eng. K Ratneswaran [8] has conducted extensive analysis using Homer Software after conducting survey for data collection and concluded this wind – diesel hybrid power system as the most economical system to elect rich the Eluvathivu Island. As per his analysis, one wind turbine (80kW) with two diesel generators (45kW + 15 kW) battery energy storage and convertor (16 kW) is the most reliable and economical hybrid system to electrify this Island. And the payback period of this project is 6 to 7 years.

M. V. P. Geetha Udayakanthi [9] has analyzed wind and solar power generation possibility of different locations in Sri Lanka. And she concluded that Sri Lanka has economically feasible power generation potential of wind and solar energy. She has further concluded that, Sothern and Western Coastal belts are most suitable for utility scale wind and solar power generation. The selected locations were simulated using HOMER software.

Feasibility study of a wind-PV-diesel hybrid system for a village in Saudi Arabia has done by S. Rehman, A.M. Mahbub, J. Meyer an L.M. Al-Hadhrami [10] of King Fahd University for Petroleum and Minerals of Saudi Arabia have concluded that, every 0.5m/s increment of wind speed will result 5% increment of wind energy contribution to the hybrid power system and the cost of energy (COE) decreased linearly.

Feasibility analysis of hybrid off grid wind–DG-battery energy system for the eco-tourism remote area was carried out by the research team of Department of Mechanical Engineering in University of Malaya, Which consists with A. Shezan, R. Saidur, K.R Ula, A. Hossain, W.T. Chong, S. Julai [11]. The research team has analyzed a complete off grid wind–diesel-battery hybrid RE model with the use of HOMER software by minimizing a unit cost of the electricity production for 2 residential hotels of the Cameron Highlands, which is a decentralized region in Malaysia. The research team has found that 15 wind turbines (10kw), 1 diesel generator (4kw), and 2 battery hybrid RE systems are most economically feasible. Further, it was found that decrement of $CO_2$ emission from the simulation result.

Another research was carried out by the Mahabub Hasan and Oishe Binty Momin [12] to evaluate the performance and feasibility of a solar-wind-diesel hybrid energy system through a computer simulation studies to achieve an efficient and cost competitive system. Finally, it was concluded that, solar-wind-diesel hybrid energy system consumes less fuel than the diesel generator which is run by only diesel and total net present cost of solar-wind-diesel hybrid energy system is less than the diesel generator. Further it was found that hybrid system will reduce the CO2 emission by 60% in the local atmosphere compared to electricity draw from the national grid.

A technical and feasibility assessment was done by Ani Vincent Anayochukwu [13], incorporating the solar PV generation to the existing diesel power system that currently supplied power to the Church. Finally it was found that the proposed system would meet around 53% of the average annual Parish Church electrical load and result in 47% reduction in diesel use and low $CO_2$ emission compared to the previously existing system.

Maamar Laidi, Salah Hanini,Brahim Abbad1, Nachida Kasbadji Merzouk and Mohamed Abbas [14] have proposed wind- Solar-Diesel Battery hybrid power system to meet energy requirement of the small houses located in the southern part of the Algeria and 47% of renewable penetration hybrid power system is most economical.

Victor O. Okinda, Nichodemus A. Odero [15], have carried out a review of techniques in optimal sizing of hybrid renewable energy system and concluded that along renewable generation is a variable alternative to the grid supply or off grid non-conventional fossil fuel base power generation for remote areas across the globe. They have further concluded that optimal sizing of components of a hybrid system is crucial for the feasibility of such system in terms of cost and reliability.

J. G. Fantidis, D. V. Bandekas and N. Vordos [16], have carried out a techno economical study of hybrid power system for a remote village in Greece to investigate the possibility of replacing diesel power generation with hybrid power system. The sensitivity analysis was carried out to understand most important parameters of the system and also define future scenarios of competitiveness between technologies.

T. Givler and p. Lilienthal [17], have been carried out a research using HOMER software NREL's micro power optimization model to explore the role of Generator in small power systems to explore the threshold load size at which it is more cost effective to include a diesel than to increase the size of the battery bank or PV array. From their analysis they have concluded that for loads ranging from 3 – 13 kWh/day to PV battery systems are cost effective and for the loads above 13kWh/day hybrid PV/generator/battery systems are cost effective depending on the reliability of the system, solar resource, and diesel fuel price.

# 3 DESIGNING OF HYBRID SYSTEM WITH HOMER PRO

The HOMER Pro [18] is a computer model developed by NREL of USA to evaluate designs of both off-grid and grid connected power systems. Inbuilt algorithms are available in the HOMER Pro software for simulation, optimization and sensitivity analysis, therefore it is easier to evaluate the many possible system configurations when inserted inputs including available technology options, component costs and resource availability.

HOMER Pro is required monthly average of daily solar radiation and wind speed values to develop a model. The software synthesizes a set of solar radiation values for each hour of the year using the Graham algorithm. Also it creates time series wind speed data using HOMER's synthetic wind speed data synthesis algorithm.

## 3.1 Simulation

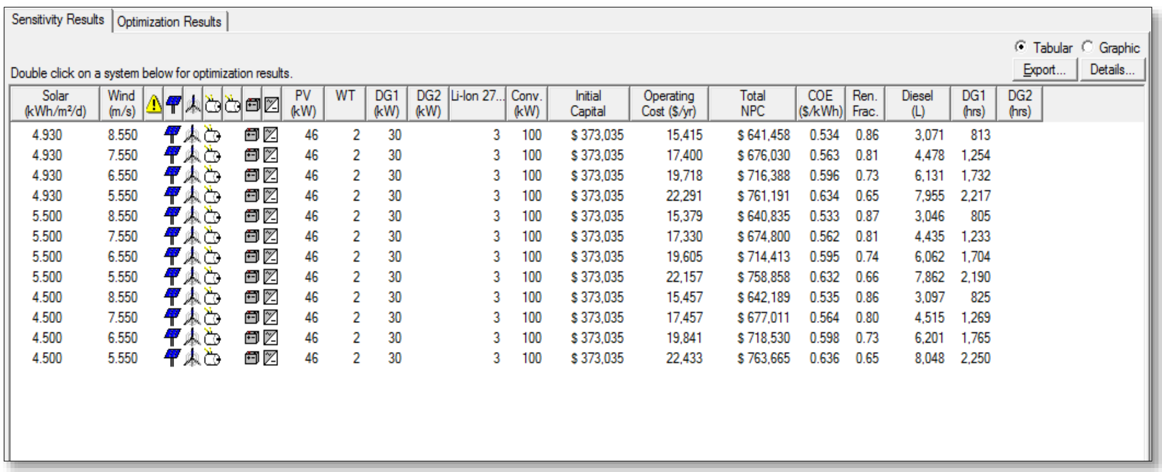
In each time step of the year, HOMER Pro simulates the operation of each system configurations by making energy balance calculations. For each time step, HOMER Pro compares the electric and thermal demand in that time step to the energy that the system can supply in that time step, and calculates the flows of energy to and from each component of the system to determine whether a configuration is feasible. Then it estimates the cost of installing and operating the system over the lifetime of the project. For systems that include batteries or fuel-powered generators, HOMER Pro also decides in each time step how to operate the generators and whether charge or discharge the batteries.

## 3.2 Optimization

HOMER Pro displays a list of possible system configurations sorted by ascending net present cost or lifecycle cost, after simulating all of the possible system configurations, which can use to compare system design options. This will help to select best system configuration for the system.

### 3.3 Sensitivity Analysis

If there is an uncertainty about the exact value of some input variable, sensitivity analysis is the option that determine how important that variable is and how the outputs change depending a range of values of that particular input variable. If it defines sensitivity variables as inputs, then HOMER repeats the optimization process for each value of each sensitivity variable that specified. For example, if you define wind speed as a sensitivity variable, HOMER will simulate system configurations for the range of wind speeds that specify. Sensitivity Analysis Window from HOMER Software is given in the ***Figure 3.1***.


Sensitivity Results | Optimization Results

Tabular Graphic

Export... Details...

Double click on a system below for optimization results.

| Solar (kWh/m²/d) | Wind (m/s) | PV (kW) | WT | DG1 (kW) | DG2 (kW) | Li-Ion 27... | Conv. (kW) | Initial Capital | Operating Cost ($/yr) | Total NPC | COE ($/kWh) | Ren. Frac. | Diesel (L) | DG1 (hrs) | DG2 (hrs) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 4.930 | 8.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 15,415 | $ 641,458 | 0.534 | 0.86 | 3,071 | 813 | |
| 4.930 | 7.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 17,400 | $ 676,030 | 0.563 | 0.81 | 4,478 | 1,254 | |
| 4.930 | 6.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 19,718 | $ 716,388 | 0.596 | 0.73 | 6,131 | 1,732 | |
| 4.930 | 5.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 22,291 | $ 761,191 | 0.634 | 0.65 | 7,955 | 2,217 | |
| 5.500 | 8.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 15,379 | $ 640,835 | 0.533 | 0.87 | 3,046 | 805 | |
| 5.500 | 7.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 17,330 | $ 674,800 | 0.562 | 0.81 | 4,435 | 1,233 | |
| 5.500 | 6.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 19,605 | $ 714,413 | 0.595 | 0.74 | 6,062 | 1,704 | |
| 5.500 | 5.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 22,157 | $ 758,858 | 0.632 | 0.66 | 7,862 | 2,190 | |
| 4.500 | 8.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 15,457 | $ 642,189 | 0.535 | 0.86 | 3,097 | 825 | |
| 4.500 | 7.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 17,457 | $ 677,011 | 0.564 | 0.80 | 4,515 | 1,269 | |
| 4.500 | 6.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 19,841 | $ 718,530 | 0.598 | 0.73 | 6,201 | 1,765 | |
| 4.500 | 5.550 | 46 | 2 | 30 | | 3 | 100 | $ 373,035 | 22,433 | $ 763,665 | 0.636 | 0.65 | 8,048 | 2,250 | |

***Figure 3-1 Sensitivity Analysis Window from HOMER Pro software***

HOMER Pro models can be used for both conventional and renewable energy technologies. Power sources and storages available in HOMER Pro are given in ***Table 3.1***;

*Table 3.1 Power sources and storages available in HOMER Pro*

| Power sources | storages |
|---|---|
| ▪ Solar Photovoltaic (PV) | ▪ Flywheels |
| ▪ Wind Turbines | ▪ Customized batteries |
| ▪ Diesel or Petrol Generators | ▪ Flow batteries |
| ▪ Hydro Power | ▪ Hydrogen |
| ▪ Biomass Power | |
| ▪ Utility Grids | |
| ▪ Fuel cells | |

## 3.4 Calculations

### 3.4.1 PV Array Power Output

HOMER uses the following equation to calculate the output of the PV array:

$$P_{PV} = Y_{PV}\, f_{PV} \left(\frac{\overline{G_r}}{\bar{G}_{r.STC}}\right)\left[1 + \propto_p \left(T_c - T_{c,STC}\right)\right]$$

Where;

$Y_{PV}$ is the rated capacity of the PV array, meaning its power output under standard test conditions [kW]

$f_{PV}$ is the PV derating factor [%]

$\bar{G}_{r.}$ is the solar radiation incident on the PV array in the current time step [kW/m2]

$\bar{G}_{r.STC}$ is the incident radiation at standard test conditions [1 kW/m2]

αP is the temperature coefficient of power [%/°C]

Tc is the PV cell temperature in the current time step [Tc,STC is the PV cell temperature under standard test conditions [25 °C]

If, it ignores the effect of temperature on the PV array, HOMER assumes that the temperature coefficient of power is zero, so that the above equation simplifies to:

$$P_{PV} = Y_{PV} f_{PV} \left( \frac{\overline{G_r}}{\bar{G}_{r.STC}} \right)$$

### 3.4.2 Wind Turbine Power Output

HOMER Pro calculates the power output of the wind turbine in each time step. This entails a three-step process, first calculate the wind speed at the hub height of the wind turbine, then to calculate how much power the wind turbine would produce at that wind speed at standard air density, and to adjust that power output value for the actual air density.

### 3.4.3 Calculating Hub Height Wind Speed

In each time step, HOMER calculates the wind speed at the hub height of the wind turbine using the inputs you specify in the Wind Resource window. If it chooses to apply the logarithmic law, HOMER calculates the hub height wind speed using the following equation:

$$U_{hub} = U_{anem} \cdot \frac{\ln(Z_{hub}/Z_0)}{\ln(Z_{anem}/Z_0)}$$

If it chooses to apply the power law, HOMER calculates the hub height wind speed using the following equation:

$$U_{hub} = U_{anem} \cdot \left( \frac{Z_{hub}}{Z_{anem}} \right)^{\propto}$$

Where:

$U_{hub}$ - the wind speed at the hub height of the wind turbine [m/s]

$U_{anem}$ - the wind speed at anemometer height [m/s]

$Z_{hub}$ - the hub height of the wind turbine [m]

$Z_{anem}$ - the anemometer height [m]

A - the power law exponent

- **Turbine Power Output at Standard Air Density**

Once HOMER has determined the hub height wind speed, it refers to the wind turbine's power curve to calculate the power output one would expect from that wind turbine at that wind speed under standard conditions of temperature and pressure.

If the wind speed at the turbine hub height is not within the range defined in the power curve, the turbine will produce no power. This follows the assumption that wind turbines produce no power at wind speeds below the minimum cutoff or above the maximum cut-out wind speeds.

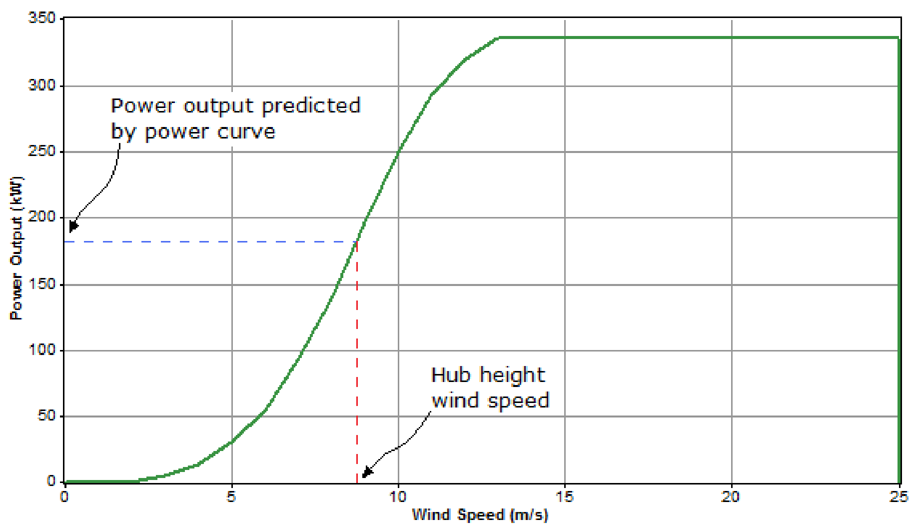



*Figure 3-2 Typical Power Curve of wind turbine*

- **Applying Density Correction**

Power curves typically specify wind turbine performance under conditions of STP (***Figure 5***). To adjust to actual conditions, HOMER multiplies the power value predicted by the power curve by the air density ratio, according to following equation:

$$P_{WTG} = \left(\frac{\rho 3}{\rho_0}\right) P_{WTG,STP}$$

Where:

$P_{WTG}$ - the wind turbine power output [kW]

$P_{WTG,STP}$ - the wind turbine power output at standard temperature and pressure kW]

$\rho$ - the actual air density [kg/m$^3$]

$\rho_0$ - the air density at standard temperature and pressure (1.225 kg/m$^3$)

- **Creates the Generator efficiency curve**

On the Generator Inputs window, when it enters the fuel curve inputs HOMER draws the corresponding efficiency curve. HOMER takes the fuel curve as a straight line. The relationship between generator's fuel consumption in units/hr (term "units" to mean the units specified for the particular fuel, whether kg, L, or m$^3$) and its electrical output is given from the following equation.

$$F = F_{0.}Y_{gen.} + F_{1.}P_{gen.}$$

Where $F_0$ is the fuel curve intercept coefficient in units/hr/kW, $F_1$ is the fuel curve slope in units/hr/kW, $Y_{gen}$ is the rated capacity of the generator in kW, and $P_{gen}$ is the electrical output of the generator in kW. Efficiency of the generator gives from the following equation:

$$\eta_{gen} = \frac{3.6\ P_{gen}}{m_{fuel.} LHV_{fuel}}$$

Where;

$P_{gen}$ - the electrical output in kW,

$m_{fuel}$ - the mass flow rate of the fuel in kg/hr

$LHV_{fuel}$ - the lower heating value (a measure of energy content) of the fuel in MJ/kg.

The factor of 3.6 arises because 1 kWh = 3.6 MJ.

