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Thesis Title : Wind characteristics and Resource Assessment around Laucala Bay Area, Suva, Fiji

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Wind Characteristics and Resource Assessment around Laucala Bay Area, Suva, Fiji

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September 2008

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Physics

Declaration of Originality

Statement by Author

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The research was completed without collaboration with any other person and all sources of information have been greatly acknowledged.

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Statement by Supervisors

We hereby declare that the work contained in this thesis is the work of Mr. Denise Chand unless other wise stated.

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Abstract

Fiji, a group of volcanic islands in the South Pacific, is located between 15°S and 22°S and longitudes 174°E and 177°W, and experiences a variable wind regime in a relatively small area. In this project wind characteristics and resource assessment for the Laucala Bay area in Suva is investigated using Wind Atlas Analysis and Application Program (WAsP). A micro-scale prediction of wind resource assessment for Nabua is carried out using WAsP. These predictions were based on the digitized map, surface roughness, orography and the obstacle groups present at the Nabua site. According to the WAsP report, Nabua is a poor candidate for wind power generation as it has a mean wind speed of 3.30 m/s and a mean power density of 40 W/m^2. WAsP also shows that if Whisper 100 turbine is installed at the Nabua site, it would have an Annual Energy Production (AEP) of 227 kWh. To validate WAsP prediction, on-site wind data were analysed and it was found that the mean wind speed was 3.05 m/s and a power density of 36 W/m^2. Statistical analysis carried out on these results showed that WAsP had tendency to over-predict wind regime. A resource grid for the greater Suva area was generated using WAsP. It showed that, within the grid there were some potential wind generation sites, one of such sites being Tamavua Heights. WAsP predicts that Tamavua Heights has an annual wind speed of 13.30 m/s, with a power density of 3286 W/m^2 and an AEP of 3.38 MWh for Whisper 100 turbines.

Acknowledgements

I want to express my heartfelt appreciation to all individuals who have in one way or the other contributed to the success of this project and my studies. Firstly, I would like to thank the University of the South Pacific (USP) for awarding a Graduate Assistant scholarship, without which it would have been very difficult for me to pursue a postgraduate qualification. My sincere gratitude goes to my supervisor Dr. Ajal Kumar in the first place for offering me this project and placing his confidence in me, for his invaluable guidance and leadership whenever I was indecisive. I am highly indebted to my co-supervisors Dr. Anirudh Singh (USP) and Mr. Rupeni Mario from the Pacific Geoscience Commission (SOPAC) for their patience in answering my searching questions and constant encouragement and advice. I have learnt a lot from my supervisors over the two years.

I would also like to thank Capt. Tevita Robanakadavu, the Head of School of Maritime and Fisheries at Fiji Institute of Technology (FIT), for his consent to use the FIT premises for the setup of the wind turbine. I also thank the Head of School of Engineering and Physics Dr. Sitaram Garimella and the Head of Physics Division Dr. Sushil Kumar for providing the divisions facilities to carry out this research.

I wish to thank the current staff of the Physics Division. My sincere gratitude goes to Dr. Than Aung for his words of motivation during the course of research which helped to broaden my horizon. I wish to express my sincere thanks to Mr. Awnesh Singh for allowing me to use MSP wind speed data for this project. My special thanks goes to the invaluable technical help provided by the technicians of the Physics Division, Mr. Radesh Lal (Chief Technician), Mr. Viti Buadromo, Mr. Amit Deo, Mr. Avinesh Rohit Lal, Mr. Neil Singh, and Mr. Joape Cawanibuka. I thank the Foundation Physics technicians Mr. Abhinay Shandil and Mr. Shanil Deo, for the help rendered in setting up the instruments and providing assistance whenever I needed. To my friends, Mr. Rajeev Lal, Mr. Abhikesh Kumar, Mr. Navindra Reddy, Mr. Shivneel Prasad, Mr. Ritesh Chand and Mr. Alvin Raju , I thank you for your critical comments and sharing the ‘ups and downs’ during the project. I would also like to thank the staff and technicians of Clay Engineering for providing the back-up service for the wind turbine whenever fault arose in the system.

I am greatly indebted to my father, mother and my sister for supporting me all the way towards the successful completion of my MSc program. Mum and dad, I thank you for instilling the discipline in me which has shaped my career. I am truly grateful to you all for bearing with me all these years.

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List of Acronyms

AEP	Annual Energy Production
DOE	Department of Energy
FEA	Fiji Electricity Authority
FIT	Fiji Institute of Technology
FMS	Fiji Meteorological Services
GW	Gigawatts
HAWT	Horizontal Axis Wind Turbines
IEA	International Energy Agency
kAh	Kilo Amp Hour
kW	Kilowatts
kWh	Kilo Watt Hour
LCD	Liquid Crystal Display
LDR	Light Dependent Resistors
MOFA	Ministry of Foreign Affairs of Japan
MSP	Marine Studies Programme
MW	Megawatts
OWC	Observed Wind Climate
PREFACE	Pacific Energy France Australia Common Endeavour
PICHTR	Pacific International Center for High Technology Research
PV	Photovoltaic
PWD	Public Works Department
RIX	Ruggedness Index
SOPAC	Pacific Islands Applied Geoscience Commission
VAWT	Vertical Axis Wind Turbines
WAsP	Wind Atlas Analysis and Application Program

Chapter 1 Introduction

1.1 Renewable Energy: An Overview

Conventional fossil energy will not be enough to meet the continuously increasing needs for energy in future. Due to the increasing global population and incomplete combustion of fossil fuels researchers have been encouraged to search for clean and pollution free sources of energy. It is now evident that renewable energy technologies play a strategic role in achieving the goals of sustainable economical development and environmental protection (Ozgur & Kose, 2006).

Renewables are resources that can be sustained or renewed indefinitely, either because of inexhaustible supplies or because of new growth. Thus renewable energy is a resource that is naturally regenerated over a short time scale and derived directly from the sun (such as thermal, photochemical, and photoelectric), indirectly from the sun (such as wind, hydropower, and photosynthetic energy stored in biomass), or from other natural movements and mechanisms of the environment (such as geothermal and tidal energy).

Renewable electricity generation capacity reached an estimated 240 gigawatts (GW) worldwide in 2007, an increase of 50 % over 2004 (World Energy, Technology and Climate Policy Outlook, 2007). Renewables represent 5 % of global power capacity and 3 % of global power generation. Globally, renewable energy resources that hold the most promise are the following: hydropower, solar thermal, PV, biomass, and wind power. Outlined below is a brief summary of the estimated renewable energy capacities in the world.

Hydropower is energy from water sources such as the ocean, rivers and waterfalls. It is the world's largest source of renewable energy used for power generation. Hydropower accounts for 19 % of the world's supply (by 2010 wind power is expected to contribute 0.6 % and solar power 0.12 %). Hydropower is also a truly global resource, as more than 150 countries generate hydroelectric power. There is about 800 GW of hydro capacity in operation worldwide, meeting 20 % of global electricity requirement. A further 101 GW is under construction and 338 GW is at the planning stage (World Energy, Technology and Climate Policy Outlook, 2007).

Solar energy is the energy produced directly by the sun and collected at the earth's surface. The sun creates this energy through a thermonuclear process that converts about 650 Mt of hydrogen to helium every second. The potential for solar energy is enormous. Each day the earth receives in the form of solar energy about 200,000 times the total world electrical-generating capacity (Solar Energy, 2007). Although the energy itself is free, the high cost of collection, conversion, and storage has limited the exploitation of solar energy. Nevertheless, researchers are experimenting with solar power in a variety of contexts.

Photovoltaic (PV), is a technology in which light is converted into electrical power. It is best known as a method for generating solar power by using solar cells packaged in modules, often electrically connected in multiples as solar photovoltaic arrays to convert energy from the sun into electricity. Total peak power of installed solar panels is around 5,300 MW as at the end of 2005 (Wikipedia, 2007). The three leading countries Japan, Germany and the USA represent 90 % of the total worldwide PV installations. Germany was the fastest growing major PV market in the world in 2005. In 2005, 837 MW of PV were installed. The German PV industry generates over 10,000 jobs in production, distribution and installation. Over 90 % of solar PV installations are in grid-tied applications in Germany (Wikipedia, 2007).

Biomass energy is an important source of energy for the majority of the world's population. With the increase in population, the use of biomass energy is expected to increase in the near future. Karekezi, Lata & Coelho's study (as cited in International Energy Agency (IEA) 1998 and IEA 2003) stated that the share of biomass in global energy consumption has remained roughly the same over the last 30 years. Traditional biomass, primarily for cooking and heating, represents 13 % (Figure 1.1) and is growing slowly or even declining in some regions as biomass is used more efficiently or replaced by modern energy forms (REN21, 2007).

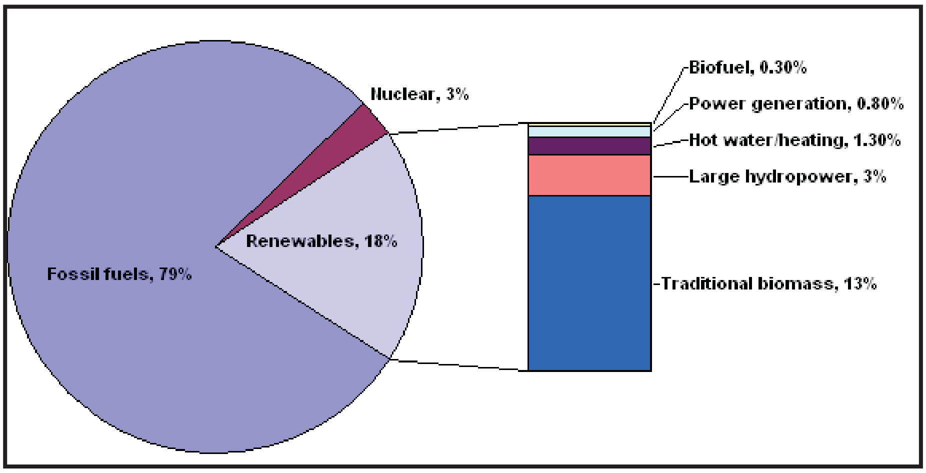


Figure 1.1 *Renewable energy share of Global final energy consumption, 2006. (after: REN21, 2007)*

According to (REN21, 2007) renewable energy supplied 18 % of the world's final energy consumption in 2006. Renewable energy replaces conventional fuels in four distinct sectors: power generation, hot water and space heating, transport fuels, and rural (off-grid) energy. Figure 1.2 shows that in power generation, renewable energy, excluding large hydropower, comprise about 5 % of global power-generating capacity and supplies about 3 % of global electricity production.

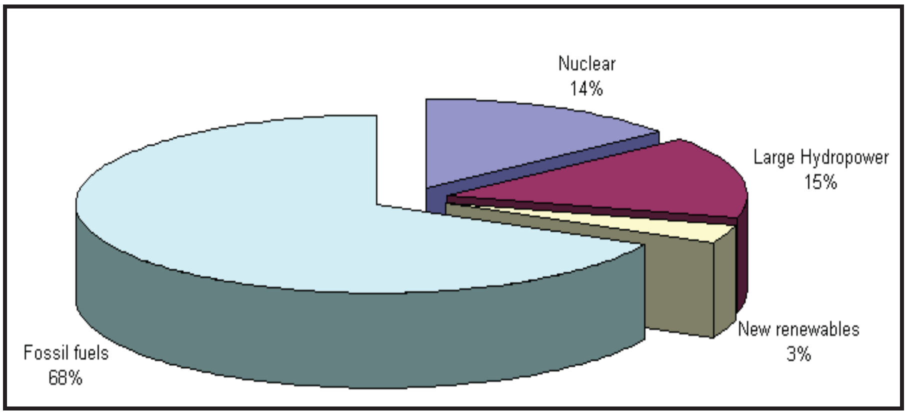


Figure 1.2 *Share of Global electricity from renewable energy, 2006. (after: REN21, 2007)*

Wind power has been gaining global prominence as a renewable energy alternative to fossil fuels. Barthelmie (2007) stated that the rapid increase in the installation of wind farms around the world over the past 15 years has made wind the fastest-growing energy source and attracts interest as one of the most cost-effective ways to generate electricity from renewable sources. Wind power development, wind power configuration, component description, wind turbine design, wind analysis softwares, economics of wind energy, and wind resource assessment are discussed in the following segments.

1.2 Wind Power Development

The use of wind as an alternative source of power has a long history. Man has been familiar with the use of windmills and pumps; sailing ships were in the past the most significant example of its technical utilization (Omer, 1998). The wind turbine is a machine which converts the power in the wind into electricity. In contrast to this a windmill is a machine which converts the wind's power into mechanical power (Manwell, McGowan & Rogers, 2004). Through out the history, people have harnessed wind in many different ways. Over 5,000 years ago, the ancient Egyptians used wind power to sail their ships on the river Nile. Later people built windmills to separate grains and to pump water. The earliest known windmills similar to large paddles were used in Iran (Wind, 2004).

The first written information on wind turbines was based on simple structural axis wind turbines during the reign of Alexander the Great. Abou-l lz who lived in Diyarbakir, Turkey, developed the first modern vertical wind turbine. The Persians used vertical axis wind turbines during 700 BC, however windmills were only established in the western world at the beginning of 12th century from Islamic world, Hill's study (as cited in Sahin, 2004). Up until the 20th century wind power was only used to provide mechanical power which pumped water or ground cereals. By 1800, about 20,000 modern windmills were in operation in France alone. Centuries later, during the industrial revolution there was a decline in the use of windmills. Despite this, in 1904, wind energy provided 11 % of the Dutch industrial energy requirements (Sahin, 2004).

The first wind turbine that generated electricity was built by the Dane, Poul LaCour in 1891. Because of increased demand and shortage of energy during World War I and II, the technology was further improved by the Danish engineers and as such during World War I (1914-1918) there were approximately 250 electricity-producing wind turbines in Denmark, of which 120 were connected to power stations (Vestergaard, Brandstrup & Goddard, 2004). Wind turbines built by Danish company F.L Smith in 1941-1942 was considered the fore-runners of modern wind turbine generators. The Smith turbines were the first examples that used modern airfoils based on the knowledge of aerodynamics (Sahin, 2004).

In the United States, the most significant early large wind turbine was the Smith-Putnam machine built at Grandpa's Knob in Vermont in the late 1930s (Manwell et al., 2004). This was the largest wind turbine than with a diameter of 53.3 m and power rating of 1.25 MW. This turbine was significant in that it was the first turbine with two blades.

In late 1950s, incentives for wind power diminished due to lack of government support, high wind turbine price value including its installation and most importantly competition imposed by other energy generating sources. However, with the oil crisis in the beginning of the 1970s and public awareness of environmental damage by fossil fuel combustion, the interest in wind-power research and development accelerated. Financial support for research and development of wind power became available. Countries like Germany, US, Spain and Denmark developed large-scale wind turbine prototypes in MW ranges. It has been universally acknowledged that today's wind turbines capacities are more advanced from those of 15 - 20 year ago. Since than, there has been advancement in understanding the aerodynamics and other fundamental technological areas, such as aerofoil design, tower interaction and noise production. Most progress, however, has occurred in areas of production quality, mass production and in improving reliability.

The global wind industry has been growing at a rate of 40 % per annum during the past five years with the top markets being Germany, Spain and US. (Vestergaard et al., 2004). Up until the early 1970s, wind energy filled a small niche market, providing mechanical power for grinding grain and pumping water. However at the beginning of the 21st century, wind energy is faced with a new set of challenges. Over the past 20 years, average wind turbine ratings have grown almost linearly, (Figure 1.3), from a mere 30 kW in 1980 to a staggering 5 MW in 2005. Thresher and Laxson (2006) reported that wind turbine designers have predicted that the machines of today are as large as they will ever be. The primary argument for limits in size is based on the "square-cube law." Roughly stated "*as a wind turbine rotor goes up in size, its power increases as the square of the rotor, while its mass increases as the cube.*"

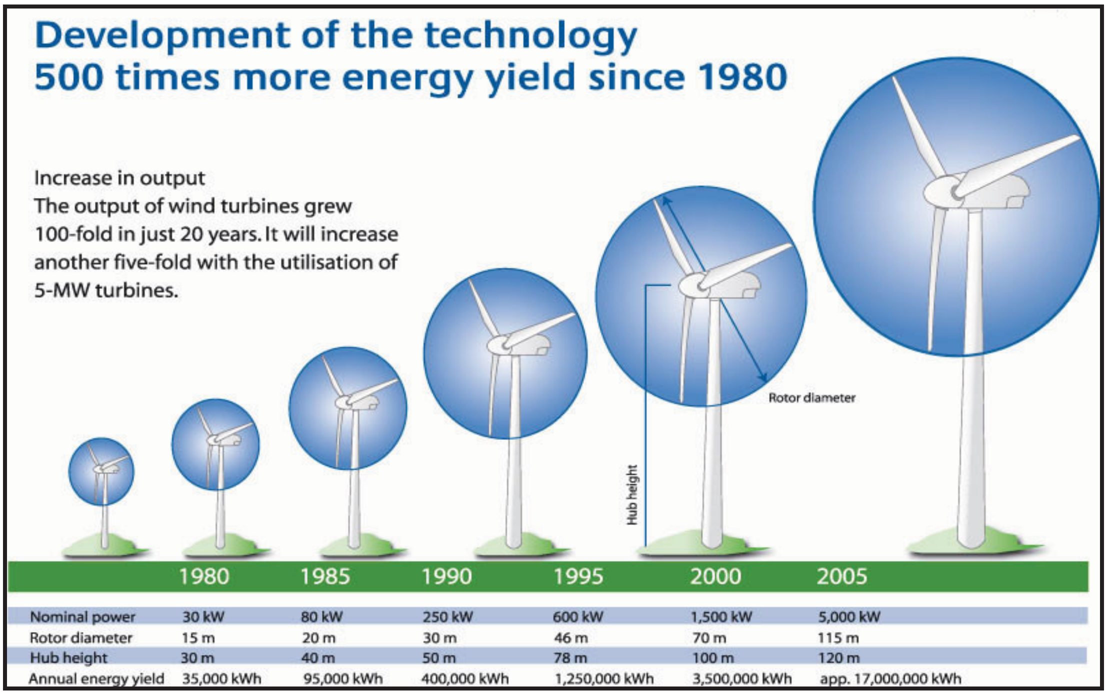


Figure 1.3 *Development of the technology: Five hundred-fold increase in energy yield since 1980.Growth: 100-fold increase in the output of wind turbines in just 20 years. It will increase another five-fold with the introduction of 5 MW turbines. (after: Renewables in Germany, 2006).*

Engineers have successfully overcome the barrier by innovation in designs and materials. Studies have shown that in recent years, blade mass has been scaling at roughly an exponent of 2.5 versus the expected 3 from Griffen's study (as cited in Thresher & Laxson, 2006). Increases in machine size have several effects on turbine erection. Larger rotor diameters and the desire to take advantage of wind shear by increasing tower heights to place rotors in higher velocity winds have been driving hub heights higher. Average turbine hub heights are now 65 meters, but a 2.5 – 3.5 MW turbine demand a hub height of 80 – 100 m. With increasing hub masses and tower heights, tower diameter must increase to withstand increased bending and buckling loads (Thresher & Laxson, 2006). Both effects can increase cost of erection.

