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DECLARATION

Statement by the Author

I Rekha Devi Pratap, declare that this thesis is my own work and that to the best of my knowledge, it contains no materials previously published, or substantially overlapping with material submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

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The research in this thesis was performed under my supervision and to my knowledge is the sole work of Rekha Devi Pratap

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In preparing my thesis I have been guided by the expertise of many people who have reviewed manuscript and provided pre – revision suggestions. I wish to acknowledge the following reviewers and express my sincere appreciation for their helpful suggestions and encouragement. Firstly, I would like to express my gratifying appreciation to my academic advisor, Dr Ajal Kumar, University of the South Pacific, for guiding and providing priceless assistance throughout the study.

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Finally, I thank my husband, Anesh Kumar for his continuous support and guidance towards the completion of this project.
ABSTRACT

In remote and interior areas of Fiji islands a diesel generator can prove to be the main source of power. However, due to an increase in the price of diesel, generating electricity from renewable sources can be a better option. Since Fiji is an island nation and sits in the trade wind belt, an almost continuous supply of wind resource available in most parts of the country this can be considered an alternating power generating source. However, it would be wise to incorporate a diesel generator as part of the hybrid system for supplying of power in cases of interruptible supply due to irregular supply of wind. To assess wind energy potential, annual wind data for the year 2012 and 2013 at Waisa was recorded through survey work. The average monthly recorded value of the wind speed varied from 3.4 ms\(^{-1}\) to 7.8 ms\(^{-1}\) whereas the annual average was found to be 5.43 ms\(^{-1}\) at 20 m a.g.l. This study presents a technical assessment of wind power potential for Waisa using statistical analysis packages to determine the wind characteristics based on the measured wind data.

The micro grid proposed for this study comprises a wind turbine generator system as the renewable energy source, a battery to store the charge and a diesel generator as a backup power supply when the wind resource is not adequate to meet the demand.

The annual energy production using a 7.5 kW wind turbine was estimated at 22,860 kWh at the height of 20 m a.g.l. The economic analysis estimated a positive NPV with a BCR greater than one. The payback period is 15 years with internal rate of return estimated at 11.5 %. The levelised cost of energy is determined as $0.106/kWh. At a fixed real rate of discount the payback period is most sensitive to perturbation in any economic indicator.

The turbine efficiency and the estimated return on the investment for the proposed configuration show considerable promise.
LISTS OF ABBREVIATIONS, UNITS AND NOMENCLATURE

ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AEP</td>
<td>Annual Energy Production</td>
</tr>
<tr>
<td>AC</td>
<td>Alternating Current</td>
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<tr>
<td>a.g.l</td>
<td>Above Ground Level</td>
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<tr>
<td>a.s.l</td>
<td>Above Sea Level</td>
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<td>COE</td>
<td>Cost of Energy</td>
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<td>DC</td>
<td>Direct Current</td>
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<td>FDoE</td>
<td>Fiji Department of Energy</td>
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<td>FEA</td>
<td>Fiji Electricity Authority</td>
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<td>FJD</td>
<td>Fijian Dollars</td>
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<tr>
<td>FSC</td>
<td>Fiji Sugar Corporation</td>
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<td>FSTE</td>
<td>Faculty of Science and Technology and Environment</td>
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<td>HAWT</td>
<td>Horizontal Axis Wind Turbine</td>
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<tr>
<td>IPPs</td>
<td>Independent Power Producers</td>
</tr>
<tr>
<td>KOICA</td>
<td>Korean International Cooperation Agency</td>
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<tr>
<td>PBP</td>
<td>Payback Period</td>
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<tr>
<td>PDF</td>
<td>Probability Density Function</td>
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<tr>
<td>PICs</td>
<td>Pacific Island Countries</td>
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<tr>
<td>PV</td>
<td>Photovoltaic</td>
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<tr>
<td>RE</td>
<td>Renewable Energy</td>
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<td>RH</td>
<td>Renewable Hybrid</td>
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<tr>
<td>RWD</td>
<td>Responsive Web Design</td>
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<tr>
<td>SDR</td>
<td>Symphonie Data Retriever</td>
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<td>SHS</td>
<td>Solar Home Systems</td>
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<tr>
<td>TI</td>
<td>Turbulence Intensity</td>
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<tr>
<td>TWIL</td>
<td>Tropik Wood Industries Ltd</td>
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<td>USP</td>
<td>University of the South Pacific</td>
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<td>VAWT</td>
<td>Vertical Axis Wind Turbine</td>
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<td>WAsP</td>
<td>Wind Atlas Application and Analysis Program</td>
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<td>WECS</td>
<td>Wind Energy Conversion system</td>
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UNITS

°C  degrees centigrade
GW  gigawatt
Hz  hertz
k  kilo
kg  kilogram
km  kilometres
kW  kilowatt
m  meters
mA  milliamps
ms⁻¹  meter per second
V  Volts

NOMENCLATURE

A  Rotor area

C  Weibull scale factor

COM  Operation and Maintenance Cost

Cₚ  Power coefficient

Cₚᶠ  Specific heat capacity of fish

i  Discount rate

k  Weibull shape factor

L  Lifetime of the project

Mₕ  Mass of fish

Mᵢ  Mass of ice

P  Power

tₖ  Final temperature of fish

tₛ  Initial temperature of fish (°C)

U  Mean wind speed

Z₀  Roughness Length

α  Power Law coefficient

σ  Standard deviation

ρ  Air density
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Chapter 1 INTRODUCTION

1.1 An overview of Renewable Energy

Renewable energy is energy generated from natural resources such as wind, sunlight, rain, tide and geothermal heat which are naturally replenished. The ever escalating energy demands and the diminishing sources of fossil fuels have been the strength behind the electricity generation form renewable sources. The renewable energy sources are also the major input to our adaptation to a post – carbon economy and will play a significant role in the future global energy division.

To supply grid connected electricity to remote areas is not profitable due to the transmission and other related costs. On the other hand, diesel generators cannot be continued as a source of power supply because they are expensive due to increasing fuel cost and high fuel transportation costs. According to Ahmad et al (2014), the best option then is use of renewable hybrids (RH) as renewable sources alone may not be applicable as these energy sources are intermittent. The wind may not blow all the time nor the sun may shine all the time thus hybridizing renewable sources with storage cell is a realistic power source option. Thus, there is need to install hybrid systems as isolated units to overcome the power problems in remote areas. Hybrid generation systems usually combine renewable energy sources such as wind, solar and hydro with diesel generators to generate electricity.

According to Ackerman (2005), the electricity generation using wind turbines has been in practice since one hundred years ago and the use of wind – diesel hybrid system came into operation since 1994 and has been growing since then. Akpinar et al (2006) mentioned that wind–turbine power systems are considered to be cheaper compared to solar hybrid power generation systems. Thus wind energy as a source of renewable hybrid has been considered in the present project. There are many other incredibly good reasons why wind energy should be considered for power generation. Firstly, wind energy is an impressive accompaniment to solar since it works day and night. In addition, the recent development in harvesting wind energy, low prices of new technology, the increased capacity of wind turbines and higher oil prices necessitate further assessment criteria for the feasibility of using wind power production
technologies. Further to this, wind energy is plentiful, clean, is widely distributed and it uses very little land.

1.2 Energy Consumption and Development

There are many forms of energy sources used globally. However, a large percentage of global electricity demand is still met by fossil fuels. The final energy consumption by fuel type (Figure 1) shows the proportional contribution from different sources.

![Energy Consumption Chart]

Figure 1.1 Estimated renewable energy share of global electricity production (REN21, 2015)

In some countries diesel generators are the only source of electricity. It is estimated that many people in the developing countries still lack grid-connected electricity. Research suggested that 1.3 billion people worldwide do not have access to grid-connected electricity or have no electricity at all (REN 21, 2015). For several reasons, the electrification of rural areas is important. Whereof, the most important ones are quality of life, enhancement of education level, health and economic growth. According to the South African International Renewable Energy Conference (2015), in today’s era, there are about 2.9 billion who lack access to clean energy which is a
major concern so that the universal energy access target is achieved. Thus, there is a need to utilize renewable sources for energy production where people are not able to afford to pay for non–renewable source of electricity or the grid – connected electricity supply is not possible.

1.3 Renewable Energy Sources

According to Drwiega (2003), the use of renewable energy sources are the only options to alleviate the dependence on fossil fuel for electricity generation. There is an increase in the use of renewable energy sources globally. Currently the renewable energy sources used for global electricity generation include hydro, solar, wind, biomass and geothermal energy generation. Renewable energy (RE) such as solar, wind, hydro and use of bio–energy technology has been utilized in the past. Some of them have had mixed success with some falling into disrepair thus there is a need to highlight the use of appropriate technology, to improvise systems, that is make it a smart system and develop the necessary local knowledge to operate and maintain systems when they are in place.

Hydro power is the world’s largest RE power source. According to the world energy council report (2015), hydropower alone accounts for 76 percent of world’s renewable energy source of power generation and is expected to double to 2000 GW by the year 2050. Currently, there are more than 150 countries globally use hydropower to generate electricity, China being the world’s largest hydropower producer. There are hybrid and renewable energy systems also being installed and operational in Fiji. The 80 MW hydro dam in Monasavu and the 40 MW hydro dam in Nadarivatu, Viti Levu Fiji have continuously been supplying electricity to most parts of Fiji. In addition to this, FEA is currently considering few other projects to move towards achieving its target of producing 90 % of the electricity using renewable energy sources by 2015 (FEA Annual report, 2013). Few other small hydro systems include the 0.8 MW Wainiqueu hydro, 6.5 MW Wainikasau hydro power station and 3 MW Nagado hydro power systems are also connected to main electricity grid.

Solar energy is abundantly available, however, the conversion technology is still expensive for developing countries but it has a massive potential for power generation. Though the high cost of collection limits the energy conversion and storage of
electricity generated from solar, the use of photovoltaic (PV) to generate electricity from solar energy is still the most common practice. The packed solar cells into modules are used to convert the energy from sun into electrical energy. Currently, solar power generation is second to hydro in terms of generating power from renewable source. Solar power contributes to 0.9 percent of the global electricity generation (REN21, 2015). The world’s largest PV is currently installed in California which has an electricity generating capacity of 550 MW of power (REN21 Report, 2015). Germany is the world leader in solar power generation. The first ever 10 kW PV systems was installed in Navutu Lautoka in 1997. Two other grid connected PV systems installed later includes a 10 kW PV system installed by the Non-Government Organization (NGO) in Tuvu Lautoka in 2011 and a 45 kW PV system funded by KOICA installed in 2012 at the USP lower campus (at Laucala Bay, Suva Fiji). More systems have been installed at large scale. A 260 kW system (second largest PV system in Fiji) at Turtle Island Resort in Mamanuca Group and a 122 kW system at Port Denarau Marina, in Nadi were also installed in 2012 (Raturi, 2013). The Fiji times reported on 23rd October, 2015 that the largest solar power system in Fiji, 500 kW systems has been established at Future Farms Limited’s Rooster chicken outlet in Ba Fiji. This system is the biggest agriculture solar powered facility in the Pacific which generates 664,000 kW of energy replacing 195,000 litres of diesel fuel.

In addition to this, solar home systems (SHS) have been installed by the FDoE under its rural electrification program. According to FDoE (2015) there are about 3680 SHS installed in Fiji and further 1200 installations are expected. The demand for solar home systems is gradually increasing every year.

Biomass also plays a very important role in terms of contribution towards power generation. Traditional biomass, commonly known as cooking and heating fuel continues to be used by people in rural areas where they have no access to grid connected electricity and are not very rich to purchase cooking fuel. The use of traditional biomass is decreasing in many countries since it is being used for power generation in modern forms. According to International Energy Agency (2015), the global electricity contribution by biomass accounts for 10 percent of the global energy supply.
In Fiji, biomass is abundant and is mainly used for cooking and crop drying in rural areas. However, on large scale it is used for power generation by two sugar mills in Fiji. The Independent Power Producers (IPP’s), Fiji Sugar Corporation (FSC) uses bagasse (a byproduct of the sugar cane crushing process) and supplies electricity to the Fiji Electricity Authority (FEA) grid in Labasa and Lautoka during crushing season. The Fiji Times reported on 30th October, 2015 that the Labasa FSC mill is expected to supply power during off cane crushing season from 2016 which will enable FEA to save a lot of foreign exchange. Power Purchase Agreement (PPA) was also signed last year by Pacific Renewable Energy Ltd to establish a 17 MW Biomass power plant and a 10 MW Tropik Gimco Biomass power plant in the western division of Viti-Levu (FEA Annual Report, 2014). In addition to this, there is a 9.3 MW biomass plant operated by Tropik Wood Industries Ltd that uses biomass from Timber Industry to generate and supply electricity to the FEA grid since May 2008.

In addition to biomass fed generation system, biogas projects have also been installed in Fiji by the FDoE. The three biogas plants currently working in Fiji are located in Waidalice (Tailevu), Waila (Naitasiri) and Benau (Savusavu).

The power generation from wind using wind turbines has been growing at a constant rate. The assessments carried out globally validate that the worlds wind resources are tremendously large and are well disseminated across almost all regions and countries. According to REN 21 (2015), wind power has continuously been growing since 2004 at an exponential rate and added 51 GW, the highest of all renewable technology, to the total of 370 GW. The REN21 report (2015) also stated that wind energy is the minimum cost choice for new power generating capacity in many countries.
The total wind power world capacity since 2004 is illustrated in the Figure 1.2.

![Figure 1.2 Bar graph showing wind power global capacity, 2004-2014](REN 21, 2015)

In 2014, 51 GW wind capacities was added bringing the total global capacity to 370 GW thus, marked an increase of 44% over the previous year. The total capacity for the top 10 countries made up to 84% of the global capacity by the end of 2014. Another 24 countries have more than 1 GW wind power market operation capacity (REN21, 2015). The technological advancement and competition in wind power technology has allowed a considerable growth in the wind market capacity resulting in an exponential increase in the added wind capacity.

### 1.4 Energy Conversion Process in Wind Turbines

The term wind energy or wind power describes the process used to generate electricity from wind. The kinetic energy in the wind is converted into mechanical power by the wind turbines. This mechanical power can then be used to run the generator which then produces electricity.

The main components of a typical Wind Energy Conversion System (WECS) consist of a wind turbine generator and control system. The actual process of generating electricity from wind involves a number of processes. The propeller blades around the
rotor are turned by the wind energy. The blades lift and rotate when wind is blown over them causing the rotor to spin. This rotor which is connected to the generator then runs the generator to generate electricity.

![Wind energy conversion systems](www.image.slidesharecdn.com)

The wind energy conversion process to generate wind energy involves the conversion of kinetic energy to electrical energy. The details of this conversion processes is discussed in detail later in sections.

### 1.4.1 Power available in wind

The steps involved in the energy conversion process to extract power from wind involve the conversion of kinetic energy to electrical energy.

The kinetic energy in air is given by;

\[
KE = \frac{1}{2} m v^2
\]  

(1.1)

Where \( m \) is the mass and \( v \) is the velocity of air
The power available in the air stream can then be calculated using:
\[ P = \frac{1}{2} m v^2 \]  \hspace{1cm} (1.2)

Where \( P \) is the mechanical power in moving air (Watts) and \( m \) is the mass flow rate (kg/s)

The mass flow rate in the above equation is given by:
\[ \text{Mass Flow rate} = \rho A v \]  \hspace{1cm} (1.3)

Where \( \rho \) is the air density (kg/m\(^3\)) and \( A \) is the area swept by the rotor blades (m\(^2\))

The available power in the wind is thus:
\[ P = \frac{1}{2} \rho A v^3 \]  \hspace{1cm} (1.4)

The power extracted by the rotor blades is calculated by taking into consideration the mass flow rate for the average wind speed. According to Betz, theoretically maximum power that can be extracted from the wind turbines is given by and is only 59.3 % of the available power in the wind.
\[ P = \frac{1}{2} \rho C_p A v^3 \]  \hspace{1cm} (1.5)

Where \( C_p \) is the maximum theoretical value of 0.593.

### 1.5 Wind Turbine Configurations

Wind turbine consists of many components. The main components include the blades, tower, rotor, gear box, generator and controller. There are two main types of wind turbines. They are classified as Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT).
1.5.1 Horizontal Axis Wind Turbine

Figure 1.4 details the configuration of a typical horizontal axis wind turbine.