The mass flow rate of the fuel is related to F, the generator's fuel consumption, but the exact relationship depends on the units of the fuel. If the fuel units are kg, then $m_{fuel}$ and F are equal, so the equation for $m_{fuel}$ is as follows:

$$\dot{m}_{fuel} = F = F_{0.} Y_{gen.} + F_{1.} P_{gen.}$$

If the fuel units are liters, the relationship between $m_{fuel}$ and F involves the density. The equation for $m_{fuel}$ is as follows:

$$\dot{m}_{fuel} = \rho_{fuel} \left(\frac{F}{1000}\right) = \frac{\rho_{fuel}\ (F_{0.} Y_{gen.} + F_{1.} P_{gen.})}{1000}$$

Where $\rho_{fuel}$ is the fuel density in kg/m$^3$. If the fuel units are m$^3$ the factor of 1000 is unnecessary, and the equation for $m_{fuel}$ is as follows:

$$\dot{m}_{fuel} = \rho_{fuel} F = \rho_{fuel}\ (F_{0.} Y_{gen.} + F_{1.} P_{gen.})$$

Let us further develop the efficiency equation for the case where the fuel units are liters. In this case, the efficiency equation becomes:

$$\eta_{gen} = \frac{3600.\ P_{gen}}{P_{fuel.}\ \left((F_{0.} Y_{gen.} + F_{1.} P_{gen.})\right) LHV_{fuel}}$$

If we divide numerator and denominator by $Y_{gen}$, the capacity of the generator, and define a new symbol $p_{gen}$ for the relative output of the generator ($p_{gen} = P_{gen}/Y_{gen}$) then the efficiency equation becomes:

$$\eta_{gen} = \frac{3600 \cdot p_{gen}}{\rho_{fuel}\left(F_0 + F_1 \cdot p_{gen}\right) \cdot \mathrm{LHV}_{fuel}}$$

That equation gives the efficiency of the generator as a function of its relative output. It is this relation that HOMER plots in the efficiency curve on the Generator Inputs window when the fuel units are L. If the fuel units are $m^3$, the efficiency equation becomes:

$$\eta_{gen} = \frac{3.6.\ P_{gen}}{P_{fuel.}\ \left((F_{0.}Y_{gen.} + \ F_{1.}P_{gen.})\right)\ LHV_{fuel}}$$

Finally, if the fuel units are kg, the efficiency equation becomes:

$$\eta_{gen} = \frac{3600.\ P_{gen}}{\left(F_{0.}Y_{gen.} + \ F_{1.}P_{gen.}\right)\ LHV_{fuel}}$$

### 3.4.4 Emission Calculations

HOMER Pro calculates the emissions of the following six pollutants:

1. Carbon Dioxide ($CO_2$)
2. Carbon Monoxide (CO)
3. Unburned Hydrocarbons (UHC)
4. Particulate Matter (PM)
5. Sulfur Dioxide ($SO_2$)
6. Nitrogen Oxides ($NO_x$)

These emissions are generated from a generator(s) while generating electricity or from a boiler while generating thermal energy. HOMER first determines kilogram (kg) of pollutant emitted per unit of fuel consumed (emission factor) for each pollutant before simulating the power system. Emission factors for carbon monoxide, unburned hydrocarbons, particular matters and nitrogen oxide are directly specified by the HOMER. HOMER does some calculation using emission factors of other pollutants, carbon and sulfur content of the fuel and following three principal assumptions.

1. Any carbon in the fuel that does not get emitted as carbon monoxide or unburned hydrocarbons gets emitted as carbon dioxide.
2. The carbon fraction of the unburned hydrocarbon emissions is same as that of the fuel.
3. Any sulfur in the *burned* fuel that does not get emitted as particulate matter gets emitted as sulfur dioxide.

It calculates the annual emission of that pollutant by multiplying these emission factors by the total annual fuel consumption values after simulation.

# 4 ELUVAITHIVU ISLAND

## 4.1 General Description

Eluvaithivu is a small island (***Figure 4.1***) covers an area of 1.7 km$^2$ located on the western side of the Jaffna Peninsula. Total population of the island is 787 persons and altogether there are 110 houses. Majority of the inhabitants are fishermen. Due to surface sand layer of the island retention of the rain water is very limited; therefore water scarcity in the island after the rainy season. With the limited water resources available in the island agricultural activities are also restricted to rainy season.

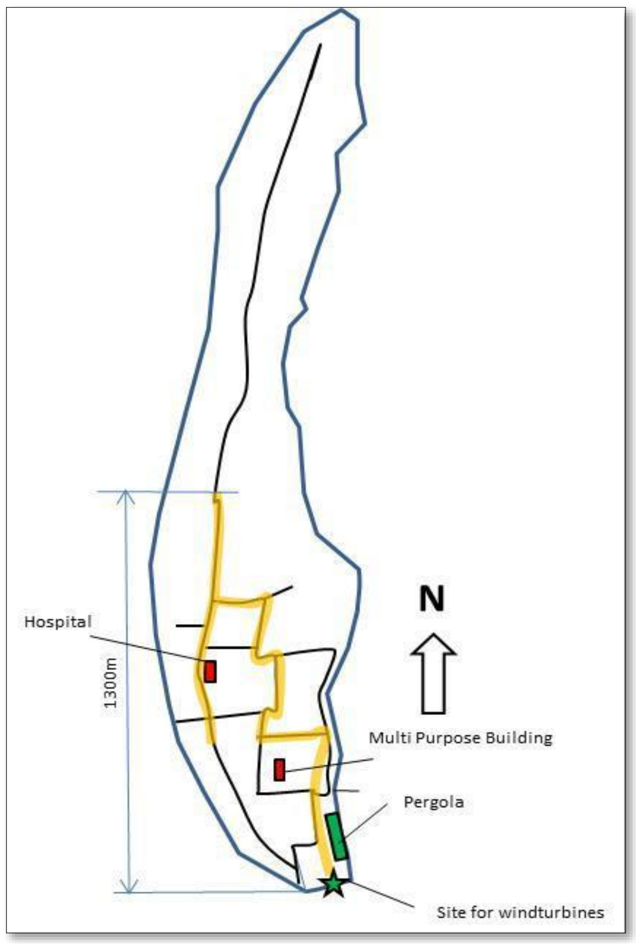



***Figure 4-1 Eluvaithivu Island map***

## 4.2 Climate Pattern

### 4.2.1 Wind Pattern

Overall climate pattern of this island is very much similar to the climatic pattern present in Northern part of Sri Lanka. North-East monsoon brings rain to this part of the country during October to December and 70% of the annual rainfall records in this period. Due to absence of meteorological station within the island meteorological data are not available. However there are two meteorological weather stations located in the Northern region of Sri Lanka, Jaffna city and Mannar. Surface wind speed data have been collecting at three hourly intervals during day time by using a mechanical cup counter anemometer mounted on a 6m mast in meteorological station in Jaffna. There are two sources of wind data are available for Mannar island. One is 6m high mast established by Meteorological Department, Which is located in the middle of the Mannar city. And other data source is 40m high mast is sited on the coast established by CEB and there are two year hourly data is available at this source. Monthly average wind data at 40m high mast is shown in the ***Table 4.1*** and ***Figure 4.2***.

***Table 4.1 .Monthly average wind data at 40 m high mast***

| Month | Average Wind Speed (m/s) |
|---|---|
| January | 4.98 |
| February | 5.08 |
| March | 4.15 |
| April | 4.36 |
| May | 7.55 |
| June | 8.30 |
| July | 8.15 |
| August | 7.30 |
| September | 6.10 |
| October | 4.90 |
| November | 4.84 |
| December | 6.30 |

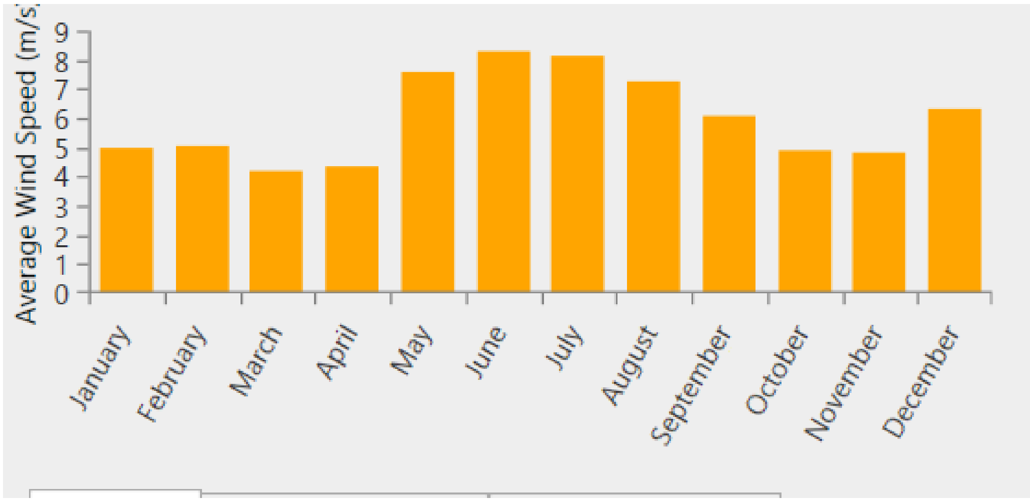



***Figure 4-2  Monthly Average Wind Speed***

### 4.2.2 Solar Radiation Pattern

Solar radiation data were not recorded at above two meteorological stations. Therefore solar radiation data were obtained from the *www.ecoweb.larc.nasa.gov* and observed that, solar radiation levels are fairly uniform over the region and vary from 3.92 – 5.95 kwh/$m^2$/day. Daily average solar radiation variation is presented in ***Table 4.2*** and ***Figure 4.3.***

*Table 4.2 Monthly average Solar Radiation Variation*

| Month | Clearness Index | Average Radiation ($kWh/m^2/day$) |
|---|---|---|
| January | 0.51 | 4.50 |
| February | 0.58 | 5.50 |
| March | 0.58 | 5.95 |
| April | 0.55 | 5.80 |
| May | 0.53 | 5.48 |
| June | 0.45 | 4.66 |
| July | 0.48 | 4.90 |
| August | 0.44 | 4.63 |
| September | 0.49 | 5.02 |
| October | 0.47 | 4.56 |
| November | 0.48 | 4.28 |
| December | 0.46 | 3.92 |

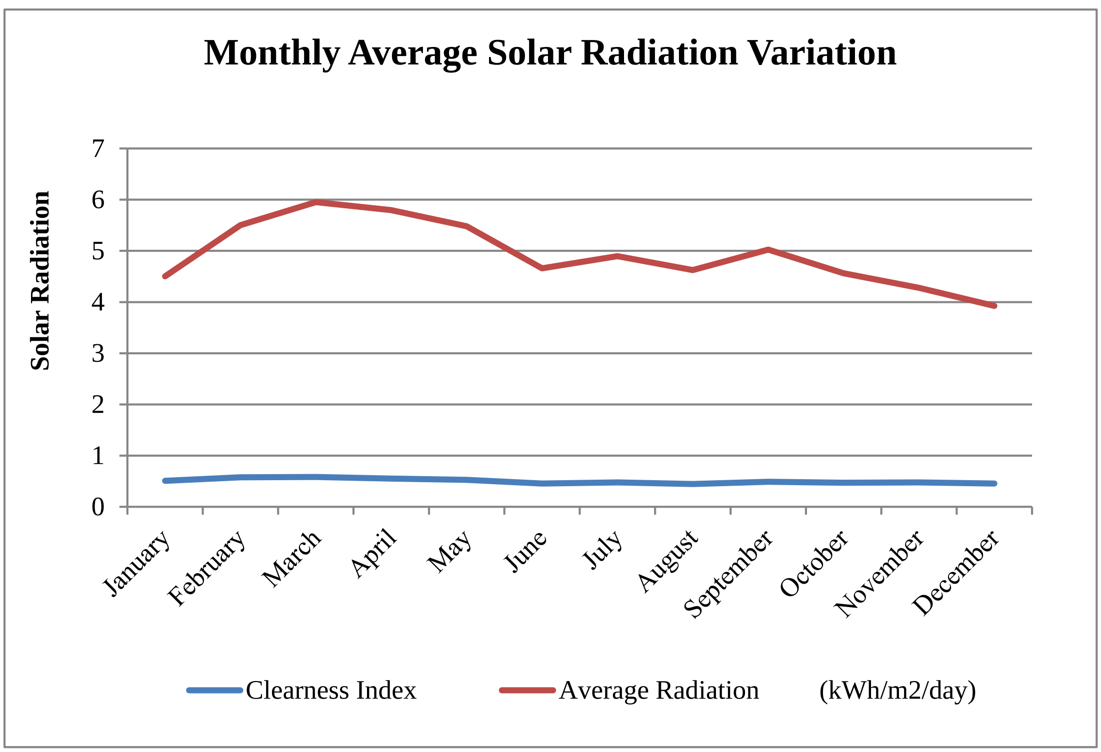



*Figure 4-3 Monthly average Solar Radiation variation*

#### 4.2.3 Level of Electrification

Before commissioning the hybrid power system electricity was supplied by using a 100 kVA diesel generator. Electricity was supplied for limited number of hours during a day (4.30 – 6.30 am and 6.00 to 10.30 pm). Annual electricity consumption was around 47,000 kWh. Monthly electricity consumption and monthly fuel consumption for electricity generation between May 2011 to May 2013 is given in the ***Table 4.3*** and ***Figure 4.4***;

***Table 4.3 Electricity delivered by Diesel Generator and fuel consumption from May 2011 to May 2013***

| **Month** | **Fuel Consumption (Lit)** | **Energy Delivery (kWh)** |
|---|---|---|
| May-11 | 1730 | 2889 |
| Jun-11 | 1840 | 2976 |
| Jul-11 | 1870 | 3330 |
| Aug-11 | 1770 | 3513 |
| Sep-11 | 1825 | 3544 |
| Oct-11 | 1845 | 3702 |
| Nov-11 | 1600 | 3353 |
| Dec-11 | 2080 | 4291 |
| Jan-12 | 1670 | 4592 |
| Feb-12 | 2105 | 4012 |
| Mar-12 | 2250 | 4472 |
| Apr-12 | 2035 | 4291 |
| May-12 | 2100 | 4157 |
| Jun-12 | 1935 | 3481 |
| Jul-12 | 2255 | 4164 |
| Aug-12 | 2150 | 3775 |

| Month | Fuel Consumption (l) | Energy Delivery (kWh) |
|---|---|---|
| Sep-12 | 2205 | 4135 |
| Oct-12 | 2245 | 4136 |
| Nov-12 | 2170 | 3874 |
| Dec-12 | 2350 | 4247 |
| Jan-13 | 800 | 4529 |
| Feb-13 | 2045 | 3853 |
| Mar-13 | 2265 | 4129 |
| Apr-13 | 2115 | 3967 |
| May-13 | 2230 | 3966 |

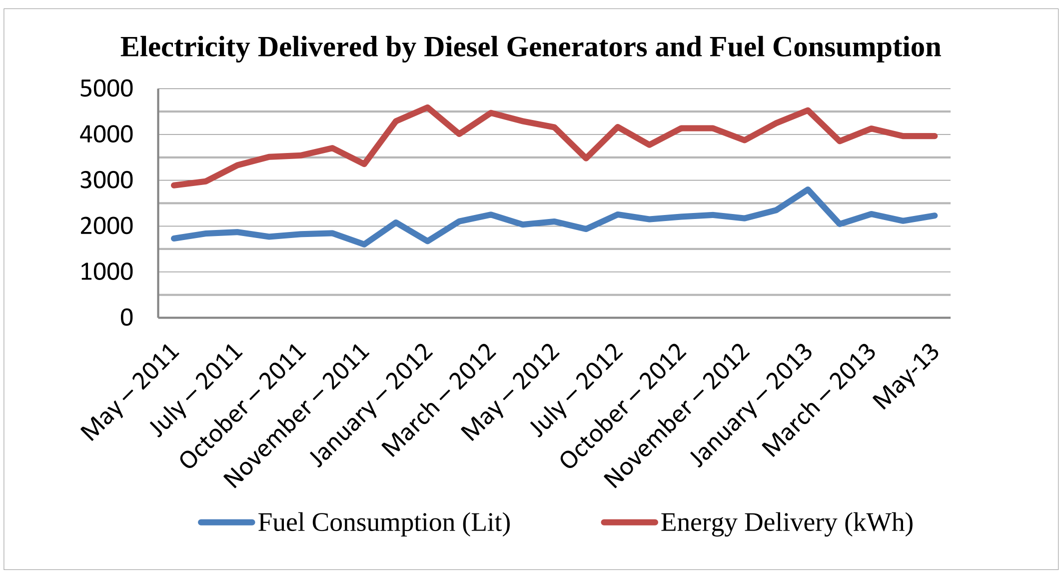



***Figure 4-4 Electricity delivered by Diesel Generator and fuel Consumption from May 2011 to May 2013***

As per the details available in CEB, the monthly electricity consumption of the houses was varied between 20kWh and 40kWh during this period.

Fuel for operating this generator was transported by using boats from main land using 210 liter barrels. The transporter charged Rs. 500.00 (US $ 3.5) per barrel to transport fuel. However up to jetty of the mainland Ceylon Electricity board transports fuel using its vehicles and staff. Ceylon Petroleum Corporation charge Rs. 4.30 per liter to Transport fuel from Colombo to Jaffna. Therefore altogether around Rs. 10.00 cost per liter to transport fuel to the island.

The old generator run in the power plant consumes excessive amounts of fuel, because the generator always operates with part load. As per the ***Table 4.3*** the average power generation of the generator was 1.89 kWh/l. Therefore the electricity generation cost in the island is above 55.00 Rs/kWh (US$ 0.4/ kWh). However Ceylon Electricity Board charged less than 5.00 Rs/kWh from most of the consumers. Therefore Ceylon Electricity Board incurred severe financial loss in every year in operating diesel generating systems in the island.

Hourly avarage load of the island delivered by the existing 100kVA Diesel generator was recorded are given in the ***Table 4.4*** and ***Figure 4.5***.