Projected masses for nacelles (the housing around the generator, gear box and other mechanical component) in the 2.5 – 3.5 MW range is between 130 and 200 tonnes. Lifting this mass requires a crane with a much greater lifting capacity than expected because of the extreme nacelle height. Crane for placing a 2.5 MW turbine on a 110 m tower would be around US$ 40,000 to US$ 50,000, whilst crane cost for erecting a 5 MW turbine on a 156 m tower would run as high as US$ 138,000 (Smith, 2001).

1.3 Wind Turbine Configurations

Common basic conversion systems are horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) configurations. At present the HAWT and VAWT designs are very efficient, however both are being rigorously tested and improved.

1.3.1 Vertical Axis Wind Turbine

The only vertical machine that has had any commercial success is the Darrieus rotor, named after its inventor the French engineer G. M. Darrieus, who first developed the turbine in the 1920s. In its basic form, the machine is made of a number of curved blades each in the shape of a toposkien, the blade section being of aerofoil shape which varies in width from minimum at its extremities to maximum at its midsections (Bhatti & Kothari, 2005).

The principal advantage of vertical axis machines, such as Darrieus rotor (Figure 1.4), is that they do not need any kind of yaw control to keep them facing into the wind. The second advantage is that the heavy machinery contained in the nacelle can be located down on the ground where it can be serviced easily.

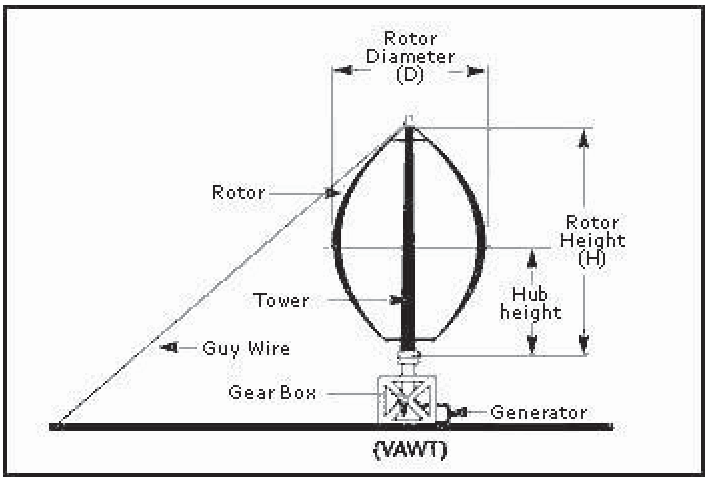


Figure 1.4 *Vertical axis wind turbines (VAWT), Darrieus, accept wind from any direction. (after: The Solar Guide, 2007).*

There are several disadvantages of VAWT, foremost being that the blades are relatively close to the ground where wind speeds are lower. The power in the wind increases as the cube of speed so there is considerable incentive to get the blades up into the faster wind speeds that exist higher up. Winds near the surface are not only lower in speeds but also more turbulent, which increases the stress on VAWTs. However, in low-speed winds, Darrieus rotors have little starting torque (Masters, 2004).

1.3.2 Horizontal Axis Wind Turbines

Today, the most common design of wind turbines and most closely studied are those that rotate about a horizontal or near horizontal axis. The energy-capturing elements are in the form of blades or sails rotating about a horizontal axis, in a vertical plane, perpendicular to the direction of the wind (Bhatti & Kothari, 2005).

The HAWT (Figure 1.5) is further categorized as either upwind or downwind machine. An upwind turbine is a type of wind turbine in which the rotor faces the wind. The basic advantage of upwind designs is that one avoids the wind shade behind the tower. By far the vast majority of wind turbines have this design. On the other hand, there is also some wind shade in front of the tower, i.e. the wind starts bending away from the tower before it reaches the tower itself, even if the tower is round and smooth. Therefore, each time the rotor passes the tower, the power from the wind turbine drops slightly. The basic drawback of upwind designs is that the rotor needs to be made rather inflexible, and placed at some distance from the tower (Masters, 2004). In addition, an upwind machine needs a yaw mechanism to keep the rotor facing the wind.

A downwind turbine is one in which the rotor is downwind (i.e. on the lee side) of the tower. Downwind machines have the theoretical advantage that they may be built without a yaw mechanism. For large wind turbines this is a somewhat doubtful advantage, since cables are needed to lead the current away from the generator. A more important advantage is that the rotor may be made more flexible. This is an advantage both in regard to weight and the structural dynamics of the machine, i.e. the blades will bend at high wind speeds, thus taking part of the load off the tower

(Masters, 2004). The basic advantage of the downwind machine is thus, that it may be built somewhat lighter than an upwind machine.

Another fundamental design for wind turbines relates to the number of rotating blades. Normally, multibladed wind mills used for water-pumping are radically different from those designed to generate electricity. Multibladed design presents a larger area of rotor facing into wind, which enables both high-torque and low-speed operations. Most modern European wind turbines have three rotor blades whilst American machines tend to have just two. With fewer blades, the turbines can spin faster which means faster spinning of shaft hence easier generation of electricity with a smaller generator (Masters, 2004).

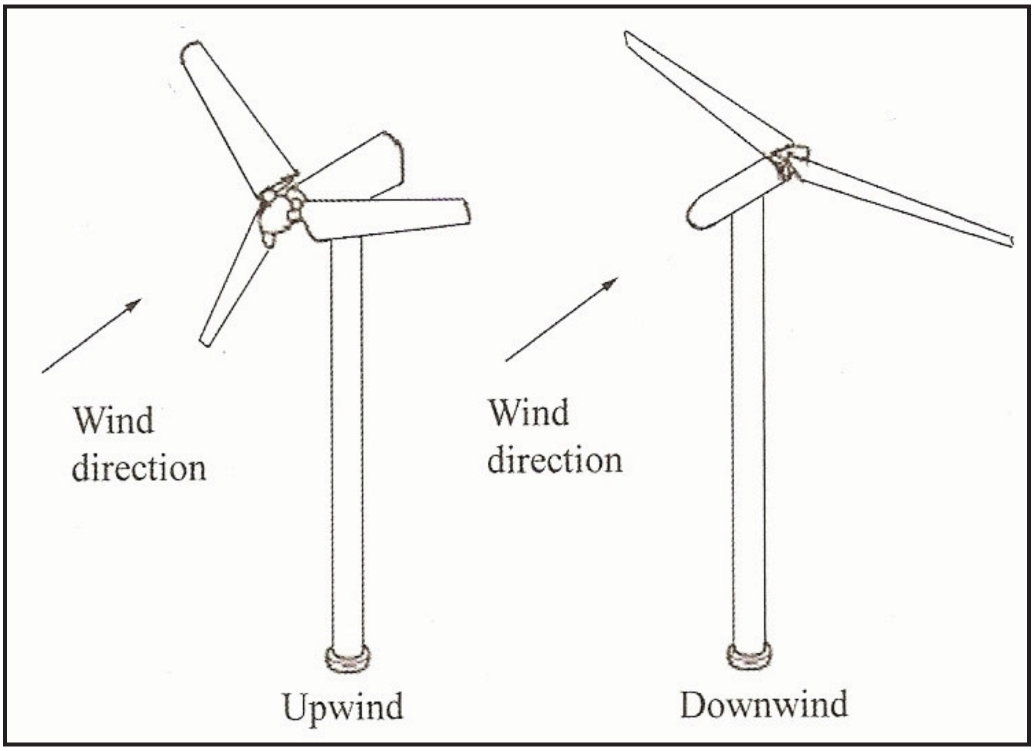


Figure 1.5 *Horizontal axis wind turbine configuration, upwind and downwind. (after: Manwell et al., 2004)*

1.4 Component Description of HAWT

The major component of a HAWT (Figure 1.6) consists of rotor, drive train, generator, nacelle and yaw system, and controls.

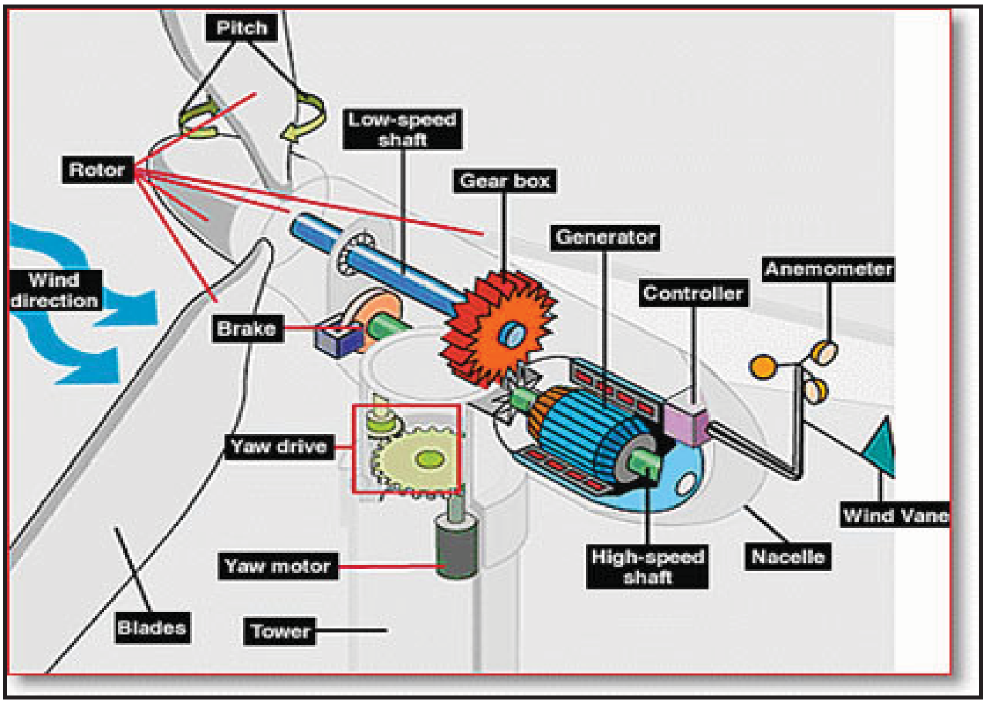


Figure 1. 6 *Main components of a HAWT (after: US Department of Energy, 2007)*

1.4.1 Rotor

The rotor consists of the hub and blades of the wind turbine. These are often considered to be its most important components from both a performance and overall cost standpoint. Most turbines today have upwind rotors with three blades. There are some downwind rotors and a few designs with two blades. Single-bladed turbines have been built in past, but are no longer in production because of poor structural designs. The blades are normally made up of fibreglass, wood or even metal (Manwell et al., 2004).

The conversion of aerodynamic power to mechanical torque is perhaps the most unique aspect of turbine operation. The ability to withstand changing aerodynamic loads and effectively extract power from the wind over a 20 - year lifespan makes wind turbines cost effective. As machines grow larger and larger, rotors must increase accordingly. A 1.5 MW turbine has a rotor of approximately 70 meters in diameter. A 3 MW rotor is roughly 99 meters in diameter. While the blade length only increases by 41 %, the blade root flap bending moment can increase by levels approaching 160 %, depending upon design (Malcolm & Hansen, 2002). The front and rear sides of a wind turbine rotor blade (Figure 1.7) have shape roughly similar to that of a long rectangle, with the edges bounded by the leading edge, the trailing edge, the blade tip and the blade root (Stiesdal, 1999). The blade root is bolted to the hub.

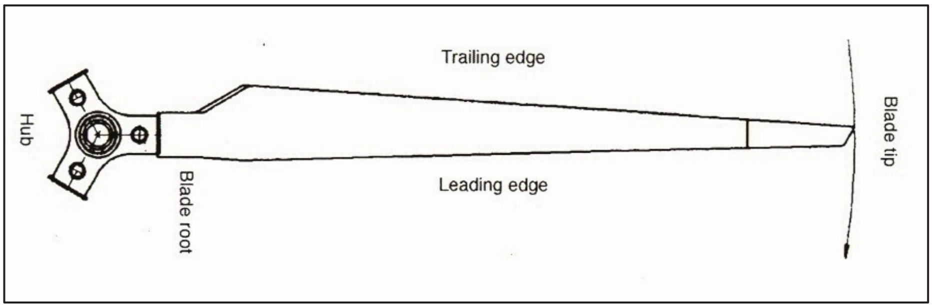


Figure 1.7 *The different components of the turbine blade. (after: Stiesdal, 1999).*

Lighter and stiffer blades are made by incorporating larger volumes of carbon fibre which would present options for both tolerating higher blade loads as well as reducing overall machine loads by reducing rotor weights (Thresher & Laxson, 2006). Blade planforms are being developed that incorporate unique inboard airfoils using truncate airfoil shapes

1.4.2 Drive Train

The drive train consists of the rotating parts of the wind turbine. These typically include a low-speed shaft (on rotor side), a gearbox, and a high-speed shaft (on the generator side). Converting torque to electrical power has historically been achieved using a speed increasing gearbox and induction generators. Thresher & Laxson (2006) stated that currently many large machines depend on a three-stage gearbox consisting of varying arrangements of planetary and parallel shaft gearing. Generators are either squirrel cage induction or wound-rotor induction, with some newer machines using the doubly-fed induction design for variable speed. But as machines continue to grow in size, additional stages and ever larger gearboxes are required.

1.4.3 Generator

Nearly all wind turbines use either induction or synchronous generator. Both of these designs entail a constant or near-constant rotational speed of the generator when the generator is directly connected to a utility network. The generator is normally connected to high speed-shaft and coverts the rotational energy of the shaft into an electrical output.

1.4.4 Nacelle and Yaw System

These components consist of the wind turbine housing, the machine bedplates or main frame, and the yaw orientation system. The nacelle cover provides protection of the contents from the weather. A yaw orientation is required to keep the rotor shaft properly aligned with the wind. The primary component is a large bearing that connects the main frame to the tower. The mechanism is controlled by an automatic yaw control system with its wind direction sensors usually mounted on the nacelle of the wind turbine (Manwell et al., 2004).

1.4.5 Control System

The control system for wind turbine is important with respect to both machine operation and power production. Manwell et al. (2004) stated that wind turbine control system includes the following components.

a. Sensors – speed, position, flow, temperature, voltage
b. Controllers – mechanical mechanisms, electrical circuit, and computers.
c. Power amplifiers – switches, electrical amplifiers, and hydraulic pumps.
d. Actuators – motors, pistons, magnets, and solenoids.

1.5 Wind Turbine Design

The general design of utility installed wind turbines is the 'Danish concept' a three-bladed turbine with the rotor upwind of the nacelle, however two bladed downwind wind turbines are also designed. Turbines can be *stall* or *pitch* controlled (which refers to how the turbines are stopped at high wind speeds). Stall - controlled turbines use the design of the blades to cause turbulence behind the blades at high wind speeds that causes the turbine to stall (i.e. stop rotating), whereas in pitch control the angle of the blades is varied usually using a hydraulic control system (Barthelmie, 2007).

The trend in general is towards variable-speed pitch control for larger machines. Marsh (2004) outlined the main advantage in terms of energy extraction, the demand for more control over power output to the grid and the affordability of more advanced controls in larger turbines. Turbines can also be fixed or variable speed that refers to the speed of the rotor. Variable speed operation is the most flexible in terms of energy capture but requires sophisticated power electronics.

Apart from domestic scale turbines that have rated capacity of 1 – 100 kW, the average rated capacity of wind turbines currently installed world-wide in 2005 was 1.5 – 2 MW. Such a turbine has a rotor diameter and tower height of the order 60 - 80 m. This is a significant increase from the size and capacity of 20 - 100 kW turbines installed in the 1970s. Power in the wind is proportional to the cube of the wind speed and the amount of energy that can be extracted is related to the square of the rotor radius. Barthelmie (2007) stated that increasing the rotor size, by a factor of almost 40 over the last 20 – 30 years has therefore been a key ingredient in the cost reduction of electricity generated using wind turbines.

1.6 Wind Analysis Software

There are various softwares that are available to carry out wind analysis. Some common software that have been used in the past and are still gaining prominence are Windographer, Homer, and WAsP.

1.6.1 Windographer

Windographer is an influential wind data analysis program. It reads data from almost any data logger, produces attractive graphs and wind roses, and does advanced statistical processing. Its automated data import process and interactive graphics save time and let users do the kind of analyses that used to be possible only for specialists. Windographer reads data from text files, excel files, and the notepad files written by the Symphonies Data Logger Systems. It can handle any time step, and wind vanes at any heights above ground, and any number of gaps or missing elements. The software also produces a huge variety of graphical and tabular for the user to visualize and describe the data (Windographer, 2007).