![Horizontal Axis Wind Turbine Diagram](www.intechopen.com)

The current installations worldwide are dominated by the horizontal axis wind turbine which comprises of the tower, blade and the nacelle. The components of nacelle are the generator, rotor and gear box which is optional for some of them. There are many varieties of HAWT. These are turbines with two and three blades and are also of twenty or more blades. Two and three blade turbines are mainly used for electricity generation where three bladed turbines are currently dominating the market for electricity generation (Panchori et al, 2007). Twenty or more bladed wind mills are mainly used for mechanical work such as pumping.

1.5.2 Vertical Axis Wind Turbine

Vertical axis wind turbines main rotor shaft is set diagonal to the wind (Figure 1.5) and is not very common due to blade fatigue and is difficult to mount on high towers so that maximum wind can be captured (Chowdhury, et.al). According to Bataineh et al
the issues associated with the early designs of VAWT have been overcome by the modern designs.

1.6 Definition of Micro grid

A micro grid is a collection of interconnected loads and distributed energy storage units which acts as a sole controllable individual. It is connected to the grid at one point only and can be connected or disconnected whenever necessary. A detail component of a micro grid system (Figure 1.6) shows the configuration of a typical setup.
The micro grid mechanisms are controlled using a distributed decision making process in order to meet the demand based on the power supply and are capable of performing in parallel or autonomously with another source. Micro grids support incorporation of growing exploitation of renewable energy sources and reduce losses through transmission and increasing the delivery efficiency. The economic and environmental benefits to consumers are maximized through smart grids. Other benefits of smart micro grid include help consumers save money, increases reliability locally and encourage economic growth and are of enormous environmental benefit (Rojas et al. 2012).

1.7 Objectives

The objective of this work is to model a wind/diesel hybrid power system for Waisa. This wind/diesel hybrid will be the first ever electricity source for the village. The broad objective of the study is to optimize a wind turbine configuration and calculate its annual energy production and identify a cogenerating diesel powered scheme and determine the economics of wind/diesel hybrid system.

This study focuses on the evaluation of wind – diesel hybrid power generation to provide uninterruptible electricity for a very small village on Vanua-Levu. This is achieved by estimating the required load and wind regime at Waisa and proposing a suitable hybrid configuration to meet the daily requirement.

1.8 Thesis Structure

The thesis is divided into six chapters and is organized as follows. Chapter 2 includes a literature review of the wind – diesel field of study providing information on work carried out on wind/diesel hybrid systems globally, regionally and locally. This chapter deals with the existing state of micro-grids focusing on wind – diesel hybrid systems in remote areas.

Chapter three discusses on the methodology used in the investigation of wind regime of the study site, Waisa village. It details the process used to carry out the modeling of
the project. It also outlines the detail procedure used in the wind data analysis of the Waisa site.

Chapter four, results and discussion section presents the results of the wind–diesel hybrid energy systems simulation. The characteristics of the wind regime at Waisa are established.

Finally, chapter five provides the summary of the main points of the previous chapters and provides suggestions for further work. This chapter also outlines recommendations for a potential wind-diesel hybrid system installation at the site.
CHAPTER 2  LITERATURE REVIEW

2.1 Introduction

Inaccessibility to grid-connected electricity and exorbitant fuel prices in rural areas in developing countries, utilization of renewable energy sources has gained prominence in the recent years. Renewable Hybrid (RH) systems have been designed and implemented globally to the areas where there is no grid connected electricity. The increasing energy demands and environmental concerns are major reasons as to why there is a need to venture into hybrid renewable energy systems and its development. The generation of power from any renewable source only is not a reliable source as these sources are dependent on environmental conditions. Thus the combined use of multiple power sources shall be a viable way to accomplish trade–off solutions.

A hybrid system is a system which combines two or more source of energy. Wind-diesel hybrid power system is a combination of wind turbines and diesel generators together with battery and converters. These systems are designed to generate utmost power from wind turbines at the same time ensuring uninterruptible power supply. This will add to the reduction in fuel consumption, thus reducing the operating cost and leading to a green environment. These Renewable Hybrid (RH) systems are designed to provide electricity to remote areas which lack access to grid connected electricity.

A fuel cost of FJD122.6 M was recorded in the year 2012 by the Fiji Electricity Authority which is equivalent to 41% of the total revenue for the following year (FEA Annual Report, 2013). Raturi (2012) has supported the notion that Pacific island countries fight back challenges depending on petroleum only for electricity generation. The utilization of off grid hybrid systems is quite common in Fiji and there are many potential areas where more systems can be installed.

The use of renewable energy sources such as stand-alone systems can be of great help and can minimize the cost of power generation thus raising the standard of living in rural areas. Fiji is a developing country with at least 25% of its population does not have access to grid connected electricity.
2.2 Development of Wind Hybrid Systems Globally

Research shows that integration of wind power into diesel for power generations has been significantly profitable both economically and environmentally. There are many successful wind–diesel hybrid systems currently operational worldwide. The world’s largest wind–diesel hybrid system is installed in Brazil that consists of twelve 900 kW wind turbines, 3 MW battery bank and five 2.87 MW diesel engines (Wind diesel hybrid, 2015). Wind-diesel hybrid systems have proven successful in Brazil. Another wind-diesel system comprising of a 225 kW wind turbine and a diesel generator supplies electricity to a remote Island community in Brazil (Remote Condition Monitoring System, 2008). Australia is another country which has wind diesel power systems presently supplying electricity to the coastal regions of Northern Australia. There are four wind-diesel power systems, ranging from 1.2 -14 MW currently operational in the country (Worldwide status of Wind 2015). In addition to this, Danvest, a subsidiary of Australian Windsal Limited has helped in installation of a wind-diesel system comprising 2x75 kW wind turbines and 1x120 kW generator set in Estonia in 2008, a 150 kW wind turbine and 160 kW diesel generator set in Malaysian Navy in 2001 (Hybrid wind diesel systems, 2011).

Kwigillingok village in Alaska was heavily dependent on the wind power and power by diesel generators. The shift from diesel and wind separately into a wind-diesel hybrid system by the villagers in 2012 has displaced 30 % of the fuel used for electricity generation (Hybrid Technologies, 2014).

In addition to the local researches, a lot more have been done and proposed by researchers globally. Many of these proposed renewable hybrid models have been trialed and have proven to be viable and feasible. Allai et al. (2015) stated that in South Algeria diesel generators are the only source of electricity and at the same time they are very costly and are also responsible for carbon-dioxide emission. Thus they recommended the use of twinning wind-diesel since these sites also have significant wind energy potential and proposed a hybrid model consisting of wind turbine generator, diesel generator and storage system. Similar hybrid model system with a variable load of 55 kWh/day of a remote health center was proposed for Jordan (Bataineh et al, 2014). Chakravathy et al. (2011) in describing the modeling and
simulation of a standalone wind-diesel micro grid system have also supported the notion that the electricity demand of remote rural places can be easily met through large potential renewable energy systems. The wind/diesel/battery system for a remote area in China was analyzed and modeled by (Kumar et al. 2013) detailed that the site average wind speed, the total load and the power generation by the diesel generator play a vital role in determining the size of the components of the model system. A similar study by Janajreh et al (2012) described that the increase in electricity demand is pushing towards generating power from alternative energy sources.

The feasibility study of using hybrid systems such as wind turbine, hydro turbine and photovoltaic in china was proposed by (Ye et al. 2010) suggested that incorporating these renewable hybrids helps in providing more stable power. Optimizing the design of stand-alone hybrid wind diesel system (Koussa et al. 2009) reported that this hybrid system was the best option for all the sites being considered in the study. These system configurations ensured that the annual costs of the system are minimized while meeting the energy needs of the remote households compared to when electricity is supplied using diesel generator only. Integrating renewable energy systems in fossil fuel based power generation systems (Nfah and Ngandum 2008) modeled a wind – diesel hybrid power system electrification in Far North Cameroon reported a reduction in fuel usage and carbon dioxide emission is achievable by using hybrid systems.

There has been ongoing research on power loss from grid. Deshmukh and Deshmukh (2008) presented a detailed method of designing and modeling renewable energy hybrid systems that can supply high quality power to the load.

It is not necessary that any site would be suitable for power production using wind. Ozgur and Kose (2006) analyzed the wind characteristics in Kutahya, and stated it is not suitable for large-scale wind farming but sounds promising for small scale power generation using small wind turbines.

The wind power technology research has been growing exponentially. Many researchers have switched to incorporating renewables into electricity generation systems rather than depending on diesel generators only and have also tried to get the most efficient energy system configuration.
2.3 Wind Energy and Resource Assessment in the South Pacific Countries

Diesel generators are the main source of electricity generation in most of the Pacific Island Countries. Most of these countries are moving towards generating electricity through renewables and renewable hybrids. Samoa’s first ever wind farm was inaugurated 2014, on the island of Upolu where 75% of Samoa’s population resides. The system consists of two 275 kW wind turbines at 55 m a.g.l. (Samoa First wind farm, 2014)

Neighboring country Tonga’s first ever wind turbine was installed at Nakolo Village in Tonga in 2013. The 11kW turbine installed has the capacity to generate about 27 MWh of electricity annually which would be sufficient to power almost 23 homes in the village every year saving 8184 liters diesel fuel (Tonga first wind turbine, 2013)

Similarly, Vanuatu’s first ever wind farm, a 2.75 MW wind farm on the island of Efate, commissioned in 2008 and has supplied 8% of overall power generated for the same year.

Niue has one of the highest wind energy intensities in the South Pacific with mean wind speed of 6 m/s at 30 m a.g.l over a two year period. Based on this recorded data, a 150 kW turbine has been installed for demonstration. With proper installation and maintenance, this wind turbine is capable of producing and supplying 10% of the total energy (Renewable Energy Opportunities, 2013).

According to a study carried out in 2006 by the e8 (non-profit international organization consisting of nine leading electricity companies) member countries, wind energy in Tuvalu has been identified as one of the renewable energy sources to be explored for power generation (Wind Study and Feasibility Report 2015). This study included the measurement of wind resource characteristics for two years which showed that there was sufficient wind power to generate electricity between the months of November and March.

A wind mapping exercise in Nauru conducted by the International Renewable Energy Agency (IRENA), 2013 reported a mean wind speed of 4.22 ms⁻¹ at 30 m a.g.l. It was estimated that a wind farm built would provide approximately 25% of the domestic energy demand for the people of Nauru.
2.4 Wind Energy and Resource Assessment in the Republic of the Fiji Islands

A fuel cost of FJD122.6 M was recorded in the year 2012 by the Fiji Electricity Authority which is equivalent to 41% of the total revenue for the following year (FEA Annual Report, 2013). Raturi (2012) has supported the notion that Pacific island countries fight back challenges depending on petroleum only for electricity generation. The utilization of off grid hybrid systems is quite common in Fiji and there are many potential areas where more systems can be installed.

There are many wind monitoring systems installed around Fiji. The FDoE (Fiji Department of Energy) is fully involved in investigating the sites which have potential to generate electricity from wind. The data from these stations shall provide a meaningful resource assessment around Fiji and the prospect of using wind technology to harvest the energy from wind can be realized.

The first ever wind power facility commissioned in Fiji is located at Butoni, Sigatoka. This farm consists of 37 x 275 kW Vergnet turbines, which generated a total of 6.8 MW of electricity in the year 2012 saving fuel cost of about FJD 3 M for the same period and 5.3 million units of electricity and a fuel saving of approximately FJD 2.3 M in 2013 (FEA Annual Report, 2013). Currently these systems are not performing to expectation due to poor maintenance and availability of spare parts. Thus there is an urgent need to properly manage Fiji’s only wind farm.

In addition to the Butoni Wind farm, wind–turbine–generators and PV hybrid system were installed in Nabouwalu in Bua in 1998. This project was operational for four years since it was commissioned but is not operating currently due to lack of maintenance (Raturi, 2012). Kumar and Nair (2013) determined the wind power potential at Benau, Savusavu in Fiji. Based on the three year data provided by the department of energy, and estimated an annual energy production of 611.83MWh from 2 x 225 kW Vesta V 27 wind turbine and 768.57 MWh from 2 x 275 kW Vergnet wind turbines.

A similar study for Wainiyaku, Taveuni (Kumar and Nair 2012) estimated an annual energy production of 6.3 GWh from a wind farm consisting of four 275 kW wind
turbine on the main land. Kumar and Nair (2013) estimated an average wind speed of 4.60 m/s and a power density of 139 W/m² at Qamu, Navua. In another study, Kumar and Prasad (2010) carried out a major wind resource assessment of the two main Islands of Fiji and estimated an average wind speed between 5 ms⁻¹ and 6 ms⁻¹ at 55 m a.g.l.

2.5 Environmental Impacts of Wind Energy Systems

Decreasing global reserves of fossil fuels threatens the long term sustainability of global economy whereas wind energy provides a variable and environmental friendly option and national energy security. Wind energy is clean source of fuel and is abundant in supply (Allai et al. 2015; Raturi, A, 2012; Koussa et al. 2008) highlighted that wind energy does not pollute the air like coal, gas and other petroleum based fuels and they do not produce atmospheric emissions that can cause greenhouse gases and acid rain.

Development of wind power also has negative environmental impacts. Noise from the turbines, the visual impact, the avian/bat mortality and the land use impacts are some of the negative impacts of wind power development (Drwiega, 2003). One of the most contentious biological issues pertaining wind turbines are the bird and bat deaths. Richard (2014) carried out a study in North America and found that 214,000 to 360,000 birds are killed annually. He further stated that this number is very small when compared to bird fatalities from other causes such as collision with radio towers (6.8 million) and those eaten by cats (1.4 to 3.7 billion).
Chapter 3  Methodology

3.1  Introduction

Power generation using single source such as wind may not be desirable to supply continuous power due to it being intermittent in nature. Hybrid arrangement of wind and diesel for power generation can help provide more reliable source of power to remote areas or areas which have no access to grid connected electricity. Successful hybrid power generation project arrangements incorporating wind involves quality wind resource assessments. According to Elliot (2002), most of the wind industries are unsuccessful due to lack of or incorrect wind resource data. Before implementing the wind/diesel hybrid system, thorough investigation of wind resource at a site must be carried out. Thus a proper and a detailed methodology arrangement are fundamental in order to be successful.
3.2 Site Description

Fiji (Figure 3.1a) is located between longitudes of 174° E and 177° W and latitudes of 15-22° S. The study area, Waisa Village, (Figure 3.1b) is located 30 km from Savusavu and 85 km from Nabouwalu, in southern Vanua Levu.

Figure 3.1a: Map of Fiji (www.fijistates.com)

Figure 3.1b: Google picture of Waisa village, Fiji
The aerial view from google earth shows sparse distributions of the houses of Waisa Village. Waisa is 16.89° S and 179.1° E and is 3.9 m above the sea level (a.s.l). The Waisa study site is remote village on Vanua-Levu, Fiji Islands. There are 15 houses with a total of about 70 occupants of which about 20 of them are school children. The nearest primary school is about five km away from the village. The students either walk to school or they travel by boat. The nearest shop is about 30 km in the Savusavu town and is about three-four hours by bus. There is neither grid-connected electricity nor any other form of renewable energy supply power to the village. One of the significant efforts of this project is to provide lighting to all the households.

Currently, the villagers use hurricane lanterns and a small solar panel which can light only one bulb, as the source of light. The village owns a diesel generator which is used for major village functions only. The fuel for this generation is purchased from Savusavu town. In addition to assess lighting needs, this study also aims to estimate power for a small ice-maker for the villagers. The power generation from renewable hybrids shall provide the alternative solution to the problems faced by the fishermen of the village. The only source of water for the village is spring water where only three houses have direct access to it. The questionnaire that was used in data collection is attached as appendix 3A.

3.3 Wind Monitoring

3.3.1 Instrumentation

Wind speed and direction are the major parameters that are frequently measured at various heights above ground level. Anemometers and wind vanes are available from wind monitoring companies in Australia and New Zealand. However, this Study used NRG wind vanes and anemometers, data loggers, mast and other ancillary item. The main instruments used are described below.