***Table 4.4 Hourly average load of the Island delivered by the existing Generators***

| **Time** | **Hourly Average Load (kWp)** |
|---|---|
| 0:00-1:00 | 3.34 |
| 1:00-2:00 | 3.45 |
| 2:00-3:00 | 3.68 |
| 3:00-4:00 | 4.26 |
| 4:00-5.00 | 5.98 |
| 5:00-6:00 | 11.85 |
| 6:00-7:00 | 9.32 |
| 7:00-8:00 | 5.18 |
| 8:00-9:00 | 3.22 |

| Time | Hourly Average Load (kWp) |
|---|---|
| 9:00-10:00 | 3.22 |
| 10:00-11:00 | 5.87 |
| 11:00-12:00 | 7.02 |
| 12:00-13:00 | 5.18 |
| 13:00-14:00 | 4.26 |
| 14:00-15:00 | 3.34 |
| 15:00-16:00 | 3.34 |
| 16:00-17:00 | 3.80 |
| 17:00-18:00 | 7.13 |
| 18:00-19:00 | 20.36 |
| 19:00-20:00 | 25.30 |
| 20:00-21:00 | 21.39 |
| 21:00-22:00 | 12.65 |
| 22:00-23:00 | 10.47 |
| 23:00-00:00 | 5.18 |

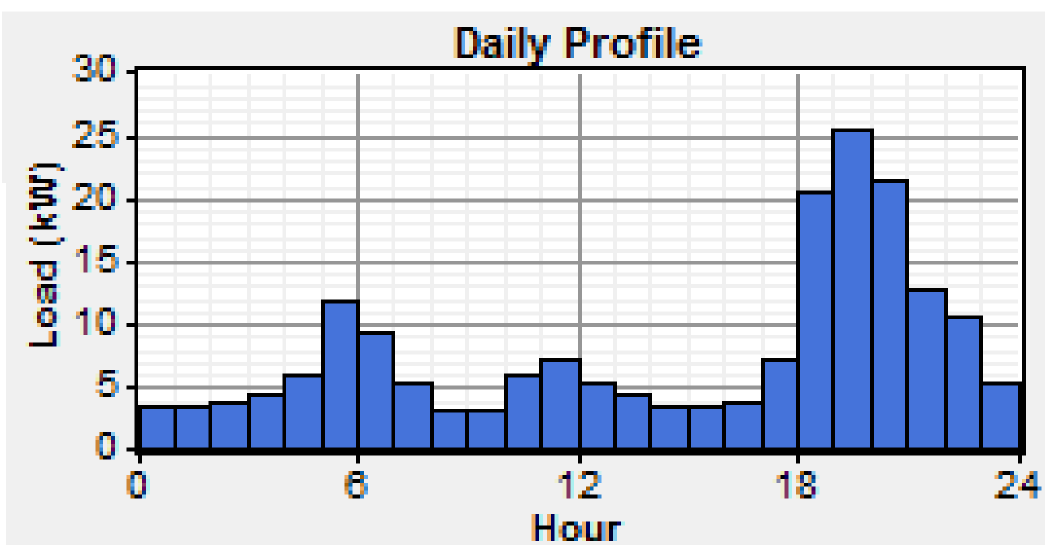



*Figure 4-5  Daily Load profile measured in kW*

## 4.3 Solar Wind Diesel Battery Hybrid Power System in Eluvaithivu

Among the all 4 inhabitant islands in northern part of the country Eluvaithivu Island was selected to implement a small pilot project for demonstrating the maturity and feasibility of hybridization of different power sources. The project was realized in a closed collaboration between Asian Development Bank (ADB) and the local electricity supplier Ceylon Electricity Board. One other objective of this pilot project was train Ceylon Electricity Board staff to prepare them for implementing similar projects on the other islands.

Solar Photo Voltaic Panels (Solar PV), Wind turbines and Diesel Generators were selected as power generating source of this pilot power plant. There are millions of combinations available with these three power sources to fulfill the requirement. Therefore it was used HOMER software to identified optimum combination.

### 4.3.1 Hybrid Power System in Eluvaithivu.

Initially simulation was done with 0.25kW Solar PV panels, 10kW wind turbines, 30kW Diesel Generators and 27.5kWLi- Iron kWh batteries. After simulating using HOMER software, it was identified that 177 numbers of 0.25kW Solar PV panels, 2 numbers of wind turbines, 1 number of Diesel generator, 3 number of Li Iron Batteries and 100kW convertor as main component of the hybrid power system. However later it was identified that transporting of 10kW wind turbine to the island is difficult. Therefore 2 numbers of 10kW wind turbines were replaces from 6 numbers of 3.5kW wind turbines. System configuration of installed Hybrid System is shown in ***Figure 4.6***.

100 numbers of 177 PV panels are directly connected to the AC load and rest is connected to DC bus, which are used to charge to batteries. 1 battery is connected to each phase of the local grid (***Annex A***).

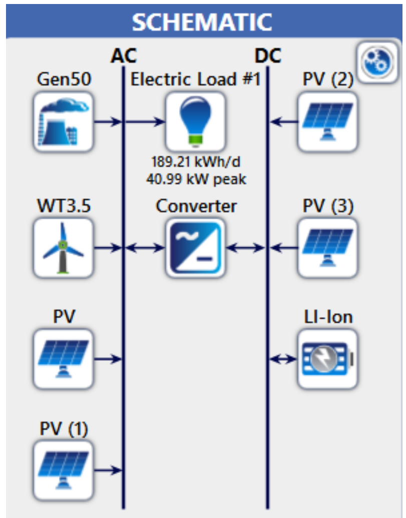



***Figure** 4-6 System configuration of installed Hybrid System as per HOMER software*

# 5 RESULTS AND DISCUSSION

## 5.1 Comparison of Base case Generator System with new Hybrid Configuration

HOMER Pro gives two different optimum results for the given inputs. The first one is for cycle charging (CC) operation and the second is for Load following (LF) operation. If system designs for CC operation, then power generated by the diesel generator is also used for battery charging other than renewable resources. But in the LF operation battery charging is done only from the renewable energy. Therefore the fuel consumption of the CC operation will be higher. However, when there is low load in the system no need to operate the generator unless power stored in the batteries is insufficient to cater the load. Once battery voltage drops to a certain level, generator operates and supplies power to the load while charging batteries. This is the reason behind the low generator running hours of the CC operation. Since generator does not charge the battery, ability to absorb renewable energy of LF operation is higher, this increases renewable fraction of LF operation. The hybrid power plant installed in Eluvathivu Island was designed to operate CC operation. The comparison of all system with Design Configuration is given in ***Table 5.1***.

***Table 5.1 Comparison of all system with Design Configuration***

| Description | Cycle Charging Operation (CC) | Load Following Operation (LF) | 100kW Diesel Generator System |
|---|---|---|---|
| COE ($) | 0.82 | 0.84 | 1.77 |
| NPC ($) | 994,438.80 | 1,018,907.00 | 2,132,852.00 |
| Renewable Fraction (%) | 45.08 | 58.14 | 0.00 |
| Generator Operating Hours | 1,650.00 | 3,165.00 | 8760.00 |
| Generator Production (kWh) | 37,929.17 | 28,907.27 | 220,242.00 |
| Generator Fuel Consumption (l) | 13,175.11 | 12,234.84 | 80,249.00 |
| Battery Annual Throughput (kWh) | 25,906.12 | 19,425.30 | 0.00 |

When it compares the results of installed hybrid configuration and base case generator system, unit cost of energy of diesel system is more than two times higher than installed hybrid system. Net present cost of the hybrid system is 2.14 times lesser than generator system. This is due to six times higher fuel consumption of the diesel generator system. This ratio will be further increased with fuel price escalations in future. If the solar radiation is available during the day time most probably total load of the island will be fulfilled by energy generated from PV panels of the hybrid system and in the night time, which has high load demand the generator will be catered the load with energy stored in batteries. According to typical diesel generator efficiency curves efficiency of the diesel generator in the generator system is low.

As per the optimized output data of the system, total unmet electricity load of the Island is almost zero. However there is a doubt about the reliability of this system since Diesel generator available in the system is not sufficient to meet the design peak of the system. This was experienced several times during last four months. The system was tripped when the peak demand has been increased more than 30kW. During these times CEB switched on diesel generator in old power station. When it analysed actual hybrid system data which are presented in ***Table 5.8***, ***Table 5.9, Table 5.10*** and ***Table 5.11***, old power station generator also provide around 600kWh per month. Also there is doubt about future performance of this system because in recent past Sri Lanka experiences abnormal weather patterns.

***Table 5.2 Discounted cash flow***

| **Year** | **Discounted cash flow** | | | | | |
|---|---|---|---|---|---|---|
| | **Hybrid System** | | **Diesel System** | | **Difference** | |
| | **Annual** | **Cumulative** | **Annual** | **Cumulative** | **Annual** | **Cumulative** |
| 0 | -$410,690 | -$410,690 | -$40,000 | -$40,000 | -$370,690 | $370,690 |
| 1 | -$16,401 | -$427,091 | -$94,949 | -$134,949 | $78,548 | $292,142 |
| 2 | -$15,928 | -$443,019 | -$130,255 | -$265,204 | $114,327 | $177,815 |

| Year | Discounted cash flow | | | | | |
|---|---|---|---|---|---|---|
| | Hybrid System | | Diesel System | | Difference | |
| | Annual | Cumulative | Annual | Cumulative | Annual | Cumulative |
| 3 | -$15,468 | -$458,487 | -$89,550 | -$354,754 | $74,082 | $103,734 |
| 4 | -$15,022 | -$473,510 | -$123,152 | -$477,905 | $108,129 | $4,396 |
| 5 | -$14,589 | -$488,099 | -$84,458 | -$562,364 | $69,869 | $74,265 |
| 6 | -$111,136 | -$599,234 | -$116,438 | -$678,802 | $5,302 | $79,567 |
| 7 | -$13,759 | -$612,994 | -$112,389 | -$791,191 | $98,630 | $178,197 |
| 8 | -$13,363 | -$626,356 | -$77,358 | -$868,549 | $63,996 | $242,193 |
| 9 | -$12,977 | -$639,333 | -$106,260 | -$974,809 | $93,283 | $335,476 |
| 10 | -$23,981 | -$663,314 | -$72,960 | -$1,047,769 | $48,978 | $384,454 |
| 11 | -$12,239 | -$675,554 | -$100,466 | -$1,148,235 | $88,227 | $472,682 |
| 12 | -$93,235 | -$768,789 | -$96,975 | -$1,245,210 | $3,739 | $476,421 |
| 13 | -$11,543 | -$780,332 | -$66,826 | -$1,312,036 | $55,283 | $531,704 |
| 14 | -$11,210 | -$791,543 | -$91,685 | -$1,403,722 | $80,475 | $612,179 |
| 15 | -$10,887 | -$802,429 | -$63,026 | -$1,466,748 | $52,140 | $664,319 |
| 16 | -$10,573 | -$813,002 | -$86,686 | -$1,553,434 | $76,113 | $740,432 |
| 17 | -$10,268 | -$823,270 | -$59,443 | -$1,612,877 | $49,175 | $789,606 |
| 18 | -$78,218 | -$901,489 | -$81,960 | -$1,694,837 | $3,742 | $793,348 |
| 19 | -$18,316 | -$919,804 | -$79,110 | -$1,773,947 | $60,795 | $854,143 |
| 20 | -$9,405 | -$929,209 | -$54,446 | -$1,828,392 | $45,041 | $899,183 |
| 21 | -$9,133 | -$938,342 | -$74,796 | -$1,903,188 | $65,662 | $964,846 |
| 22 | -$8,870 | -$947,212 | -$51,350 | -$1,954,538 | $42,480 | $1,007,326 |
| 23 | -$8,614 | -$955,826 | -$70,718 | -$2,025,256 | $62,104 | $1,069,429 |
| 24 | -$65,620 | -$1,021,447 | -$68,260 | -$2,093,516 | $2,640 | $1,072,069 |
| 25 | $40,749 | -$980,697 | -$39,336 | -$2,132,852 | $80,085 | $1,152,154 |

Initial capital cost of the current system was $ 410,690 which more than 10 times higher than the capital cost of old system. ***(Table 5.2)*** However due high fuel cost of the old system project discounted payback will be less than 4 years and present worth value of the project will be $ 1,152,154. Therefore investment for this project is viable.

## 5.2 Analysis of Future Electricity Demand

Sensitivity analysis was carried out to check how the new hybrid power system will be behaved in future, when scaled average Electrical load of the Island increases. Scaled average load was increased from 190 to 250 kWh/day by 5kWh/day increments.

| Sensitivity | Architecture | | | | | | | | | Cost | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Electric Load #1 Scaled Average (kWh/d) | PV (kW) | PV (1) (kW) | PV (2) (kW) | PV (3) (kW) | WT3.5 | Gen50 (kW) | LI-Ion | Converter (kW) | Dispatch | COE ($) | NPC ($) | Operating cost ($) | Initial capital ($) | Fuel cost ($) |
| 190 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.810 | $981,304 | $32,661 | $410,690 | $11,993 |
| 195 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.796 | $990,262 | $33,174 | $410,690 | $12,394 |
| 200 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.783 | $998,154 | $33,625 | $410,690 | $12,836 |
| 205 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.771 | $1.01M | $34,189 | $410,690 | $13,197 |
| 210 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.756 | $1.01M | $34,458 | $410,690 | $13,546 |
| 215 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.744 | $1.02M | $34,881 | $410,690 | $14,003 |
| 220 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.734 | $1.03M | $35,415 | $410,690 | $14,456 |
| 225 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.723 | $1.04M | $35,877 | $410,690 | $14,847 |
| 230 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.714 | $1.05M | $36,439 | $410,690 | $15,308 |
| 235 | 11.5 | 13.5 | 9.75 | 10.5 | 6 | 30.0 | 3 | 100 | CC | $0.703 | $1.05M | $36,794 | $410,690 | $15,624 |



***Figure 5-1 HOMER Window of Sensitivity analysis of Scaled Average electrical load***

By analyzing sensitivity of the system using HOMER Pro it was observed that the designed configuration of the system cannot fulfill electrical requirement more than 235kWh/day. Renewable fraction of the system decreases with load increases since annual Electricity generation from Solar PV and Wind turbines are remaining same and Diesel Generator generates more power to cater additional requirement of the load. During the analysis it was identified that when daily average load increases the electrical efficiency of the diesel generator slightly increases and amount of excess energy decreases. This means overall efficiency of the hybrid power system goes high. Cost of energy will decrease linearly when load increases. The effecting variables for cost of energy are cost of fuel and operating cost. Both of these two variables also vary linearly with the load, as shown in the ***Figure 5.2***. The results of the sensitivity analysis are tabulated in ***Table 5.3***. However total unmet load increases, which implies some capacity shortage of the system when average load increases. HOMER Pro illustrated that the system can sustain for 235kWh/day scaled average load. There is a doubt about system reliability with fluctuations of renewable resources.

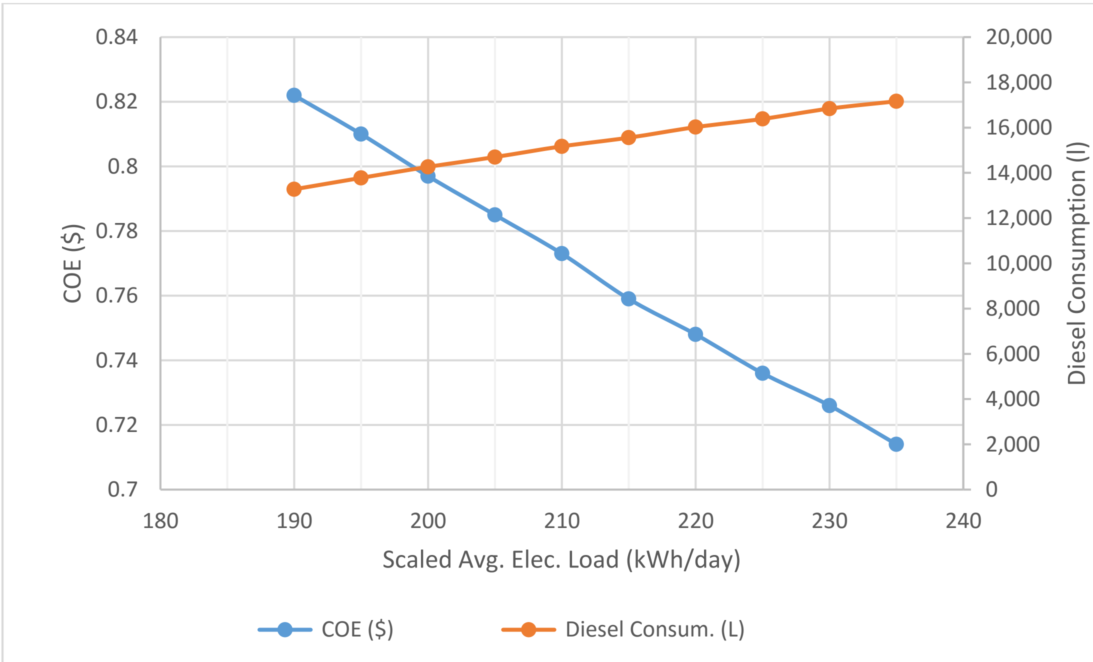



***Figure 5-2 Variation of Fuel Consumption and Cost of Energy with Annual scale average load***

## 5.3 Possible Expansion of the current System

### 5.3.1 Add Component to the system

1. Add components to the system

It is necessary to analysis how the system can be further improved to reduce cost of energy, fuel consumption and emissions. Four possible expansions were considered for the analysis and their results are tabulated in ***Table 5.4***.

1. Add additional 2.25kW module of PV panel to East oriented roof of pergola
2. Add additional 2.25kW module of PV panel to West oriented roof of pergola

3. Add additional 3.5kW wind turbine
4. Increase capacity of the Diesel Generator up to 50kW

Capacity of solar PV module is 2.25kW. According to the results tabulated ***Table 5.4***, PV production is not varied with the orientation of the panel. Annual electricity production increment of both orientations is almost same. When it is added additional Solar PV module to the system (capital cost will be increased by $ 4,050), total energy generated by Solar PV will be increased by 3,373 kWh per year for east oriented roof and 3,389kWh per year for west oriented roof and cost of energy will be increased by $0.004 per kWh for both cases. However the amount of excess energy of the system will be also increased by 3,387 kWh/year for east roof and 3,388 kWh/year for west roof. That implies that all the additional energy generated by PV panels is accounted as excess energy. Therefore, there is no impact to the system when PV capacity increases. The investment for increasing PV capacity is not a viable option.