1.6.2 HOMER

HOMER is a computer model that simplifies the task of evaluating design options for both off-grid and grid-connected power systems for remote, stand-alone and distributed generation (DG) applications. HOMER's optimization and sensitivity analysis algorithm allows evaluation of the economic and technical feasibility of a large number of technology options and to account for variation in technology costs and energy resource availability. HOMER models both conventional and renewable energy technologies. It can do analysis for solar photovoltaic (PV), wind turbine, run-of-river hydro power, generator: diesel, gasoline, biogas, alternative and custom fuels, co-fired, electric utility grid, micro-turbine, and fuel cell at once. It also takes into account for load and storage sources (NREL, 2007).

1.6.3 Wind Atlas Analysis and Application Program (WAsP)

WAsP is a PC - program for horizontal and vertical extrapolation of wind data developed at Risø. Mortensen, Heathfield, Myllerup, Landberg and Rathmann (2004) have described several models incorporated in this software to describe the wind flow over different terrains and close to sheltering obstacles. WAsP consists of five main calculation blocks:

Analysis of raw data This option enables an analysis of any time-series of wind measurements to provide a statistical summary of the observed, site-specific wind climate. This part is implemented in a separate tool, the observed wind climate (OWC) Wizard.

Generation of wind atlas data Analyzed wind data can be converted into a regional wind climate or wind atlas data set. In a wind atlas data set the wind observations are cleaned' with respect to site-specific conditions. The wind atlas data sets are site independent and the wind distributions have been reduced to some standard conditions.

Wind climate estimation Using a wind atlas data set calculated by WAsP or one obtained from another source such as the European Wind Atlas – the program can estimate the wind climate at any specific point by performing the inverse calculation as is used to generate a wind atlas. By introducing descriptions of the terrain around the predicted site, the models can predict the actual, expected wind climate at that site.

Estimation of wind power potential The total energy content of the mean wind is calculated. Furthermore, an estimate of the actual, annual mean energy production of a wind turbine can be obtained by providing WAsP with the power curve of the wind turbine in question.

Calculation of wind farm production Given the thrust coefficient curve of the wind turbine and the wind farm layout, WAsP can finally estimate the wake losses for each turbine in a farm and thereby the net annual energy production of each wind turbine and of the entire farm, i.e. the gross production minus the wake losses.

WAsP has been successfully used in complex, forest terrain in the central North Island, New Zealand to investigate the potential of developing a wind farm for the Kinleith pulp and paper mill (Reutter, Flay & Mclntosh, 2005). Further to this, WAsP has been also used by Landberg & Mortensen 1993; Mortensen & Petersen 1997; Bowen & Mortensen 1996, 2004.

1.7 Economics of Wind Energy

Since 1990, global wind energy capacity has doubled every three years. Each doubling of capacity has been accompanied by a fall of 15 % in the price of wind turbines. This fall has been the result of a number of factors, including improvements in energy productivity, because machines have become more reliable, and because of a trend towards larger machines. The price of wind energy is now close to the price of electricity from conventional fossil sources in certain locations (Renewables, 2004).

Generally, the cost of generating electricity from wind comprises of: capital cost i.e. building the power plant and connecting it to the grid, running costs-operating, fuelling and maintaining the plant, and financing. The cost of repaying investors and banks is also an important aspect of generation cost.

1.7.1 Current Pricing Trends

In order to understand trends in wind-generated electricity prices, it is necessary to examine the prices and price trends of wind turbines, wind farms and their energy productivity. These depend on factors such as location, the size of the machines, and the size of the wind farm. Energy production depends on the site wind speed and has a crucial effect on energy prices. Although list price (Table 1.1) of wind turbines is only a guide to actual costs, with many orders being placed at lower prices, the overall trend from 1990 to 2004 is strongly downward.

Table 1.1 *On shore wind turbine list prices US$ /kW (after: Renewables, 2004)*

Year	List price(US$) /kW
1990	1400
1992	1260
1994	940
1996	910
1998	900
2000	900
2002	875
2004	850

As the market has grown, wind power has shown a dramatic fall in cost. The production cost of a kilowatt hour (kWh) of wind power is one fifth of what it was 20 years ago. In 1982, the average list price of Danish-produced wind turbines was US$ 1770/kW, and in 1997 the average price reduced to US$ 850/kW. The price, however, varies for different turbine sizes and producers. In 1997, the list price of a Danish 150 – 500 kW wind turbine (with a hub height of 30 – 40 m) ranged from US$ 750 -1200/kW and the list price of a 550 – 750 kW wind turbine (with a hub height of 40 – 45 m) ranged from US$ 690 - 850/kW. Moreover, prices of wind turbines seem to vary from one country to another. According to a Neij's study (as cited in Sahin, 2004), the average price in 1995 was US$ 790 - 980/kW in Europe and US$ 500/kW in the USA.

Sahin (2004) stated that, over the past years, costs have reduced by some 20 %. Wind is already competitive with new coal-fired plants and in some locations it can challenge gas, currently the cheapest option. Wind energy production continues to improve in ways, which reduce cost and improve efficiency. Electricity from the wind costs about 7 – 11 US cents per kWh and is predicted to fall to about 5 US cents/kWh. Wind energy projects are simple and cheap to maintain. Land rental fees paid to farmers provide valuable additional income in rural communities. The construction work is mostly undertaken by local companies providing local employment and long-term jobs are created for maintenance work. In the UK, for instance, developers have contracted to build wind farms for a price of less than 3 US cents/kWh, comparable with that of gas.

The cost of wind power generation falls as the average wind speed rises, and it is shown that at an average site with a speed of greater than 7.5 m/s and a cost per installed kilowatt of US$ 700, wind can be cost competitive with gas (Wind Force, 2002). With wind energy, and many other renewables, the fuel is free. Therefore once the project has been paid for, the only costs are operation and maintenance and fixed costs such as land rental. The capital cost is high, between 75 % and 90 % of the total for onshore projects.

1.7.2 Cost Comparison with other Electricity Generation Technologies

It is difficult to compare the actual cost of producing electricity from other energy sources because many of the benefits of renewable energy (e.g. no pollution and never ending supply) do not have a universally accepted price. However, it is important to try and compare ‘like with like’ when contrasting wind generation costs with those of the fossil fuel sources and so prices bid into the non-fossil obligation (BWEA, 2007).

At current electricity prices, the cheapest wind plant, those with easy access and economies of scale are now fully competitive with gas (Figure 1.8), if sites have an average good wind speed of greater than 7.5 m/s. The price of electricity from new thermal plant is based on European data, and has changed little since 2001 with gas on an upward price trend.

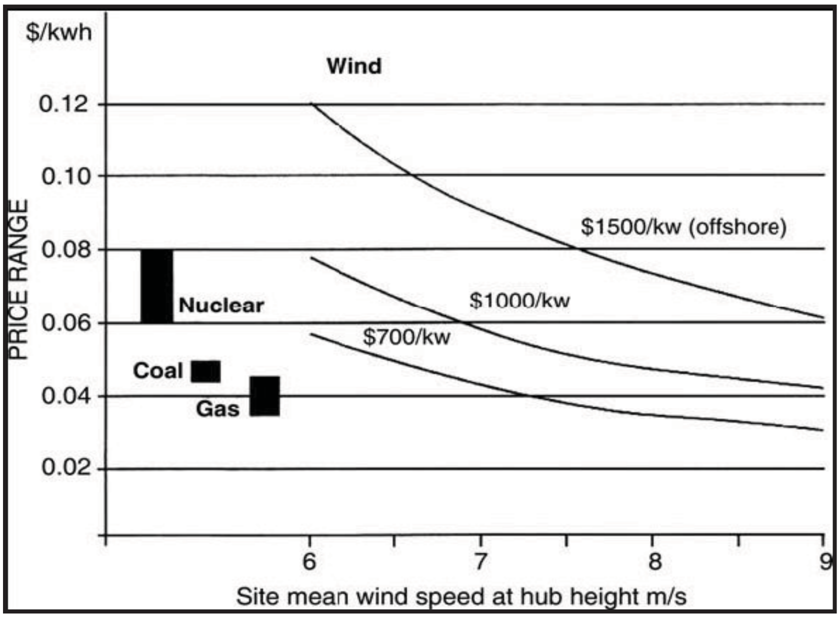


Figure 1.8 *Cost comparison for different energy sources. (after: Anderson's study (as cited in Sahin, 2004)*

However, the lower capacity factor of wind power means that to produce a given quantity of electricity, it is necessary to install 2 – 2.5 times more generating capacity than with fossil fuel plants (Sahin, 2004). This tends to make wind energy more expensive in the initial phase of the life cycle. On the other hand, there is no fuel cost during the lifetime of a wind power generating plant.

The cost of producing electricity from wind varies between different countries; however the trend everywhere is same i.e. wind energy is getting cheaper (Figure 1.9). The cost is coming down for various reasons. The turbines themselves are getting cheaper as technology improves and the components can be made more economically. The productivity of these newer designs is also better, so more electricity is produced from more cost-effective turbines. There is also a trend towards larger machines. This reduces infrastructure costs as fewer turbines are needed for the same output.

The cost of financing is also falling as wind turbine manufacturers are gaining confidence in the technology. Wind power should become even more competitive as the costs of using conventional energy technologies rise.

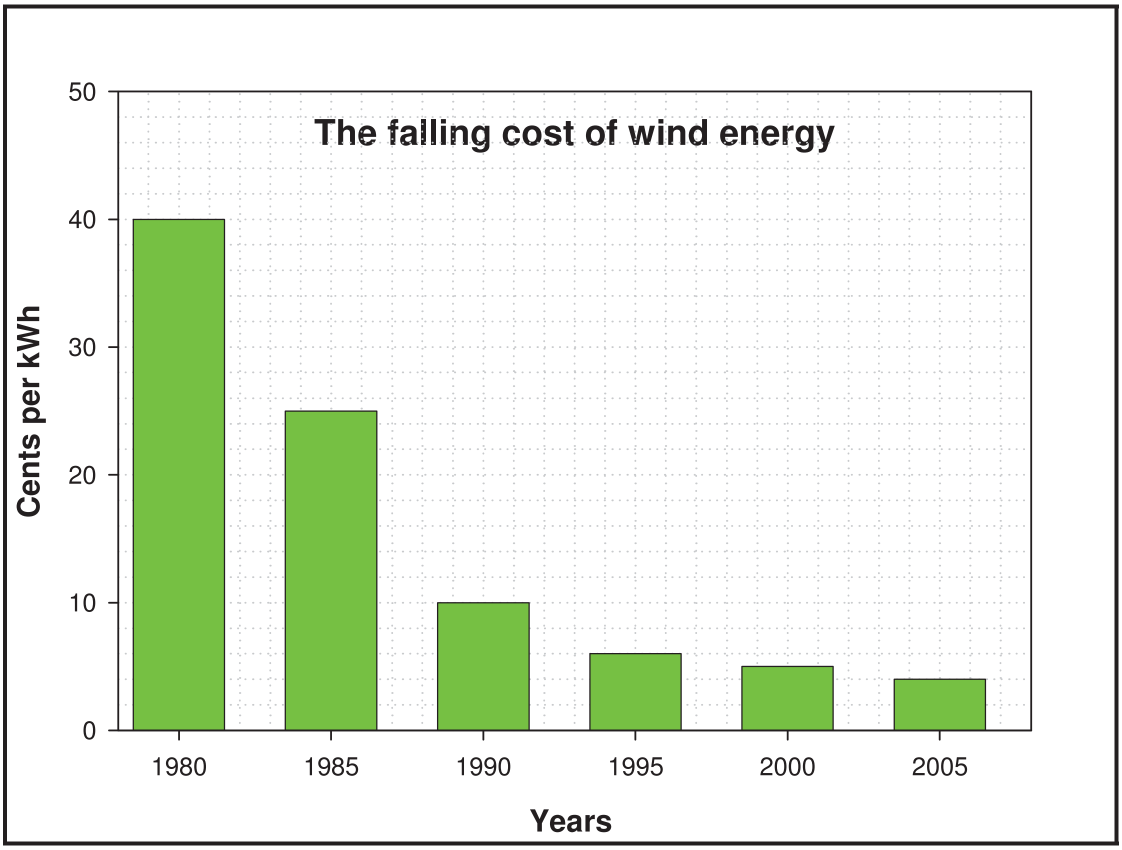


Figure 1.9 Falling cost of wind energy (after: BWEA, 2007).

1.7.3 Prospect of Wind Energy

The wind industry has already delivered impressive reductions in cost and improvements in productivity over the last 20 years. As a result, wind energy generation prices are almost on par with those of fossil fuels.

The wind energy capacity continues to double every three to four years as expected, and if each doubling of capacity is accompanied by a 15 % reduction in wind turbine production costs, than there will be a reduction of 20 % in installed costs by 2010, resulting in an installed cost of about US$ 1100/kW. There have been several estimates of future cost trends and Renewables, (2004) have estimated are US$ 617-1208/kW for onshore installations by 2010. Offshore costs are expected to fall somewhat faster than this as the industry gains more experience in this sector. The corresponding range of estimates is US$ 1510-1785/kW. Generation costs are expected to fall a little faster as the larger machines capture high wind speeds.

Although there is some uncertainty over future costs, it may be noted that the price of electricity from wind plant is effectively fixed once the plant has been constructed, setting aside possible variations in interest rates. By contrast, the future prices of fossil fuels are very uncertain, and can cause the cost of electricity to change after the plant has been constructed, unless long-term fuel contracts can be secured, which is unlikely in the present political climate.

The future prices of gas are extremely uncertain, and Renewables (2004) have suggested that the premium needed to guarantee fixed gas prices over a ten-year period is around $US 0.5/kWh. As a result, the emphasis in the short-term may well be on coal. Due to the distorted market, the uncertainty over future fossil fuel prices and the continuing downward trend in wind energy prices means that the outlook for wind energy is bright. By 2010, and possibly earlier than that, the installation of wind energy may well result in lower costs to electricity consumers compared with the continued exploitation of fossil fuel energy sources.

1.8 Wind Resource Assessment

1.8.1 Global Wind Resource Assessment

Few studies have been made of the world's wind resources, with the most detailed research confined to the continent of Europe and the US. However, those assessments which have been carried out confirm that the world's wind resources are extremely large and well distributed across almost all regions and countries. Lack of wind is unlikely to be a limiting factor on global wind power development. When specific analysis has been produced on individual countries or regions, this has often shown an even greater resource than the global picture suggests. Grubb and Meyer (1994) estimated that the world's wind resources have the capacity to generate 53,000 TWh of electricity per year. This is almost four times the International Energy Agency's (IEA) figure (13,663 TWh) for global electricity consumption in 2003 (Global Wind Energy Outlook, 2007).

Global Wind Energy Outlook (2007) stated that a study by German Advisory Council on Global Change, "World in Transition – Towards Sustainable Energy Systems" (2003) calculated that the global technical potential for energy production from both onshore and offshore wind installations was 278,000 TWh per year. The report than assumed that only 10–15 % of this potential would be realizable in a sustainable fashion, and scaled down to approximately 39,000 TWh per year as the contribution from wind energy in the long term. This represented 35 % of the 1998 figure (112,000 TWh) for total world primary energy demand.

North America was found to have the greatest wind power potential, although some of the strongest winds were observed in Northern Europe, whilst the southern tip of South America and Tasmania also recorded significant and sustained strong winds (Global Wind Energy Outlook, 2007).The global wind energy industry has been growing at the staggering rate of nearly 30 % per year for the last 10 years, and experts predicted that there is no end in sight for this boom. Whilst a larger proportion of this development is happening in Europe, other markets, especially Asia and North America are catching up fast (Global Wind Energy Outlook, 2007).

In the year 2007, a total of 20,000 MW of wind turbine installation took place. This took the total installed wind energy capacity to 93,864 MW (Table 1.2) up from 74,223 MW in 2006. This is an increase of 31 % compared with the 2006 market, and represents an overall increase in global installed capacity of about 27 %. This development shows that the global wind energy industry is responding fast to the challenge of manufacturing at the required level, and manages to deliver sustained growth. Global Wind Energy Outlook (2007) stated that the international market is expected to have an annual turnover in years to come of more than US$ 18 billion, with an estimated 150,000 people employed around the world.

***Table 1.2** Global statistics of top 10 total installed capacity at the end of 2007. (after: Global Wind Energy Outlook, 2007).*

	MW	% of global total
Germany	22,247	23.7
Spain	16,818	17.9
US	15,145	16.1
India	7,845	8.4
PR China	5,906	6.3
Denmark	3,125	3.3
Italy	2,726	2.9
France	2,454	2.6
UK	2,389	2.5
Portugal	2,150	2.3
Rest of the world	13,060	13.9
Total top 10	80,805	86.1
Total	**93,864**	**100.0**

The Global Wind Energy Outlook (2007) reported that Europe remains the leading market for wind energy. New installations represented just 43 % of the global total, down from nearly 75 % in 2004. For the first time in decades, more than 50 % of the annual wind market was outside Europe, and this trend is likely to continue into the future. While Europe, North America and Asia continue to see the most important additions to their wind energy capacity, the Middle East/North Africa region increased its wind power installations by 42 %, reaching 538 MW at the end of 2007. In addition, new capacity was added in Egypt, Morocco and Iran.

1.8.2 Regional Wind Resource Assessment

Growth in the Pacific region was led by New Zealand with 151 MW in new capacity, which nearly doubled the country's total installations, reaching 322 MW. While Australia had an exceptionally weak year with only 7 MW of new installations, the change in government at the end of 2007 spurs hopes for a brighter future for wind energy.