3.3.1.1 Anemometer

Two RNRG #40C, anemometers (Figure 3.2) were installed at 20 and 34 m a.g.l to measure the wind speeds and directions for this study.
Two RNRG #40C anemometers (Figure 3.2) were used for speed measurement.

![Figure 3.2: RNRG #40C cup anemometer](www.renewablenrgsystems.com)

The RNRG anemometer (#40C) consists of 3 cups and measured wind speeds (between 1 ms\(^{-1}\) and 96 ms\(^{-1}\)) and is compatible with NRG loggers. It consists of four pole magnets that are used to induce low level AC sine wave voltage and produce an output signal which is directly proportional to the wind speed. Other specifications are attached in appendix 3A.

### 3.3.1.2 Wind Vane

The prevailing wind direction is vital for identifying the wind direction so that the layout of the wind turbine can be optimized and the output be maximized. Figure 3.3 shows the wind vane installed at the site to measure the prevailing wind directions.

![Figure 3.3: RNRG 200P wind vane](www.renewablenrgsystems.com)
The RNRG #200P wind vane has a very precise plastic potentiometer that is directly connected to the vane. A constant DC excitation voltage is applied due to the rotation of the vane and thus DC voltage is produced by the potentiometer. NRG #200P wind vanes have range of 0° to 360°. All other specifications of NRG #200 P wind vane is attached in Appendix 3B.

3.3.1.3 Data logger

The wind speed and wind direction measurements were continuously recorded at every 10 minutes interval for the period of one year. The data for August 2012 to August 2013, at the mast location were retrieved and cleaned and used to analyze the energy potential of Waisa Village. The anemometer and wind vane outputs were recorded using a data logger which is housed in the controller box and managed by USP KOICA Project management. At the observation site, the parameters measured included the wind speed, wind direction and solar radiation.

![Figure 3.4: Wind monitoring station at Waisa](image)

The wind monitoring system at the study site (Figure 3.4) was setup by Faculty of Science and Technology and Environment (FSTE) through KOICA funding. The wind speed and wind direction were measured and recorded at the site. The wind monitoring tower at the Waisa site has two NRG anemometers at a height of 34 m and one other at 20 m a.g.l to record the wind speeds and a wind vane mounted at a height of 20 m a.g.l for wind direction. In addition, a pyronometer is mounted at 6 m a.g.l to record the daily insolation. The data were recorded on Symphonie PLUS3 data logger kept in a
closed box at the site and retrieved through wireless transmission at USP data bank. The data logger sampled data every 10 seconds and then averaged it for the 10 minute interval.

All the data measured at the site were stored in a data logger (Figure 3.5) at the site. Initially the data were transmitted to USP data bank using iridium satellite (IPack). However, this transfer was terminated at the expiring of the contract with the local mobile company. The remaining data were retrieved during the site visits.

![Symphonie PLUS3 Data Logger and Accessories](www.renewablenrgysystems.com)

Figure 3.5 NRG symphonie PLUS3 data logger
(www.renewablenrgysystems.com)

Symphonie PLUS3 data logger is especially designed for wind industry which is controlled by the microprocessor and has an ultralow power. The communication IPacks allows the internet transfer of data through emails. Satellite IPacks are also connected at the back of Symphonie PLUS3 data logger which enables remote internet communications. They have 15 channels and fixed averaging 10 minute intervals where the averages, standard deviations and other statistical values are calculated and written on the SD card. All other specifications of symphonie PLUS3 data logger is attached in appendix 3C.

The Symphonie PLUS3 data logger (Figure 3.5) was installed in an enclosed box at the site that recorded the wind speed and standard deviation at 10 minutes interval. The programmed data logger recorded specified data in respective channels; channel one
and two recorded the wind speed at 34 m a.g.l and speeds at 20 m a.g.l. These data were retrieved and used for analysis in this project.

3.4 Wind Analysis Techniques

Literature showed that different techniques have been used to investigate the wind resource assessment. According to Emery et al. and Manwell et al. (2002) there are four main methods used in wind data analysis. Carta et al. (2013) highlighted that the site–data–based modeling method, which involves direct use of data, has most commonly been used in the investigation of wind resource assessment analysis. Thus, the same has been used for the purpose of this study. This study analyzed one complete year’s data. The wind statistics such as wind speed, standard deviation, wind direction and turbulence have been determined. The general wind resource characteristics are of direct use to other aspects of wind energy. The site–specific wind characteristics that are relevant to wind turbines include the mean wind speed, the wind speed distribution with respect to height and time, the turbulence in the wind and the distribution of the wind speed direction. The analytical methods used to determine these parameters are discussed below.

3.4.1 Mean Wind Speed

Mean wind speed is one of the main characteristics which decide whether it is viable to install a wind turbine in a selected area. The mean wind speed at the hub height of the wind turbine is the most significant feature in measuring the wind resource at a site. The output energy of the wind turbines increases with an increase in the wind speed. The wind speed distribution with the hub height and with respect to the time also affects the output of the turbine used for power generation.

3.4.2 Wind Speed Distribution

Diurnal, seasonal and annual wind speed changes have large effects on the energy yield of the wind turbines. The change in wind speed causes an impact output on the output of the wind turbine. The wind speed distribution was obtained directly using the windographer software.
3.4.2.1 Variation in wind speed with the height

It is necessary to discover the potential of wind resource before making plans to use wind energy. The first step in this discovery involves the measurement of the wind speed data at the potential sites for at least few years. Akpinar and Akpinar, 2005 and Ozgurand Ramazan, 2006 have carried out research projects to measure the wind energy potentials of all the regions in Maden, Agin, Elazig and Keban in Turkey. Annual data based on the wind energy characteristics were studied for all these regions and was found that Maden has the best potentials for wind power generation.

According to Manwell et al (2009) and Rehman et al (2005), the average wind speed increases with the increase in height. The wind speed increases rapidly with the increase in height thus it is important to interpolate the speed of the wind at the hub height of the wind turbine or the standard height. The vertical wind profile as described by Oyedepo et al (2012), using the logarithmic law and power law as shown below:

\[
\frac{V}{V_0} = \ln\left(\frac{H}{Z_0}\right) / \ln\left(\frac{H_0}{Z_0}\right)
\]

(3.1)

The power law as described mathematically is given as:

\[
\frac{V}{V_0} = \left(\frac{H}{H_0}\right)^\alpha
\]

(3.2)

Where \(V_0\) is wind speed at measured height (ms\(^{-1}\)), \(V\) is wind speed at the hub height (ms\(^{-1}\)), \(H_0\) is measuring height (m), \(H\) is hub height (m), \(Z_0\) is roughness length, \(\alpha\) is power law coefficient.

The increase in wind speeds with respect to height depends on prevailing wind speeds and surface type. Wind shear is one important parameter in deciding the wind turbine yield and fatigue. Wind shear simply explains that there is a change in wind speed with height and depends on the type of surface the wind is blowing and the prevailing wind speeds at other heights. The wind shear in the wind industry is commonly assumed to follow the power law. The details of the power law exponents are given later in this chapter.
3.4.2.2 Power Law Exponent

Power law exponent is used to describe the wind speeds over a greater range of heights and has been used to depict wind speeds at elevated heights. An exponent of value approximately 1/7 is the generally accepted value of the power law exponent by most researchers. This value can be accepted under normal conditions such as well exposed sites and low roughness length. However, this was verified using the wind speed measured at 20 m and 34 m a.g.l.

If the wind speeds at two different heights are known. According to Farrugia (2002), the power law exponent relation is given as:

$$\alpha = \frac{\ln \left( \frac{V}{U_0} \right)}{\ln \left( \frac{H}{h_0} \right)}$$  \hspace{1cm} (3.3)

3.4.2.3 Variation of wind speed with time

There is a continuous variation in wind speed at any given location that can be divided into inter-annual, annual, diurnal and short-term fluctuations. Inter-annual variations are variations over more than a year whereas annual variations are seasonal or monthly averaged wind speeds. Likewise, the daily variations are called diurnal discrepancies and short variations which may differ from less than a second to less than ten minute intervals are called short term variations.

Diurnal and short term variation are determined, however the data was insufficient to determine the inter-annual variation. At least three year’s data is required to observe any inter-annual variation at the measuring site.

3.4.3 Turbulence Intensity

Turbulence intensity (TI) is one of the vital characteristic in determining the power output. According to Marshall (2005), the higher turbulence level causes a decrease in power production. The wind speed standard deviation is the most important parameter in determining the turbulence. Manwell et al. (2002), described the three different levels of turbulence intensity: values less than or equal to 0.1 indicated low levels of turbulence, moderate levels to 0.25 and greater than 0.25 indicated higher levels. The turbulence intensity is mathematically determined by the expression:
\[ TI = \frac{\sigma}{\bar{U}} \]  

Where \( \sigma \) is the standard deviation of wind speed (ms\(^{-1}\)), \( \bar{U} \) is the mean wind speed (ms\(^{-1}\))

### 3.4.4 Distribution of Wind Direction

Distribution of wind direction is vital for the design of a wind farm and may be carried out in three steps. This involves measuring the time wind blows in each direction followed by the mean wind speed in each direction. The wind direction varies as the wind speed changes. The two can then be combined by multiplying the time with the cubic speed for each direction individually to get the energy distribution. According to Manwell et al. (2002), the seasonal variations may vary up to 30 degrees whereas the average monthly wind speeds may change directions up to 180 degrees. The wind direction distribution was obtained as a wind rose using windographer software.

### 3.5 Rayleigh distribution

The Rayleigh distribution function is the simplest probability function as it involves only one variable, the mean wind speed. This probability density function widely used is described by Manwell et al. (2002) as:

\[ P(U) = \frac{\pi}{2} \left( \frac{U}{\bar{U}^2} \right) \exp \left[ -\frac{\pi}{4} \left( \frac{U}{\bar{U}} \right)^2 \right] \]  

Where \( P(U) \) is the probability of having a wind speed of \( U \) ms\(^{-1}\), \( U \) is the unsteady wind speed component (ms\(^{-1}\)), \( \bar{U} \) is the mean wind speed (ms\(^{-1}\))

The above is used to determine the statistical distribution of the wind speed at any site.

While the cumulative distribution is given by the expression:

\[ F(U) = 1 - \exp \left[ -\frac{\pi}{4} \left( \frac{U}{\bar{U}} \right)^2 \right] \]  

Where \( F(U) \) represents the probability that the wind speed is smaller than or equal to a given wind speed
3.6 Weibull distribution

A generalized expression for the probability density distribution is needed to calculate the mean power from a wind turbine over a range of mean wind speeds. Though the Weibull probability distribution function involves the values of two parameters, it is viable to use Weibull distribution as the high wind speed variations and deviations can easily be described by the Weibull probability distribution function. This expression is described by Manwell et al. (2002) as:

\[ P(U) = \frac{k}{c} \left( \frac{U}{c} \right)^{k-1} \exp \left[ - \left( \frac{U}{c} \right)^k \right] \]  

(3.7)

Where \( P(U) \) is the probability density function, \( U \) is the unsteady wind speed component (ms\(^{-1}\)), \( c \) is the scale parameter with units of speed ms\(^{-1}\).

Similar to Rayleigh distribution, the cumulative distribution function given by the expression:

\[ F(U) = 1 - \exp \left[ - \left( \frac{U}{c} \right)^k \right] \]  

(3.8)

Where \( k \) = unit less shape parameter and given by the expression:

\[ k = \left( \frac{\sigma_u}{\bar{U}} \right)^{-1.086} \]  

(3.9)

Where \( \sigma_u \) is the standard deviation of the wind speed, and scale parameter \( c \) (ms\(^{-1}\)) is given by the expression:

\[ c = \frac{\bar{U}}{r(1+\frac{1}{k})} \]  

(3.10)

where \( r(x) \) is the usual gamma function is given by:

\[ r(x) = \int_0^\infty e^{-t} t^{x-1} dt \]  

(3.11)

and is approximated by:
\[
gr(x) = (\sqrt{2\pi x})(x^{x-1})(e^{-x}) \left(1 + \frac{1}{12x} + \frac{1}{288x^2} - \frac{139}{51840x^3} + \ldots\right) \tag{3.12}\]

The following expression can be used to calculate the value of \( c \):

\[
\frac{c}{\beta} = \left(0.568 + \frac{0.433}{k}\right)^{\frac{1}{2}} \tag{3.13}\]

### 3.7 Data Analysis Tools

The investigative approaches engaged in the wind–diesel hybrid system analysis are described below. For the purpose of this project, Windographer, Sigma Plot and Microsoft Excel have been accessed for analysis. Windographer is wind data analysis software which fabricates graphs and wind roses and also performs sophisticated statistical analysis. Windographer is able to read data form excel files, text files and many other forms of files. It can also take in any number of data and carry out the required analysis which is tedious to perform manually. Calculations and analysis carried out using windographer saves time and provides a satisfactory estimate. For the purpose of this project the wind data collected was analysed using the above software since a turbine is intended to be installed at the measuring site. Other wind analysis software such as WAsP was not utilized since there was no immediate need to predict the wind regime at any other site. However, for future use, WAsP can be used with the current data to determine the wind climate in the due proximity of the measured site. Moreover, WAsP the most versatile software on hand was not used since there was no need for extrapolation around the site.

### 3.8 Load Requirement

#### 3.8.1 Daily Load Demand

The field visit to Waisa revealed that energy for lighting was their first priority, followed by a possible ice-maker machine and a television set. The use of Light Emitting Diode (LED) light bulbs and energy saving bulbs has been considered in this analysis instead of incandescent lamps. Other subsidiary components needed for the hybrid was determined based on the daily load requirement for the village.
3.8.2 Estimating the Size of an Ice – Maker

A technical survey has been carried out to estimate the size of the ice maker needed to fulfill the ice requirements of the people of Waisa. A survey was carried out to find the total amount of fish caught per fishing trip and thus the amount of ice needed to preserve them was also estimated. This calculation of ice requirement is based on the total mass of fish needed to be preserved, the specific heat capacity of fish, the latent heat of fusion of ice and the initial and final temperature of fish.

According to Graham et al. (2006), the amount of ice required to preserve $M$ kg of fish is given by the formula:

$$M_i = \frac{(M_f)(C_{pf})(t_s-t_c)}{L_i}$$

(3.14)

Where $M_i$ is the mass of ice (kg), $M_f$ is the mass of fish (kg), $C_{pf}$ is the specific heat capacity of fish, $t_s$ initial temperature of fish (°C), $t_c$ final temperature of fish (°C).

The total daily energy required by the load was calculated by dividing the mean daily load with the conversion efficiency:

$$\text{Corrected mean daily load} = \frac{\text{mean daily load}}{\text{conversion efficiency}}$$

(3.15)

3.9 System Configuration

The hybrid system is designed on the premise that each household would be allowed to use light adding up to 100W, 10 tube lights for the church, 10 tube lights for the community hall with a power outlet for TV and separate power outlet for ice-maker machine. The limit to the individual household shall be controlled by a fuse to regulate the usage to below 100W.

The purpose of this study is to determine an optimum hybrid system of the required load. The mean daily energy consumption in Watt–hours per day (Whd^{-1}) for the village was calculated by adding the total power rating of all the lights, the power consumption by the TV and the ice maker which is then multiplied by the duty cycle, that is the number of hours the lights and the TV and the ice maker are in use.
Daily Energy Consumption =

\[(\text{Power Rating of Light (Total)} + \text{Power Rating of TV} + \text{Power Rating of Ice maker}) \times \text{hours used}\]

Based on the electricity demand of the village, the data were analyzed and the size of each of the component of the wind–diesel hybrid system was determined. According to Ahmad et al (2014), systems sizing is vital as it helps minimize the cost of power generation. A suitable system sizing for the required load was carried out after carrying out a detailed data analysis. Firstly, a suitable wind turbine was chosen based on the demand load and the power curve provided by the manufacturer.

In wind-diesel hybrid power systems a battery bank is required for storage of irregular wind energy. A back up diesel generator is also essential during periods of low wind speed to charge the battery.