With the initial capital of $ 18,000 it can be added another 3.5kW wind turbine to the system. Then the total electricity generated by wind will be increased by 2,749kWh per year and electricity generated by diesel generator reduced by 1,351 kWh per year. Fuel consumption will be reduced by 463 liter per year while increasing renewable fraction by 2%. However, cost of energy will be increased by $ 0.01 per kWh. Net present value of the system also increases from around $ 12,000. Therefore investment for increasing wind power capacity is also not a viable option.

Current capacity of the diesel generator is not sufficient to meet the designed peak of the system. Therefore it was analyzed system performance with higher generator capacity. The selected Diesel generator capacity was 50kW, which is the next higher capacity than design peak of the system. Generator Electricity production and excess energy of the system will be reduced by 922kWh/year and 1,261 kWh/year respectively. However Cost of energy will be increased by $ 0.027 per kWh. NPC will be increased by around $ 32, 000. Therefore this is also not an economically viable option. However this needs to be considered in future with the increment of electricity demand of the Island.

### 5.3.2 Change Tilt angle of the PV panels

Angle of slope of the PV panels also affecting factor of PV energy production. Therefore a sensitivity analysis was carried out to identify the effect of PV angle. Result of such analysis is tabulated in ***Table 5.5.***

Cost of energy decreases linearly with the increment of the tilt angle of PV panels. The results show that, total electricity production, PV Electricity production as well as excess energy of the system will be reduced almost same amount increment of angle of the PV panels. Tilt angle of slope of PV panels will not be affected to the fuel consumption of the system. This result gives an idea about PV energy production of the installed hybrid system. Most of the energy generated by PV is calculated as excess energy.

## 5.4 Analyze system performance with different weather conditions

### 5.4.1 Variation of solar radiation

Solar radiation of the site is between 3.92-5.95 kWh/m$^2$/day. It was carried out a sensitivity analysis to investigate the importunacy of the solar radiation to the system performance. Sensitivity input, solar radiation was increased by 0.5 kWh/m$^2$/day intervals from 3.5 to 6.0. The results are tabulated in ***Table 5.6.*** Result of Sensitivity analysis is given in the ***Figure 5.3.***

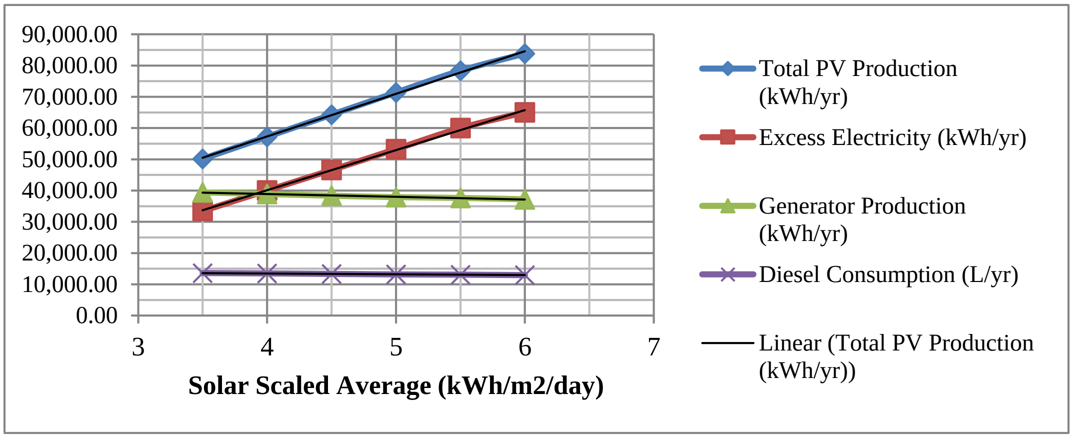



***Figure 5-3 Result of Sensitivity Analysis***

As per the ***Figure 5.3,*** total PV production curve and Excess Electricity curve are almost parallel to each other when solar radiation increases. This means that additional electricity production due to increment of solar radiation will be accounted as excess energy of the system. There is no any significant reduction in generator electricity production. Therefore the effects of change solar radiation will not be affected to the performance of the system. This result implies that if other conditions remaining same, the system can be operated even the locations which has very low solar radiation.

### 5.4.2 Variation of wind speed

Monthly average 60m height wind speed of the site is between 4.149-8.3 m/s. It was carried out a sensitivity analysis to investigate the importunacy of the wind speed to the system performance. Sensitivity input, wind was increases by 0.5 m/s intervals from 2.0 to 8.0. The results are tabulated in ***Table 5.6***.

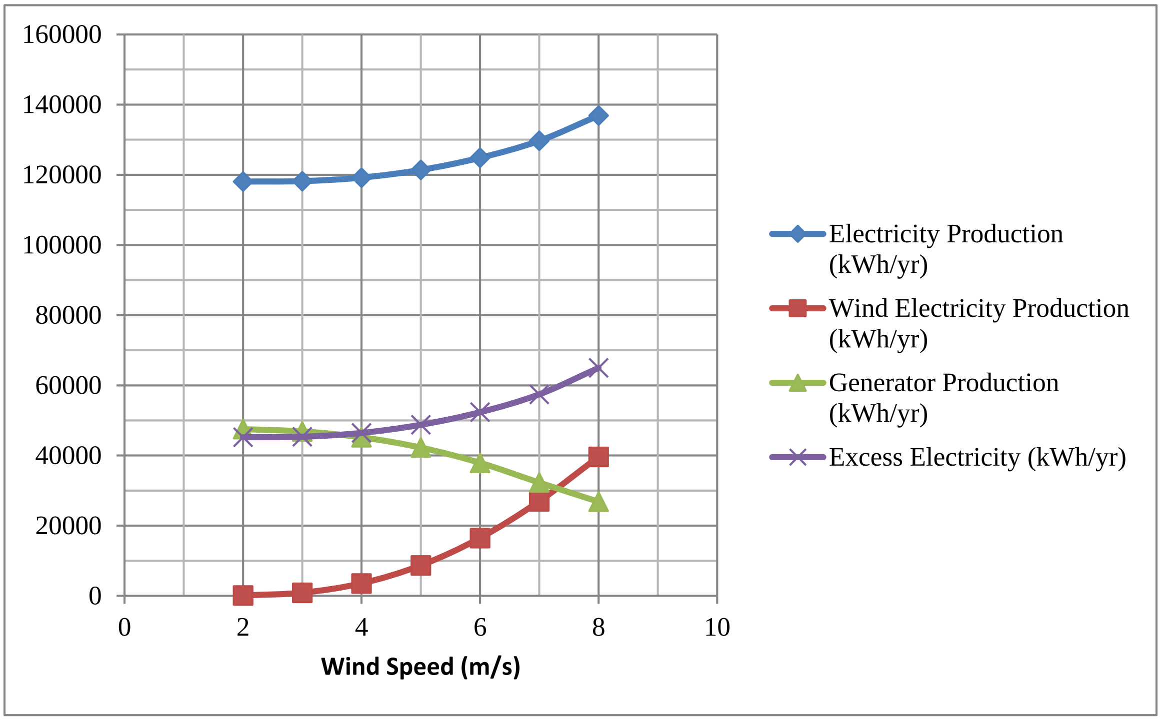



***Figure 5-4 Variation of Electricity Production of Wind, Generator and Excess Electricity with wind speed***

***Figure 5.4,*** shows that, Wind speed up to 4 m/s system performance remains same. Wind electricity portion of the system is almost zero in this range of wind speeds, due to low power generation (less than 0.1kW) by the wind turbines in this range of wind speeds. There is a rapid increment of wind electricity when wind speed above 4m/s and rapid decrease of the generator production and cost of energy due to rapid reduction of fuel consumption. This implies that the role of generator will be substituted by wind turbines in high wind speeds. And also there is a rapid increment of renewable fraction of the system when wind speed exceeds 4m/s. Renewable fraction of the system will increase more than 6% when wind speed increase 1m/s. Therefore from the above results the effects of change wind speed will be an affecting factor to the performance of the system.

***Table 5.3 Sensitivity Scaled Average Electricity Load***

| **Description** | **Sensitivity** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Scaled Avg. Electrical Load (kWh/day) | 190 | 195 | 200 | 205 | 210 | 215 | 220 | 225 | 230 | 235 |
| COE ($) | 0.822 | 0.81 | 0.797 | 0.785 | 0.773 | 0.759 | 0.748 | 0.736 | 0.726 | 0.714 |
| NPC ($) | 996,452 | 1,006,893 | 1,016,755 | 1,026,282 | 1,034,838 | 1,040,058 | 1,049,419 | 1,055,354 | 1,064,094 | 1,069,679 |
| Renewable Fraction (%) | 44.88 | 44.24 | 43.65 | 43.46 | 42.78 | 42.2 | 41.79 | 41.52 | 41.09 | 41.07 |
| Total Electricity Production (kWh/yr) | 125,143 | 126,602 | 128,044 | 129,212 | 130,762 | 132,272 | 133,657 | 134,941 | 136,368 | 137,460 |
| PV Electricity Production (kWh/yr) | 70,425 | 70,425 | 70,425 | 70,425 | 70,425 | 70,425 | 70,425 | 70,425 | 70,425 | 70,425 |
| Wind Electricity Production (kWh/yr) | 16,492 | 16,492 | 16,492 | 16,492 | 16,492 | 16,492 | 16,492 | 16,492 | 16,492 | 16,492 |
| Generator Electricity Production (kWh/yr) | 38,226 | 39,685 | 41,126 | 42,295 | 43,845 | 45,354 | 46,740 | 48,024 | 49,450 | 50,543 |
| Electrical Consumption(kWh/yr) | 69,346 | 71,169 | 72,990 | 74,807 | 76,628 | 78,466 | 80,294 | 82,117 | 83,938 | 85,764 |
| Excess Electricity (kWh/yr) | 52,356 | 51,939 | 51,567 | 50,802 | 50,555 | 50,271 | 49,817 | 49,318 | 48,908 | 48,189 |
| Unmet load (kWh/yr) | 4.11 | 5.94 | 10.45 | 18.37 | 21.63 | 9.16 | 6.17 | 7.74 | 11.66 | 11.3 |
| Diesel Consumption (L/yr) | 13,275 | 13,779 | 14,266 | 14,700 | 15,173 | 15,556 | 16,023 | 16,386 | 16,843 | 17,166 |
| Gen. Running /(Hours/yr) | 1,660 | 1,721 | 1,772 | 1,847 | 1,858 | 1,801 | 1,848 | 1,832 | 1,861 | 1,859 |
| $CO_2$ (kg/yr) | 34,761 | 36,081 | 37,357 | 38,493 | 39,733 | 40,736 | 41,957 | 42,908 | 44,106 | 44,951 |

*Table 5.4 Identification of Possible Expansion of the Current System*

| Case | Current System | Add. PV module for East Oriented roof | Add. PV module for West Oriented roof | Add. Wind Turbine | Increase Gen. capacity |
|---|---|---|---|---|---|
| West Oriented PV Capacity (kW) | 9.75 | 9.75 | 12 | 9.75 | 9.75 |
| East Oriented PV Capacity (kW) | 10.5 | 12.75 | 10.5 | 10.5 | 10.5 |
| Number of Wind Turbine | 6 | 6 | 6 | 7 | 6 |
| Generator Capacity | 30 | 30 | 30 | 30 | 50 |
| COE ($) | 0.824 | 0.828 | 0.828 | 0.834 | 0.851 |
| NPC ($) | 994,439 | 998,848 | 999,343 | 1,006,050 | 1,026,504 |
| Operating cost ($) | 33,241 | 33,261 | 33,290 | 32,875 | 34,676 |
| Total Initial capital ($) | 413,690 | 417,740 | 417,740 | 431,690 | 420,690 |
| Initial capital of PV ($) | 81,450 | 85,500 | 85,500 | 81,450 | 81,450 |
| Initial capital of Wind Turbine ($) | 108,000 | 108,000 | 108,000 | 126,000 | 108,000 |
| Initial capital of Generator ($) | 18,000 | 18,000 | 18,000 | 18,000 | 25,000 |
| O&M ($) | 3,557 | 3,624 | 3,625 | 3,735 | 5,606 |
| Renewable Fraction (%) | 45.08 | 45.29 | 45.21 | 47.03 | 46.42 |
| Total Fuel (L/yr) | 13,175 | 13,130 | 13,152 | 12,712 | 12,411 |
| Elec. Production (kWh/yr) | 124,847 | 128,220 | 128,236 | 126,244 | 123,925 |
| PV Elec. Production (kWh/yr) | 70,425 | 73,947 | 73,905 | 70,425 | 70,425 |
| Wind Elec. Production (kWh/yr) | 16,492 | 16,492 | 16,492 | 19,241 | 16,492 |
| Generator Production (kWh/yr) | 37,929 | 37,780 | 37,839 | 36,578 | 37,007 |
| Elec. Consumption (kWh/yr) | 69,059 | 69,059 | 69,060 | 69,060 | 69,063 |
| Excess Elec (kWh/yr) | 52,351 | 55,738 | 55,739 | 53,815 | 51,090 |
| Unmet load (kWh/yr) | 4.203 | 4.022 | 3.873 | 3.224 | 0 |
| Carbon Dioxide (kg/yr) | 34,500 | 34,381 | 34,439 | 33,289 | 32,491 |
| Generator Running (Hours/yr) | 1,650 | 1,649 | 1,653 | 1,597 | 1,399 |

***Table 5.5 Sensitivity of Tilt Angle of the PV Panels***

| **Description** | **Sensitivity** | | | |
|---|---|---|---|---|
| PV Slope (°) | 5 | 10 | 15 | 20 |
| COE ($) | 0.827 | 0.826 | 0.825 | 0.824 |
| NPC ($) | 997,403 | 996,053 | 994,954 | 994,439 |
| Operating cost ($) | 33,410.6 | 33,333.3 | 33,270.4 | 33,240.9 |
| Fuel cost ($) | 13,310.7 | 13,250.4 | 13,198.4 | 13,175.1 |
| O&M cost ($) | 3,557.66 | 3,557.33 | 3,557.12 | 3,557.12 |
| Renewable Fraction (%) | 44.54 | 44.77 | 44.98 | 45.07 |
| Electricity Production (kWh/yr) | 127,865 | 127,166 | 126,132 | 124,847 |
| Total PV Production (kWh/yr) | 73,072.5 | 72,533.7 | 71,648.3 | 70,425.3 |
| Wind Electricity Production (kWh) | 16,492.1 | 16,492.1 | 16,492.1 | 16,492.1 |
| Generator Production (kWh/yr) | 38,300.1 | 38,139.9 | 37,991.9 | 37,929.2 |
| Electricity Consumption (kWh/yr) | 69,059.2 | 69,059.2 | 69,059.1 | 69,059.3 |
| Excess Electricity (%) | 43.29 | 42.97 | 42.52 | 41.93 |
| Excess Electricity (kWh/yr) | 55,349 | 54,648.9 | 53,626.8 | 52,350.7 |
| Unmet load (kWh/yr) | 4.226 | 4.290 | 4.346 | 4.203 |
| Diesel Consumption (L/yr) | 13,310.7 | 13,250.4 | 13,198.4 | 13,175.1 |
| Generator Running (Hours/yr) | 1,672 | 1,661 | 1,654 | 1,650 |
| Carbon Dioxide (kg/yr) | 34,855.4 | 34,697.6 | 34,561.3 | 34,500.4 |
| Generator O&M Cost ($) | 50.16 | 49.83 | 49.62 | 49.5 |
| Battery annual Throughput (kWh/yr) | 26,081.3 | 26,080.5 | 25,989.4 | 25,906.1 |

*Table 5.6 Sensitivity Solar Scaled Average*

| Description | Sensitivity | | | | | |
|---|---|---|---|---|---|---|
| Solar Scaled Avg. (kWh/m²/day) | 3.5 | 4.0 | 4.5 | 5.0 | 5.5 | 6.0 |
| COE ($) | 0.830 | 0.829 | 0.827 | 0.824 | 0.823 | 0.821 |
| NPC ($) | 1,000,948.0 | 1,000,024.0 | 997,510.5 | 994,363.7 | 993,029.3 | 990,190.9 |
| Operating cost ($) | 33,613.5 | 33,560.6 | 33,416.7 | 33,236.6 | 33,160.2 | 32,997.7 |
| Fuel cost ($) | 13,586.7 | 13,477.8 | 13,323.0 | 13,167.7 | 13,091.3 | 12,947.5 |
| O&M ($) | 3,556.3 | 3,557.3 | 3,557.5 | 3,557.1 | 3,557.1 | 3,556.7 |
| Renewable Fraction (%) | 42.9 | 43.7 | 44.5 | 45.1 | 45.5 | 46.1 |
| Electricity Production (kWh/yr) | 106,053.8 | 112,600.7 | 119,115.8 | 125,749.9 | 132,466.4 | 137,515.2 |
| Total PV Production (kWh/yr) | 50,151.6 | 57,204.1 | 64,266.7 | 71,361.3 | 78,334.7 | 83,820.7 |
| Wind Electricity Production (kWh) | 16,492.1 | 16,492.1 | 16,492.1 | 16,492.1 | 16,492.1 | 16,492.1 |
| Generator Production (kWh) | 39,410.1 | 38,904.5 | 38,357.0 | 37,896.5 | 37,639.6 | 37,202.5 |
| Electricity Consumption (kWh/yr) | 69,060.2 | 69,060.7 | 69,058.8 | 69,059.3 | 69,059.9 | 69,059.9 |
| Excess Electricity (%) | 31.6 | 35.6 | 39.1 | 42.4 | 45.3 | 47.3 |
| Excess Electricity (kWh/yr) | 33,492.2 | 40,050.0 | 46,588.9 | 53,255.3 | 59,988.2 | 65,044.9 |
| Unmet load (kWh/yr) | 3.2 | 2.8 | 4.7 | 4.1 | 3.5 | 3.5 |
| Diesel Consumption (L) | 13,586.7 | 13,477.8 | 13,323.0 | 13,167.7 | 13,091.3 | 12,947.5 |
| Generator Running /Hours | 1,625.0 | 1,661.0 | 1,668.0 | 1,652.0 | 1,652.0 | 1,640.0 |
| Carbon Dioxide (kg/yr) | 35,578.2 | 35,292.9 | 34,887.7 | 34,481.0 | 34,281.0 | 33,904.5 |
| Generator O&M Cost ($) | 48.8 | 498 | 50.0 | 49.6 | 49.6 | 49.2 |
| Battery Annual Throughput (kWh) | 26,078.5 | 26,078.2 | 26,074.0 | 25,903.5 | 25,820.3 | 25,839.1 |