In the South Pacific, couple of wind resource assessment and wind turbine installation has been done. Foremost, Mangaia Island, one of the Southern Cook Islands, was beneficiary of PREFACE (Pacific Energy France Australia Common Endeavour) project in which two 20 kW wind turbines were installed. These turbines installed in January 2004, are connected with the diesel generators to the local grid and supply electricity to three villages. The yield of the turbines was estimated to be between 94,000 and 104,000 kWh per annum. In 2004, one of the wind turbines failed through the separation of its blades. Apart from this accident, no clear reason has been found as to why the yield is only 20 - 25 % from the amount estimated by the feasibility study (Cloin, 2004).

In Papua New Guinea (PNG), a small wind / solar hybrid system was introduced by the Chinese Government through a grant of almost $US 350,000 in 2001. This grant provided for 50 sets of 500 W wind / solar hybrid system for demonstration purposes and is used to provide lighting for the health centers and meeting venues or community halls in rural areas (Vere, 2004). Out of the 7 units that were installed 3 were reported to be working properly. One of the working units is used at the University of Papua New Guinea for training purposes.

Zieroth (2006) stated that New Caledonia had the most wind energy experience in the region. There are four projects operational, two on the main island of Grande Terre, (Plum 2.7 MW wind farm), one in Lifou (10 x 60 kW), and one in lle des Pins (3 x 60 kW). Plum wind farm project consists of 20 Vestas 225 kW generators on 32 meter lattice towers and fed into a 15 kV distribution network that peaks at around 6 MW and reaches its lowest loads at 2.5 – 3 MW.

1.8.3 Wind resource assessment in Fiji

Prasad (1999) in a study on wind power in Fiji determined that the average wind power flux over the windiest areas is between 42 and 140 W/m^2 (wind speed between 4 and 6 m/s). Taking into account the scenario for Fiji, power in the wind can be utilized to provide mechanical power (for water pumping) and for electricity generation. There is good potential for use of small scale wind turbines, using battery storage to provide power to remote communities and for remote telecommunication installations.

The hybrid wind-solar-diesel power system in Nabouwalu in Vanua Levu, Fiji, was a successful example of the use of wind power and solar energy to generate electricity, however it is currently not in operation due to lack of maintenance. The 720 kWh/day hybrid power plant for the provincial center at Nabouwalu in Vanua Levu, Fiji was designed by Pacific International Center for High Technology Research (PICHTR) to integrate renewable indigenous resources with the existing diesel-generator electricity distribution mini grid. The Ministry of Foreign Affairs of Japan (MOFA) covered equipment capital cost.

Ownership was transferred to Department of Energy (DOE) and maintenance was assigned to the Public Works Department (PWD). Operations and maintenance cost (including battery replacement) was supposed to be covered by the consumers. Operators were trained by PICHTR with an operation and maintenance guideline based on the Hawaii hybrid system (Vega, 2004). It provided power through 89 electrical meters besides un-metered streetlights.

In Fiji, government has put in place strategies through its Strategic Development Plan to become a 100 % renewable energy power utility by 2011. The Fiji Electricity Authority (FEA) has entered into a $FJ26 million wind farm power contract with a French company Vergnet. The total project cost was $FJ 30M and have been commissioned in October 26, 2007.

Vergnet a supplier of water and wind energy systems supplied the wind turbines which were assembled and installed by FEA at Butoni, in Sigatoka. This is the first grid connected wind farm in Fiji. FEA installed 37 Vergnet turbines along the Butoni ridge line to create a 10 MW wind farm. The turbines are 55 meters high, have two blades and generate electricity between wind speeds of 4 and 20 m/s. Each turbine has a rated power capacity of 275 kW. The wind farm in total has a capacity of 10 MW, based on wind data for the area; it is anticipated to produce 11.5 GWh of electric energy annually to the FEA grid (Wind Prospect, 2005).

This new addition from Butoni is to increase the total generation capacity comprising of hydro, wind, and diesel close to 166 MW on Viti Levu, Fiji. The current maximum power demand in Viti Levu is close to 110 MW. The completion of this project will bring to a total of FJ$ 58 million that FEA has invested in renewable power secure in the last 3 years to protect Fiji's energy supply.

The wind energy potential for selected area in Fiji can be obtained from a combination of detailed measurements of the wind climate/profile of specific location, together with predictions produced by software e.g. WAsP. To ascertain the reliability of such a methodology, one first needs to check the predictions of WAsP against actual measurements actual measurements carried out in the field. This will provide a way of assessing the predictive capacity of the software, thus increasing the confidence level in using this technique of assessing wind power potentials.

1.8.4 Aims and Objectives of the Research

The main purpose of this study is to investigate the wind characteristics and carry out a resource assessment around Laucala Bay, Suva. The specific aims of the study were to:

a) Construct observed wind climate (OWC) at Laucala Bay and at Nabua site.
b) Use WAsP to predict the regional wind climate at Nabua and verify using the measured data, and
c) Determine a wind regime pattern over greater Suva area.

To achieve the specific aims the objectives of the study were:

1) To build a 4 year (2004-2007) wind regime at Laucala Bay using the existing Marine Studies Programme (MSP) measured data.

2) To install a 900 W wind turbine at Laucala Bay site and measure its annual energy production (AEP).

3) To construct an electrical circuit for a light sensor lamp and build appropriate hardware.

4) To measure wind speed and direction at the Nabua site and develop its OWC.

5) To digitize map for greater Suva area for WAsP use.

6) To predict the mean wind speed, direction, power density and AEP at the Nabua site using WAsP.

7) To compare the WAsP prediction to the measured values obtained at Nabua site and justify.

8) To construct a wind resource grid for greater Suva area using WAsP.

9) To carry out a brief economic analysis for installing a 900 W wind turbine in the greater Suva area.

1.9 Thesis Structure

This thesis is divided into 5 chapters. In the chapters that follow Chapter 2 examines the methodology that is used in this project. It details the general requirement for the successful implementation of the project. The techniques used in installing the data measuring equipment, instrumentation and measurement techniques are outlined. This chapter concludes with a brief introduction of the Wind Atlas Analysis and Application Program (WAsP) software. The theory of wind power is presented within appropriate sections in the thesis.

Chapter 3 details the analytical tool and the analysis of the results obtained by measurements and WAsP predictions. Results obtained from WAsP software such as observed wind climate profiles, vector map of the project site, and turbine editing forms the basis of analysis. The chapter also considers power and thrust curve editing and wind resource mapping. Chapter 4 presents a discussion of the results obtained in the preceding chapter. Finally, chapter 5 presents the summary and conclusions of the work undertaken and provides suggestions for further work and overall conclusions.

Chapter 2 Methodology

2.1 Overview

Successful wind power development projects hinge on quality wind resource assessments and understanding of the variables affecting the wind resource. Wind power is strongly influenced by the wind resource behaviour that fluctuates with a host of variables including topology, altitude, meteorological conditions, and complex weather patterns. Obstructions and complex terrain complicate the measurement process and require careful analysis of quality wind data as well as correlation to historical data from an existing monitoring station. Urban settings can present some of the most complex terrains for wind assessment. Within urban settings, long-term wind data monitoring projects are essential to fully characterize wind patterns throughout the year and to account for interaction of wind, weather and building induced effects. In order to gain success in these kinds of wind resource assessment projects, it is vital to implement a proper methodology arrangement.

Before visiting any prospective monitoring sites the various factors influencing urban wind energy resource were compiled. The site selection criteria that proved particularly critical in the assessment of possible host sites are the degree of exposure to SE/NE prevailing winds during peak season, physical characteristics of existing and available instrument mounts, location with respect to prevailing winds, building or property manager interest and cooperation, (equipment installation support, security/controlled roof access, and opportunities for promotion/education), ground-mounted tower sites (land use, topography, and soil properties, security, controlled access to towers and data loggers, and zoning, aesthetics, and obstructions within 10 m), proximity to turbulence-causing obstructions, (other buildings/structures and hills and ridgeline trees).

During subsequent site selection meetings and site visits the above criteria were used to assess the suitability of particular sites. In this chapter the project approach is first described. This is followed by the study area, field sites, instrumentation, system description, measurement technique and finally WAsP application.

2.2 Project Approach

The procedural and investigative approaches employed for this wind resource assessment project are described below. The key elements discussed within the approach include: i) site review and selection criteria, ii) monitoring system selection and equipment installation, iii) data collection/quality control processes, and iv) wind data normalization and generic wind turbine energy output analyses process description. For this project three wind monitoring stations were chosen: the Laucala Bay site, the Marine Studies Programme (MSP) site and the Nabua site. The monitoring instruments were set up at the Laucala Bay site, however due to insufficient data other wind speed data were obtained from the MSP site. Data from the MSP site were later corrected and were used to determine the wind regime for the Laucala Bay area. Once this was done, WAsP software was used to determine the wind regime for the Nabua site. This was later compared with the data measured at the Nabua site.

2.3 Study Area

Fiji (Figure 2.1) lies in the heart of the Pacific Ocean midway between the equator and the South Pole. It is located between longitudes 174° E and 177° W of Greenwich and latitudes 15° and 22° S. Fiji's Exclusive Economic Zone contains approximately 330 islands of which about a third are inhabited. The zone covers approximately 1.3 million km^2 of the South Pacific Ocean.

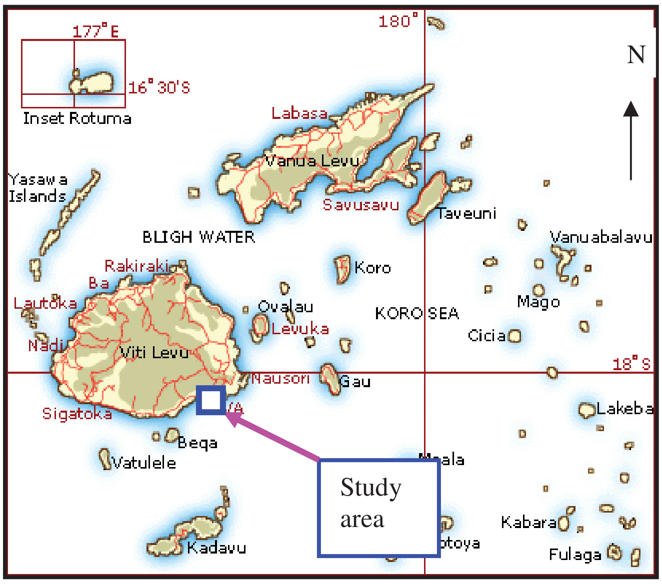


Figure 2.1 *Map of Fiji of showing the study area (after: http: www.scaruffi.com/travel/Fiji.)*

Suva, the capital of Fiji is situated at 179° E and 18° S and has a population of approximately 86,000. The peripheral of Suva, which includes Lami and Nasinu towns, has a population of 106,993 (Statistical News, 2007).

According to Fiji Meteorological Service (FMS), Suva experiences a wet season between the months of November and April (FMS, 2007). The rainfall is greatly influenced by the islands topography and the prevailing south-east trade winds which are persistent during the months of June to November. According to the FMS's temperature data, the annual average ambient temperature for Suva is approximately 25°C and changes only 2-3°C between the coolest months (July to September) and the warmest months (December to March). The study was carried out at two different sites (Nabua and Laucala Bay) within the Suva area.

2.4 Field Sites

2.4.1 Laucala Bay Site Description and Assessment

The experimental (Laucala Bay) site is located (18°09.06 S and 178°27.01 E) a few meters from the coast. The site (Figure 2.2) was chosen after reconnaissance visits around greater Suva area. It was chosen because it was secured (fenced), it had an unobstructed SE wind, an easy access (close to the laboratory) and lay outside the residential area of suburb. This site belongs to the Fiji Institute of Technology (FIT) and was kindly leased to us by the Head of Maritime School & Fisheries Capt. Tevita Robanakadavu. The site is immediately adjacent to the major Queen Elizabeth driveway and opposite a gymnasium. The site is the best candidate for wind turbine testing because it is located upwind from the prevailing SE and NE peak season winds. There are a few trees (approximately 5 m high) in the immediate area of the wind turbine. On this site a Whisper 100 (900 W) wind turbine was installed.

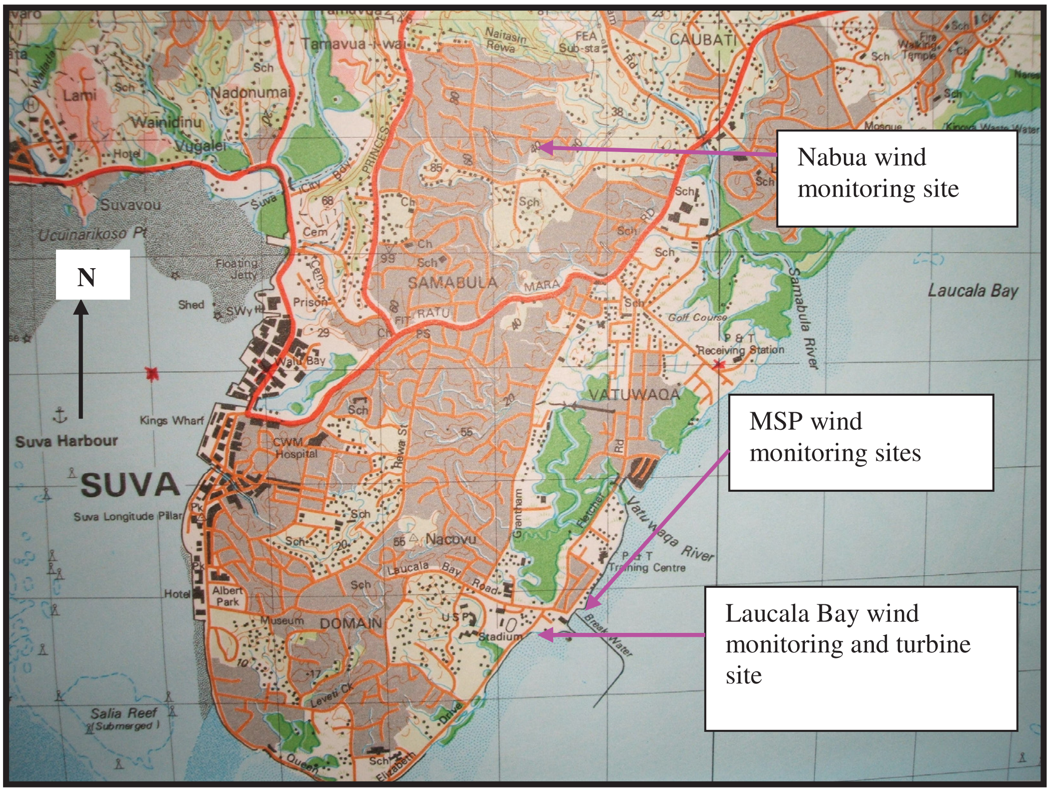


Figure 2.2 *Map of Suva showing the study area. Scale 1:50,000*

2.4.2 Marine Studies Programme (MSP) Site

The MSP site (18°09.05 S and 178°27.25 E) is located at the lower campus of the University. It has a previously installed wind monitoring instruments (an anemometer and a wind vane). The monitoring instruments are mounted on the building, site (a) (Figure 2.3) adjacent to the sea at a height of 10 m. The site experiences an unobstructed ocean breeze mainly from SE extending to NE. This station was set by one of the MSc research students to obtain the wind characteristics for the MSP site. Another site MSP site (b) 5 m away from the MSP site was located at the water edge. The MSP sites are about 200 m from the study (Laucala Bay) site.

Only five months of data were collected during this project, therefore to obtain more reliable results, data from the MSP site were used. The data from MSP site were later corrected using the on-site measured data at the Laucala Bay site. Once this data were corrected, a four year period data were constructed which was sufficient to determine the wind resource characteristics for the entire Laucala Bay area.

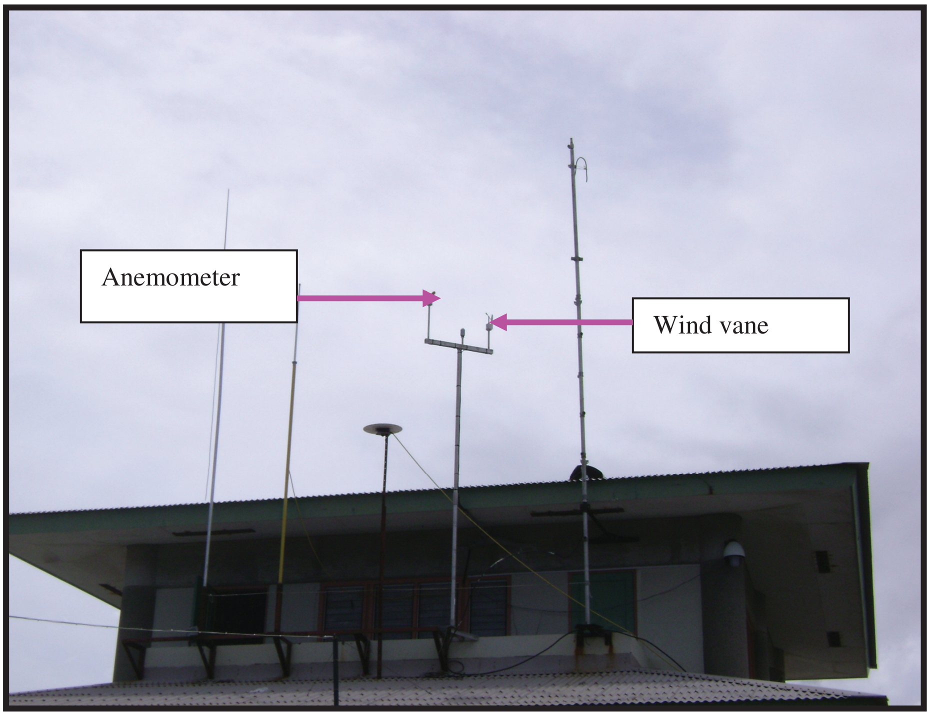


Figure 2.3 *Wind monitoring station at MSP.*

2.4.3 Nabua Site

Nabua site (18°06.934 S and 178°27.263 E) is located opposite the Mineral Resource Department (MRD), at the corner of Mead Road and Sukanaivalu Road, was the second wind monitoring site for this study. Previously a 10 / 20 Vergent wind turbine was installed at this site. Nabua experiences an ocean breeze mainly from SE extending to NE. The monitoring site was confined to 500 m^2, and has an embankment which rises to approximately 100 m above the surrounding area.