### 3.9.1 Determination of the Turbine Size

The inputs for the wind turbine model are wind speed, radius of the wind turbine, air density, mechanical speed of the rotor, the cut-in, cut-out and rated wind speed, and power reference for the pitch angle controller. The size of the wind turbine was determined using the annual load demand. The search for the wind turbine selection was based on the type of turbine, the cost of turbine, the wind tower height, the cut-in wind speed and the weight of the turbine. The turbine selection was also chosen keeping in mind the availability of the wind resource at the selected site. Horizontal axis wind turbines are rarely used in Fiji, hence vertical axis wind turbine is investigated.

Based on the energy output of individual wind turbines and the wind regime at the candidate site, a few wind turbines were initially selected. The final selection was based on the economics, monthly and annual average wind speeds at the site, the lowest wind speed recorded in a month and the cut in wind speed of the turbine. The lowest wind speed recorded was evaluated and a wind turbine with a cut–in wind speed lower than this was chosen for the purpose of this project.
3.9.2 Battery Capacity

Batteries are core component of stand–alone systems because the excess generated power needs to be stored and used up later when the wind is calm. Storage expertise is vital so that there is a continuous supply of power to the load (Bataineh, et al 2014). Batteries with charge controller will prevent the batteries from over charging. According to Panchori et al (2007) and Rojas et al (2012), deep cycle lead acid battery is a good option for renewable energy stand – alone systems because it can be discharged to 20 % of the full capacity and still can be recharged. Batteries are vital components in an off–grid power supply systems. Batteries in wind turbine systems may be used to store charges and reused later when needed. For this study the battery was sized based on the load requirement and the turbine capacity.

3.9.3 Hardware Components

3.9.3.1 Diesel Generators

The existing diesel generator, currently used, will be employed as the other component of the hybrid.

3.9.3.2 Controller and the dump load

These components are part of the package of the wind turbines; hence it will not be acquired separately.

3.9.3.3 The Inverter

The peak power demand should not exceed the rated power output of the inverter and should be sized closer to the average power demand (Yazdanpanah, 2014). In this study the inverter is sized to the maximum power requirement.

3.9.3.4 Sensor and Hardware Logic

A smart system is a system which provides an uninterrupted supply with minimum energy loss. Thus application sensors and hardware logics are required. For this configuration a smart design is necessary to ensure that the above criterion is incorporated. Thus for this study, a supervisory controller with sensors and switches are chosen to provide optimum power delivery with no interruption.
3.10 Hybrid System Design

The purpose of this study is to choose an appropriate wind turbine to meet the daily load requirement. However, due to intermittent nature of wind, the system is designed to switch to battery bank during low wind periods. The diesel generator is used to charge the battery in the event the excess output from the wind turbine is not sufficient to complete the charging process. At low wind speed the output from the turbine is required to charge the battery and any excess is then dumped. Similarly any excess from the turbine during its supply is first directed to charge the battery and then dump the extra once the battery is fully charged.

3.11 Wind Energy Economics

The economic analysis is one of the vital processes in selecting the source of energy supply. To very small turbine users, the cost analysis may be of less interest however, when the cost of electricity is compared with that of the grid connected supply (Fiji Electricity Authority) will be challenging. A comprehensive analysis based on capital recovery factor, net – present value and the cost of energy were calculated to determine the economics of the hybrid system. The methodology employed to calculate these quantities are described in the following sections.

3.11.1 Capital Recovery Factor

The capital recovery factor (CRF) is the amount of each future payment required to gather a given present value when the number of payments and the discount rate are known as given by Manwell et al (2002) is:

$$CRF = \frac{r}{1-(1+r)^{-N}} \quad \text{if } r \neq 0 \quad (3.16)$$

Where $N$ is the number of payments to be made and $r$ is the discount rate

and

$$CRF = \frac{1}{N} \quad \text{if } r = 0 \quad (3.17)$$
3.11.2 Present Value of Annual Cost

The sum of all pertinent present values is called the net present value (NPV). Cost version of net present value, NPV ($C_A$) is considered if only the cost factors are considered. The design with the lowest NPV$_c$ is favorable when more than one system is being considered and is expressed (Manwell et al. 2002) as:

$$NPV = (C_A)_{1-n} = C_1 \left(1 + m \left[\frac{(1+i)^n-1}{i(1+i)^n}\right]\right)$$  \hspace{1cm} (3.18)

Where, $C_A$ annual cost of operation, $I$ real discount rate, $n$ lifetime of the project, $m$ is the percentage of $C_{OM}$, $C_1$ is the capital investment.

Where real discount rate is calculated using the expression:

$$I = \frac{1+i}{1+e_a} - 1$$  \hspace{1cm} (3.19)

Where $i$ is the discount rate, $e_a$ is the apparent escalation rate

The apparent escalation rate is evaluated using the expression:

$$e_a = [(1 + e)(1 + r)] - 1$$  \hspace{1cm} (3.20)

Where $e$ is the escalation rate and $r$ is the inflation rate

3.11.3 Net Present value of savings

The present value of all the savings over the life time of the project, assuming the project is able to deliver a benefit of $B_A$ annually through the sales of electricity is given:

$$NPV(B_A)_{1-n} = B_A \left[\frac{(1+i)^n-1}{i(1+i)^n}\right]$$  \hspace{1cm} (3.21)

Where, $B_A$ is the annual benefit through the sale of electricity
3.11.4 Net Present Value

Net present value (NPV) is defined as the sum of all savings and costs of the project. It is best given by the expression:

\[ NPV = NPV(B_A)_{1-n} - NPV(C_A)_{1-n} \]  
(3.22)

Any project with a negative net present value is not viable.

3.11.5 Cost of Energy

The cost of energy as defined by Rehman et al. (2009) is simply the price of a unit of electricity per dollar. In very simple terms it is the minimum breakeven price. The cost of energy is used to express the revenues or costs that may occur in unbalanced intervals or once is given by Manwell et al. (2002) as:

\[ COE = \frac{NPV(C_A)_{1-n}}{nE_A} \]  
(3.23)

Where

NPV \((C_A)\) is the net present value of all the cost and \(E_A\) is the annual energy production

3.11.6 Pay Back Period (PBP)

The payback period is the time it takes to pay back for the system is defined as:

\[ PBP = -\frac{\ln\left(1 - \frac{IC_I}{B_A - mC_I}\right)}{\ln(1+t)} \]  
(3.24)

3.11.7 Benefit cost ratio

Benefit cost ratio (BCR) is defined as the ratio of all benefits to the present value of all costs. Higher BCR values are desirable whereas BCR greater than 1 is acceptable.

\[ BCR = \frac{NPV(BA)_{1-n}}{C_I + NPV(CA)_{1-n}} \]  
(3.25)
Chapter 4  Results and Discussion

4.1 Introduction

Wind data from September 2012 to August 2013 was used to analyse a possible hybrid system for Waisa. Parts of these data were retrieved from KOICA data bank housed at USP and the remainder was downloaded from the measuring site. Using the wind statistics, the load requirement, the financial and installation constraints, and a wind diesel hybrid system is proposed for Waisa.

4.2 Wind Statistics

Wind is intermittent in nature thus the electricity generation from wind is not steady. Hence the average wind speed for a longer period, at least one year period must be recorded (Lu et al., 2002) in order to analyse and calculate the mean power delivered by the wind turbines.

The total power delivered by a wind turbine depends on three variables: the wind velocity, the air density and the diameter of the turbine blades and can be calculated using equation 1.5. The mean power delivered by a wind turbine can also be calculated using the power curve of the wind turbine. However, this power can only be calculated if the probability density function of the wind speed is known. According to Manwell et al (2002), the Rayleigh and the Weibull probability distributions are most commonly used in analysis of wind data.

An existing 34 m mast, which was put up in 2012 has two anemometers, NRG # 40C anemometers and two wind vanes, NRG # 200P, at a height of 34 m and an anemometer and one wind vane at a height of 20 m. The parameters analyzed in this section comprise wind speed, wind direction and turbulence. The central idea of this study is to design a hybrid system to meet the daily requirements of Waisa village in Vanua-Levu.

4.2.1 Daily wind speed distribution

The daily wind speed variation at the study site (Figure 4.1) shows that the wind speed is between 3 ms$^{-1}$ and 8 ms$^{-1}$ at 20 m a.g.l. Appendix 4A provides the daily wind speed average for the whole year.
A similar study was carried out by Shaahid (2015) in Saudi Arabia recorded wind speeds between 3.3 ms\(^{-1}\) and 5.6 ms\(^{-1}\) at a height of 37 m a.g.l.

![Figure 4.1: Daily wind speed distribution (September 2012 – August 2013)](image)

The variation in monthly wind speed clearly indicates the periods of maximum and minimum wind speeds. The wind speed variation shows the similar pattern for all the months. The mean of daily means was 5.43 ms\(^{-1}\) with a standard deviation of 3.15 ms\(^{-1}\).

### 4.2.2 10 minutes daily mean

Extracting wind energy for electricity generation demands a long period of wind data. The wind parameters shall be directly measured at the turbine site. However, it could be measured in the close vicinity (approximately 5 km) and reliably extrapolated to the turbine site using software like WAsP. Other techniques like measure and correlate can also be used that requires a short duration of monitoring at the turbine site. The accuracy of estimate depends besides geographical features the duration of wind measurement. A medium term approximately 5 years wind data is desired but shorter term of three years is sufficient to absorb the seasonal variations. However, for feasibility study a one year’s complete data is adequate to estimate the general features of wind regime (Youm et al, 2005). The accuracy of the measurement depends on the characteristics of the instrument used to measure the wind parameters.
The time series of wind speeds (figure 4.2) shows the instantaneous 10 minutes wind speed at 20 m a.g.l for one year.

It is evident from the ten minute mean wind speed pattern that the wind had gusts over 10 ms\(^{-1}\) and occasionally over 13 ms\(^{-1}\). There was a momentarily wind speed of 25 ms\(^{-1}\) but it occurred once during the measuring period. The 25 ms\(^{-1}\) peak was due to cyclone Evan which affected the Fiji group of Islands. It was found that the data fit in to the meteorological conditions except on the 27\(^{th}\) day of March due to extreme weather conditions.

### 4.2.3 Diurnal wind pattern

The diurnal pattern for a Julian day 46 (15\(^{th}\) February) was investigated. The mean diurnal profile for Julian day 46 and the annual mean was plotted (Figure 4.3) because this day recorded the lowest wind speed. The 10 minute average wind speed is greater than the annual mean during the latter part of the day. This diurnal variation shows that the wind speed on 15\(^{th}\) February was a minimum at 01:00 to 02:00 h and gradually increased to a maximum of over 10 ms\(^{-1}\) at 23:00 h.
Figure 4.3 Wind speed pattern at 20 m a.g.l for 15\textsuperscript{th} February, 2013

4.2.4 Turbulence Intensity at the Meteorological mast

The turbulence intensity at the measuring site was 0.59, calculated using equation 3.10. Turbulence, a sudden change in wind speed, decreases with the increase in height above the ground. High turbulence leads to reduced production of energy and may increase the wear and tear of the turbines. It may also increase the vibrant loads on the blades. Short term change in wind speeds is the change in wind speeds from several seconds to several minutes. The long term variations pertinent for assimilation in the power system include the seasonal and inter annual fluctuations caused by climatic effects. A value of 0.59 indicates a high level of turbulence (Manwell et al. 2002). The turbulence in the wind affects the power production and causes the dissemination of noise from the turbines. Other effects of turbulence induced by climatic effect were not investigated. Turbulence concentration increases with obstruction such as buildings, trees and sheer mountain tops.
4.2.5 Monthly wind speed distribution

The monthly mean wind speed (Figure 4.4) shows the relative wind regime for individual months compared to the annual mean wind speed.

![Wind Speed at 34 m a.g.l](image1)

Figure 4.4 Monthly mean wind speed variation at Waisa site at 20 m and 34 m a.g.l.

The wind speeds at Waisa are higher than 3 ms\(^{-1}\) for 12 hours between 12 am and 12 pm (Figure 4.4). The average annual wind speed at 34 m a.g.l and 20 m a.g.l was greater than greater than 5.43 ms\(^{-1}\) for three quarter of the year, from April 2012 to December 2013. Shaahid (2015) carried out a research in Saudi Arabia showed higher wind speeds recorded during summer months. The average wind speed at a height of 34 m a.g.l was 5.64 ms\(^{-1}\) while at 20 m a.g.l is 5.43 ms\(^{-1}\). Another study carried out by Phelan et al (2013) in Ireland recorded a mean wind speed between 4 ms\(^{-1}\) and 6 ms\(^{-1}\) at a height of 10 m a.g.l. A similar study was carried out by Nfah and Ngundam (2008) found that wind speeds between 3 and 6 ms\(^{-1}\) were used to supply electricity to a typical secondary school. According to Ozgur (2006), a wind speed of 5 ms\(^{-1}\) to 6 ms\(^{-1}\) may not be possible for large scale electricity generation. However, it is promising for small scale power generation.

The variation in monthly wind speed clearly indicates the periods of maximum and minimum wind speeds. The monthly average wind speed and standard deviations are attached as appendices 4B and 4C respectively. February showed the minimum and July showed the maximum wind speed. Other researchers (Kumar and Prasad, 2010;
Kumar and Nair, 2011; Kumar and Deo, 2006) showed the similar trend for other regions in Fiji.

### 4.2.6 Quarterly mean wind speed distribution pattern

The quarterly mean wind speed at 20 m a.g.l was calculated (Figure 4.5) and the variation in the wind speed for every quarter of the year was investigated.

![Average quarterly wind speed](image)

Figure 4.5 Quarterly average wind speeds at Waisa (2012)

The first quarter recorded the lowest mean wind speed of 3.75 ms\(^{-1}\). There was a gradual increase in the average wind speed from the first quarter to the last quarter. From July to December, the mean wind speed was greater than the annual mean. It is evidenced from the data (Figure 4.4) that months of February and March recorded lowest wind speed resulting in the lowest mean for the first quarter. The detail quarterly average wind speed table is attached as appendix 4D.

### 4.2.7 Fitting Weibull distribution

Windographer was used to plot the measured probability distribution together with the Weibull probability distribution function (Figure 4.6). The shape parameter \(k\) and the scale parameter \(c\) were obtained using the equations 3.5 and 3.6 respectively. The values of \(k\) and \(c\) calculated using expression 3.9 and 3.10 respectively were 1.76 and 4.8 ms\(^{-1}\).
A similar study carried out by Maatallah (2012) in Tunis, Tunisia using cumulative method at a height of 30 m a.g.l recorded yearly shape factor $k$ of 1.9 and scale parameter $c$ of 6.5 ms$^{-1}$. A Weibull distribution for which $k = 2$ is a special case of Weibull distribution and it equals the Rayleigh distribution (Manwell, 2002).

Figure 4.6  Comparison of estimated Weibull probability with the actual probability at 20 m a.g.l (Windographer output)
4.2.8 Comparison of statistical distributions

The wind data at the site were analyzed using the Rayleigh and Weibull distribution. The comparison was made between the two distributions to determine which distribution best describes the data.

Rayleigh and Weibull probability distribution were calculated using equations 3.2 and 3.4 respectively. The manual calculation was carried out using excel. The Rayleigh and Weibull probability distribution patterns (Figure 4.7) do not differ significantly from the actual probability distribution.

![Figure 4.7 Weibull and Rayleigh probability distribution at 34 m a.g.l](image)

The probabilities of occurrences for different intervals are shown below (Table 4.1).

Table 4.1: Probability of occurrences for different wind speed intervals  

<table>
<thead>
<tr>
<th>Wind speed interval (ms⁻¹)</th>
<th>Manual calculation</th>
<th>Rayleigh estimation</th>
<th>Weibull estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Estimate</td>
<td>Δ (%)</td>
<td>Estimate</td>
</tr>
<tr>
<td>2-5</td>
<td>31</td>
<td>39</td>
<td>21</td>
</tr>
<tr>
<td>5-10</td>
<td>48</td>
<td>44</td>
<td>-9</td>
</tr>
<tr>
<td>10-19</td>
<td>8</td>
<td>6</td>
<td>-33</td>
</tr>
<tr>
<td>Total</td>
<td>87</td>
<td>89</td>
<td></td>
</tr>
</tbody>
</table>
The probability that the average wind speed at the Waisa site will be somewhere between 2 and 19 ms$^{-1}$ was calculated. This was then compared with the Rayleigh and Weibull distribution to actually find out which of the two best compares with the calculated value. The measured probability distribution that the wind speed remains between 2 and 19 ms$^{-1}$ was 87%, calculated using excel. The Rayleigh and Weibull probability distributions were also calculated to assess which of the two is closest to the actual calculated probability. The probability calculated using Rayleigh distribution was 89% while the Weibull distribution estimated 80% with a difference of 9%. When compared to the actual probability distribution pattern the Rayleigh distribution differs by 2% while the Weibull probability distribution differed by 7%. The result shows that both the methods of calculating the probability correlate well with the actual probability. The value of $k$ was 1.76 hence Weibull probability cannot be approximated to Rayleigh probability distribution (Manwell et. al. 2002).