*Table 5.7 Sensitivity wind speed*

| **Description** | **Sensitivity** | | | | | | |
|---|---|---|---|---|---|---|---|
| Wind Scaled Average (m/s) | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 | 7.00 | 8.00 |
| COE ($) | 0.86 | 0.85 | 0.85 | 0.83 | 0.81 | 0.78 | 0.75 |
| NPC ($) | 1,035,754 | 1,031,121 | 1,020,749 | 1,000,435 | 981,236 | 945,231 | 907,285 |
| Operating cost ($) | 35,777.38 | 35,512.23 | 34,918.56 | 33,755.80 | 32,656.91 | 30,596.07 | 28,424.11 |
| Fuel cost ($) | 14,748.75 | 14,536.67 | 14,042.31 | 13,084.08 | 11,979.57 | 10,235.78 | 8,517.52 |
| O&M Cost ($) | 5,109.50 | 5,083.40 | 5,034.80 | 4,935.80 | 4,938.50 | 4,788.20 | 4,580.30 |
| Renewable Fraction (%) | 31.12 | 32.09 | 34.43 | 38.93 | 44.81 | 53.18 | 61.08 |
| Elec. Production (kWh/yr) | 117,615 | 117,719 | 118,768 | 120,787 | 124,534.10 | 129,236.90 | 136,436.50 |
| Total PV Elec. Prod. (kWh/yr) | 69,939 | 69,939 | 69,939 | 69,939 | 69,939.77 | 69,939.77 | 69,939.77 |
| Wind Elec. Prod. (kWh/yr) | 106.30 | 881.82 | 3,545.15 | 8,676 | 16,479.06 | 26,963.74 | 39,619.63 |
| Gen. Prod. (kWh/yr) | 47,569 | 46,898 | 45,283 | 42,171 | 38,115.27 | 32,333.37 | 26,877.06 |
| Elec. Consum. (kWh/yr) | 69,062 | 69,063 | 69,063 | 69,059 | 69,060.72 | 69,062.53 | 69,063.47 |
| Excess Elec. (kWh/yr) | 44,762.43 | 44,889.85 | 46,022.34 | 48,213.59 | 52,062.31 | 57,000.48 | 64,527.59 |
| Unmet load (kWh/yr) | 1.08 | 0.04 | 0.00 | 3.71 | 2.76 | 0.94 | 0.00 |
| Diesel Consumption (L/yr) | 14,748.75 | 14,536.67 | 14,042.31 | 13,084.08 | 11,979.57 | 10,235.78 | 8,517.52 |
| Generator Running/(Hours/yr) | 1,780.00 | 1,751.00 | 1,697.00 | 1,587.00 | 1,590.00 | 1,423.00 | 1,192.00 |
| Carbon Dioxide (kg/yr) | 38,610.26 | 38,055.06 | 36,760.89 | 34,252.38 | 31,360.91 | 26,795.90 | 22,297.72 |
| Battery Annual Throughput (kWh/yr) | 28,224.20 | 28,074.60 | 27,484.58 | 26,478.99 | 25,717.78 | 24,019.91 | 21,627.56 |

## 5.5 Comparison of System Performance Using Actual Generation Data

This hybrid plant was commissioned by the end of year 2016 and energy dispatch data are available with the Deputy General Manager (North) of Ceylon Electricity Board. Such data for month of October, November and December 2016 are presented in ***Table* 5.8** to ***Table 5.11***. These data was included energy generation from new and old diesel generators, total of wind and Solar energy production and energy consumption data. There is an uncertainty about fuel consumption data since there is no proper way to obtain daily fuel consumption only refilling data available and their accuracy also doubtful. Therefore, fuel consumption data has not taken for the analysis.

In the optimum design condition annual total unmet load is 0.000111 kWh per year. That means the designed system can fulfill almost all the electricity required. However when it analysis actual data of October 2016, 640kWh of electricity was generated by old 100kVA generator. The amounted of energy generated by the 100kVA for the month November, December and January 2017 are 637,697 and 601 respectively. This was due to poor generator sizing as discussed in clause 5.1.

*Table 5.8 Eluvaithivu Hybrid System Energy Dispatch - October 2016*

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Unit (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 10/1/2016 | 276.15 | 0 | 0 | 181.42 | 255.55 | 125.06 | 201.93 |
| 10/2/2016 | 264.68 | 0 | 0 | 188.98 | 211.24 | 110.73 | 187.13 |
| 10/3/2016 | 269.50 | 0 | 0 | 183.86 | 291.64 | 113.82 | 161.50 |
| 10/4/2016 | 277.41 | 0 | 0 | 195.12 | 218.09 | 160.45 | 214.83 |
| 10/5/2016 | 305.87 | 0 | 0 | 199.76 | 199.60 | 111.87 | 161.70 |
| 10/6/2016 | 281.54 | 0 | 0 | 192.02 | 138.47 | 141.66 | 201.61 |
| 10/7/2016 | 245.98 | 0 | 0 | 197.51 | 264.21 | 37.50 | 156.50 |
| 10/8/2016 | 330.07 | 0 | 0 | 193.93 | 197.53 | 103.57 | 166.65 |
| 10/9/2016 | 293.22 | 0 | 0 | 201.11 | 186.64 | 122.42 | 185.07 |
| 10/10/2016 | 302.33 | 0 | 0 | 195.28 | 215.37 | 149.42 | 218.63 |
| 10/11/2016 | 279.21 | 0 | 0 | 193.57 | 61.20 | 151.06 | 193.73 |
| 10/12/2016 | 300.78 | 0 | 0 | 213.84 | 142.00 | 114.26 | 188.94 |
| 10/13/2016 | 331.88 | 0 | 0 | 211.90 | 307.11 | 136.36 | 206.05 |
| 10/14/2016 | 316.71 | 0 | 0 | 201.94 | 103.10 | 113.93 | 183.65 |
| 10/15/2016 | 302.57 | 0 | 0 | 204.93 | 143.73 | 115.61 | 190.67 |
| 10/16/2016 | 255.68 | 0 | 32 | 111.41 | 265.54 | 128.96 | 202.19 |
| 10/17/2016 | 131.55 | 0 | 176 | 159.05 | 119.69 | 127.08 | 185.35 |
| 10/18/2016 | 289.38 | 0 | 0 | 196.62 | 156.50 | 105.00 | 177.42 |

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Unit (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 10/19/2016 | 255.69 | 93 | 0 | 139.23 | 229.84 | 145.29 | 210.67 |
| 10/20/2016 | 203.61 | 147 | 81 | 65.69 | 264.49 | 115.04 | 182.72 |
| 10/21/2016 | 114.42 | 0 | 146 | 174.28 | 198.98 | 112.76 | 189.56 |
| 10/22/2016 | 255.63 | 63 | 0 | 176.68 | 221.23 | 115.46 | 177.82 |
| 10/23/2016 | 280.49 | 25 | 0 | 196.54 | 254.06 | 100.46 | 163.05 |
| 10/24/2016 | 287.41 | 108 | 0 | 182.37 | 218.70 | 140.91 | 192.56 |
| 10/25/2016 | 264.36 | 117 | 0 | 136.72 | 222.74 | 61.32 | 161.44 |
| 10/26/2016 | 146.42 | 13 | 115 | 145.78 | 275.17 | 135.76 | 192.56 |
| 10/27/2016 | 292.26 | 131 | 0 | 200.70 | 211.12 | 98.42 | 186.96 |
| 10/28/2016 | 284.18 | 37 | 0 | 196.90 | 181.40 | 111.36 | 140.30 |
| 10/29/2016 | 304.17 | 47 | 0 | 138.94 | 89.73 | 159.54 | 205.78 |
| 10/30/2016 | 197.24 | 92 | 90 | 194.06 | 123.98 | 123.32 | 177.96 |
| 10/31/2016 | 260.38 | 134 | 0 | 159.38 | 73.75 | 119.33 | 178.84 |
| **Total** | **8200.77** | **1007** | **640** | **5529.51** | | | |

*Table 5.9 Eluvaithivu Hybrid System Energy Dispatch - November 2016*

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Energy Output (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 11/1/2016 | 284.54 | 186 | 23 | 146.18 | 239.55 | 158.18 | 220.49 |
| 11/2/2016 | 156.68 | 69 | 68 | 134.79 | 243.57 | 117.71 | 189.54 |
| 11/3/2016 | 276.90 | 152 | 0 | 185.85 | 306.77 | 109.60 | 155.53 |
| 11/4/2016 | 287.48 | 24 | 0 | 192.72 | 219.31 | 141.71 | 201.56 |
| 11/5/2016 | 297.57 | 94 | 0 | 197.11 | 125.00 | 125.85 | 189.66 |
| 11/6/2016 | 302.76 | 159 | 0 | 196.06 | 190.33 | 133.60 | 190.12 |
| 11/7/2016 | 289.70 | 187 | 0 | 123.57 | 127.23 | 141.83 | 195.52 |
| 11/8/2016 | 191.52 | 11 | 71 | 166.75 | 35.48 | 147.90 | 185.86 |
| 11/9/2016 | 255.51 | 228 | 0 | 176.49 | 78.24 | 118.97 | 180.05 |
| 11/10/2016 | 282.37 | 146 | 0 | 180.92 | 276.05 | 161.70 | 216.20 |
| 11/11/2016 | 271.66 | 132 | 0 | 116.11 | 242.35 | 132.38 | 181.12 |
| 11/12/2016 | 187.33 | 46 | 96 | 179.43 | 113.50 | 100.24 | 171.37 |
| 11/13/2016 | 274.69 | 115 | 0 | 161.32 | 302.53 | 132.24 | 198.39 |
| 11/14/2016 | 270.24 | 165 | 0 | 183.16 | 306.80 | 100.78 | 161.63 |
| 11/15/2016 | 274.67 | 117 | 0 | 168.43 | 267.11 | 115.10 | 198.49 |
| 11/16/2016 | 221.42 | 102 | 0 | 140.30 | 174.54 | 75.70 | 158.54 |
| 11/17/2016 | 253.43 | 151 | 0 | 165.34 | 191.79 | 101.12 | 171.80 |

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | **Total Renewable Energy Output (kwh)** | **New Generator Energy Output (kwh)** | **Old Power Station Energy Output (kwh)** | **Energy Consumption (kWh)** | **Total Renewable Energy Output (kWh)** | **Generator Energy Output (kWh)** | **Total Electrical Consumption (kWh)** |
| 11/18/2016 | 292.47 | 130 | 0 | 169.25 | 78.73 | 96.67 | 174.55 |
| 11/19/2016 | 245.30 | 139 | 19 | 104.45 | 164.63 | 107.83 | 201.08 |
| 11/20/2016 | 160.92 | 61 | 98 | 101.38 | 53.47 | 175.15 | 197.69 |
| 11/21/2016 | 167.20 | 73 | 107 | 146.05 | 75.11 | 139.23 | 191.71 |
| 11/22/2016 | 223.93 | 126 | 45 | 120.87 | 200.40 | 144.46 | 214.72 |
| 11/23/2016 | 177.18 | 0 | 81 | 183.67 | 287.92 | 114.50 | 181.00 |
| 11/24/2016 | 285.10 | 102 | 0 | 183.33 | 279.27 | 137.91 | 202.43 |
| 11/25/2016 | 274.98 | 119 | 0 | 178.73 | 218.18 | 133.85 | 183.99 |
| 11/26/2016 | 280.53 | 110 | 0 | 175.81 | 190.42 | 139.76 | 205.96 |
| 11/27/2016 | 266.84 | 135 | 0 | 174.88 | 89.18 | 148.16 | 230.00 |
| 11/28/2016 | 256.60 | 120 | 0 | 164.03 | 191.88 | 93.14 | 137.81 |
| 11/29/2016 | 272.32 | 122 | 0 | 74.43 | 93.04 | 79.99 | 158.13 |
| 11/30/2016 | 187.73 | 126 | 29 | N/A | 150.52 | 166.02 | 191.34 |
| **Total** | **7469.57** | **3447** | **637** | | | | |

*Table 5.10 Eluvaithivu Hybrid System Energy Dispatch - December 2016*

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Unit (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 12/1/2016 | 294.71 | 51 | 0 | N/A | 107.54 | 113.14 | 203.03 |
| 12/2/2016 | 144.28 | 77 | 125 | N/A | 261.65 | 30.00 | 149.12 |
| 12/3/2016 | 179.23 | 56 | 114 | N/A | 134.12 | 94.31 | 196.05 |
| 12/4/2016 | 263.65 | 115 | 0 | N/A | 112.23 | 47.27 | 158.09 |
| 12/5/2016 | 257.68 | 95 | 0 | N/A | 60.02 | 133.04 | 168.91 |
| 12/6/2016 | 268.11 | 107 | 0 | N/A | 227.30 | 143.30 | 205.71 |
| 12/7/2016 | 280.17 | 135 | 0 | N/A | 167.53 | 148.41 | 221.06 |
| 12/8/2016 | 275.44 | 126 | 0 | N/A | 266.07 | 87.10 | 165.54 |
| 12/9/2016 | 279.22 | 162 | 0 | N/A | 229.23 | 110.37 | 188.47 |
| 12/10/2016 | 266.57 | 140 | 0 | N/A | 239.90 | 137.37 | 201.23 |
| 12/11/2016 | 281.70 | 105 | 0 | N/A | 286.86 | 126.90 | 194.12 |
| 12/12/2016 | 293.33 | 54 | 0 | N/A | 268.11 | 99.15 | 171.56 |
| 12/13/2016 | 273.98 | 85 | 0 | N/A | 145.01 | 113.05 | 188.02 |
| 12/14/2016 | 297.51 | 144 | 0 | N/A | 231.48 | 136.88 | 205.75 |
| 12/15/2016 | 294.34 | 130 | 0 | N/A | 274.95 | 101.97 | 188.85 |
| 12/16/2016 | 316.71 | 97 | 0 | N/A | 274.49 | 110.87 | 187.60 |

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Unit (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 12/17/2016 | 314.76 | 129 | 0 | N/A | 226.75 | 107.66 | 175.00 |
| 12/18/2016 | 292.96 | 83 | 0 | N/A | 97.88 | 122.22 | 200.41 |
| 12/19/2016 | 304.3 | 101 | 0 | N/A | 282.76 | 72.09 | 173.13 |
| 12/20/2016 | 392.80 | 232 | 0 | N/A | 236.15 | 110.43 | 197.33 |
| 12/21/2016 | 253.29 | 153 | 0 | N/A | 235.20 | 107.56 | 180.28 |
| 12/22/2016 | 285.48 | 131 | 0 | N/A | 42.80 | 135.24 | 150.35 |
| 12/23/2016 | 284.56 | 130 | 0 | 32.44 | 105.74 | 122.71 | 194.82 |
| 12/24/2016 | 308.87 | 148 | 85 | 199.36 | 84.81 | 120.00 | 206.15 |
| 12/25/2016 | 317.7 | 162 | 0 | 213.65 | 159.73 | 143.40 | 198.90 |
| 12/26/2016 | 329.29 | 168 | 0 | 146.28 | 311.80 | 76.87 | 174.90 |
| 12/27/2016 | 197.81 | 74 | 99 | 194.35 | 179.36 | 108.14 | 187.43 |
| 12/28/2016 | 295.00 | 94 | 0 | 220.08 | 299.93 | 99.90 | 178.01 |
| 12/29/2016 | 322.99 | 104 | 0 | 236.33 | 276.57 | 103.94 | 198.83 |
| 12/30/2016 | 343.74 | 133 | 0 | 156.06 | 200.99 | 119.47 | 257.96 |
| 12/31/2016 | 240.56 | 77 | 274 | N/A | 110.71 | 105.74 | 193.92 |
| **Total** | **8,750.74** | **3,598.00** | **697.00** | | | | |