The monitoring site (Figure 2.4) which shows has the debris of the crashed 10/20 Vergent wind turbine is provided with a small solar powered monitoring cottage. The site was chosen so that a detailed wind assessment is carried out to validate WAsP prediction and to recommend an appropriate replacement turbine. The crashed turbine (10/20 Vergent) was installed as a demonstration turbine without any investigation of the wind resource at the site. This site is slightly elevated and free of obstruction within 50 m from the tower. The monitoring cottage is downstream from the mast evidenced by the bent banana and coconut leaves in Figure 2.4.

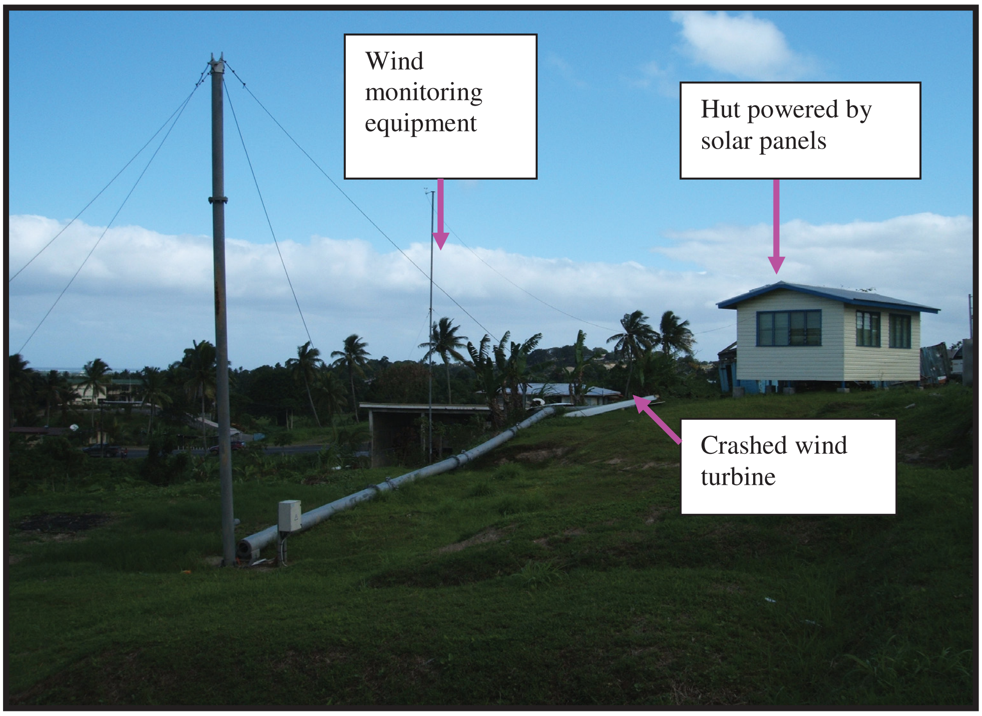


Figure 2.4 *Wind monitoring station at Nabua, Suva*

2.5 Instrumentation

2.5.1 Whisper 100 Turbine Configurations

A Whisper 100 wind turbine (Figure 2.5) was manufactured by Southwest Windpower Company of United States of America (USA). The Whisper 100 turbine has a smaller rotor diameter (2.1 m) for sustained high winds. The turbine is rated at 900 W at 12.5 m/s. The rotor diameter, weight and other features (Table 2.1) of the turbine shows the specification of the generic components of the turbine. The Whisper 100 turbine is designed to operate at a site with medium to high wind speed averaging of 5.4 m/s and greater with a cut-in speed of 3.4 m/s. The Whisper 100 turbine provides more than 100 kWh per month, 3.4 kWh per day, in a 5.4 m/s average wind.

One of the key features of the Whisper 100 turbine is the side-furling angle-governor (Figure 2.6) that protects the turbine in high winds by turning the alternator and blades out of the wind, reducing turbine exposure. Unlike other wind turbines that lose as much as 80 % of their output when furled, the angle-governor allows the Whisper 100 turbine to achieve maximum output in any wind.

Figure 2.5 *Whisper 100 wind turbine.*

Table 2.1 *Whisper 100 turbine specification (Southwest Windpower, 2007)*

Parts	**Specifications**
Rotor Diameter	7 ft / 2.1 m
Weight	22.56 kg
Mount	6.35 cm pipe
Start-up wind speed, cut-in wind speed (v_c)	7.5 mph / 3.4 m/s
Voltage	12 V DC
Rated power	900 W @ 28 mph / 12.5 m/s
Turbine controller	Whisper controller
Body	Cast Aluminium
Blades	3-Polypro/carbon glass reinforced
Over speed Protection	Patented side-furling
Kilowatt Hours Per Month	100 kWh/mo at 12 mph / 5.4 m/s
Survival Wind Speed (furling wind speed) (v_f)	120 mph / 55 m/s

Figure 2.6 *Side-furling Angle-Governor for Whisper 100 turbine (after: Southwest Windpower, 2007).*

2.5.2 Controller and Load Bank

Unlike many other small wind systems, the Whisper 100 turbine is supplied with a controller (Figure 2.7) that includes a diversion load to ensure quiet safe operation of the wind turbine when the batteries are charged. The controller protects both the wind turbine and the battery. Optional liquid crystal display (LCD) displays mounted on the controller receive real time data on the performance of the Whisper 100 turbine. Two 6 V Trojan batteries (Figure 2.8) were chosen for the load bank and were connected in series to match the turbine voltage of 12 V. Each battery rated at 600 Ah was located in the battery house at the base of the tower along side the controller.

Figure 2.7 *Whisper 100* turbine *controller*

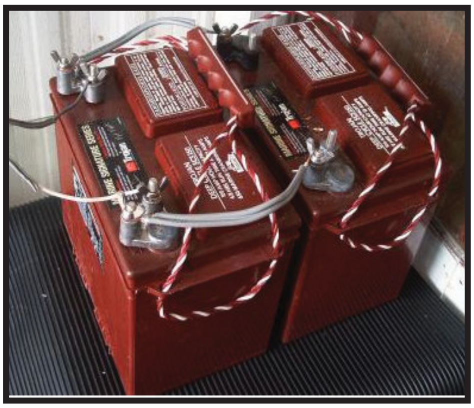


Figure 2.8 *Trojan batteries (load bank)*

2.5.3 Anemometer, Wind Vane and Data Logger

2.5.3.1 Anemometer

At both wind monitoring stations (Laucala Bay and Nabua sites) a pulse output cup anemometers A101M model was used to measure the wind speed. This instrument (Figure 2.9) consists of three cup assembled centrally to a vertical shaft for rotation. Atleast one cup always faces the incoming wind. The aerodynamic shape of the cups convert wind pressure force to rotational torque. The cup rotation is nearly linearly proportional to the wind speed over a specific range.

A101M anemometers are made from anodized aluminium alloy, stainless steels, and weather resisting plastics for all exposed parts. The bearings (stainless steel shaft running in two precision corrosion - resistant ball-races) are protected from the entry of moisture droplets and dust resulting in an instrument suitable for permanent exposure to the weather including marine environments. For this research, A101M model anemometer was used, which had a rotor spindle that turns a multi-slotted disc, interrupting the beam from a light-emitting diode. The output (a sinusoidal wave) is obtained by amplification of the signal from an opto - electronic sensor in the path of the light beam. The transducer in the anemometer converts the rotational movements into electrical signals, which is sent through a wire to a data logger. The output pulses are used to obtain direct readings in metres per second. The three cup rotor is attached by means of a patented gravity-sensitive fastener which will not release unless the anemometer is inverted (Vector Instruments, 2007).

Figure 2.9 *Pulse output A101M anemometer used for wind speed monitoring at Laucala Bay and Nabua sites.*

The general characteristics of the A101M (Table 2.2) outlines the system components, characteristics and its mechanical properties. It shows the robustness, durability and its sensitivity. Anemometer mountings can introduce uncertainties equally as significant as those caused by calibration and design. For both Laucala Bay and Nabua site, a boom-mounted anemometer was used. The boom lied at an angle of 45º to the wind direction. The distance of the anemometer from the tower was 1.5 m. Petersen, Mortensen, Landberg, Højstrup and Frank (1997) stated the distance should be atleast 1.5 tower diameter, but preferably 3 or more to reduce the error in wind speed measurement caused by the tower. In this project the outside tower diameter was 73 mm hence, this complies with Petersen's study about boom mountings of the cup anemometer.

Table 2.2 *General characteristics of pulse output anemometer A101M*

System components	
Sensors	3 cup anemometers
Transducer	LED & photodiode combination
Signal conditioner	Transistors
Recorder	Data logger
Characteristics of measurements	
Resolution	0.1 m/s
Accuracy	1 % of full range output
Maximum wind speed	75 m/s
Error	± 1 m/s
Distance constant	5 m
Temp range	- 40 to + 70 ºC (operating)
Threshold	0.15 m/s
Mechanical	
Weight	310 g / 30 g rotor
Fixing	¼ BSC / UNC screw into base
Materials	Anodized aluminium alloy, stainless steel and weather resisting plastics

2.5.3.2 Wind Vane

Wind direction is normally measured with a wind vane. A conventional wind vane consists of a broad tail that the wind keeps on the downwind side of a rotating vertical shaft and a counterweight at the upwind end to provide a balance at the junction of the vane and shaft. Friction at the shaft is reduced with the bearings, and so the vane requires a minimum force to initiate movement.

In this research a potentiometer wind vane (low torque) W200P/L was used. The instrument (Figure 2.10) incorporates a precision wire-wound potentiometer as shaft angle transducer enabling wind direction sensed by the fin to be accurately determined when connected to suitable measuring equipment, such as a data logger. The potentiometer has the lowest possible torque consistent with long life and reliability, the small gap at north being filled with an insulating material to ensure smooth operation over the full 360° (Vector Instruments, 2007). These wind vanes have a fixed reference that is to say that it must be aligned with north during installation and fixed in that position/orientation during operation.

The low 2 kΩ resistance of the potentiometer is no barrier to low power operation as most applications where power is critical use data loggers which are capable of energizing the potentiometer only for a short interval during the actual measurement. The precision potentiometer used in this wind vane is connected with 2 - wires to each end of the track and one to the wiper enabling its use in a variety of bridge and potentiometric measurement. These wind vanes are constructed from anodized aluminium alloys and stainless steels for exposed parts. Combined with a hard plastic (upper) bearing and precision ball-races, the result is an instrument suitable for continuous exposure to the weather, with a long service interval.

Figure 2.10 *Potentiometer wind vane (low torque) W200P/L used for wind direction monitoring at the Nabua and Laucala Bay sites.*

The general characteristics (Table 2.3) shows the sensors, transducer types, resolution and other pertinent features of W200 P/L wind vane.

Table 2.3 *General characteristics of potentiometer wind vane W200P/L*

System components	
Sensors	Balanced vane
Transducer	Precision conductive plastic potentiometer
Signal conditioner	Transistors
Recorder	Data logger
Characteristics of measurements	
Resolution	± 0.25º
Accuracy	± 4º in steady winds > 3 /s
Maximum wind speed	75 m/s
Error	± 1 m/s
Service life	12 years
Life of potentiometer	2 x 10^7 cycles (4 years typical exposure)
Potentiometer Resistance:	2000 Ohms (+/- 3%)
Potentiometer Voltage	1 V to 5 V
Temp range	- 30 to + 70 ºC (operating)
Threshold	0.5 m/s

2.5.3.3 Data Recording System

In the development of wind measurement program one must select reliable data recording system display to record and analyze the data obtained from the sensors and transducers. For this study CR10 (digital type) data loggers were used. These data loggers were supplied by Campbell Scientific Inc (1991).

The CR10 is fully programmable datalogger/controller in a small, rugged, sealed module which is powered by a 12V DC source. The data logger was programmed before it was subjected to any measurement. The program consisted of a group of instructions entered into a program table designed to execute every 10 seconds. When the table was executed, the instructions are executed in sequence from beginning to end. The interval at which the table was executed generally determined the interval at which the sensors are measured.

The CR10 has 64 kB of Random Access Memory (RAM), divided into five areas. These areas are input, intermediate, and final storage in the measurement, and data processing. Whilst the total size of these areas remains constant, memory may be reallocated between the areas to accommodate different measurement and processing needs (Campbell Scientific, Inc, 1991).

2.5.4 Security and Sensor Lights

Night activated circuit (Figure 2.11) was built using LDR (Light Dependent Resistors). During night time the LDR had a high resistance of (1 MΩ), hence the current flowed through R_2 (10 kΩ) resistor. Since R_2 and R_3 are both 10 kΩ resistances the 12 V is divided equally, with each of the resistance R_2 and R_3 having 6 V. As a result the voltage in the non-inverting input (+) of operational amplifier 'op-amp' LM 324N is 6 V dc. Due to LDR having a high resistance, the current flowing through it, is very small, thereby the (-) input for the op-amp is very small the high current through the (+) input, Hence the LM 324N IC becomes operational biasing the transistor BC 109 that switches on the relay (IN 4002) on. This allows the current to flow through the contact of the relay thereby lighting up the lamps.

In the day time, the LDR is approximately 80 Ω. That allows the current to flow through it. This causes the voltage at the input of inverting (-) op-amp LM 324 high compared to the voltage across the non-inverting (+) LM 324. When the voltage across the non-inverting (+) input is low the op-amp will not function. Hence, the transistor BC 109 will not be biased and the relay is not switch on thereby restricting the bulb from switching on. The system was built to discharge the batteries and also provide (security) during the night.

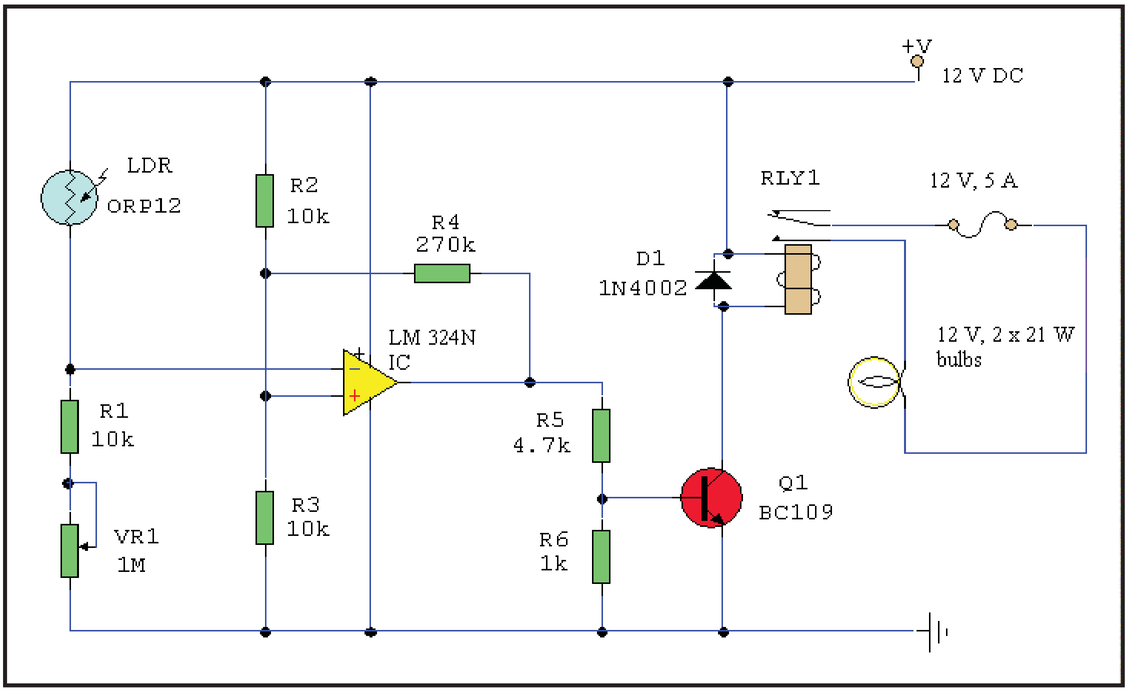


Figure 2.11 *Night activated circuit diagram for the discharge load*

2.5.5 Wind Atlas Analysis and Application (WAsP) Software

Wind Atlas Analysis and Application Program (WAsP) was used in the analysis of the data from Nabua and Laucala Bay site. WAsP (8.3) is licensed software purchased from the Wind Energy and Atmospheric Physics Department at Risø National Laboratory.

WAsP (described in chapter 1) is a PC program for predicting wind climates and power productions from wind turbines and wind farms. The predictions are based on wind data measured at stations in the same wind region. The program includes a complex terrain flow model, a roughness change model and a model for sheltering obstacles. WAsP modelling involved:

- analysing observed wind data to calculate regional wind climate (wind atlases) and,
- applying wind atlas to a particular turbine site to calculate an estimated wind climate and power output.

Three aspects of WAsP analysis was performed in detail, namely observed wind climate (OWC) plots, Map editor, and Turbine editor. After the installation process, WAsP license was validated by dongle ID and its unlocking key. Initially the quick tutorial was followed through and with guidance from the supervisor. This provided sufficient training in the use of this software for this project.