4.3 Wind speed comparison

It is important to obtain wind speed at the hub height of the wind turbine. This has been acknowledged in many studies in the current literature (Manwell et al, 2002, Wan et al, 2009). For the purpose of this study the wind speed at 2 different heights were taken. The two measurements were recorded at 20 m and 34 m a.g.l. The hub heights of the chosen turbine (7.5 kW) are 16 m, 20 m and 24 m. The measurements recorded at 20 m were used for analysis because the turbine also has a hub height of 20 m.
The average wind speed measured at two different heights at Waisa site is shown (Figure 4.8) below. The minimum was recorded in the month of February while the maximum was recorded during the month of July.

![Figure 4.8 Monthly averages of wind speed measured at Waisa](image)

The two anemometers at 34 m a.g.l recorded almost same values while the anemometers at 20 m a.g.l recorded wind speed lower than that at 34 m a.g.l. The two sets of data (Figure 4.9) were plotted to test out the relationship between the recorded data with two anemometers at the same height.
The plot shows the relationship between two sets of data at 34 m a.g.l. The linear relationship is given by:

\[
\text{Speed at 34 m} = 1.0132(\text{speed at 34 m}) - 0.1752, \quad R^2 = 0.9751
\]  \hfill (4.1)

Walpole (1972) defined \( R \) as the measure of the speeds measured at 34 m and the value of \( R^2 \) ranges from 0 to 1. A value close to 1 indicates a strong relationship while a value close to zero corresponds to a very weak relationship. Thus the value of 0.965 indicates a strong relationship between the two sets of wind speed measured at 34 m a.g.l. Hence any of the two sets of data measured can be used for further analysis. Appropriate statistical tests must be carried out to find the consistency of the mean wind speed at different heights and more than one set of wind speeds recorded at the same height. This is done to determine if there is any significant difference between the two sets of wind speeds recorded at 34 m. The sample t–test is carried out to test if the two sample means at 34 m are equal. The result \( t = 1.26, \alpha = 10\% \) indicates that there was no significance difference between the mean of two sets of wind speeds.
It was also necessary to investigate the relationship (Figure 4.10) between the wind speeds at 20 m and 34 m a.g.l. The relationship obtained can then be used to construct a wind regime at a desired altitude and even used to estimate the wind speed beyond 34 m a.g.l.

The linear relationship between the two sets of data measured at two different heights is described by:

\[
\text{Speed at 34 m} = 1.013(\text{speed at 20 m}) + 0.153, \quad R^2 = 0.9651
\]  

(4.2)

Independent sample t–tests were carried out to determine the relationship between two groups depended on the same variable. The t–test, using \( \alpha = 0.10 \) showed that the mean wind speed at 34 m is more than the mean wind speed at 20 m a.g.l. However, expression 4.2 may be used to interpolate the wind speed between 20 and 34 m a.g.l. Generally, expression (3.2) for power law (\( \alpha = 0.14 \)) is used to extrapolate the wind speed. Using this expression and comparing with the relationship stated in equation 4.2, results (table 4.2) were obtained.
Table 4.2: Estimated and measured mean wind speeds at different heights

<table>
<thead>
<tr>
<th></th>
<th>Measured mean at 20 m</th>
<th>Estimated at 34 m using equation 3.2 (ms$^{-1}$)</th>
<th>Estimated at 34 m using equation 4.2 (ms$^{-1}$)</th>
<th>Measured at 34 m (ms$^{-1}$)</th>
<th>Estimated at 34 m using equation 3.2 (ms$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.43</td>
<td>5.85</td>
<td>5.65</td>
<td>5.63</td>
<td>6.26</td>
</tr>
</tbody>
</table>

From the table above, estimated wind speed using equation 4.2 gives the better approximation. Hence, equation 4.2 is used to extrapolate the wind at 55 m a.g.l yield an annual mean of 6.26 ms$^{-1}$.

The increase in wind speed due to height difference was calculated and plotted. Figure 4.11 shows the increase in wind speed at 55 m a.g.l. The wind speed also increases with the increase in height.

![Figure 4.11: Average monthly wind speed variation at 34 m and 55 m a.g.l](image)

**Figure 4.11**  Average monthly wind speed variation at 34 m and 55 m a.g.l

### 4.4 Wind direction

Wind speed and wind direction at the Waisa site were measured for 12 months. The software analysis and validation for synchronized 10 minute average data for Waisa site was carried out.
The sequential wind speed distribution and various frequencies of wind directions (Figure 4.12) shows the wind rose.

![Wind Rose Diagram](image)

**Figure 4.12** Waisa village wind direction distributions

It is evident from figure 4.12 that the wind is predominantly easterly. It should be borne in mind that the site is very close to open sea and there are no obstacles in between.

### 4.5 Daily load requirement

The system load constitutes of lights at 240 V AC, 150 W AC for TV and 890 W AC for an ice maker machine. The daily load demand Waisa village is attached as appendix 4E. The duty cycle for the load was decided to be 10 hours per day. The inverter efficiency as affirmed by the company is 90%. The size of the ice-maker was decided based on the approximate weight of fish that the villagers caught. It was found that total number of fishing boat is 3 having a capacity of about 40 kg fish per trip per boat. Thus giving a total weight capacity around 120 kg per trip. Commonly, the fishermen in Waisa village fish only twice a week, that is, 8 trips in a month and fishing is successful within 7 months only. So, based on this survey, the total amount of ice demand is about 24 kg per day to preserve 120 kg of fish, which adds up to 1920 kg for 96 days of fishing in a year. Based on the survey work and interviews, the
minimum requirement for the village is tabulated below. The total daily requirement for the village was calculated using the expression 3.14. The details are explained in appendix 4F.

Table 4.3 The annual energy demand of Waisa

<table>
<thead>
<tr>
<th>Load</th>
<th>Annual Energy demand (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>5475</td>
</tr>
<tr>
<td>Church Hall (Television and Ice – maker and light)</td>
<td>5256</td>
</tr>
<tr>
<td>Total</td>
<td>11,923.33 (corrected mean load)</td>
</tr>
</tbody>
</table>

4.5.1 Daily fuel requirement

All the houses have a very small portable solar panel (Figure 4.13) which charges a solar lantern and is able to charge mobile phones. This gadget was purchased from the Department of Energy in the year 2013. There is one generator (2kVA) which is only used for the major functions like wedding and any other religious functions happening in the village church.

Figure 4.13 (a) Portable solar panel (b) Diesel generator system (December, 2014)

The village church has no solar power. Any other daily functions happening in the church uses kerosene lantern as the source of light. More than 50% of the source of power for the village comes from kerosene lantern. The total cost of fuel used by the
diesel generator and for fishing is determined later in chapter 4. The daily fuel usage per household was also calculated to find out the total fuel used by the villagers annually. The economics of fuel (Table 4.4) shows the amount and type of fuel used at Waisa village.

Table 4.4: Fuel budget of Waisa

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Kerosene</th>
<th>Diesel</th>
<th>Premix</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Litres used</td>
<td>Cost ($)</td>
<td>Litres used</td>
</tr>
<tr>
<td>Weekly</td>
<td>105 (1 litre daily x 15 household)</td>
<td>131.25</td>
<td>35</td>
</tr>
<tr>
<td>Monthly</td>
<td>420</td>
<td>525</td>
<td>140</td>
</tr>
<tr>
<td>Annual</td>
<td>5460</td>
<td>6,825</td>
<td>1820</td>
</tr>
<tr>
<td>Total cost of fuel used annually</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the survey work the total cost of the fuel used by the villager’s is estimated as $11,481.40.

4.6 Turbine selection

The turbine is to supply the load all the time. However, due to the intermittent nature of wind, it may not be possible. Hence there is a need to optimize bearing in mind the cost and other pertinent features of the wind turbine. The main characteristics of few turbines investigated (Table 4.5) shows their characteristics and annual energy production (AEP) estimated by windographer.
Table 4.5: Different turbine specifications

<table>
<thead>
<tr>
<th>Turbine name</th>
<th>Endurance s-250</th>
<th>Enair -160</th>
<th>Bergey Excel- R</th>
<th>Bergey Excel-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
<td>5 Kw</td>
<td>7.5 kW</td>
<td>7.5 kW</td>
<td>10 kW</td>
</tr>
<tr>
<td>Cut-in-wind speed</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Hub height at which AEP is calculated</td>
<td>19.2</td>
<td>20</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>AEP</td>
<td>5,891</td>
<td>18,373</td>
<td>10,782</td>
<td>11,917</td>
</tr>
</tbody>
</table>

Also to estimate any errors in estimation, a turbine with a hub height of 20 m is most appropriate. The actual procurement of individual turbine, their life-time guarantee and physical attributes and AEP of the turbines were considered. The specifications of all the selected turbines are attached in appendix 4G. Based on all these Enair 7.5 kW is a better choice for Waisa. Hence all further estimates are based on Enair 7.5 kW turbine.

4.6.1 Enair 7.5 kW Turbine

The specifications of Enair 160 -7.5 kW wind turbine (Table 4.6) shows the pertinent features that were considered to make the appropriate choice.

Table 4.6: Specifications of Enair 7.5 kW turbine

<table>
<thead>
<tr>
<th>Model – Enair 160- 7.5 kW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power</td>
</tr>
<tr>
<td>Maximum Power</td>
</tr>
<tr>
<td>Rotor Diameter</td>
</tr>
<tr>
<td>Cut in speed</td>
</tr>
<tr>
<td>Cut out speed</td>
</tr>
<tr>
<td>Efficient Generation range</td>
</tr>
<tr>
<td>Swept area</td>
</tr>
<tr>
<td>Design lifetime</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Voltage</td>
</tr>
<tr>
<td>Working temperature</td>
</tr>
<tr>
<td>Tower</td>
</tr>
<tr>
<td>Power control</td>
</tr>
</tbody>
</table>
The manufacturers power curve (Figure 4.14) shows the cut-in, cut-out and rated power of the 7.5 kW wind turbine.

![Power Curve](image)

**Figure 4.14** Manufacturers power curve for 7.5 kW wind turbine (redrawn)

The power curve shows that power production increases non–produced linearly between 4 ms\(^{-1}\) and 12 ms\(^{-1}\) and no power is when the wind speed is below 2 ms\(^{-1}\). The maximum power extracted is less than 9 kW. The percentage of the time the turbine will produce electricity is given in Table 4.7.
Table 4.7 Percentage of the time the wind speed is greater than cut-in (2 ms⁻¹) wind speed.

<table>
<thead>
<tr>
<th>Month</th>
<th>% of the times the wind speed is greater than 2 ms⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>84.4</td>
</tr>
<tr>
<td>Feb</td>
<td>75.8</td>
</tr>
<tr>
<td>Mar</td>
<td>77.5</td>
</tr>
<tr>
<td>Apr</td>
<td>87.0</td>
</tr>
<tr>
<td>May</td>
<td>80.3</td>
</tr>
<tr>
<td>Jun</td>
<td>81.3</td>
</tr>
<tr>
<td>Jul</td>
<td>96.0</td>
</tr>
<tr>
<td>Aug</td>
<td>83.5</td>
</tr>
<tr>
<td>Sept</td>
<td>88.8</td>
</tr>
<tr>
<td>Oct</td>
<td>91.3</td>
</tr>
<tr>
<td>Nov</td>
<td>92.8</td>
</tr>
<tr>
<td>Dec</td>
<td>95.1</td>
</tr>
<tr>
<td>Annual average percentage</td>
<td>86.2</td>
</tr>
</tbody>
</table>

Considering the demand of Waisa of 2.7 kW (Appendix A) and according to the power curve (Figure 4.14), the turbine will directly supply the load if the wind speed is 6.5 ms⁻¹. Using Rayleigh probability (equation 3.6) distribution, the probability that the wind speed is greater than 6.5 ms⁻¹ is equal to 0.68. Using Weibull probability distribution,(equation 3.8) the probability that the wind speed is greater than 6.5 ms⁻¹ is 0.82. This implies that 82 % of the time the turbine is estimated to directly supply the electricity. However, using cumulative probability it is estimated that the turbine would meet the demand 86 % of the time.

4.6.2 Fitting equation to power curve

The power curve of 7.5 kW Enair wind turbine was generated using the manufacturers data sheet and the equation of the curve was derived. This was done so that the power produced by the turbine at wind speeds interpolated between the values stated in the
manufacturers data sheet. The derived power curve of the equation of the 7.5 kW wind turbine is defined as:

\[ P(kW) = \frac{8.4}{1 + \exp\left(\frac{1(u-7.5)}{1.7}\right)} \tag{4.1} \]

Where \( u \) is the instantaneous wind speed (ms\(^{-1}\)).

The derived power curve and the manufacturer’s power curve (Figure 4.15) are plotted.

![Figure 4.15: Relation between the manufacturers and derived power curve](image)

The power curve equation was derived to calculate the AEP from continuous measured wind speed data since the data sheet of Enair 7.5 kW wind turbine only provides power produced at discrete wind speed. When comparing the AEP predicted by windographer, calculated AEP served as a reference.

4.6.2.1 Error comparison between the derived power curve and the manufacturers power curve

The accuracy of the curve was used to determine the error in the derived power curve. The percentage difference between the derived value and the manufacturer’s value (table 4.8) was calculated and compared.
Table 4.8: Error in estimated power of Enair 7.5 kW wind turbine

<table>
<thead>
<tr>
<th>Wind speed (ms(^{-1}))</th>
<th>Manufacturers value (kW)</th>
<th>Estimated value(kW)</th>
<th>% error</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.2</td>
<td>0.3</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>0.99</td>
<td>0.95</td>
<td>-4.2</td>
</tr>
<tr>
<td>6</td>
<td>2.59</td>
<td>2.46</td>
<td>-5.3</td>
</tr>
<tr>
<td>8</td>
<td>4.72</td>
<td>4.86</td>
<td>2.9</td>
</tr>
<tr>
<td>10</td>
<td>6.95</td>
<td>6.83</td>
<td>-1.8</td>
</tr>
<tr>
<td>12</td>
<td>7.95</td>
<td>7.84</td>
<td>-1.4</td>
</tr>
<tr>
<td>14</td>
<td>8.10</td>
<td>8.22</td>
<td>1.5</td>
</tr>
<tr>
<td>16</td>
<td>8.24</td>
<td>8.34</td>
<td>1.2</td>
</tr>
<tr>
<td>18</td>
<td>8.43</td>
<td>8.38</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

The derived power curve and the manufacturer’s power curve are compared for accuracy. The derived power curve resembles very closely to the manufacturers power curve. The underestimation and overestimation in the % error column are signified by the negative and positive values respectively. At very low wind speed the derived curve overestimates the power by 33 %. However, this error is of least significant since 2 ms\(^{-1}\) is the cut-in-wind speed of the turbine. Thus the determined power curve is sufficient to estimate the AEP in absence of manufacturer’s power curve.

4.7 Turbine output

4.7.1 Monthly output using equation

In case of wind turbine not been able to supply the power to the load, a diesel generator is used to supply the deficit load. The most effective turbine as described by Kanthhwal (2012) is the one which produces the same amount of energy as required annually. The average monthly energy output from 7.5 kW Turbine (Table 4.9) shows the accumulated values, however daily output is much important single factor to determine how much is produced on daily basis.
Table 4.9 indicates that monthly average power produced by the turbine is higher during summer months. A similar study carried out by Shaahid (2015) also recorded high power generated during summer months as compared to other months. This is a positive characteristic because the load is also higher during summer for Christmas gathering and other social events.