*Table 5.11 Eluvaithivu Hybrid System Energy Dispatch – January 2017*

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Unit (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 1/1/2017 | 243.73 | 0 | 123 | 174.2 | 41.07 | 145.01 | 218.04 |
| 1/2/2017 | 229.73 | 42 | 105 | 196.1 | 226.43 | 106.98 | 153.74 |
| 1/3/2017 | 264.59 | 68 | 38 | 204.7 | 274.77 | 149.03 | 211.84 |
| 1/4/2017 | 291.35 | 110 | 0 | 191.5 | 55.57 | 142.62 | 191.36 |
| 1/5/2017 | 280.68 | 109 | 0 | 188.2 | 52.44 | 117.60 | 166.24 |
| 1/6/2017 | 274.24 | 111 | 0 | 198.0 | 273.57 | 108.08 | 171.29 |
| 1/7/2017 | 274.51 | 119 | 17 | 104.7 | 240.75 | 95.82 | 131.86 |
| 1/8/2017 | 143.30 | 0 | 125 | 177.7 | 239.99 | 138.36 | 204.84 |
| 1/9/2017 | 294.14 | 131 | 0 | 190.5 | 266.10 | 142.93 | 228.66 |
| 1/10/2017 | 286.71 | 151 | 0 | 140.9 | 257.40 | 110.22 | 193.44 |
| 1/11/2017 | 189.72 | 57 | 99 | 184.7 | 106.29 | 138.16 | 197.36 |
| 1/12/2017 | 280.22 | 129 | 0 | 193.9 | 89.50 | 139.27 | 206.60 |
| 1/13/2017 | 290.75 | 123 | 0 | 193.1 | 216.04 | 117.11 | 177.62 |
| 1/14/2017 | 288.9 | 118 | 0 | 206.6 | 124.02 | 172.00 | 196.56 |
| 1/15/2017 | 278.82 | 105 | 0 | 191.3 | 244.27 | 140.40 | 208.46 |
| 1/16/2017 | 274.03 | 83 | 0 | 180.9 | 73.01 | 109.62 | 149.59 |
| 1/17/2017 | 265.21 | 96 | 0 | 191.0 | 316.61 | 105.93 | 165.24 |

| Date | Actual System | | | | HOMER Pro Output | | |
|---|---|---|---|---|---|---|---|
| | Total Renewable Energy Output (kwh) | New Generator Energy Output (kwh) | Old Power Station Unit (kwh) | Energy Consumption (kWh) | Total Renewable Energy Output (kWh) | Generator Energy Output (kWh) | Total Electrical Consumption (kWh) |
| 1/18/2017 | 259.01 | 90 | 0 | 164.1 | 291.02 | 115.29 | 193.40 |
| 1/19/2017 | 239.68 | 79 | 0 | 210.9 | 293.52 | 112.54 | 201.79 |
| 1/20/2017 | 306.13 | 164 | 0 | 161.8 | 287.42 | 137.10 | 197.31 |
| 1/21/2017 | 211.29 | 59 | 94 | 226.8 | 199.55 | 111.88 | 196.04 |
| 1/22/2017 | 302.39 | 60 | 0 | 226.2 | 239.98 | 138.95 | 213.60 |
| 1/23/2017 | 303.63 | 73 | 0 | 229.9 | 112.07 | 114.46 | 187.65 |
| 1/24/2017 | 297.58 | 128 | 0 | 218.2 | 126.33 | 104.70 | 179.44 |

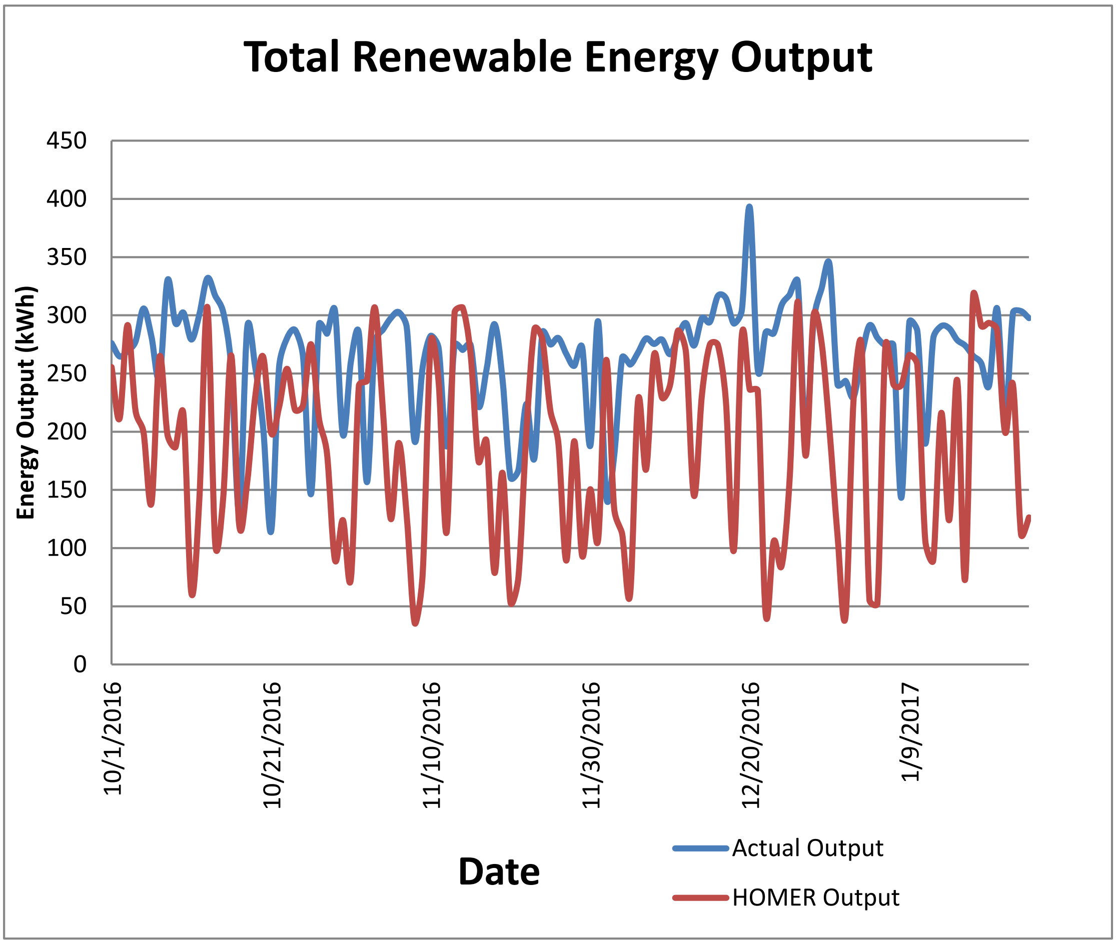



***Figure 5.5 Actual and predicted renewable energy outputs***

***Figure 5.5*** shows the actual renewable output data and renewable energy output data obtained through HOMER Pro. Data is available for the period 116 days starting from October 01 2016 to January 24 2017. As per the above figure it was identified that pattern of actual output variation and pattern of the HOMER Pro prediction is nearly similar to each other. That means HOMER Pro also can predict most of the seasonal variations. However most of the time HOMER Pro under estimated the renewable energy production of the system

During the period of December to February Sri Lanka is experienced northeast monsoon. Therefore normally during the selected period wind speed of the Elevathivu Island is high and due to rainy season Island receive low amount of solar radiation. HOMER prediction is based on above conditions. But in the last year weather patterns were totally different when compared with historical data. This may be a reason for under estimating by the software.

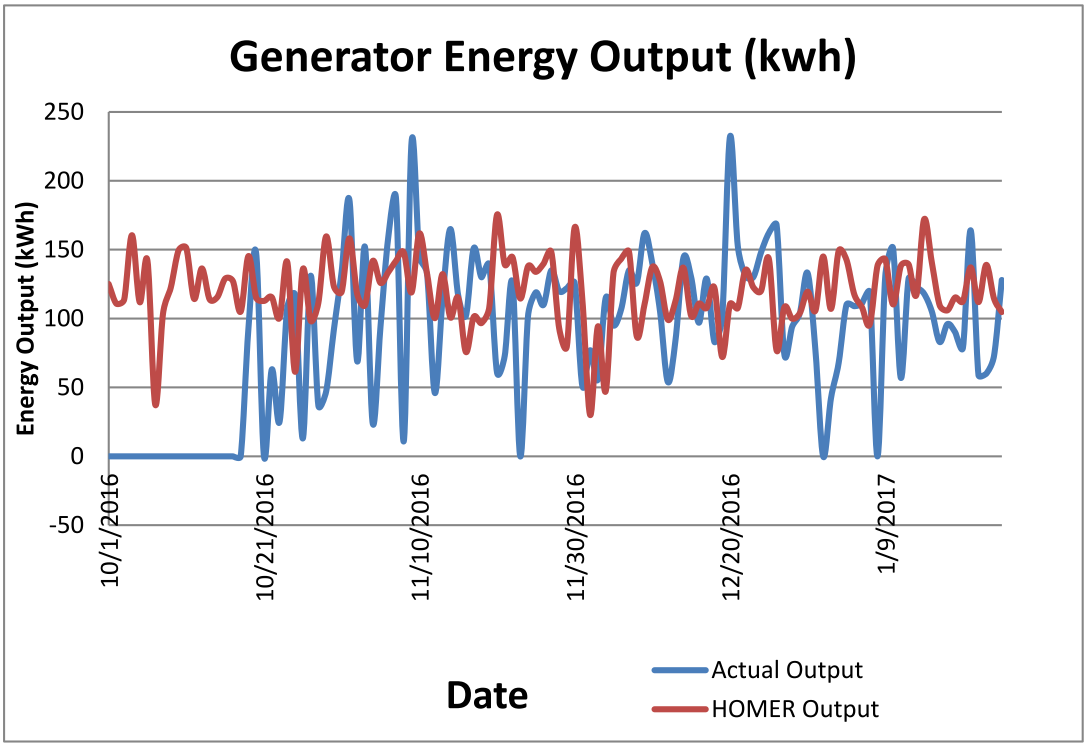



***Figure 5.6 Actual and predicted energy outputs of diesel generator***

***Figure 5.6*** shows the actual energy output data and output data obtained through HOMER Pro for electricity generated by diesel generator. Data is available for the period 116 days starting from October 01 2016 to January 24 2017. As per the above figure it cannot any relationship between actual output variation and output data predicted by HOMER Pro. However most of the time HOMER Pro is over estimated the energy production by the diesel generator. This may due to high wind speed during time period. As discussed in clause 5.4.2 increment in wind speed will reduce energy generation of the generator.

Variation of actual energy consumption of the Island is plotted with HOMER pro predicted energy consumption value is illustrated in ***Figure 5.7***. Data is available for the period 90 days starting from October 01 2016 to January 24 2017. As per the ***Figure 5.7,*** actual and predicted energy consumption data are nearly equal to each other.

Average of the actual data and predicted values are 174kWh/day and 187kWh /day respectively. As per clause 5.3 of this thesis maximum scaled average that system can sustain is 235kWh per day.

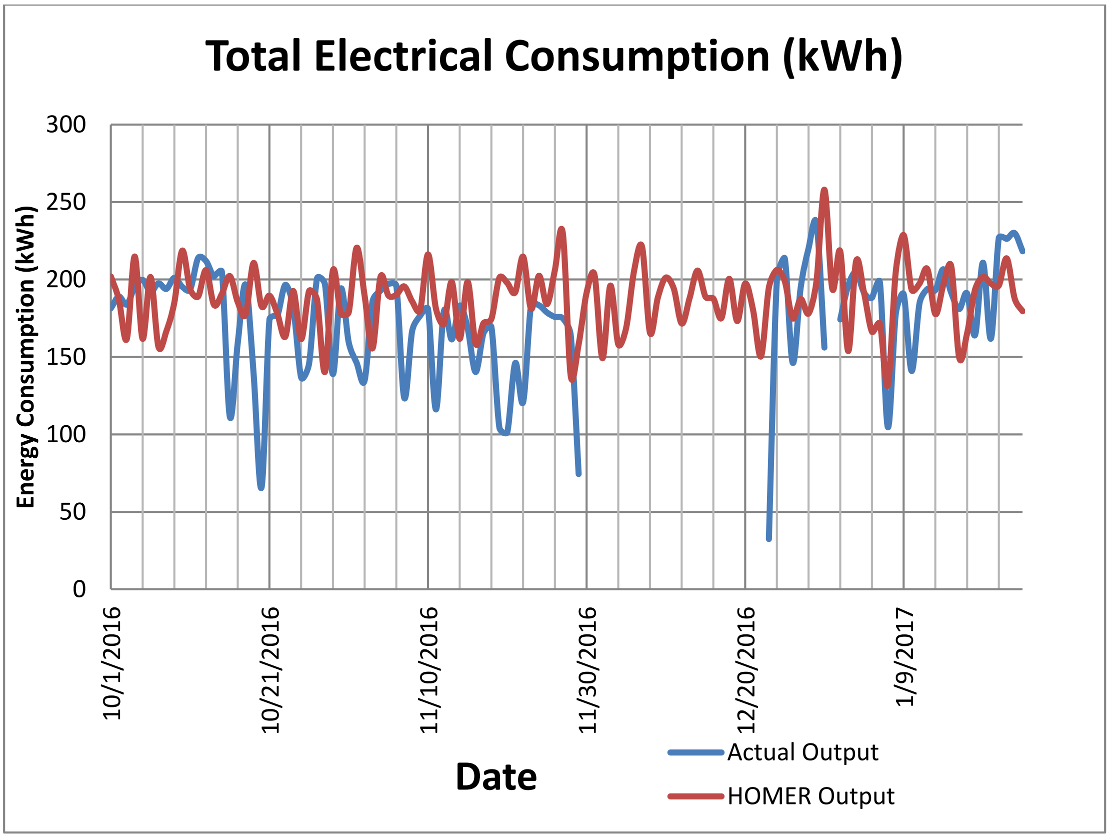



***Figure 5.7 Actual and Predicted energy consumption***

# 6 CONCLUSION

Hybrid power system is identified as most economical solution for providing electricity to communities currently isolated from the national grid and mostly main land. There is a lot of research work available for optimizing techniques and optimized hybrid power system design. As identified, most of these optimized hybrid power systems have not been realized due to some reasons including high initial cost. Therefore literature highlighting performance of hybrid power system is not many available to study.

During the study, performance of the installed hybrid power system was compared with previously used stand-alone diesel system (base case) to identify the feasibility of the project. It was identified that discounted payback of the project is less than 4 years. However, when compared with actual outputs of the installed power system in Eluvathivu with outputs predicted using HOMER Pro software, it was identified that HOMER Pro gives over-estimated energy outputs for diesel generator electricity generation and electrical energy consumption and under estimate total renewable energy generation. This is due to inaccuracies in wind energy estimation. HOMER calculates wind energy using monthly average wind speeds. Therefore accuracy of the wind energy estimation is not in a satisfactory level. If HOMER under-estimates wind energy generation then automatically electricity generation using diesel generator will be over-estimated since there is a no effect of solar radiation on system performances as discussed in 5.4. Fuel cost of the generator is the one of the most significant factor of calculating net present cost and cost of energy, which are the optimizing parameters of HOMER Pro. Therefore it can be observed that actual discounted payback of the installed hybrid power system even low than HOMER predicted.

During the sensitivity analysis it the system performances was analysed for different future demands, possible expansion and under different weather conditions and found that maximum average load that power system can sustain is 235kWh/day, system designed for optimized combination of each power generating and storing sources, other important findings of the thesis are wind speed is a dominant factor of the power system performance and solar radiation not very much affecting the system performances. Also 1 m/s of increment of wind speed for wind speed above 4m/s will result more than 6% increment in renewable fraction of the system.

Capital cost of batteries will contribute higher amount of total capital cost of the project. It is more than 35% of the total capital cost and around 42% of total NPV of the project since high replacement cost. Therefore, selection of batteries is a very important factor when designing a hybrid power system. Amount of electricity stores in the batteries depends on solar radiation and average wind speed data values. In every second values of solar radiation and wind speed are varied. Only provision is available in HOMER to enter monthly average values. Therefore, selection of capacity of batteries will not be accurate.

CEB planned to improve the reliability of the power system by adding new generator which is going to synchronize with the available 30kW generator to avoid power system failure during peak time. These results are based on only 4 months actual data since the power system has been commissioned recently. Therefore, it is recommended to analyse performance of new hybrid power system in future by considering at least one year generation data.

The system comprises with several power sources. Therefore with the absent of one source other power sources can fulfill system requirement at least for some extend. Hence reliability of the hybrid power system is higher than base case diesel generators. Fuel consumption data of base case system and actual hybrid system, will be described importance of hybrid systems, since there is a significant reduction in fuel consumption in hybrid system and Carbon Dioxide emissions. Renewable faction of actual system also higher than HOMER estimated. Therefore the actual system is more environmentally friendly then designed.

# 7 REFERENCES


[1] REN21 Secretariat, "Renewables 2016 Global Status Report," REN21 Secretariat, France, 2016.

[2] "Global Trends in Renewable Energy Investment 2016," Frankfurt School of Finance & Management gGmbH , 2016.

[3] "https://docs.google.com/file/d/0BwtHKWY5sCyVclpMR3pMM1lYVWM/edit," [Online].

[4] "Oxford Business Group," 2017. [Online]. Available: https://www.oxfordbusinessgroup.com/analysis/sustainable-generation-role-renewable-power-sources-set-expand.

[5] Ceylon Electricity Board, "Long Term Generation Expansion Plan 2015 -2034," July 2015.

[6] Ministry of Power and Energy, "Energy Empowered Nation," Sri Lanka Energy Sector Development Plan for a Knowledge based Economy, 2015.

[7] D. M. Lal, B. B. Dash and A. Akella, "Optimization of PV/Wind/Micro-Hydro/Diesel Hybrid Power System in," *International Journal on Electrical Engineering and Informatics - Volume 3,* p. 1, 3 November 2011.

[8] K. Ratneswaran , "Hybrid Power System for Eluvaithivu Island Sri Lanka," *Master of Science Thesis*, pp. 1 - 61, 2011.

[9] M. G. Udayakanthi, "Design of a Wind-Solar Hybrid Power Generation System in Sri Lanka," *KTH Industrial Engineering and Management*, pp. 1 - 61, 2015.

[10] S. Rehman, A. M. Mahbub, . J. Meyer and . L. M. Al-Hadhrami, "Feasibility study of a wind-pv-diesel hybrid power system for a village".

[11] S. A. Shezan, R. Saidur, K. R. Ullah, W. T. Chong and S. Julai, "Feasibility analysis of a hybrid off-grid wind–DG-battery energy system for the eco-tourism remote areas," vol. 17, December 2015.

[12] M. Hasan and O. B. Momin, "Performance Analysis and Feasibility Study of Solar-Wind-Diesel Hybrid Power system in Rural Areas of Bangaladesh," *International Journal of Engineering Research and General Science*, pp. 410 - 420, September 2015.

[13] A. V. Anayochukwu, "Feasibility Assessment of PV Diesel Hybrid Power system for an Isolated off Grid Catholic Church," *Renewable Energies Reaseach Nucleus*, pp. 49 - 63, 2013.

[14] M. Laidi, S. Hanini, B. Abbad, N. K. Merzouk and M. Abbas, "Study of a Solar PV-Wind-Battery Hybrid Power System for a Remotely Located Region in the Southern Algerian Sahara: Case of Refrigeration," pp. 30-38, 2012.