2.5.5.1 Model Description

WAsP generalizes a set of surface wind observations into regionally representative wind climatology by modelling the wind flow across the landscape. In the analysis mode (Figure 2.12) the statistics derived from a set of long-term wind speed and direction data from a long-term reference site are extrapolated to the top of the boundary layer by fitting to a Weibull distribution and modelling the effects due to obstacles, terrain roughness, and orography at the reference site. Jimenez, Durante, Lange, Kreutzer, and Tambke (2006) stated that the resulting wind speed and direction statistics are known as “wind climate” and are representative of the geostrophic wind over the region. In the application mode a prediction of the wind resource at a candidate site is generated from the wind climate data by extrapolating down from the top of the boundary layer, effectively applying the reverse of the analysis process.

2.6 System Description

This section describes the system components that have been used to determine the wind characteristics around Laucala Bay area. Briefly the entire system had the following components: 900 W wind turbine, controller and load bank, security sensor light, anemometer and wind vane, and data recording system. Further to this, WAsP software was utilized to analyze the data that were obtained using the instruments. The components of the system have been described in detail in the next sub-topics.

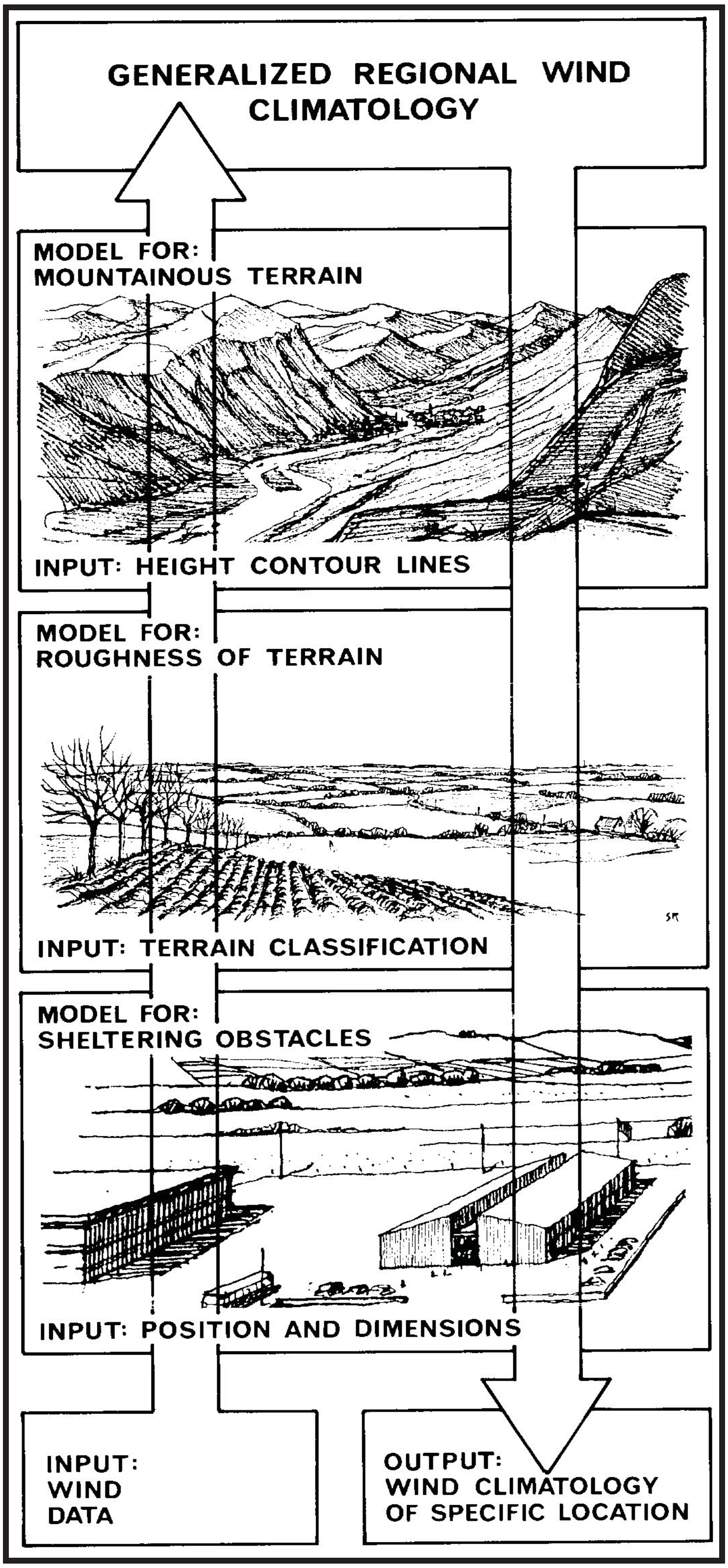


Figure 2.12 *The Wind atlas methodology of WAsP. Meteorological models that was used to calculate the regional wind climatologies from the raw data. In the reverse process the application of wind atlas data — the wind climate at any specific site may be calculated from the regional climatology (after: Mortensen. N. G. et al, 2004).*

2.6.1 Whisper 100 Turbine Installation

The site was prepared and the ground cleared of any debris, prior to the installation. On this site locally purchased Whisper 100 wind turbine was installed.

Foremost, measurements were taken for the guy wire radius (8 m) and four appropriate spots were identified for it. Guy wire supports of 1.2 m deep were dug and foundation was laid and left to dry for 48 hours. The "Augur" type anchors (Figure 2.13) were used to terminate guy wires. This anchor configuration (Augur type) was determined by the soil type at the site. The soil around the coast is generally sandy loam.

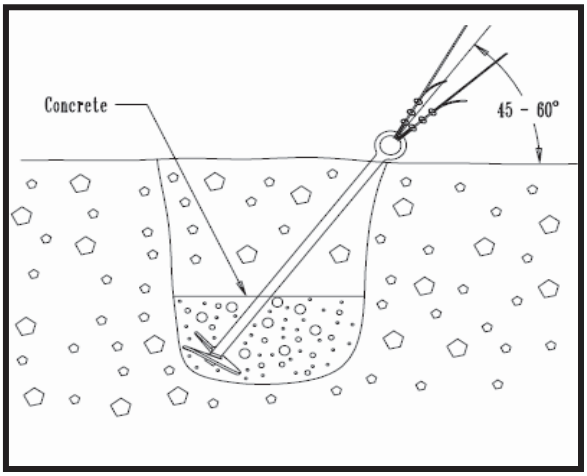


Figure 2.13 *Auger type anchor for guy wire support (after: Southwest Windpower, 2007)*

Selecting appropriate tower geometry and height was the next step in the installation process. The "Whisper" land tower kit was designed for a 73 mm outside diameter. The design of this tower kit allowed steel pipe to with-stand severity of the wind at the site location. Considering the soil type, and momentary wind gusts, a 15 m cylindrical steel tower was chosen for the site.

The tower base and anchors were arranged as shown in Figure 2.14. The tower was assembled on the ground on a calm day and than hoisted up into position. It was ensured that the anchor points and base position were in a line when sighted from anchor to anchor. This insured that the forces on the guy wires were equally distributed and properly balanced. After this the tower base was built and secured with concrete. Further to this the tower and the turbine were assembled. While the assembled tower was still on the ground, the guy wires were attached to the sides and rear of the tower. Next, the gin pole was assembled. The purpose of the gin pole is to raise and lower the tower with ease. An electric motor was used to manoeuvre the gin pole. Tower was pulled up about 15° at a time, stopped to see if the guy wires were correctly positioned. This process was continued until the tower was vertical. The guy wires were finally adjusted.

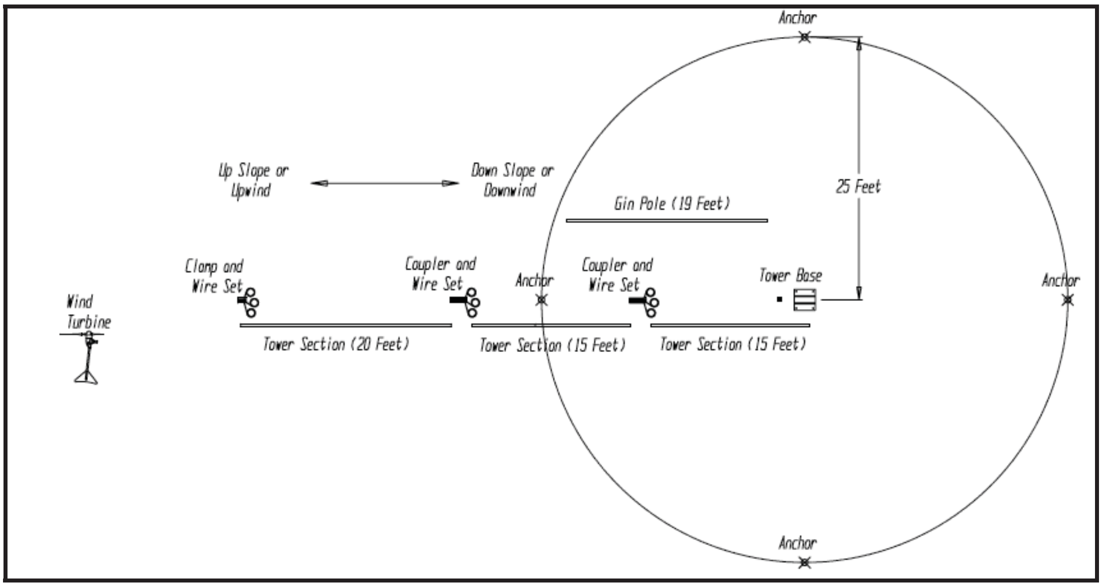


Figure 2.14 *The layout details show the dimensions of the tower and the gin pole. The anchor positions are also illustrated. (after: Southwest Wind Power, 2007).*

After the turbine was hoisted, necessary work on the battery and the controller were carried out. Two 6 V deep cycle “Trojan” batteries were chosen and connected in series setting the battery and turbine voltage to 12 V. Each battery was rated at 600 Ah. The battery bank was located 1.5 m from the base of the tower. A wind generator test was also carried out, as follows.

- Ground test: resistance to the ground was checked with a multi-meter on wires of which the resistance exceeded 10,000 Ω.
- Open circuit test: when the wires were disconnected the wind generator rotor spun freely.
- Short circuit test: when all wires were short circuited the rotor turned hard and smooth.
- Phase to phase test: when any two wires were short circuited the generator rotor turned lumpy as though there were smooth and bumpy portions of the rotor.

These tests confirmed that the wind generator was not damaged and was ready to be used. Next, Whisper controller (Figure 2.15) was assembled and wired. The controller has a digital display which shows voltage, energy (kWh), charge (kAh), and history of these parameters. The controller was placed in a weather proof box built in the laboratory. After the controller was checked, the turbine was switched on.

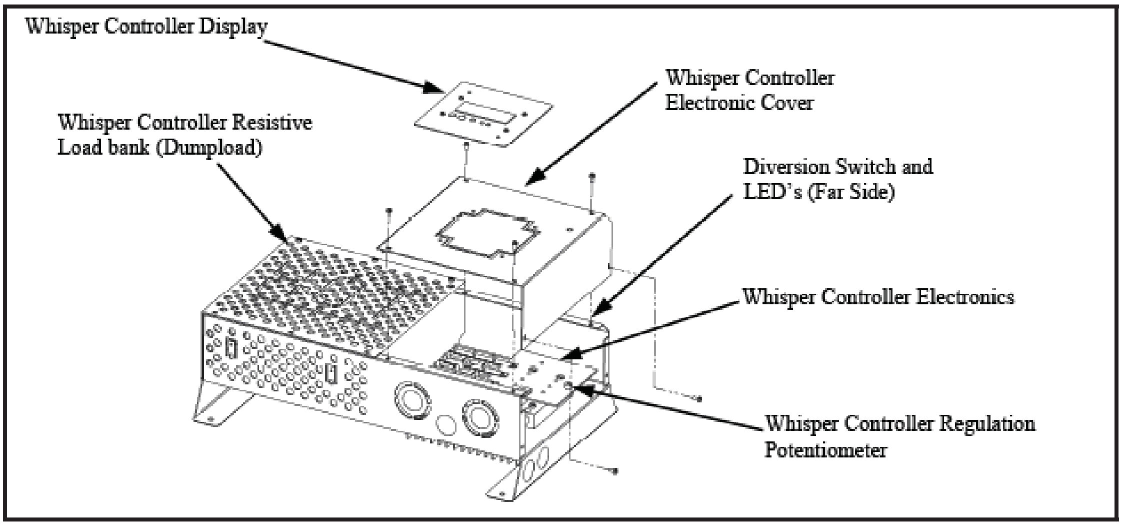


Figure 2.15 *Whisper controller components (after: Southwest Wind power, 2007).*

2.6.2 Anemometer, Wind Vane and Batteries

To determine the wind characteristics, an anemometer and a wind vane (Figure 2.16) were mounted at 10 m height on the wind turbine mast. Initially there was a delay in acquiring the anemometer and wind vane from overseas New Zealand hence, these instruments were later mounted on the mast using a cherry picker. The anemometer and wind vane were mounted on an extended arm bolted to the mast. The wires of the instruments were cable tied to the mast. This ensured that the wires remained intact during high wind speed. These wires were run through an electrical conduit to a CR10 data logger in the controller house.

The CR10 data logger, together with its keyboard/display and back-up storage module was powered by 12V DC. The power was supplied by the two Trojan batteries which the wind turbine continuously charged when in operation. The program table of the data logger was set to execute every 10 seconds, however the data recorded were the average for the 10 minute intervals. The data were downloaded using a laptop on a weekly basis.

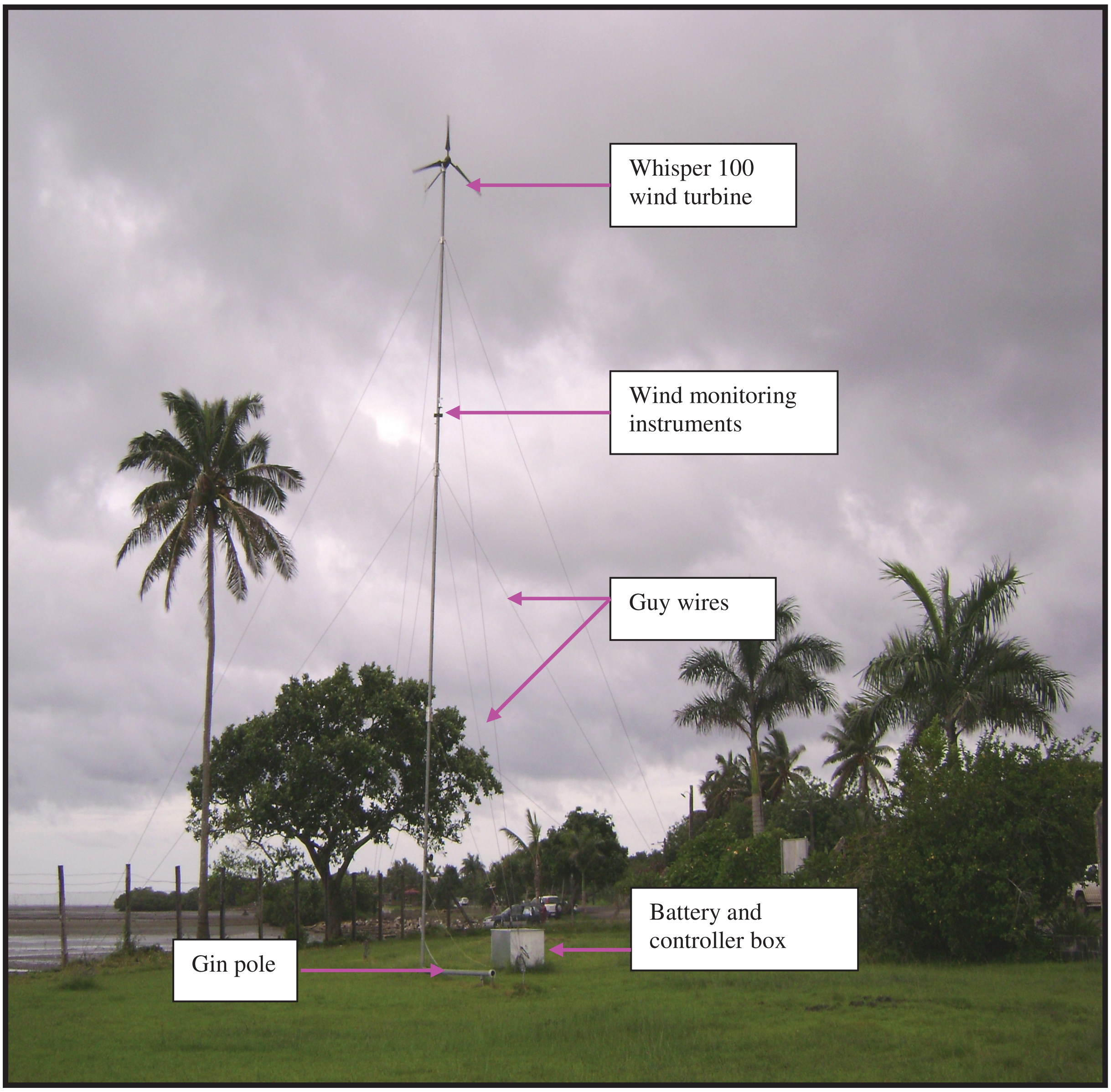
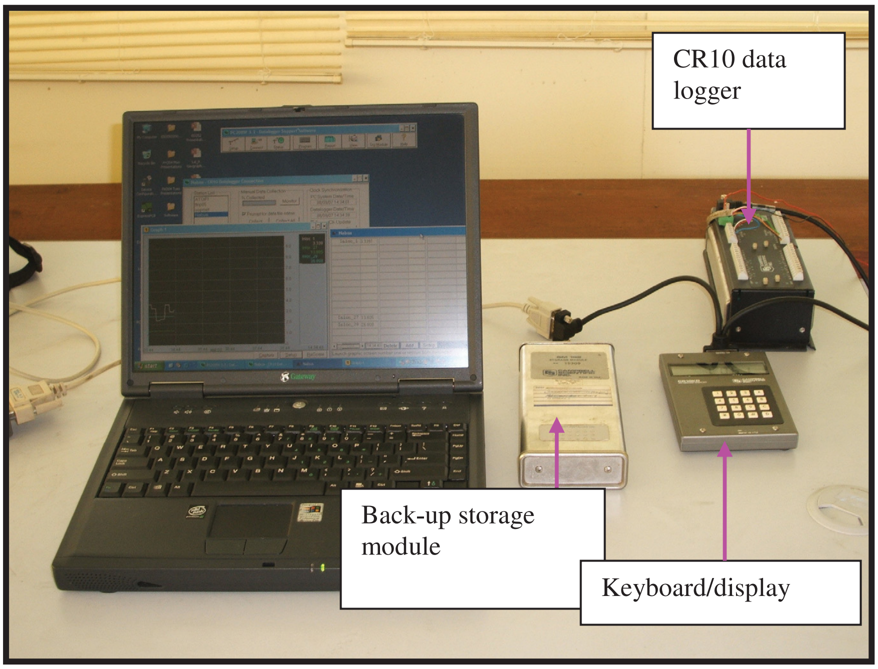


Figure 2.16 *Whisper 100 wind turbine installed at the Laucala Bay site*

2.6.3 Data Acquisition

The outputs from the anemometer and wind vane were recorded using a data logger housed in the battery and controller box. The CR10 data logger, together with its keyboard/display and back-up storage module (Figure 2.17) was powered by a 12V battery. A back-up storage module was used to prevent data loss due to any disruption in the power supply. The data logger was programmed with a set of instructions that were entered into a program table. The program table was set to execute every 10 seconds, however the data recorded was the average for the 10 minutes intervals. Every week, the data from the storage module were retrieved using a laptop. These data were than analyzed using WAsP 8.3 software.