4.7.2 Monthly output using windographer software.

Data for one complete year (September 2012 to August 2013) recorded at an interval of every 10 minutes was analyzed using windographer software. The calculation includes analysis of raw wind data, estimation of wind power potential and calculation of the annual energy output of the system. The AEP depends on the turbine characteristics and the power density. The AEP for a 7.5 kW Enair wind turbine at Waisa site is 23, 435 kWh(Table 4.10) also shows the gross and net AEP of a 7.5 kW Enair wind turbine are estimated.
4.7.3 Software and manual calculation

The manual calculation of AEP using the derived power curve was compared with the results of the windographer analysis. The result (Table 4.11) shows the difference in the two values of AEP.

<table>
<thead>
<tr>
<th>Windographer prediction</th>
<th>Manual estimate</th>
<th>Δ AEP</th>
<th>% Δ in AEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEP (kWh)</td>
<td>15,675</td>
<td>22,861.71</td>
<td>7,186.71</td>
</tr>
</tbody>
</table>

The 10 minute raw data was used to calculate the actual AEP using excels spreadsheet. The AEP was calculated using Windographer. Thus was done so that the comparison can be carried out to determine the difference between the two AEP values. The AEP calculated using Windographer is equal to 15,675 kWh whereas the derived equation for power curve gives the total of only 22,861 kWh.

4.8 Turbine performance

The size of the wind turbine and other components of the hybrid system play a very important role in the power production and the load demand. The role of wind–diesel hybrid power systems as defined by Thomas Ackerman in Wind Power in Power Systems: “A technically effective wind–diesel system supplies firm power using wind power to reduce fuel consumption while maintaining the acceptable power quality. In order to be economically viable, the investment in the extra equipment that is needed to incorporate wind power, including the wind turbines themselves, must be recouped by the value of the fuel savings and other benefits. As the ratio of the installed wind capacity to the system load increases, the required equipment needed to maintain a
stable AC grid also increases, forcing an optimum amount of wind power in a given system. This optimum is defined by limits given by the level of technology used in the system, the complexity of the layout chosen and the power quality required by the user. For this reason the optimal design must be based on careful analysis, not simply the maximum amount of wind energy”.

The annual energy demand for the village was calculated. Three to five lights per household, a Television set and an ice maker consumes an estimate of 11,923 kWh annually. Windographer was used to calculate the annual energy production of few turbines using the recorded data. According to the demand load and the minimum wind speed recorded, Enair 7.5 kW wind turbine with a cut-in wind speed of 2 ms\(^{-1}\) is sufficient enough to provide the energy to the 15 houses and church of Waisa village.

### 4.8.1 Monthly performance of the turbine

To verify the actual variation of the daily wind speed and the cut-in wind speed the daily average for each month is plotted with the cut-in wind speed. The daily wind speed pattern for each month (Figure 4.16) is plotted together with the cut-in and the mean wind speed required for the turbine to directly meet the load.
Daily wind speed pattern for March

- Cut-in wind speed
- Average wind speed
- Turbine directly supplies

Days

Average wind speed (m/s)

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31

Daily wind speed pattern for April

- Cut-in wind speed
- Average wind speed
- Turbine directly supplies

Days

Average wind speed (m/s)

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29

Daily wind speed pattern for May

- Cut-in wind speed
- Average wind speed
- Turbine directly supplies

Days

Average wind speed (m/s)

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31

Daily wind speed pattern for June

- Cut-in wind speed
- Average wind speed
- Turbine directly supplies

Days

Average wind speed (m/s)

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31

Daily wind speed pattern for July

- Cut-in wind speed
- Average wind speed
- Turbine directly supplies

Days

Average wind speed (m/s)

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31

Daily wind speed pattern for August

- Cut-in wind speed
- Average wind speed
- Turbine directly supplies

Days

Average wind speed (m/s)

1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31
Figure 4.16  The daily wind speed variation for each month

It is evident from the graphs that the wind speed recorded at Waisa site falls within the cut-in (2 ms\(^{-1}\)) and the cut-out (19 ms\(^{-1}\)) for all the months except for the month of August where the wind speed is below the cut-in between 21\(^{st}\) August to 23\(^{rd}\) August. The turbine will produce power 86.2 % of the times during the year. February recorded the lowest wind speeds where the turbine will be able to produce power during 75 % of the times and the highest percentage was recorded in July where 96 % of the time the turbine will be able to produce power. The daily average wind speeds recorded at Waisa site is always below 19 ms\(^{-1}\) (cut-out wind speed).
4.8.2 Daily turbine output

It is important to determine the days of the month and even hour of the day when the turbine is not able to directly meet the demand. This is based on the assumption that the load requirement is constant all the day. Even though during the day the light requirement could be neglected, but for calculation purposes, it is assumed that the light is switched on 24 hours. This calculation is carried out using the derived equation of the power curve.

From 12 midnight till 4 am a total of 15 kWh of energy is assumed to be consumed (Figure 4.17) by the light only. While from 4 am till 7 am in the morning daily the total energy consumption increases to 30 kWh and reduces to half till 6 pm and fluctuates to 30 kWh till midnight.

![Energy Requirement Chart]

Figure 4.17: Daily energy requirement for Waisa

The estimated daily output (Figure 4.18) shows the performance of the turbine. A close inspection of figure 4.16 reveals that months of February and March are the critical months, hence only February is further analyzed for daily turbine output.
The daily output of February 8th (Figure 4.18) shows the turbine contribution on the least windy day.

Figure 4.18: Turbine contribution during the least windy day

The results showed that February is the least windy month. The turbine contribution and the daily load demand (Figure 4.19) is plotted to show the days where battery may be used due to insufficient wind supply.

Figure 4.19: Turbine contribution during the least windy month
4.8.3 Suitability of the turbine for electricity supply

The suitability of the turbine was determined primarily based on the ability to meet the desired load demand. However, other factors such as the capital cost, civil works, procurement and ease of transporting to the site and lifetime were considered. Based on the above criteria, Enair 7.5 kW turbine was chosen.

4.9 Hybrid system

The design of a hybrid power system is affected by many factors. In order to reduce high fuel costs and to provide increased energy, hybrid systems have been developed by introducing renewable power into existing isolated grids (Lin, 2012 and Xu et al, 2013). According to Manwell et al. (2002), the mismatch between the load and the power produced by the hybrid affects the performance of the system and has explained the rules of the hybrid system. However, for this study a hybrid systems sole purpose is to extract maximum possible energy from the turbine and use stored energy (battery) when the turbine output is not sufficient. The diesel generator is used as a backup to charge (top up) the battery only when the turbine has not fully charged the battery.

4.9.1 Hybrid design rules

In this study the proposed hybrid design is suggested based on the following premises; Firstly, the wind turbine should directly meet the instantaneous load requirement of the village. However, any extra power produced from wind should charge the battery bank and any further excess is then dumped. Secondly, in the absence of wind, power is drawn directly from the battery bank. Thirdly, the diesel generator is only switched on to charge the battery only. Once the battery bank is fully charged, the generator is switched off. Fourthly, the battery is discharged to only 50% of the capacity.
The arrangement (Figure 4.20) is suggested for the remote location to utilize wind to its maximum and then battery storage source and diesel generator only to charge the battery when a need arises.

The wind/diesel/battery hybrid system comprises of a 7.5 kW wind turbine, 2 kVA diesel generator, 225 Ah battery bank, 5 kW inverter, controller and load. The demand is not critical, hence the project is allowing for a single day of battery storage. The demand for Waisa is estimated at 112.5 Ah/day (Appendix 4E), allowing 50% depth of discharge, the battery is estimated to have a capacity of 225 Ah. The mean daily demand for Waisa is estimated at 29.4 kWh d\(^{-1}\), with an estimated power requirement of 2.7 kW. Thus, the inverter is chosen to be greater than 2.7 kW. This is to buffer any unexpected power usage at the community hall. Thus, to avoid damage and any disruption to supply, an inverter of 5 kW output is chosen for this project.

Figure 4.20  The remote wind–diesel hybrid power system
The controller supervises all connection and disconnection and is automated i.e. (automated supervisory controller). It automates the direct turbine connection, diesel connection for charging the battery bank, dump load connection and battery storage to load connection. The microprocessor controls in the inverter ensure that the generator always runs optimally loaded. It runs for just sufficient hours each day to ensure the battery is adequately recharged. The total amount of electricity consumed remains the same, however the savings come from reduced generator maintenance and fuel costs because the diesel is always optimally loaded. The turbine will be directly connected to the micro grid and will supply power. Once the power supplied by the turbine is less than the load, the system will automatically switch onto the battery which will then be the source. A sensor in the controller will continuously compare the load with the output of the turbine using supplied algorithm. The battery bank charge will be monitored by battery sensor, continuously checking the battery status, effectively cutting off from the wind turbine when fully charged. If the charge of the battery is greater than 20 % of its capacity, the system will run smoothly and will continue to supply power to the 240V with an input of 24 V inverter. Under low wind conditions, as the battery bank charge reduces to less than 20 %, the sensor switch will then cut off from the battery and will start the diesel generator. The diesel generator is on when there is not enough wind to supply the load which will then supply to the load and the excess will be used to charge the battery.

A fast acting dump load controller will also be connected to maintain the quality and frequency of the system. A dump load is tacit to exit as there will be cases when there will be a good supply of wind, there will be excess power produced from the wind turbines. All power produced in excess of the systems requirements can be dissipated. When there is enough wind to supply the load directly and the battery is fully charged, the excess power will be dumped in the dump load which is rated same as the turbine. This is necessary as there may be times when the battery is fully charged and the load is zero so all the power produced must be dumped. An optimum size battery bank is necessary for this system of wind – diesel as most of the energy produced by the wind turbine is during the day and the maximum energy consumption is happening during night time. Thus the energy produced must be stored and used when required at night. Therefore, for this project, deep cycle lead acid batteries are used for energy storage.
The battery capacity is the energy stored in the battery and is measured in ampere hours (Ah).

### 4.9.2 Wind contribution

The energy contribution by each source is detailed in table 4.12 below.

<table>
<thead>
<tr>
<th>Months</th>
<th>Energy required per month (kWh/month)</th>
<th>Monthly wind contribution (kWh/month)</th>
<th>Load to be met by the Diesel generator (kWh/month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>911.4</td>
<td>1204.93</td>
<td>-</td>
</tr>
<tr>
<td>February</td>
<td>823.2</td>
<td>638.24</td>
<td>184.96</td>
</tr>
<tr>
<td>March</td>
<td>911.4</td>
<td>739.28</td>
<td>172.12</td>
</tr>
<tr>
<td>April</td>
<td>882</td>
<td>2068.87</td>
<td>-</td>
</tr>
<tr>
<td>May</td>
<td>911.4</td>
<td>2107.08</td>
<td>-</td>
</tr>
<tr>
<td>June</td>
<td>882</td>
<td>2210.15</td>
<td>-</td>
</tr>
<tr>
<td>July</td>
<td>911.4</td>
<td>2762.32</td>
<td>-</td>
</tr>
<tr>
<td>August</td>
<td>911.4</td>
<td>2124.25</td>
<td>-</td>
</tr>
<tr>
<td>September</td>
<td>882</td>
<td>2149.28</td>
<td>-</td>
</tr>
<tr>
<td>October</td>
<td>911.4</td>
<td>1971.76</td>
<td>-</td>
</tr>
<tr>
<td>November</td>
<td>882</td>
<td>2364.16</td>
<td>-</td>
</tr>
<tr>
<td>December</td>
<td>911.4</td>
<td>2521.39</td>
<td>-</td>
</tr>
<tr>
<td>Total</td>
<td>10,731</td>
<td>22,861.71</td>
<td></td>
</tr>
</tbody>
</table>

### 4.9.3 Wind energy value

The daily energy requirement for Waisa is 29.4 kWh. According to the manufacturers, 2kVA diesel generator set produces 1.6 kW and consumes about 0.5 litres of diesel every hour. A total 2.6 kg of carbon-dioxide is emitted by burning a litre of diesel fuel (Carbon-dioxide emission, 2016). To provide this energy, the current diesel set (2kVA) available has to run 19 hours and will consume 9.5 litres of diesel daily and producing 24.7 kg of carbon-dioxide. Hence if the estimated load is supplied only by diesel generator, a total of 3467.5 litres of diesel fuel will be consumed emitting 9015.5 kg of
carbon-dioxide annually. However, using the proposed hybrid system, the diesel consumption (Table 4.12) reduces to approximately 112 litres producing 290.1 kg of CO₂ annually.

4.10 Economic analysis

The use of renewable power sources to generate electricity is not only pollution free but reduces the fuel consumption resulting in producing lesser CO₂. In any system, the power generation cost has to be minimized using proper system sizing and load matching. The economics analysis of the micro–grid was carried out using the method stated by Mathew (2006).

4.10.1 Life cycle costing analysis

The economic analysis of the system is based on the assumption that the capital cost, the cost of batteries and inverter and including the installation cost of this wind turbine is estimated at $25,000. The cost was worked out based on the information provided by the supplier (Enair Company). The annual operation and maintenance cost was taken as 4% of the capital cost as affirmed by Manwell et al. (2002). The lifetime of the system was taken as 20 years with estimated battery life of 10 years and with two replacements during lifetime of the project. Presently the electricity price is $0.35 per kWh and IPPs sell power to FEA at $0.27 per kWh. The system comprises a 7.5 kW wind turbine with an annual energy output of 15,675kWh.
Based on the above assumptions the Capital Recovery Factor, CRF calculated using equation 3.17, the Net Present Value, NPV, calculated using equation 3.22 and the Payback Period, PBP calculated using equation 3.24 are shown in table 4.13 below.

<table>
<thead>
<tr>
<th>Capital cost (FJD)</th>
<th>25,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Energy production (kWh)</td>
<td>15,675</td>
</tr>
<tr>
<td>Annual returns from electricity sales (BA) (FJD)</td>
<td>4,257</td>
</tr>
<tr>
<td>Annual operation &amp; management and land rent (FJD)</td>
<td>1000</td>
</tr>
<tr>
<td>Net Present Value of cost (FJD)</td>
<td>8,514</td>
</tr>
<tr>
<td>Net Present Value of Benefits (FJD)</td>
<td>60,003</td>
</tr>
<tr>
<td>Net Present Value (FJD)</td>
<td>26,500</td>
</tr>
<tr>
<td>Payback Period (years)</td>
<td>≈ 15</td>
</tr>
<tr>
<td>Benefit cost ratio</td>
<td>1.79</td>
</tr>
<tr>
<td>Cost of Energy (FJD/kWh)</td>
<td>0.106</td>
</tr>
</tbody>
</table>

The real discount rate ($i$) assumed as the difference between the nominal interest rate and inflation was approximated as 10%. This was based on the combination of inflation and the increase in price of electricity in comparison with the general inflation. The annual operation and maintenance cost of 4% of the capital cost is based on the assumption that the maritime climate and presence of corrosive substance in the atmosphere determines the degree of maintenance required for the turbine, battery bank and the supervisory controller. The annual return from the sale of electricity was assumed at the current rate of $0.27/kWh and the present accumulated present value of all benefits over the life (20y) of the project is estimated at $60,100.

The accumulated net present value of all the costs including the capital investment is estimated at $26,500 and the break-even capacity factor for the generating costs are equal to the selling cost is estimated at 0.24.

The fundamental quest for an economic analysis is to determine the payback time of the project. For this project the payback time is estimated at 15.3 y, lower than the life time of the project (20y).
The Benefit cost ratio (BCR), the ratio of the accumulated present value of all the benefits to the accumulated present value of all costs, including the initial investment is estimated at 1.15 (>1) hence the project is feasible. The internal rate of return (calculated using successive bisection iterations) is estimated at 11.57% and thus with this as the discounted rate, the net present value of the project is zero. Hence, this project may be financed by an IPP at a maximum interest rate of 11.57%.

The levelised cost of energy is estimated at $0.106/kWh using the procedure outlined earlier. This is lower than the $0.27/kWh the sale price by IPP.

The comprehensive economic analysis strongly indicates that the proposed project is economically viable.