[15] V. O. Okinda and N. A. Odero, "A REVIEW OF TECHNIQUES IN OPTIMAL SIZING OF HYBRID," *International Journal of Research in Engineering*, pp. 153 - 161, November 2015.

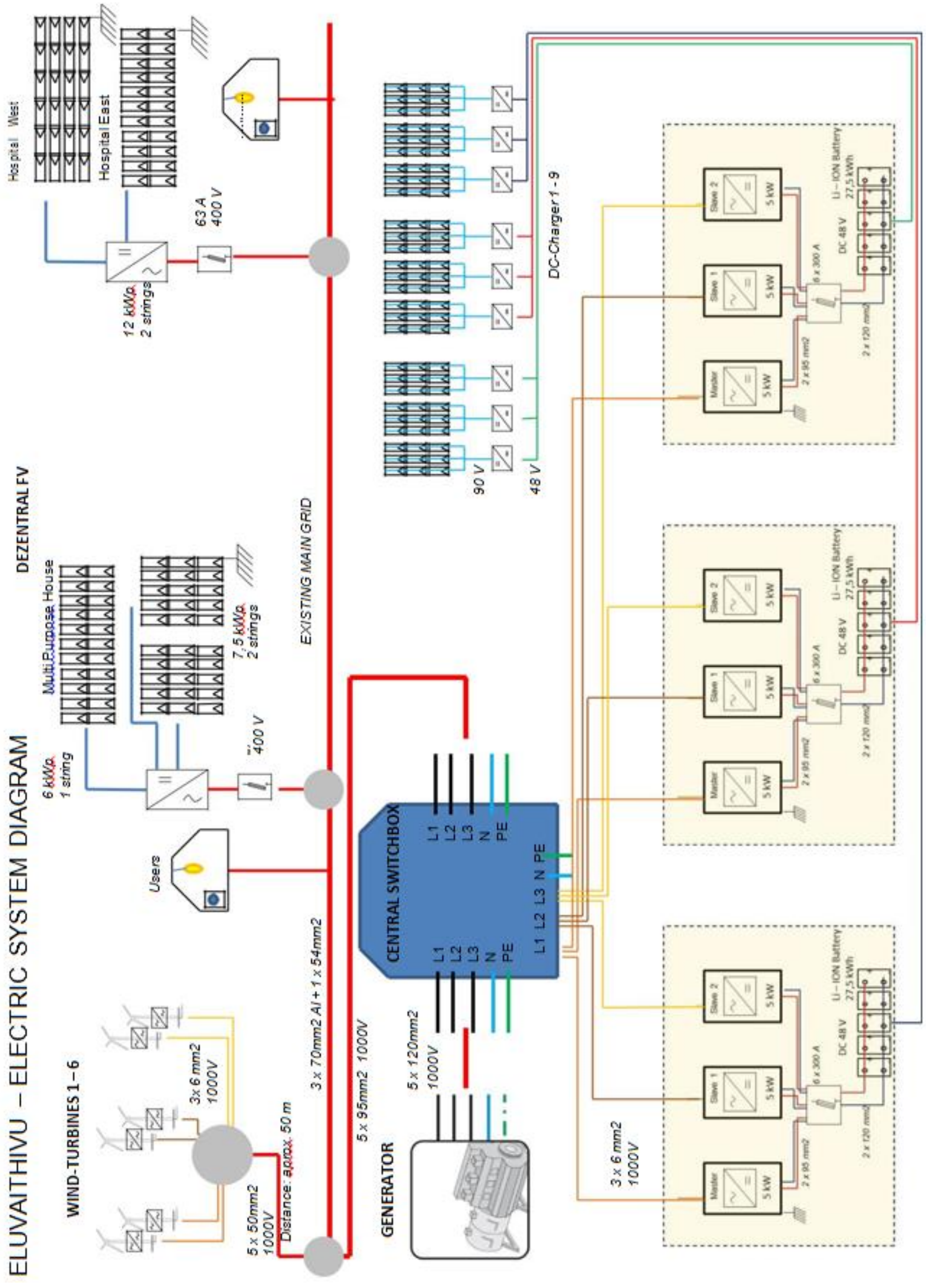
[16] J. G. FANTIDIS, D. V. BANDEKAS and . N. VORDOS, "Techno-economical study of hybrid power system for a remote village in Greece," *Recent Researches in Energy, Environment and Sustainable Development*, pp. 30 - 35.

[17] T. Givler and P. Lilienthal, "Using HOMER® Software, NREL's Micropower Optimization Model, to Explore the Role of Gen-sets in Small Solar Power Systems," 2005.

[18] Laboratory, National Renewable Energy, "HOMER, The Micropower Optimization Model".

[65] H. S. Jacobus, "Solar-Diesel Hybrid Power System Optimization and Experimental Validation," *Thesis Submitted to the faculty of the Graduate School of the University of Maryland*, pp. 1 - 102, 2010.

[66] R. Saidur, W. T. Chong, K. R. Ullah and S. Julai, "Feasiility Analysis of a hybrid off-gridwind-DG-Battery energy system for eco- tourism remote areas," *ResearchGate*, 12 August 2015.


ELUVAITHIVU – ELECTRIC SYSTEM DIAGRAM
WIND-TURBINES 1 - 6
3x 6 mm2 1000V
5 x 50mm2 1000V
Distance: aprox. 50 m
3 x 70mm2 Al + 1 x 54mm2
5 x 95mm2 1000V
GENERATOR
5 x 120mm2 1000V
Users
6 kWp 1 string
Multi Purpose House
400 V
7,5 kWp 2 strings
DEZENTRAL FV
EXISTING MAIN GRID
CENTRAL SWITCHBOX
L1 L2 L3 N PE
90 V
48 V
DC-Charger 1 - 9
12 kWp 2 strings
63 A 400 V
Hospital West
Hospital East
3 x 6 mm2 1000V
Master
Slave 1
Slave 2
5 kW
DC 48 V
LI – ION Battery 27,5 kWh

## Input Summary

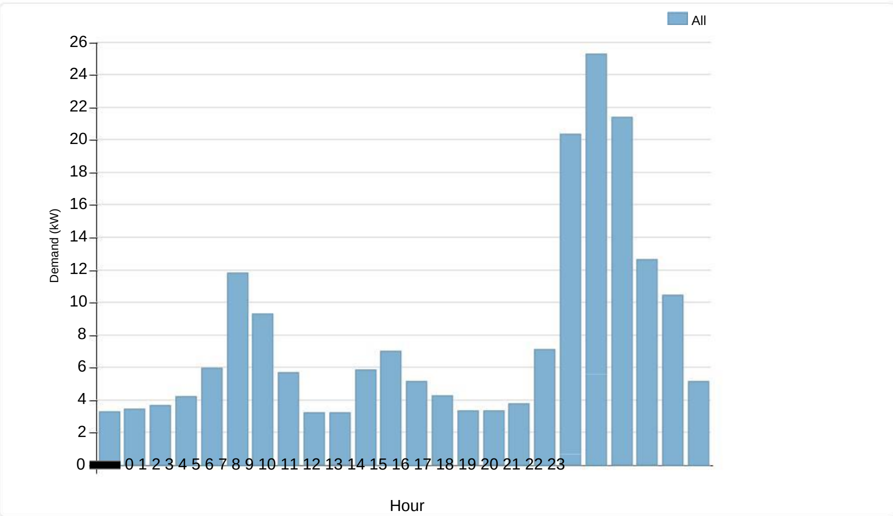
| | |
|---|---|
| Project title | Eluvathivu |
| Author | |
| Notes | |

## Project Location

| | |
|---|---|
| Location | Unnamed Road, Sri Lanka |
| Latitude | 9 degrees 41.33 minutes North |
| Longitude | 79 degrees 48.72 minutes East |
| Time zone | Asia/Colombo |

## Load: Electric1

| | |
|---|---|
| Data source | Synthetic |
| Daily noise | 10% |
| Hourly noise | 20% |
| Scaled annual average | 189.215 kWh/d |
| Scaled peak load | 40.9879 kW |
| Load factor | 0.1923 |




## Microgrid Controller: HOMER Cycle Charging

| Quantity | Capital | Replacement | O&M |
|---|---|---|---|
| 1 | $0.00 | $0.00 | $0.00 |

| | |
|---|---|
| Minimization strategy | Economic |
| Setpoint state of charge | 80 |
| Allow multiple generators to operate simultaneously | Yes |
| Allow systems with generator capacity less than peak load | Yes |
| Allow diesel off operation | Yes |

## Microgrid Controller: HOMER Load Following

| Quantity | Capital | Replacement | O&M |
|---|---|---|---|
| 1 | $0.00 | $0.00 | $0.00 |

| | |
|---|---|
| Minimization strategy | Economic |
| Allow multiple generators to operate simultaneously | Yes |
| Allow systems with generator capacity less than peak load | Yes |
| Allow diesel off operation | Yes |

## PV:AC West

| Size | Capital | Replacement | O&M |
|---|---|---|---|
| 1.00 | $1,800.00 | $1,800.00 | $30.00 |

| | |
|---|---|
| Sizes to consider | 11.5 |
| Lifetime | 25 yr |
| Derating factor | 90% |
| Tracking system | No Tracking |
| Slope | 20.000 deg |
| Azimuth | 90.000 deg |
| Ground reflectance | 0.0% |

## PV:AC East

| Size | Capital | Replacement | O&M |
|---|---|---|---|
| 1.00 | $1,800.00 | $1,800.00 | $30.00 |

| | |
|---|---|
| Sizes to consider | 13.5 |
| Lifetime | 25 yr |
| Derating factor | 90% |
| Tracking system | No Tracking |
| Slope | 20.000 deg |
| Azimuth | -90.000 deg |
| Ground reflectance | 0.0% |

## PV:DC West

| Size | Capital | Replacement | O&M |
|---|---|---|---|
| 1.00 | $1,800.00 | $1,800.00 | $30.00 |

| | |
|---|---|
| Sizes to consider | 9.75 |
| Lifetime | 25 yr |
| Derating factor | 90% |
| Tracking system | No Tracking |
| Slope | 20.000 deg |
| Azimuth | 90.000 deg |
| Ground reflectance | 0.0% |

## PV:DC East

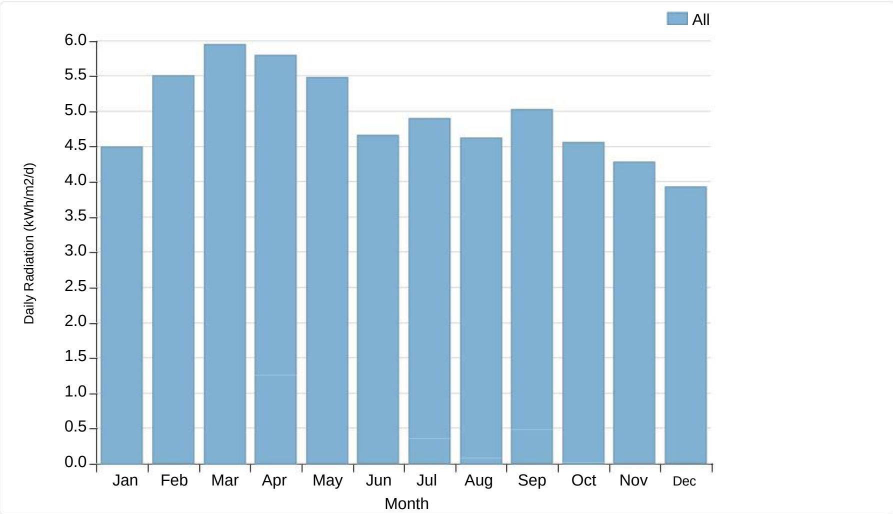
| Size | Capital | Replacement | O&M |
|---|---|---|---|
| 1.00 | $1,800.00 | $1,800.00 | $30.00 |

| Size | Capital | Replacement | O&M |
|---|---|---|---|

| | |
|---|---|
| Sizes to consider | 10.5 |
| Lifetime | 25 yr |
| Derating factor | 90% |
| Tracking system | No Tracking |
| Slope | 20.000 deg |
| Azimuth | -90.000 deg |
| Ground reflectance | 0.0% |

## Solar Resource

| | |
|---|---|
| Scaled annual average | 4.90 kWh/m2/d |



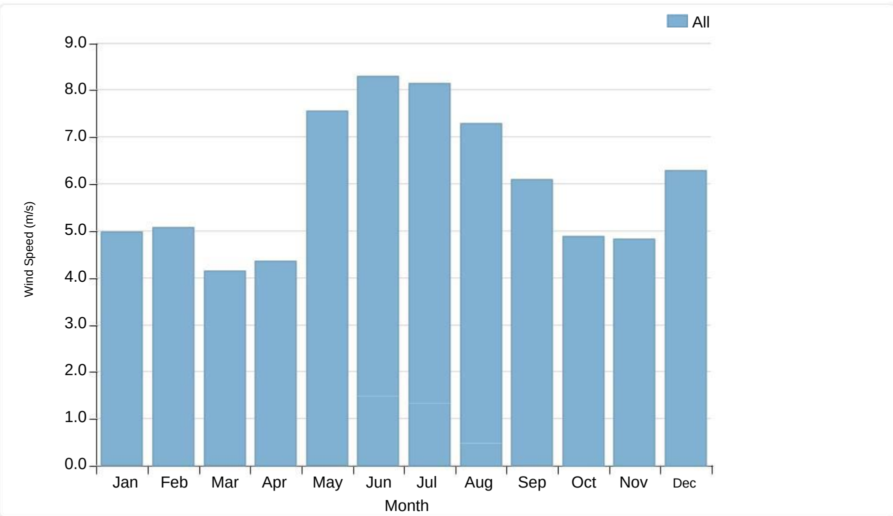

;

## Wind Turbine:Windspot 3.5

| Quantity | Capital | Replacement | O&M |
|---|---|---|---|
| 1 | $18,000.00 | $18,000.00 | $180.00 |

## Wind Resource

| | |
|---|---|
| Scaled annual average | 6.00 |




;

## Generator:50kW Genset

| Size | Capital | Replacement | O&M |
|---|---|---|---|
| 1.00 | $500.00 | $500.00 | $0.03 |

| | |
|---|---|
| Sizes to consider | 0,30 |
| Lifetime | 15,000 hrs |
| Min. load ratio | 25% |
| Heat recovery ratio | 0% |
| Fuel used | Diesel |
| Fuel curve intercept | 0.0330 L/hr/kW |
| Fuel curve slope | 0.2730 L/hr/kW |

## Fuel: Diesel

| | |
|---|---|
| Price | $ 1.00/L |
| Lower heating value | 43.2 MJ/kg |
| Density | 820.00 kg/m3 |
| Carbon content | 88.0% |
| Sulfur content | 0.4% |

## Battery:Li-Ion 27.5 kWh

| Quantity | Capital | Replacement | O&M |
|---|---|---|---|
| 1 | $48,160.00 | $38,528.00 | $190.00 |

| | |
|---|---|
| Quantities to consider | 3 |

## Converter

| Size | Capital | Replacement | O&M |
|---|---|---|---|
| 100.00 | $61,760.00 | $0.00 | $500.00 |

| | |
|---|---|
| Sizes to consider | 0,100 kW |
| Lifetime | 25 yr |
| Inverter can parallel with AC generator | Yes |

## Economics

| | |
|---|---|
| Annual real interest rate | 3% |
| Project lifetime | 25 yr |
| Capacity shortage penalty | $0/kWh |
| System fixed capital cost | 0 |
| System fixed O&M cost | 0 |

## System control

| | |
|---|---|
| Timestep length in minutes | 60 |
| Multi-Year enabled | No |
| Allow systems with multiple generators | Yes |
| Allow systems with multiple wind turbine types | No |
| Battery autonomy threshold | 2 |
| Maximum renewable penetration threshold | 55 |

| | |
|---|---|
| Warn about renewable penetration | Yes |

## Optimizer

| | |
|---|---|
| Maximum simulations | 10000 |
| System design precision | 0.01 |
| NPC precision | 0.01 |
| Minimum spacing | 0 |
| Focus factor | 50 |
| Optimize category winners | Yes |
| Use base case | Yes |

## Emissions

| | |
|---|---|
| Carbon dioxide penalty | $ 0/t |
| Carbon monoxide penalty | $ 0/t |
| Unburned hydrocarbons penalty | $ 0/t |
| Particulate matter penalty | $ 0/t |
| Sulfur dioxide penalty | $ 0/t |
| Nitrogen oxides penalty | $ 0/t |

## Constraints

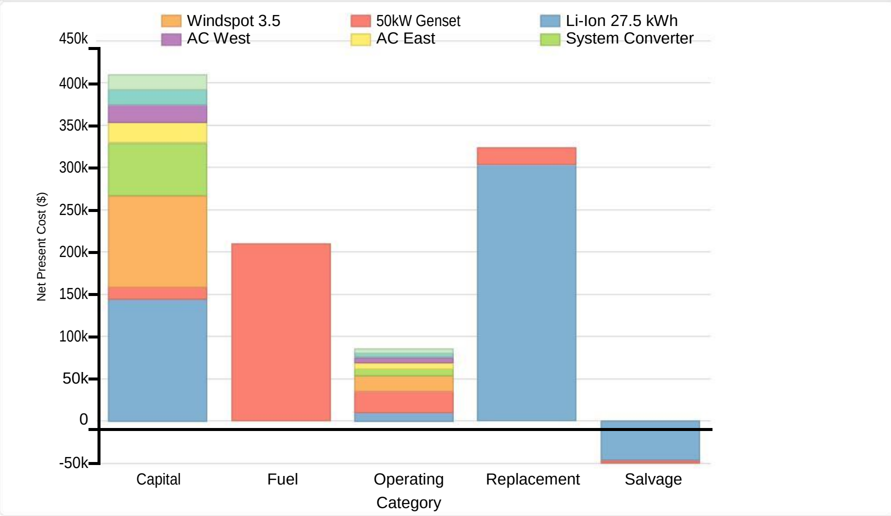
| | |
|---|---|
| Maximum annual capacity shortage | 0 |
| Minimum renewable fraction | 0 |
| Operating reserve as percentage of hourly load | 10 |
| Operating reserve as percentage of peak load | 0 |
| Operating reserve as percentage of solar power output | 25 |
| Operating reserve as percentage of wind power output | 50 |