2.7 Measurement Technique

2.7.1 Wind Speed and Direction

For all the three sites, wind speed and direction data were recorded using anemometers and wind vanes as stated in sections 2.5.3 and 2.6.2. Output from the anemometer and wind vanes were connected to the data logger that executed the readings at 10 seconds and provided a 10 minute average for both the wind speed and direction data.

2.7.2 Data Recording and Retrieval

The wind monitoring sites were equipped each with a CR10 data logger, a back-up storage module and a display pad to continuously record the wind speed and direction data. Section 2.5.3.3 described the programming of the data logger which was done with the assistance from Mr. Viti Buadromo, senior technician, physics. The program was written using LoggerNet 3.3.1 software provided by the Campbell Scientific Inc. The program with complete annotation, explaining the commands necessary for execution is given in Appendix A.

2.7.3 Battery Discharge Method

After a brief operation the controller was rendered out of operation due to overloading. It was realized that the "resistive load bank" was unable to survive the extra heat generated. Hence a battery discharge method was employed to regularly discharge the batteries. This was achieved by switching two lamps automatically when the irradiance was reduced. A light sensing lamp (Figure 2.18) was used to take off the extra energy produced by the turbine. This also provided security at night.

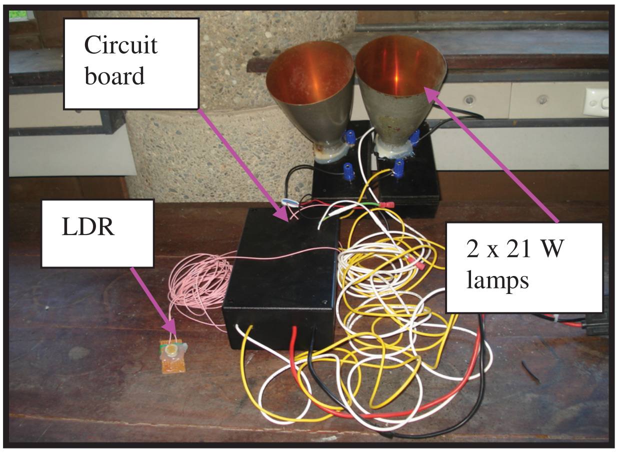


Figure 2.18 *Light sensor lamps*

2.8 WAsP Application

WAsP based its estimations using data from the Laucala Bay measurement data as input. The field site was visited to obtain an accurate description of any obstacles close to the site and a roughness description around the turbine tower. A roughness map of the study area was established. The regional wind regime for Laucala Bay was calculated and using the Laucala Bay data, wind regime of Nabua was predicted. This was later validated by the on-site wind data measured at Nabua. Modelling for sheltering, obstacles and roughness of terrain was done to determine the generalized regional wind climatology for the Laucala Bay site. This was used to determine the output wind climatology at the Nabua site. The model was applied to a digitized map with an area of about 4 km x 5 km for the region under investigation.

2.8.1 Observed Wind Climate (OWC) Wizard

A tabular summary of the frequency of occurrence of wind speed versus wind direction is required by WAsP when calculating a wind atlas from the site data. The tabular summary was contained in an observed wind climate file (OWC or *.tab file). OWC wizard program produced OWC files from raw wind speed and direction measurements. The time-series of wind speed and direction data were transformed into a table that described a time-independent summary of the conditions found at the measuring site. The OWC (Figure 2.19) consisted of a series of dialog boxes which guided through the process of creating the OWC file from the raw data files. The sequences of the dialog boxes were as follows:

1. Welcome by the wizard.
2. Providing details of the site, (anemometer height, longitude, and latitude values).
3. Adding data sets to the following sequences. (selecting data from the data files, explaining the data structure, specifying rows to be used, defining adjustments to the imported data, defining the speed and directions limits and reviewing of the data sets
4. Choosing the output settings
5. Saving the OWC or tab files
6. Reviewing the mean values of speed and power density
7. Viewing and saving the html-reports summarizing the OWC-wizard.

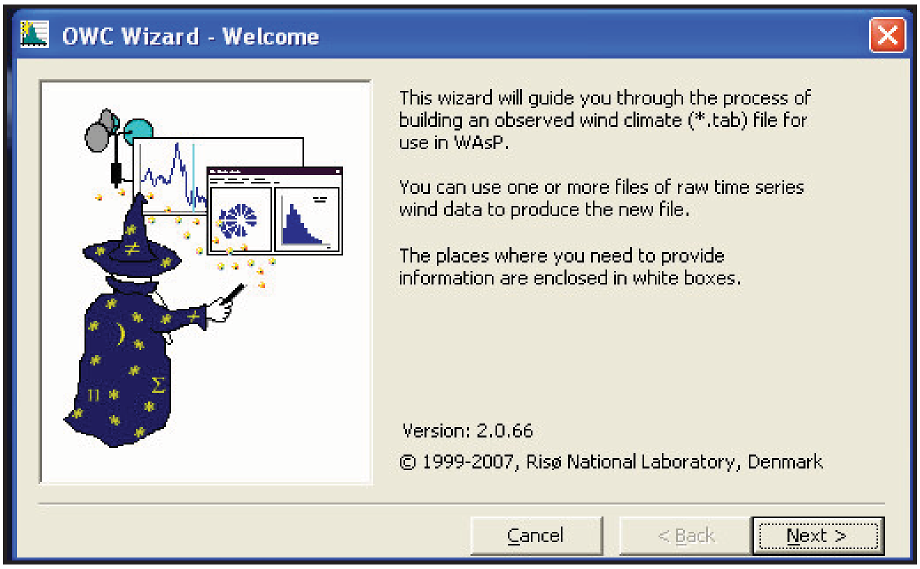


Figure 2.19 *OWC wizard*

Foremost some basic or standard information about the site was entered into the wizard. The anemometer height and GPS location for the Laucala Bay site (Figure 2.20) shows the anemometer was placed at 10 m with longitudes and latitudes as

178°27.01 E and18°09.06 S respectively. It should be borne in mind that latitudes South are entered as negative values.

Once the site specifications were entered, the next step was to manage the data sets. Raw data was imported to notepad files (Figure 2.21) before it was added to the OWC wizard.

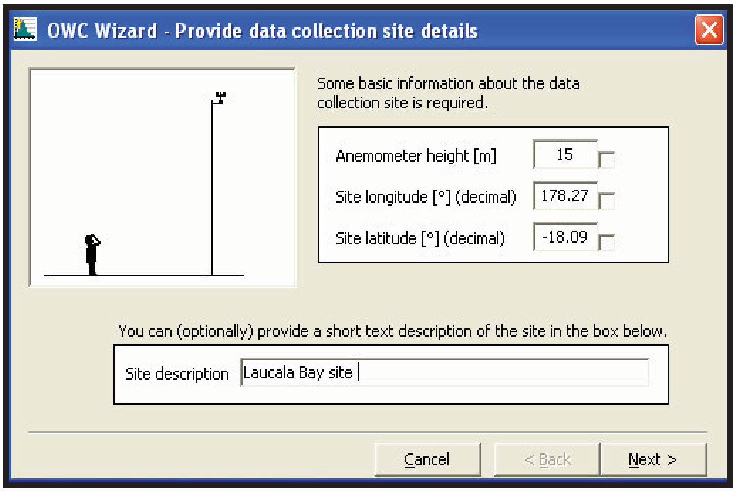


***Figure 2.20** OWC wizard- providing details for Laucala Bay site*

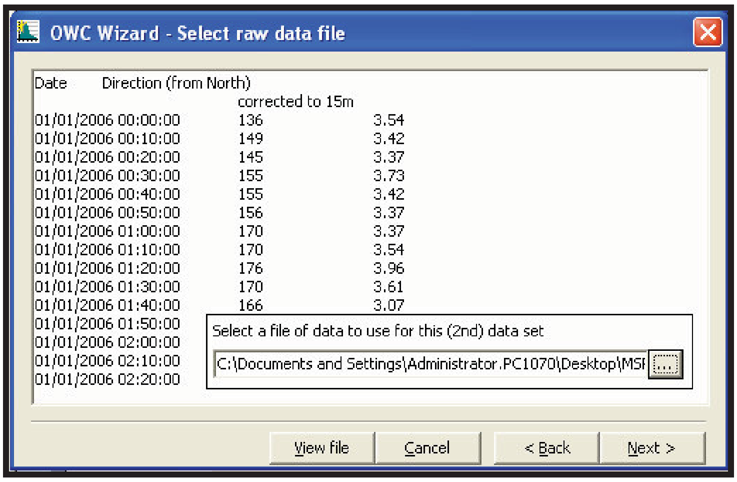


***Figure 2.21** OWC showing of data collection site details*

Before any data could be analyzed the information on the structure of the data was entered for the wizard to interpret the contents of the files. The wizard eliminated the header rows of the imported raw data. The speed and direction data were specified as shown in the dialogue box of Figure 2.22. Moreover in the dialogue box, (Figure 2.23) information on the number of sectors for wind direction to be split and centre angle sector was required to determine how the data are organized in the OWC file. The final dialogue box (Figure 2.24) shows the status of the wizard with information on the mean wind speed, mean power density and percentage discrepancy. A report Figure 2.25) was generated to view the details analyzed by the OWC wizard for MSP site.

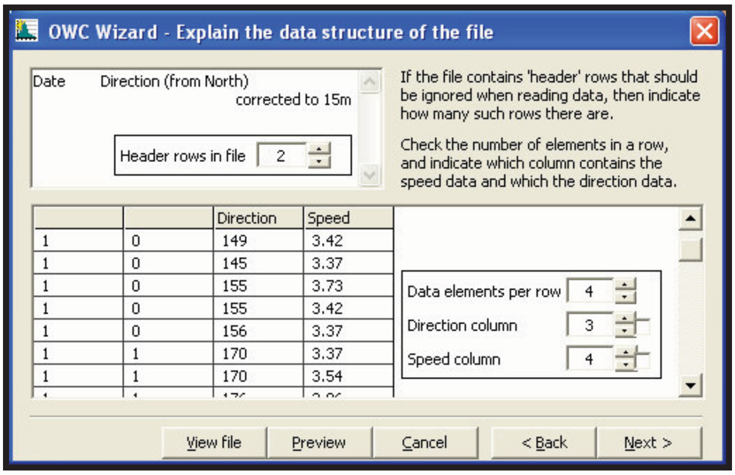


Figure 2.22 *OWC explaining the data structure of the sector file*

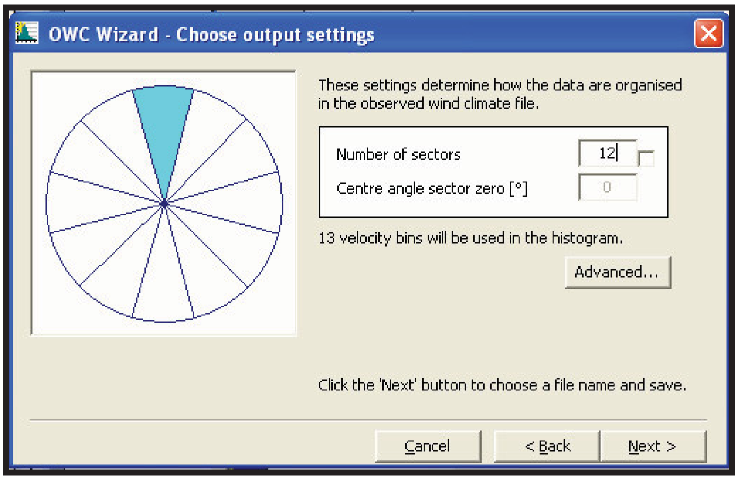


Figure 2.23 *Setting the output for wind directions*

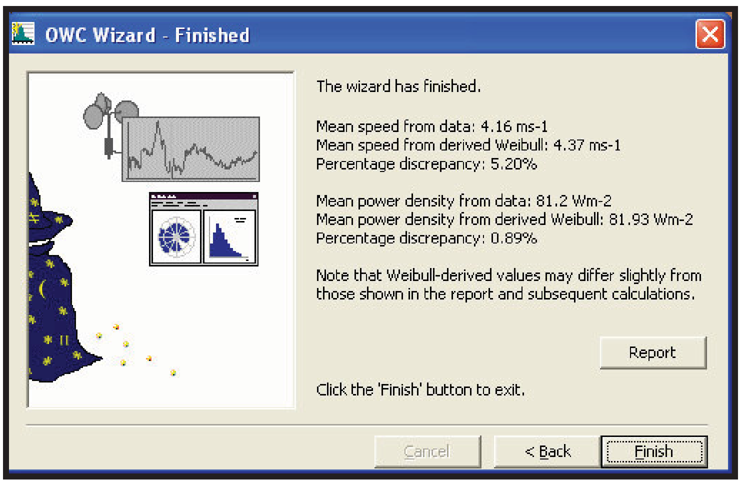


Figure 2.24 *OWC wizard finished shows various parameters that were analyzed.*

'Laucala Bay' Observed Wind Climate

Produced on 8/27/2007 at 4:48:32 PM by licensed user: Denise Chand, University of the South Pacific, Fiji using WAsP version: 8.03.0032.

Site description: 'Laucala Bay site'; Position: -18.09°N 178.27°E; Anemometer height: 15 m a.s.l.

Parameter	Measured	Weibull fit	Discrepancy
Mean wind speed [m/s]	4.16	4.37	5.18
Mean power density [W/m²]	81.20	82	0.85

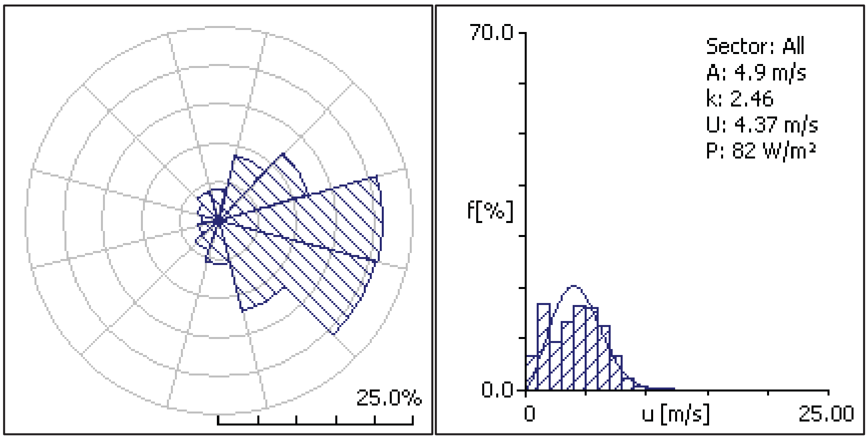


Figure 2.25 *OWC report, showing the wind rose and wind distribution.*

2.8.2 The WAsP Map Editor

The map editor is a WAsP utility program, which allowed inspecting; editing and creating (digitize) digital topographical maps for WAsP. WAsP digital map contains a topographical terrain description for use in the wind flow modelling in WAsP. It contained two windows, the main window contained general information and options whilst the display window showed the digital map in a spatial view with options containing map details.

For this study, a contour map of the greater Suva area was obtained from the Pacific Islands Applied Geoscience Commission (SOPAC). MapInfo software was installed to open and use this map. The map was opened, and zoomed to the desired area and a print screen shot was taken as shown in Figure 2.26.