4.10.2 Avoided costs

The avoided amount of diesel fuel to generate electricity annually is estimated at 3467 litres and at the current price of $1.64 per litre amounts to $5686. However, using the proposed hybrid system, only 6 litres of diesel fuel will be used annually costing around $10.
4.10.3 Sensitivity analysis

A sensitivity economic analysis (Table 4.14) was carried to determine the perturbation of the economic parameters of the project and determine and its effect on the levelised cost of energy.

Table 4.14: Results of sensitivity economic analysis

<table>
<thead>
<tr>
<th>Capital investment (FJD 000)</th>
<th>Cost of energy (c/kWh)</th>
<th>Payback period (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>6.4</td>
<td>5.54</td>
</tr>
<tr>
<td>16</td>
<td>6.8</td>
<td>6.13</td>
</tr>
<tr>
<td>17</td>
<td>7.2</td>
<td>6.76</td>
</tr>
<tr>
<td>18</td>
<td>7.7</td>
<td>7.46</td>
</tr>
<tr>
<td>19</td>
<td>8.1</td>
<td>8.22</td>
</tr>
<tr>
<td>20</td>
<td>8.5</td>
<td>9.06</td>
</tr>
<tr>
<td>21</td>
<td>8.9</td>
<td>10</td>
</tr>
<tr>
<td>22</td>
<td>9.4</td>
<td>11.06</td>
</tr>
<tr>
<td>23</td>
<td>9.8</td>
<td>12.26</td>
</tr>
<tr>
<td>24</td>
<td>10.2</td>
<td>13.65</td>
</tr>
<tr>
<td>25</td>
<td>10.6</td>
<td>15.31</td>
</tr>
<tr>
<td>26</td>
<td>11.1</td>
<td>17.32</td>
</tr>
<tr>
<td>27</td>
<td>11.5</td>
<td>19.89</td>
</tr>
</tbody>
</table>

The sensitivity analysis is plotted (Figure 4.21) to show the capital investment, cost benefit ratio and payback period effect on the relative cost of energy.
The sensitivity analysis (Figure 4.21) indicates that the payback period is most sensitive to change in capital investment. The maximum capital investment for this project is estimated at $27,000 with a payback time of approximately 20 years (an increase of 113%) at the fixed real rate of discount of 10%. This is equivalent to the lifetime of the project. The cost of energy then increases by 35% and is $0.115/kWh.

4.11 Barrier and incentives to wind deployment and challenges

The development of wind and other renewable energy resources are limited by certain barriers. However, with appropriate measures in place outlined by the government policies shall overcome these barriers. Government willingness and incentives will strengthen IPP’s to consider integrating renewable energy to the existing grid. Specifically the barriers to wind energy development include high initial cost, costs in constructing transmission lines, wind variability and intermittency. According to Blanco (2009), other hurdles include market barriers, price distortions, commercialization barriers faced by new technologies and failure of the market to value the public benefits. Targeted measures may be adopted to address specific
barriers to wind energy and promote investments. These incentives could be in the form of market incentives and tax incentives. Resource availability is sometimes cited as a barrier since wind energy deployment is very site specific, but many sites in Fiji have wind resources that are sufficiently adequate to consider wind technology as an alternative source for energy.
CHAPTER 5  CONCLUSIONS AND SCOPE FOR FURTHER WORK

5.1 Conclusions

The wind characteristics and wind power potential at the Waisa site was assessed and the wind regime pattern was determined. The wind regime at the study site was constructed using the data collected from September 2012 to August 2013. The wind direction and the wind speed at the Waisa site at the height of 20 m above the ground level were recorded with the help of KOICA project managed by USP.

In this project, a hybrid power generating system was modeled using a wind turbine and a diesel generating system for a remote site. The components of the wind – diesel generator set were defined and each component of the set was discussed in detail. The results suggested that wind turbine and the wind/diesel/battery hybrid power system is a dependable source of electricity generation and may be considered as an alternative arrangement to utilise the natural resource.

This study of wind energy potential in Waisa concludes that Waisa has a significant wind potential. The results showed that 68 % of the time the proposed turbine will be able to supply directly while 32 % of the power is derived from storage i.e. battery bank that is charged by wind or diesel generator depending on the status of the wind regime at the time.

However, the study showed that during February and March, the turbine is not able to meet directly the load requirement and hence diesel is used to charge the battery bank. On the least windy day most of the load is met by the battery bank. However, the frequencies of this occurrence need to be established by further assessment.

Overall, the annual average wind speed at Waisa site is moderate. The annual average wind speed at the height of 20 m a.g.l was 5.43 ms\(^{-1}\). This translates to an annual energy production of approximately 22, 900 kWh estimated by a 7.5 kW wind turbine calculated manually using the raw wind speed data. However, other software, WAsP predicted an AEP of about 15, 700 kWh. The results suggested that the daily load demand of about 30 kWh can be met with the proposed system.

A comprehensive economic analysis was carried out to determine whether it is viable to implement the project. The cost of energy was estimated at FJD 0.0106/kWh with a
payback period of 15 years. The sensitivity analysis indicated that a maximum capital investment of $27,000 at real discounted rate of 10% is the cut off for this project.

The hybrid system discussed in the project is the key to a cost-efficient, stable and sustainable power supply to Waisa Village. By combining wind turbines, diesel generators and deep cycle batteries it is possible to reduce the consumption of fossil fuels, and, even more, with lower the production costs of energy (LCOE) and a reduction in CO₂ emission. Thus, this proposed system is envisaged to provide clean, affordable and reliable source of electricity to the people of Waisa.

5.2 Recommendations and Further Work

Wind/diesel hybrid power system and a diesel generator plant are yet to be considered as an alternative means to electrify the off grid rural population in Fiji. The high initial capital costs are the major hindrance to the hybrid systems. The hybrid power systems can be a viable option if the wind resource assessment, system sizing and the economic analysis are accurately determined. The present data may be used to analyze wind turbine prospects using appropriate extrapolation techniques. To further reduce diesel consumption used for charging batteries during daytime, a suitably sized PV module shall be chosen to meet the requirement. However, diesel shall then only be used to meet the load during unavailability of wind and for charging the battery during night time.

Since this study used only a year’s data, a more detailed resource assessment is required for good analysis. Wind speed and direction shall be measured for at least three years to remove any seasonal and other effects which were not evident in the measurement used for the present analysis (Weisser, 2003). It is crucially important that wind speed measurement is carried out between 50 and 60 m a.g.l to consider a larger turbine for a micro grid to provide larger load directly without any storage.

This study had restricted the load to lights only for residents other than the community hall, a detailed load assessment for the village is required to provide 24 hours uninterrupted power. There is a need to assess the need for a water pump requirement and possible mechanical workshop to consider as an additional load for further expansion. It is suggested that for future expansion, population growth and the need for electrical technology is appropriately assessed.
REFERENCES


Richard, M. G. (2014). Wind Turbines kill around 300,000 birds annually, house cats around 3,000,000,000. Renewable Energy.


Yazdanpanah, M. A (2014). Modeling and Sizing optimization of Hybrid photovoltaic wind power generation system

APPENDICES

APPENDIX 3A
QUESTIONNAIRE

Name of the village ______________________________________________________

Time and date of the day of the visit: ______________________________________

The weather of the day of the visit: ________________________________________

Accessibility to the site and the road type: _________________________________

Is there any existing grid – connected electricity in the village: ______________

Distance from Labasa town to the site: _____________________________________

Brief description of the terrain at the site: __________________________________

1. How many people are there in your family?

2. How many of the above are adults and how many are school children?

3. Are there any existing renewable energy (RE) installments in the village?

   (i) What type of renewable energy source is being used?

   (ii) What is the size of the renewable energy source being used?

4. What is the major source of electricity to the village?

   (i) Is there any diesel generator used to supply electricity to the village?

   (ii) What is the rating of the generator?
(iii) How long do you use the source?

(iv) What electrical appliances/devices do you use?

(v) How many lights do you use?

(vi) How much fuel do you use per week to run the generator?

(vii) What is the cost of fuel per litre?

(b) If you do not have the generator system, what source of light do you use?

(i) How much kerosene/benzene do you use per week?

(ii) How far is the closest shop used for refilling fuel?

4. What is the major source of income?

(i) Do you buy ice for fishing?

(ii) How much ice do you buy per week?
5. Do you prefer to have light source and power supply or light source and an ice plant for the village?

6. What are the services provided in the village (hospital, shopping centre, school)?
APPENDIX 3B

SPECIFICATIONS OF NRG 40C ANEMOMETER

RNRG 40C ANEMOMETER

The 40C Anemometer offers field-proven measurement accuracy at an economical price.

<table>
<thead>
<tr>
<th>RNRG 40C Anemometer</th>
<th>MEASNET Calibrated (#1900)</th>
<th>RNRG 40C Anemometer</th>
<th>CPH MEASNET Calibrated (#4350)</th>
</tr>
</thead>
</table>

### DESCRIPTION

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>3 Cup Anemometer</th>
<th>3 Cup Anemometer</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Applications</th>
<th>Wind resource assessment</th>
<th>Wind resource assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Meteorological studies</td>
<td>Meteorological studies</td>
</tr>
<tr>
<td></td>
<td>Environmental monitoring</td>
<td>Environmental monitoring</td>
</tr>
</tbody>
</table>

| Sensor range        | 1 m/s to 96 m/s (2.2 mph to 215 mph) (highest recorded) | 1 m/s to 96 m/s (2.2 mph to 215 mph) (highest recorded) |

| Instrument compatibility | All RNRG loggers | All RNRG loggers |

### OUTPUT SIGNAL

| Signal type          | Low level AC sine wave, frequency linearly proportional to wind speed | Low level AC sine wave, frequency linearly proportional to wind speed |

<table>
<thead>
<tr>
<th>Anemometer Transfer Function</th>
<th>Consensus Transfer Function: Scale Factor (Slope): 0.765 m/s/Hz (1.711 mph/Hz) Offset: 0.35 m/s (0.78 mph)</th>
<th>See individual calibration report</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refer to the white paper &quot;The Maximum Type 40 Anemometer Calibration Project&quot; for more information on the consensus transfer function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All RNRG 40C Anemometers are calibrated per IEC 61400-12-1, Annex F</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Output voltage at threshold</th>
<th>80 mV (peak-to-peak) minimum</th>
<th>80 mV (peak to peak) minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage at 60Hz</td>
<td>12 V (peak-to-peak) typical</td>
<td>12 V (peak-to-peak) typical</td>
</tr>
<tr>
<td></td>
<td>Output amplitude NOT proportional to wind speed</td>
<td>output amplitude NOT proportional to wind speed</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Each anemometer individually calibrated, calibration reports provided via electronic download</th>
<th>Each anemometer individually calibrated, calibration reports provided via electronic download</th>
</tr>
</thead>
</table>

| Output signal range | 0 Hz to 125 Hz (at 96m/s, highest recorded) | 0 Hz to 125 Hz (at 96m/s, highest recorded) |

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Accuwind (Riso-R-1556) Classification:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Class 2.4A</td>
</tr>
<tr>
<td></td>
<td>• Class 7.7B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Accuwind (Riso-R-1556) Classification:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Class 2.4A</td>
</tr>
<tr>
<td></td>
<td>• Class 7.7B</td>
</tr>
<tr>
<td>RESPONSE CHARACTERISTICS</td>
<td>IEC 61400-12-1 operational standard uncertainty:</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td></td>
<td>± 0.14 m/s at 10 m/s for Class A</td>
</tr>
<tr>
<td></td>
<td>± 0.45 m/s at 10 m/s for Class B</td>
</tr>
<tr>
<td></td>
<td>Refer to calibration sheet for information on calibration uncertainty</td>
</tr>
<tr>
<td></td>
<td>Refer to application note &quot;#40C Anemometer Uncertainty&quot; for definitions and more information</td>
</tr>
</tbody>
</table>

**RESPONSE CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Distance constant (63% recovery)</th>
<th>2.55 m (8.37 feet) at 5m/s per ASTM D 5096-02</th>
<th>2.56 m (8.40 feet) at 10m/s per ASTM D 5096-02</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment of inertia</td>
<td>1.01 x 10^-4 kg-m^2</td>
<td>1.01 x 10^-4 kg-m^2</td>
</tr>
<tr>
<td></td>
<td>74.5 x 10^-6 S-ft^2</td>
<td>74.5 x 10^-6 S-ft^2</td>
</tr>
<tr>
<td>Swept diameter of rotor</td>
<td>190 mm (7.5 inches)</td>
<td>190 mm (7.5 inches)</td>
</tr>
</tbody>
</table>

**INSTALLATION**

<table>
<thead>
<tr>
<th>Mounting</th>
<th>Onto a 13 mm (0.5&quot;) diameter mast with cotter pin and set screw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tools required</td>
<td>0.25 inch nut driver,</td>
</tr>
<tr>
<td></td>
<td>petroleum jelly, electrical tape</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------------------------------</td>
</tr>
</tbody>
</table>

**ENVIRONMENTAL**

<table>
<thead>
<tr>
<th>Operating temperature range</th>
<th>-55 °C to 60 °C (-67 °F to 140 °F)</th>
<th>-55 °C to 60 °C (-67 °F to 140 °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating humidity range</td>
<td>0 to 100% RH</td>
<td>0 to 100% RH</td>
</tr>
</tbody>
</table>

**PHYSICAL**

<table>
<thead>
<tr>
<th>Connections</th>
<th>4-40 brass hex nut/post terminals</th>
<th>4-40 brass hex nut/post terminals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>0.14 kg (0.3 lbs)</td>
<td>0.14 kg (0.3 lbs)</td>
</tr>
</tbody>
</table>
| Dimensions                   | • 3 cups of conical cross-section, 51 mm (2”) dia.  
• 81 mm (3.2”) overall assembly height | • 3 cups of conical cross-section, 51 mm (2”) dia.  
• 81 mm (3.2”) overall assembly height |

**MATERIALS**

<table>
<thead>
<tr>
<th>Cups</th>
<th>One piece injection-molded black polycarbonate</th>
<th>One piece injection-molded black polycarbonate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body</td>
<td>Housing is black ABS plastic</td>
<td>Housing is black ABS plastic</td>
</tr>
<tr>
<td>Shaft</td>
<td>Beryllium copper, fully hardened</td>
<td>Beryllium copper, fully hardened</td>
</tr>
<tr>
<td>Bearing</td>
<td>Modified Teflon, self-lubricating</td>
<td>Modified Teflon, self-lubricating</td>
</tr>
<tr>
<td>Magnet</td>
<td>Indox 1, 25 mm (1 inch) diameter, 13 mm (0.5 inch) long, 4 poles</td>
<td>Indox 1, 25 mm (1 inch) diameter, 13 mm (0.5 inch) long, 4 poles</td>
</tr>
<tr>
<td>Coil</td>
<td>Single coil, bobbin</td>
<td>Single coil, bobbin wound, 4100</td>
</tr>
<tr>
<td></td>
<td>wound, 4100 turns of #40 wire, shielded for ESD protection</td>
<td>turns of #40 wire, shielded for ESD protection</td>
</tr>
<tr>
<td>---------------------</td>
<td>------------------------------------------------------------</td>
<td>------------------------------------------------</td>
</tr>
<tr>
<td><strong>Boot</strong></td>
<td>Protective PVC sensor terminal boot included</td>
<td>Protective PVC sensor terminal boot included</td>
</tr>
<tr>
<td><strong>Terminals</strong></td>
<td>Brass</td>
<td>Brass</td>
</tr>
</tbody>
</table>
## APPENDIX 3C

### SPECIFICATIONS OF 200P WIND DIRECTION VANE

<table>
<thead>
<tr>
<th>DESCRIPTION</th>
<th>200P Wind Direction Vane (#1904)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>Continuous rotation potentiometric wind direction vane</td>
</tr>
</tbody>
</table>
| Applications         | • Wind resource assessment  
                       |   • Meteorological studies  
                       |   • Environmental monitoring |
| Sensor range         | 360° mechanical, continuous rotation |
| Instrument compatibility | All Symphonie Data Loggers         |