# System Report

## System architecture

| | | | |
|---|---|---|---|
| PV | AC West | 12 | kW |
| PV #2 | AC East | 14 | kW |
| PV #3 | DC West | 10 | kW |
| PV #4 | DC East | 11 | kW |
| Wind Turbine | Windspot 3.5 | 6 | |
| Generator | 50kW Genset | 30 | kW |
| Storage | Li-Ion 27.5 kWh | 3 | strings |
| Converter | System Converter | 100 | kW |
| Dispatch Strategy | HOMER Cycle Charging | | |

## Cost summary



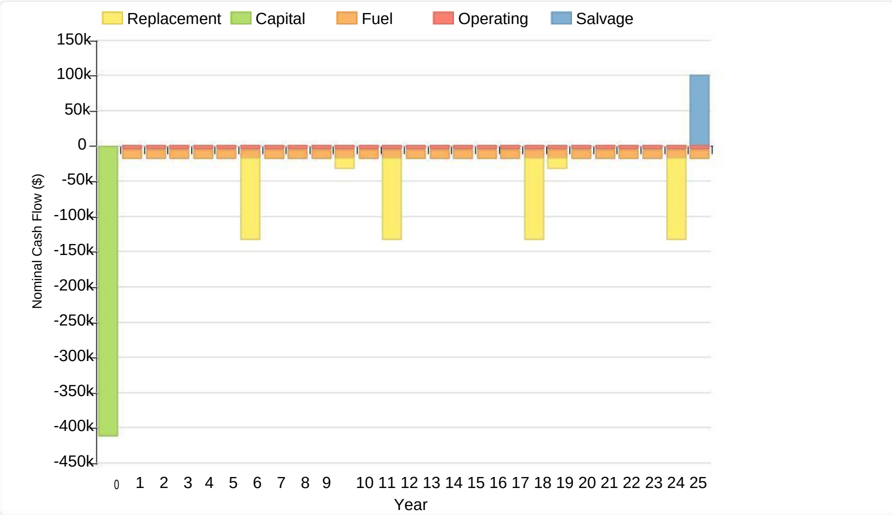

Cost Summary

| | | |
|---|---|---|
| Total net present cost | 981215 | $ |
| Levelized cost of energy | 0.813 | $/kWh |

## Net Present Costs

| Component | Capital | Replacement | O&M | Fuel | Salvage | Total |
|---|---|---|---|---|---|---|
| AC West | 20,700 | 0 | 6,027 | 0 | 0 | 26,727 |
| AC East | 24,300 | 0 | 7,076 | 0 | 0 | 31,376 |
| DC West | 17,550 | 0 | 5,110 | 0 | 0 | 22,660 |
| DC East | 18,900 | 0 | 5,503 | 0 | 0 | 24,403 |
| Windspot 3.5 | 108,000 | 0 | 18,869 | 0 | 0 | 126,869 |
| 50kW Genset | 15,000 | 20,015 | 25,001 | 209,273 | -2,526 | 266,764 |
| HOMER Cycle Charging | 0 | 0 | 0 | 0 | 0 | 0 |
| Li-Ion 27.5 kWh | 144,480 | 303,818 | 9,958 | 0 | -46,336 | 411,921 |
| System Converter | 61,760 | 0 | 8,735 | 0 | 0 | 70,495 |
| System | 410,690 | 323,833 | 86,280 | 209,273 | -48,861 | 981,215 |

| Component | Capital | Replacement | O&M | Fuel | Salvage | Total |
|---|---|---|---|---|---|---|
| AC West | 1,185 | 0 | 345 | 0 | 0 | 1,530 |
| AC East | 1,391 | 0 | 405 | 0 | 0 | 1,796 |
| DC West | 1,005 | 0 | 293 | 0 | 0 | 1,297 |
| DC East | 1,082 | 0 | 315 | 0 | 0 | 1,397 |
| Windspot 3.5 | 6,182 | 0 | 1,080 | 0 | 0 | 7,262 |
| 50kW Genset | 859 | 1,146 | 1,431 | 11,978 | -145 | 15,269 |
| HOMER Cycle Charging | 0 | 0 | 0 | 0 | 0 | 0 |
| Li-Ion 27.5 kWh | 8,270 | 17,390 | 570 | 0 | -2,652 | 23,578 |
| System Converter | 3,535 | 0 | 500 | 0 | 0 | 4,035 |
| System | 23,507 | 18,536 | 4,939 | 11,978 | -2,797 | 56,163 |



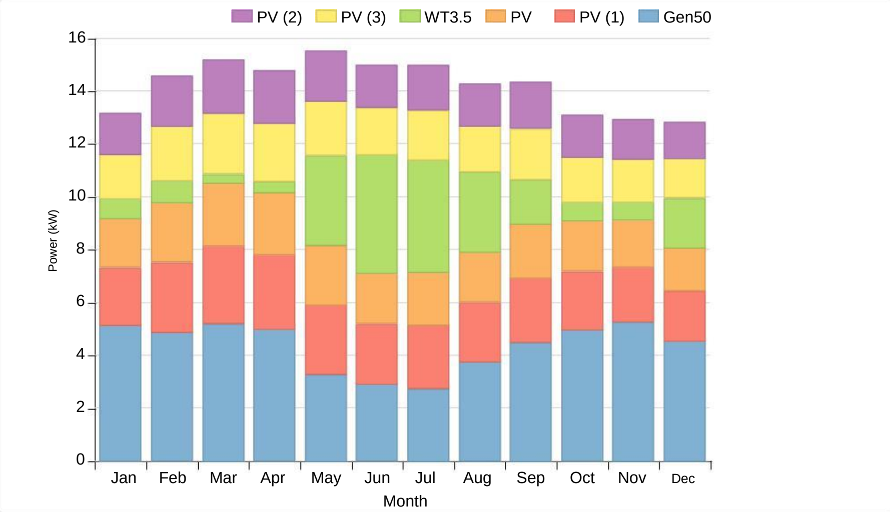

## Electrical

| Quantity | Value | Units |
|---|---|---|
| Excess electricity | 52071 | kWh/yr |
| Unmet load | 3 | kWh/yr |
| Capacity shortage | 9 | kWh/yr |
| Renewable percent | 45 | % |

| Component | Production(kWh/yr) | Percent (%) |
|---|---|---|
| PV | 17,661 | 14 |
| PV | 20,985 | 17 |
| PV | 14,973 | 12 |
| PV | 16,321 | 13 |
| Generator | 38,111 | 31 |
| Wind Turbine | 16,492 | 13 |
| Total | 124,543 | 100 |

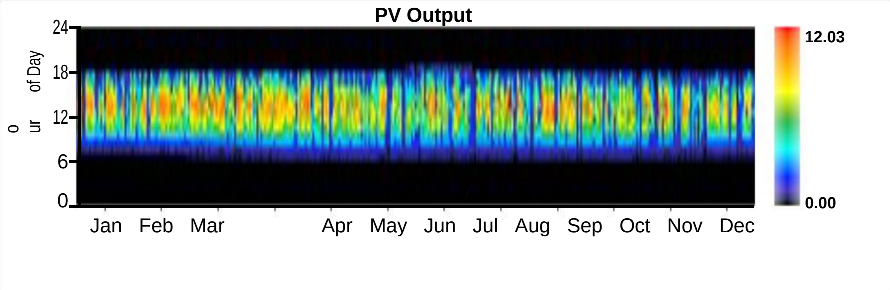
| Load | Consumption(kWh/yr) | Percent (%) |
|---|---|---|
| AC primary load | 69,061 | 100 |
| DC primary load | 0 | 0 |

| T t l Load | Consumption(kWh/yr) 69,061 | Percent (%) 100 |
|---|---|---|




## PV:AC West

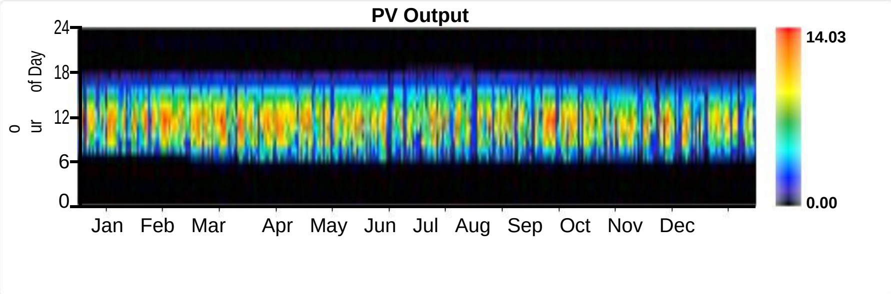
| Quantity | Value | Units |
|---|---|---|
| Rated capacity | 12 | kW |
| Mean output | 2 | kW |
| Mean output | 48.39 | kWh/d |
| Capacity factor | 17.53 | % |
| Total production | 17661 | kWh/yr |
| Minimum output | 0.00 | kW |
| Maximum output | 12.03 | kW |
| PV penetration | 25.57 | % |
| Hours of operation | 4358 | hrs/yr |
| Levelized cost | 0.087 | $/kWh |




## PV:AC East

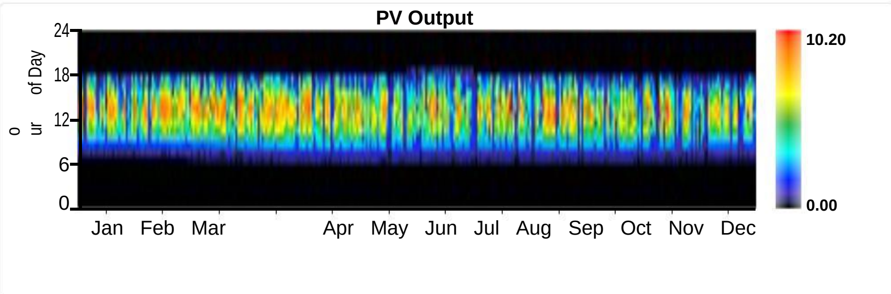
| Quantity | Value | Units |
|---|---|---|
| Rated capacity | 14 | kW |
| Mean output | 2 | kW |
| Mean output | 57.49 | kWh/d |
| Capacity factor | 17.74 | % |
| Total production | 20985 | kWh/yr |
| Minimum output | 0.00 | kW |
| Maximum output | 14.03 | kW |
| PV penetration | 30.38 | % |

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 4358 | hrs/yr |
| Levelized cost | 0.086 | $/kWh |



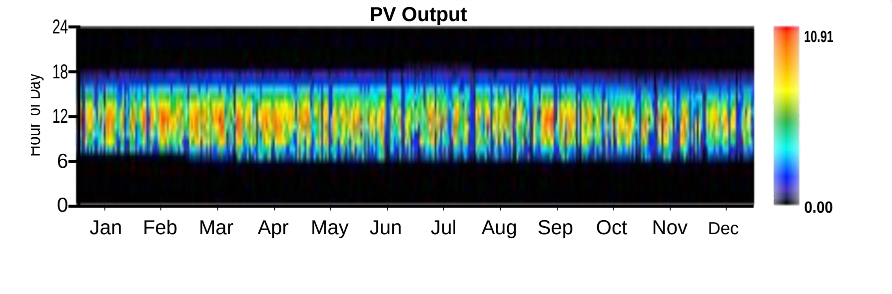

## PV:DC West

| Quantity | Value | Units |
|---|---|---|
| Rated capacity | 10 | kW |
| Mean output | 2 | kW |
| Mean output | 41.02 | kWh/d |
| Capacity factor | 17.53 | % |
| Total production | 14973 | kWh/yr |
| Minimum output | 0.00 | kW |
| Maximum output | 10.20 | kW |
| PV penetration | 21.68 | % |
| Hours of operation | 4358 | hrs/yr |
| Levelized cost | 0.087 | $/kWh |




## PV:DC East

| Quantity | Value | Units |
|---|---|---|
| Rated capacity | 11 | kW |
| Mean output | 2 | kW |
| Mean output | 44.72 | kWh/d |
| Capacity factor | 17.74 | % |
| Total production | 16321 | kWh/yr |
| Minimum output | 0.00 | kW |
| Maximum output | 10.91 | kW |
| PV penetration | 23.63 | % |
| Hours of operation | 4358 | hrs/yr |
| Levelized cost | 0.086 | $/kWh |

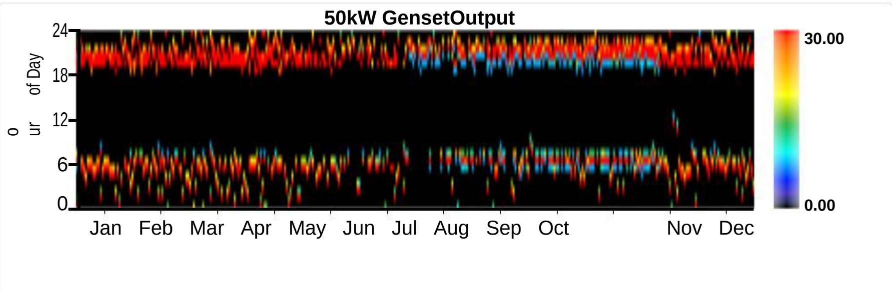



## Wind Turbine:Windspot 3.5

| Quantity | Value | Units |
|---|---|---|
| Total rated capacity | 18 | kW |
| Mean output | 2 | kW |
| Capacity factor | 10.46 | % |
| Total production | 16492 | kWh/yr |
| Minimum output | 0.00 | kW |
| Maximum output | 22.53 | kW |
| Wind penetration | 23.88 | % |
| Hours of operation | 8760 | hrs/yr |
| Levelized cost | 0.440 | $/kWh |

## Generator:50kW Genset

| Quantity | Value | Units |
|---|---|---|
| Hours of operation | 1590 | hrs/yr |
| Number of starts | 707 | starts/yr |
| Operational life | 9 | yr |
| Fixed generation cost | 2.89 | $/hr |
| Marginal generation cost | 0.27 | $/kWh |
| Electrical production | 38111 | kWh/yr |
| Mean electrical output | 24 | kW |
| Min. electrical output | 8 | kW |
| Max. electrical output | 30 | kW |
| Fuel consumption | 11978 | L/yr |
| Specific fuel consumption | 0.31 | L/kWh |
| Fuel energy input | 117867 | kWh/yr |
| Mean electrical efficiency | 32 | % |



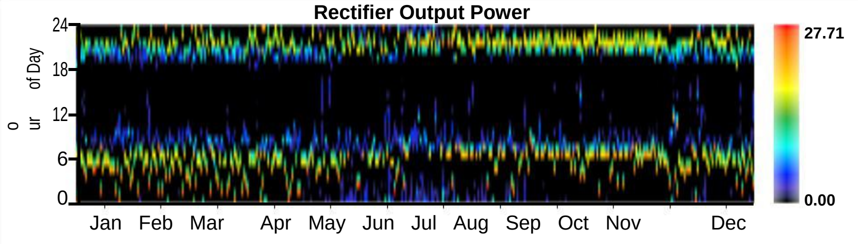
## Battery:Li-Ion 27.5 kWh

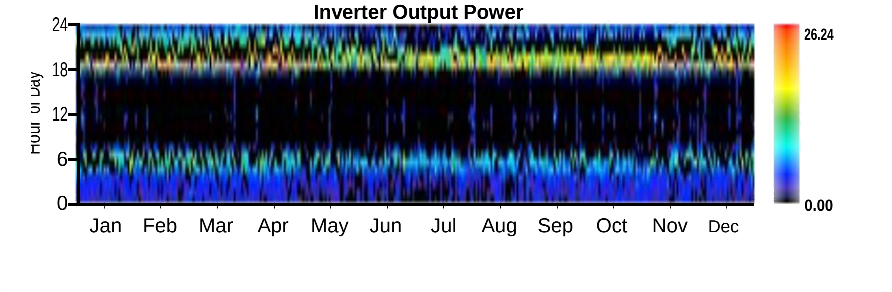
| Quantity | Value |
|---|---|
| String size | 1 |
| Strings in parallel | 3 |
| Batteries | 3 |
| Bus voltage | 48 |

| Quantity | Value | Units |
|---|---|---|
| Nominal capacity | 76 | kWh |
| Usable nominal capacity | 46 | kWh |
| Autonomy | 6 | hr |
| Battery wear cost | 0.065 | $/kWh |
| Average energy cost | 0.199 | $/kWh |
| Energy in | 26209 | kWh/yr |
| Energy out | 25193 | kWh/yr |
| Storage depletion | 34 | kWh/yr |
| Losses | 982 | kWh/yr |
| Annual throughput | 25713 | kWh/yr |

## Converter

| Quantity | Inverter | Rectifier | Units |
|---|---|---|---|
| Capacity | 100 | 95 | kW |
| Mean output | 3 | 2 | kW |
| Minimum output | 0 | 0 | kW |
| Maximum output | 26 | 28 | kW |
| Capacity factor | 3 | 2 | % |
| Hours of operation | 3,975 | 2,058 | hrs/yr |
| Energy in | 26,310 | 21,591 | kWh/yr |
| Energy out | 24,994 | 20,512 | kWh/yr |
| Losses | 1,315 | 1,080 | kWh/yr |






## Emissions

| Pollutant | Emissions | Units |
|---|---|---|
| Carbon dioxide | 31358 | kg/yr |
| Carbon monoxide | 196 | kg/yr |
| Unburned hydrocarbons | 9 | kg/yr |
| Particulate matter | 1 | kg/yr |
| Sulfur dioxide | 77 | kg/yr |
| Nitrogen oxides | 184 | kg/yr |