### OUTPUT SIGNAL

<table>
<thead>
<tr>
<th>Signal type</th>
<th>Analog DC voltage from conductive plastic potentiometer, 10K ohms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transfer function</td>
<td>Output signal is a ratiometric voltage</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Potentiometer linearity within 1%</td>
</tr>
<tr>
<td>Dead band</td>
<td>8° Maximum, 4° Typical</td>
</tr>
<tr>
<td>Output signal range</td>
<td>0 V to excitation voltage (excluding deadband)</td>
</tr>
<tr>
<td>RESPONSE CHARACTERISTICS</td>
<td></td>
</tr>
<tr>
<td>--------------------------</td>
<td>--</td>
</tr>
<tr>
<td>Threshold</td>
<td>1 m/s (2.2 mph)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>POWER REQUIREMENTS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Supply voltage</td>
<td>Regulated potentiometer excitation of 1 V to 15 V DC</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INSTALLATION</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Mounting</td>
<td>Onto a 13 mm (0.5 inch) diameter mast with cotter pin and set screw</td>
</tr>
<tr>
<td>Tools required</td>
<td>0.25 inch nut driver, petroleum jelly, electrical tape</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ENVIRONMENTAL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature range</td>
<td>-55 °C to 60 °C (-67 °F to 140 °F)</td>
</tr>
<tr>
<td>Operating humidity</td>
<td>0 to 100% RH</td>
</tr>
<tr>
<td>Lifespan</td>
<td>50 million revolutions (2 to 6 years normal operation)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>PHYSICAL</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Connections</td>
<td>4-40 brass hex nut/post terminals</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>0.14 kg (0.3 pounds)</td>
</tr>
<tr>
<td>-------------</td>
<td>---------------------</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• 21 cm (8.3 inches) length x 12 cm (4.3 inches) height</td>
</tr>
<tr>
<td></td>
<td>• 27 cm (10.5 inches) swept diameter</td>
</tr>
</tbody>
</table>

**MATERIALS**

<table>
<thead>
<tr>
<th><strong>Wing</strong></th>
<th>Black UV stabilized injection molded plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Body</strong></td>
<td>Black UV stabilized static-dissipating plastic</td>
</tr>
<tr>
<td><strong>Shaft</strong></td>
<td>Stainless steel</td>
</tr>
<tr>
<td><strong>Bearing</strong></td>
<td>Stainless steel</td>
</tr>
<tr>
<td><strong>Boot</strong></td>
<td>Protective PVC sensor terminal boot included</td>
</tr>
<tr>
<td><strong>Terminals</strong></td>
<td>Brass</td>
</tr>
</tbody>
</table>
# APPENDIX 3D

## SPECIFICATIONS OF SYMPHONIE PLUS3 DATA LOGGER

### SPECIFICATIONS

<table>
<thead>
<tr>
<th>SymphoniePLUS®3 Data Logger (#5504)</th>
</tr>
</thead>
</table>

## DESCRIPTION

<table>
<thead>
<tr>
<th>Instrument type</th>
<th>15 channel Internet-enabled micropower wind energy data logger</th>
</tr>
</thead>
</table>
| Applications    | Wind resource assessment  
|                 | Turbine power performance verification  
| Sensor compatibility - counter channels | NRG Systems #40C anemometer or compatible  
|                 | NRG Systems Class 1 anemometer  
|                 | Opto anemometer  
|                 | Reed switch anemometer  
| Sensor compatibility - analog channels | NRG Systems #200P direction vane  
|                 | NRG Systems #110S temperature sensor  
|                 | Li-Cor #200SZ pyranometer  
|                 | NRG Systems #BP20 absolute pressure (requires optional iPack power)  
|                 | NRG Systems RH-5X relative humidity (requires optional iPack power)  

## DATA COLLECTION

| Counter channels | Channels 1-3 and 13-15 are always counter inputs supporting:  
|------------------|-------------------------------------------------------------|
|                  | NRG Systems #40C anemometer or compatible  
|                  | NRG Systems Class 1 anemometer  

<table>
<thead>
<tr>
<th>Feature</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opto anemometer</td>
<td></td>
</tr>
<tr>
<td>Reed switch anemometer</td>
<td></td>
</tr>
<tr>
<td>Maximum counter input frequency</td>
<td>2500 Hz</td>
</tr>
<tr>
<td>Analog channels</td>
<td>Channels 7-12 are always analog inputs:</td>
</tr>
<tr>
<td></td>
<td>- Channels 7 and 8 dedicated for NRG Systems #200P direction vane</td>
</tr>
<tr>
<td></td>
<td>- Channels 9-12 use analog Signal Conditioning Modules (SCMs) to configure each channel for a particular sensor</td>
</tr>
<tr>
<td>Flex channels</td>
<td>Channels 4-6 are 'Flex' Channels</td>
</tr>
<tr>
<td></td>
<td>- Analog or Counter</td>
</tr>
<tr>
<td></td>
<td>- Accept Signal Conditioning Modules (SCMs) to configure the channel for a particular sensor type</td>
</tr>
<tr>
<td>Sampling interval</td>
<td>1 second</td>
</tr>
<tr>
<td>Averaging interval</td>
<td>10 minute fixed</td>
</tr>
<tr>
<td>Real time clock</td>
<td>Internal battery-backed with leap year correction, 2000 to 2099</td>
</tr>
<tr>
<td>Storage medium</td>
<td>128MB NRG formatted SD Card, non-volatile FLASH</td>
</tr>
<tr>
<td>Maximum data storage</td>
<td>672 files</td>
</tr>
<tr>
<td>File format</td>
<td>- Windows compatible</td>
</tr>
<tr>
<td></td>
<td>- One (1) 14KB binary file per day</td>
</tr>
<tr>
<td></td>
<td>- Header includes site, serial number, and sensor information</td>
</tr>
<tr>
<td>Software</td>
<td>Symphonie Data Retriever (SDR) for Windows</td>
</tr>
</tbody>
</table>
- Scales raw data
- Creates measurement database for each site
- Creates basic reports
- Maintains site and sensor information
- Configures iPacks

**Reader**

Windows compatible SD Card reader

**Parameters recorded for each channel**

- Each data interval is time-stamped
- Average
- Standard deviation
- Min*
- Max*

* Min and Max not used for wind direction vanes

**Data delivery**

- SD Card
- Internet email via GSM, CDMA, or Iridium Satellite with optional iPack

**RESOLUTION**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Resolution</th>
</tr>
</thead>
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<td>Analog measurement resolution</td>
<td>0.1% of full scale (1024 counts)</td>
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<td>Counter average stored resolution</td>
<td>0.1% of the value stored</td>
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<tr>
<td>Analog average stored resolution</td>
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<tr>
<td>Standard deviation</td>
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<td><strong>stored resolution</strong></td>
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### CONFIGURATION

**User interface**
- Liquid Crystal Display (LCD) 4 x 20 characters
- 16 key pad (6 navigation keys plus numeric/phone pad) with audible feedback

**Configurable parameters**
- Clock
- Time zone
- Site number
- Display scaling (defaults are provided for each channel based on the channel type)

**iPack options**
- iPack configured via serial port connection to your PC
- Serial connection direct to iPack or through logger’s iPack access port
- Symphonie Data Retriever for Windows integrates iPack settings

### CONNECTIONS

**Sensor wiring**
- Sensors connected to field wiring panel
- Field wiring panel plugs into logger
- Ground stud connects to earth ground with included ground cable

**Expansion slots**
- Three (3) SCM slots accept analog or counter SCMs
- Four (4) SCM slots accept only analog SCMs

**Communication ports**
- Male DB25 interfaces to one optional iPack communications module
- iPack access port provides a connection to the iPack programming port without dismounting the iPack or logger

### POWER
<table>
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<th>REQUIREMENTS</th>
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<tr>
<td>Batteries</td>
<td>Two (2) 1.5 Volt D-Cell Batteries (included)</td>
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<tr>
<td></td>
<td>- Nominal voltage: 1.5 Volts</td>
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<tr>
<td></td>
<td>- Minimum voltage: 0.9 Volts</td>
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<tr>
<td></td>
<td>- Battery life approximately one year, depending on configuration</td>
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<tr>
<td>External power input</td>
<td>Provided by any iPack</td>
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<tr>
<td>External solar input</td>
<td>Provided by any iPack</td>
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<tr>
<td>Other</td>
<td>Optional iPacks provide 12V power required by some sensors. PV/Battery only iPack provides power to sensors and logger for stand-alone configurations.</td>
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<th>INSTALLATION</th>
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<tr>
<td>Mounting</td>
<td>• Mounts with 4 bolts (included) to keyed slots inside of metal shelter box</td>
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<tr>
<td></td>
<td>• Shelter box attaches to tower with hose clamps</td>
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<tr>
<td>Tools required</td>
<td>• Screwdriver for input terminals (included)</td>
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<td>• 8 mm (5/16 inch) wrench or nut driver for logger mounting screws and logger ground nuts</td>
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<th>ENVIRONMENTAL</th>
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<td>Operating temperature range</td>
<td>-40 °C to 65 °C (-40 °F to 149 °F)</td>
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<td></td>
<td>Note: display readable -30 °C to 55 °C (-22 °F to 130 °F)</td>
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<tr>
<td>Operating humidity range</td>
<td>0 to 100% RH non-condensing</td>
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<td>PHYSICAL</td>
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</tr>
<tr>
<td>--------------------------</td>
<td>-----------------------------------------------------------------</td>
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<tr>
<td>Weight</td>
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<td>Dimensions</td>
<td>(Including Field Wiring Panel) 22.2 cm height, 18.8 cm width, 7.7 cm depth (8.7 x 7.4 x 3.0 in.)</td>
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<tr>
<td>MATERIAlS</td>
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<tr>
<td>Faceplate</td>
<td>Injection molded black ABS</td>
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<td>Buttons</td>
<td>White elastomer dome keypad</td>
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<tr>
<td>Wiring panel</td>
<td>Fiberglass-epoxy terminal board, sealed gold plated pins, zinc plated screws and terminals</td>
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<tr>
<td>Enclosure</td>
<td>Weatherproof polycarbonate</td>
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### APPENDIX 4A

**DAILY WIND AVERAGES FOR ONE YEAR PERIOD**

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<th>Jun</th>
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### APPENDIX 4B

**ANNUAL AVERAGE MONTHLY WIND SPEED FOR THE PERIOD OF ONE YEAR**

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<th>Anemometer I Average wind speed at 34 m (ms(^{-1}))</th>
<th>Anemometer II Average wind speed at 34 m (ms(^{-1}))</th>
<th>Average wind speed at 20 m (ms(^{-1}))</th>
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APPENDIX 4C
MONTLY AVERAGE STANDARD DEVIATION

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<th>Standard deviation II at 34 m (m/s)</th>
<th>Standard deviation at 20 m (m/s)</th>
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APPENDIX 4D

QUARTERLY WIND SPEED PATTERN

January-March seasonal variation in average wind speed

![Graph showing average wind speed variations from January to March.]

April-June seasonal variation in average wind speed

![Graph showing average wind speed variations from April to June.]

Days

Average wind speed (m/s)
July-September seasonal variation in average wind speed

October-December seasonal variation in average wind speed
## APPENDIX 4E

### THE DAILY LOAD DEMAND

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<tr>
<th>House Number</th>
<th>Number of adults</th>
<th>Number of children</th>
<th>Total number of Watts per household (W)</th>
<th>Average daily duty cycle (H/day)</th>
<th>Mean energy daily demand (Wh/day)</th>
<th>Mean daily load (Ah/day)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>10</td>
<td>1000</td>
<td>4.17</td>
</tr>
</tbody>
</table>

**Community hall (light, icemaker, television)**

|               |                 |                   | 1200                                   | 12                               | 14,400                           | 50                      |

**Total** | 44               | 30                | 2700                                  | 29                               | 400                              | 112.5                  |
APPENDIX 4F

CORRECTED MEAN DAILY LOAD CALCULATION

Corrected mean daily load (kWh) \[= \frac{\text{mean daily load}}{\text{conversion efficiency}}\]

\[= \frac{29.4}{0.9}\]

\[= 32.67 \text{ kWh}\]

Annual energy demand \[= 32.67 \times 365\]

\[= 11,923.33 \text{ kWh}\]
APPENDIX 4G

MANUFACTURES POWER OUTPUT TABLE OF ENAIR 7.5 KW WIND TURBINE

<table>
<thead>
<tr>
<th>Wind Speed (m/s)</th>
<th>Power Output (kW)</th>
<th>Wind Speed (m/s)</th>
<th>Power Output (kW)</th>
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<td>TECHNICAL SPECIFICATIONS OF ENAIR 7.5 KW WIND TURBINE</td>
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<td></td>
</tr>
<tr>
<td>-----------------------------------------------------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of blades</td>
<td>3</td>
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</tr>
<tr>
<td>Material propellers</td>
<td>Fiberglass with epoxy resins</td>
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</tr>
<tr>
<td>Generator</td>
<td>200 RPM</td>
<td>24 poles</td>
<td>magnets</td>
</tr>
<tr>
<td>Power</td>
<td>10500 W</td>
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</tr>
<tr>
<td>Rated power curve</td>
<td>7500 W</td>
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<td></td>
</tr>
<tr>
<td>Voltage</td>
<td>48, 220</td>
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</tr>
<tr>
<td>Wind Class</td>
<td>IEC / NVN I – A</td>
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<td></td>
</tr>
<tr>
<td>Sense grio</td>
<td>Schedule</td>
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</tr>
<tr>
<td>Area Sweep</td>
<td>116.8 m²</td>
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<tr>
<td>Weight</td>
<td>375 Kg</td>
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<tr>
<td>Applications</td>
<td>Isolated Batteries, connection to the mains connections</td>
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</tr>
<tr>
<td>Wind to start</td>
<td>2 m / s</td>
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</tr>
<tr>
<td>Rated speed</td>
<td>11 m / s</td>
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<td></td>
</tr>
<tr>
<td>Speed regulation of variable pitch</td>
<td>14 m / s</td>
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</tr>
<tr>
<td>Working temperature</td>
<td>-65 ° to + 60 °</td>
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<td></td>
</tr>
<tr>
<td>Efficient generation range</td>
<td>Of 2-40 m / s</td>
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</tr>
<tr>
<td>Survival</td>
<td>60 m / s</td>
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</tr>
<tr>
<td>Kind</td>
<td>Upwind Horizontal</td>
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</tr>
<tr>
<td>Orientation</td>
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<td>Power control</td>
<td>Passive system variable pitch Centrifugal</td>
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<tr>
<td>Transmission</td>
<td>Direct</td>
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<tr>
<td>--------------</td>
<td>--------</td>
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</tr>
<tr>
<td>Brake</td>
<td>Electrical switching phases by</td>
<td></td>
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<tr>
<td>Charge controller:</td>
<td>Configurable load controller batteries 7 différentes types of batteries and filters PWM microimpulsos and referral to progressively braking resistor.</td>
<td></td>
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</tr>
<tr>
<td>Investor</td>
<td>Compatible with most wind market investors. Recommended investors SMA and Aurora power One, both located between 98-95% efficiencies and optimized algorithms microprocesador - MPPT.</td>
<td></td>
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</tr>
<tr>
<td>Noise</td>
<td>Minimized: due to the design of the blades and the low speed of work. DB 3% more than the ambient noise of the wind. Sealed design with metal elements cataforesis, more paint</td>
<td></td>
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<tr>
<td>Corrosion protection</td>
<td>UV resistant and antioxidation and cataphores is treatments on all parts, more saline insulation epoxy paints.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Useful life</td>
<td>over 25 years</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tower</td>
<td>16, 20 and 24 m, swing, guyed or lattice</td>
<td></td>
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</tr>
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</table>
TABLE SHOWING THE POWER OUTPUT OF ENDURANCE S-250 5 KW WIND TURBINE

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<tr>
<th>wind speed (m/s)</th>
<th>Power output (kW)</th>
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</thead>
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<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0.005</td>
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<td>0.24</td>
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POWER CURVE OF ENDURANCE S-250 5 KW TURBINE
TABLE SHOWING THE POWER OUTPUT OF 7.5 KW (BERGEY EXCEL-R) WIND TURBINE

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<td>1</td>
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<tr>
<td>20</td>
<td>3</td>
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</table>
TABLE SHOWING THE POWER OUTPUT OF 10 KW (BERGEY EXCEL-R) WIND TURBINE

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</table>

POWER CURVE OF (BERGEY EXCEL – S) 10 KW TURBINE