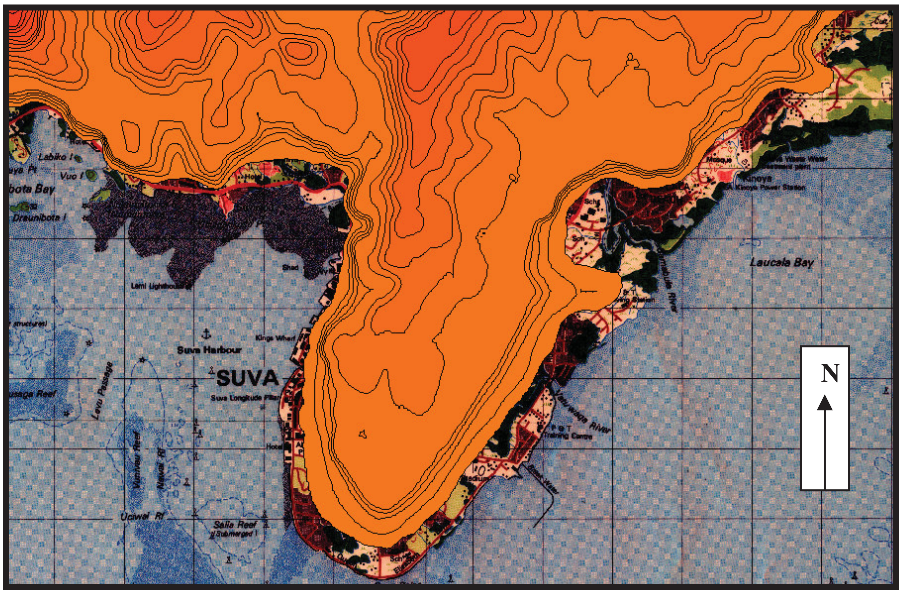


Figure 2.26 *Print screen shot for the study area showing contour heights.*

The above map was loaded as a background map which was later calibrated using the Suva map (topographical map, Fiji map series 31) obtained from the Department of Lands and Surveys, Suva, Fiji. Once the calibrated scale was loaded the map was ready to be digitized. Digitization was carried out painstakingly taking in account for the different roughness areas that were present. Different roughness lines that were present on the same contours were later joined together. Lines ending on the boundary were anchored by adding boundary nodes. The digitized map (Figure 2.27) was later used by the WAsP map editor to carry out further calculations for the Nabua site.

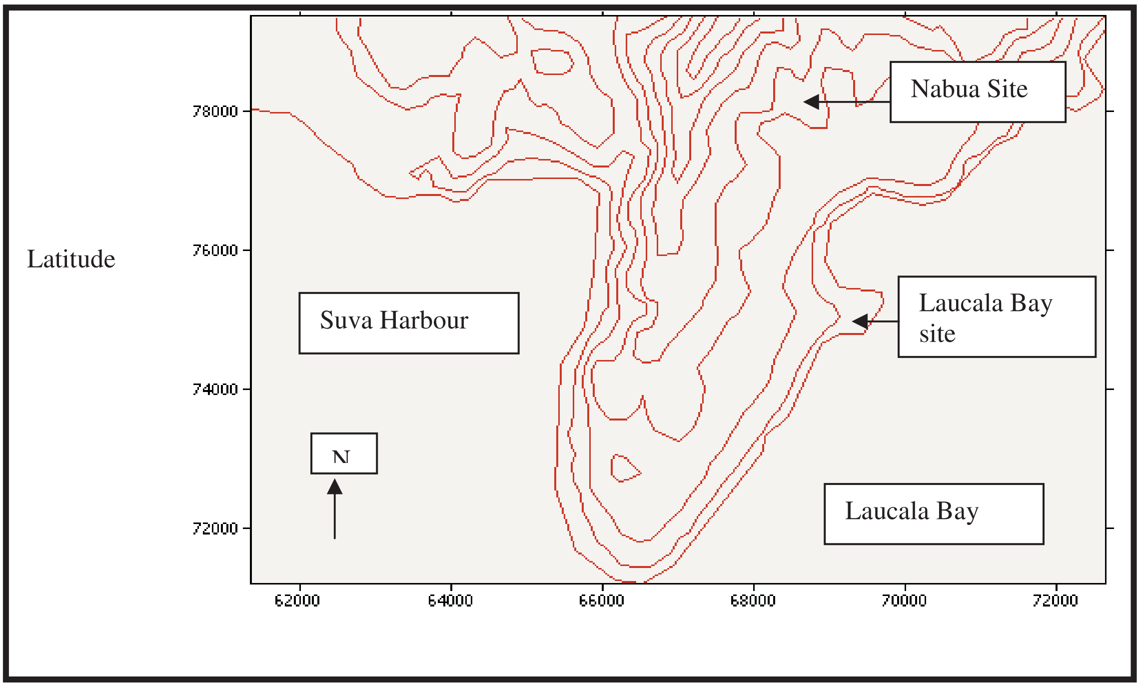


Figure 2.27 *Roughness map of the greater Suva area.*

2.8.3 Turbine Editor

The turbine editor was the third utility required by WAsP software. Turbine editor was used to create a turbine performance curve that showed the power curve as well as the thrust curve. The wind speed, power and thrust coefficient data were added in the turbine editor table as illustrated in Figure 2.28. Once the information was supplied a power curve and thrust curve output was obtained which were used by WAsP to determine the resource assessment for Laucala Bay area.

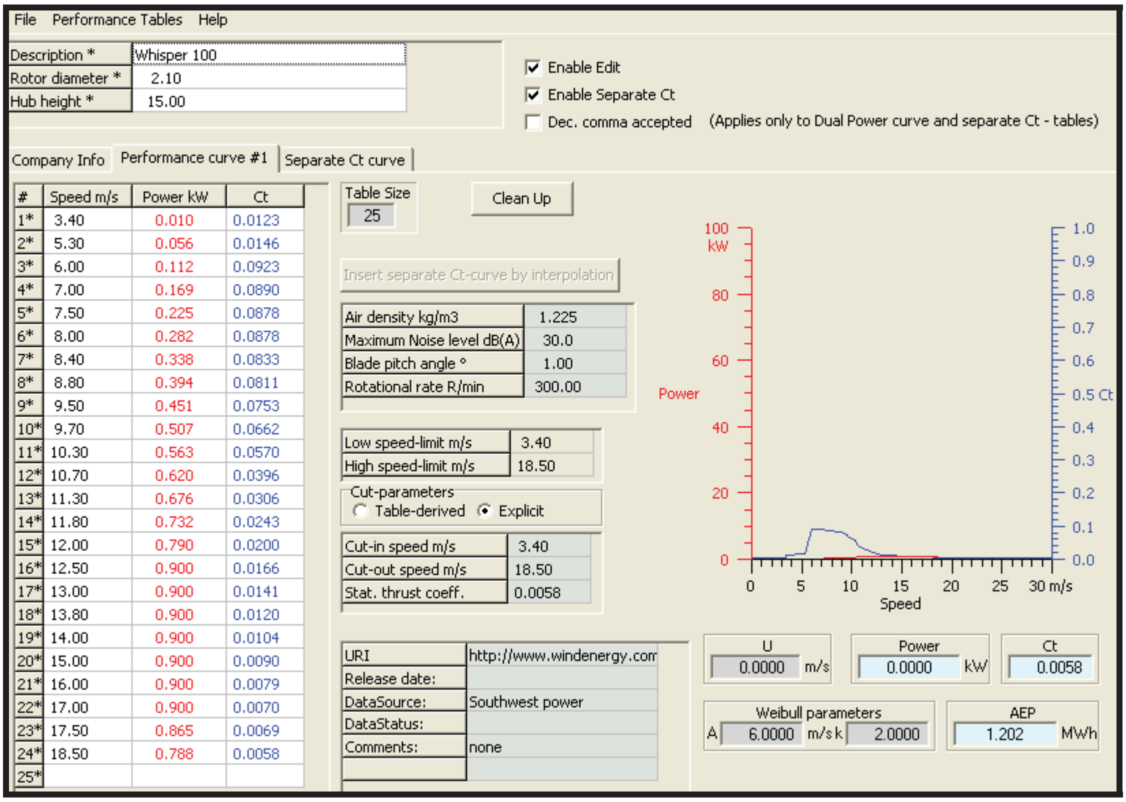


Figure 2.28 *WAsP turbine editor window used for data input to get the power curve and thrust curve.*

Chapter 3 Results and Analysis

3.1 Overview

Wind speed and direction (10 minute average) data were measured using the setup described in section 2.5.3. In this section statistical analysis is carried for the MSP and Laucala Bay Site followed by WAsP modelling which determined the resource grid for the greater Suva area. Furthermore, statistical analysis is also carried out for the Nabua site. The WAsP prediction is than compared with the measured data obtained for Nabua site.

3.2 Wind Resource Statistics

3.2.1 The Mean Wind Speed

The mean wind speed is found by averaging wind speed over time. The average is taken to separate the short-term fluctuations (due to turbulence) from the long-term changes. The mean wind speed is defined (by Strataridakis, White & Greis, 1998) as

$$U = \frac{1}{\Delta T} \int_{t_o - T/2}^{t_o + T/2} u dt \tag{3.1}$$

where U is the mean wind speed averaged over some short time period, u is the instantaneous wind speed component along the wind direction at time t_o, ΔT is the time interval over which the average is taken, and T is the time.

3.2.2 Turbulence Intensity

Turbulence intensity, the ratio of the standard deviation of the wind speed to the mean was calculated for both sites. The time period is normally no more than an hour and by convention in wind energy engineering it is usually equal to 10 minutes. The sample rate for this research was 10 Hz. The turbulence intensity, *TI,* is thus given by:

$$TI = \frac{\sigma_u}{U} \tag{3.2}$$

where σ_u is the standard deviation, given in sampled form by:

$$\sigma_u = \sqrt{\frac{1}{N_s - 1}\sum_{i=1}^{N_s}(u_i - U)} \qquad (3.3)$$

where Ns = number of samples during each interval and u_i = turbulent wind expressed as a sequence. Turbulent intensity is frequently in the range of 0.1 – 0.4. In general the highest values of turbulent intensities occur at the lowest wind speeds, but the lower limiting value at a given location will depend on the specific terrain features and surface conditions at the site.

3.3 Wind Speed and Direction Correction and Adjustment

A flow diagram (Figure 3.1) represents the steps taken in order to correct the Laucala Bay wind data. MSP site had two wind monitoring stations (a) on the roof top and (b) near the sea front. Using the site (b) data, site (a) data was corrected and a correlation graph (Figure 3.2) was obtained. This was necessary to construct a 4 year corrected wind data for the MSP site. A correlation plot (Figure 3.5) was drawn using the 5 months data from the Laucala Bay site and the corrected data for the MSP site and with the equation obtained from the plot the MSP data was further adjusted to produce a four year data for the Laucala Bay site.

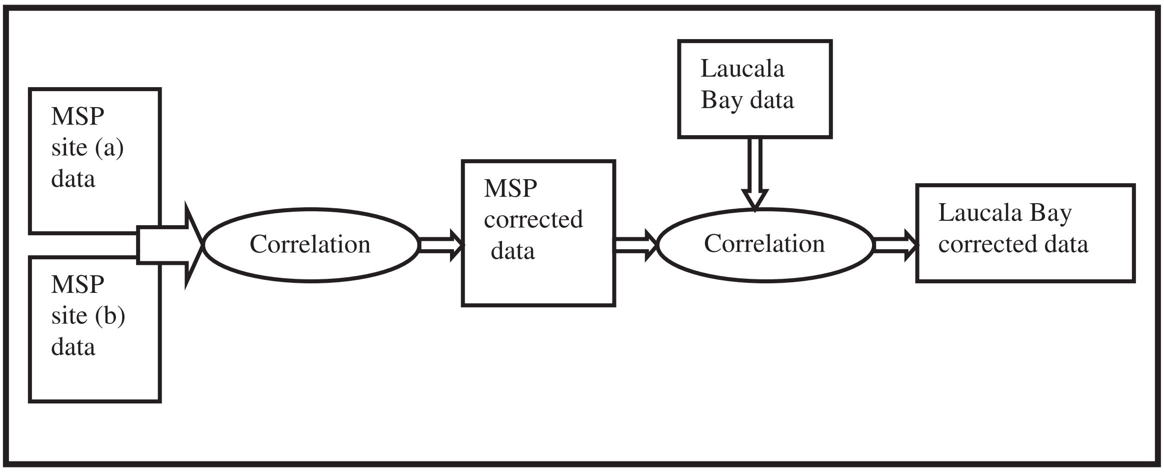


Figure 3.1 *Flow diagrams shows the steps taken to construct Laucala Bay wind data*

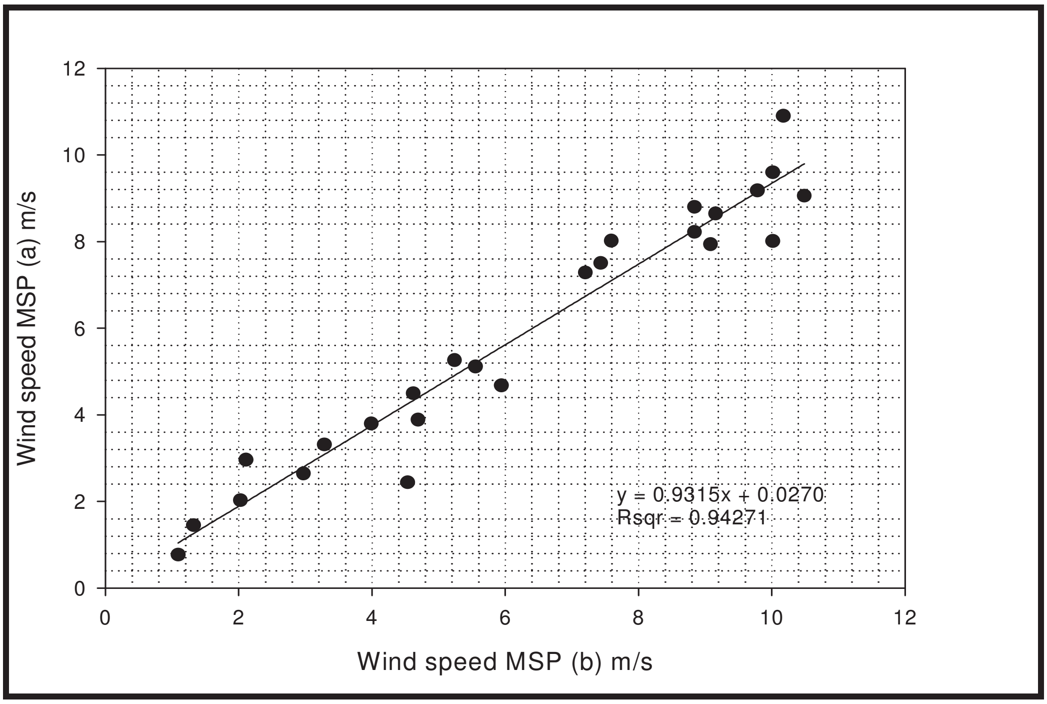


Figure 3.2 *Correlation of wind speed data at the MSP sites*

3.4 Marine Studies Programme (MSP) Site

3.4.1 Wind Structure and Statistics

At the MSP site two wind monitoring station were based. One situated next to the sea front whilst the other was placed 5 meters away on the roof top. In order to eliminate the effect of the roof the data from the roof top was correlated with the sea front data using the technique outlined in Figure 3.1. This correlated MSP data (Figure 3.2) was later used to construct a long-term data for the Laucala Bay site. The annual mean (Table 3.1) shows the annual average wind speed, turbulence intensity and wind direction for a four year period (2004-2007). A detailed monthly mean data are given in Appendix B (Table B1 and B2)

Table 3.1 *The mean annual wind characteristics at MSP site.*

	2004	**2005**	**2006**	**2007**
Mean wind speed (m/s)	4.60	4.54	4.80	4.44
Turbulence intensity	0.53	0.50	0.55	0.59
Wind direction (º)	142	139	147	145
[1]**Power density (W/m²)**	59	57	67	53

[1] Power density in this case was calculated from the formula P/A = $= \frac{1}{2}\rho u^3$

The variation of the monthly mean wind speed (Figure 3.3) at MSP site shows the period of maximum and minimum wind speed. A diurnal pattern of Julian day 147 at MSP site (Figure 3.4) shows the variation in the wind speed on the same day for each of the four years.

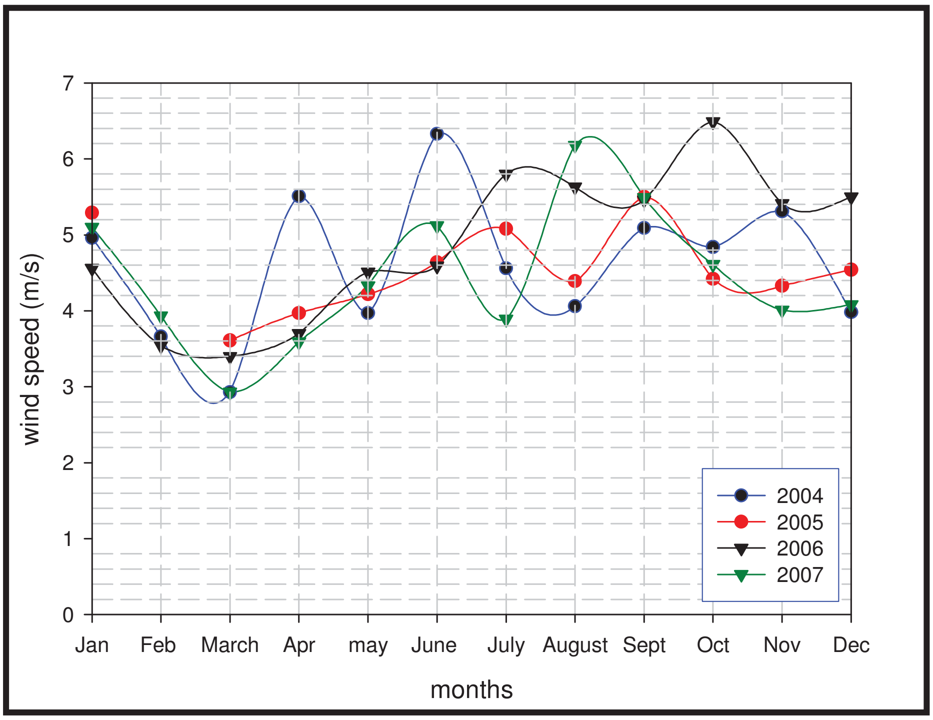


Figure 3.3 *Mean wind variation for the MSP site for past 4 years (2004-2007).*

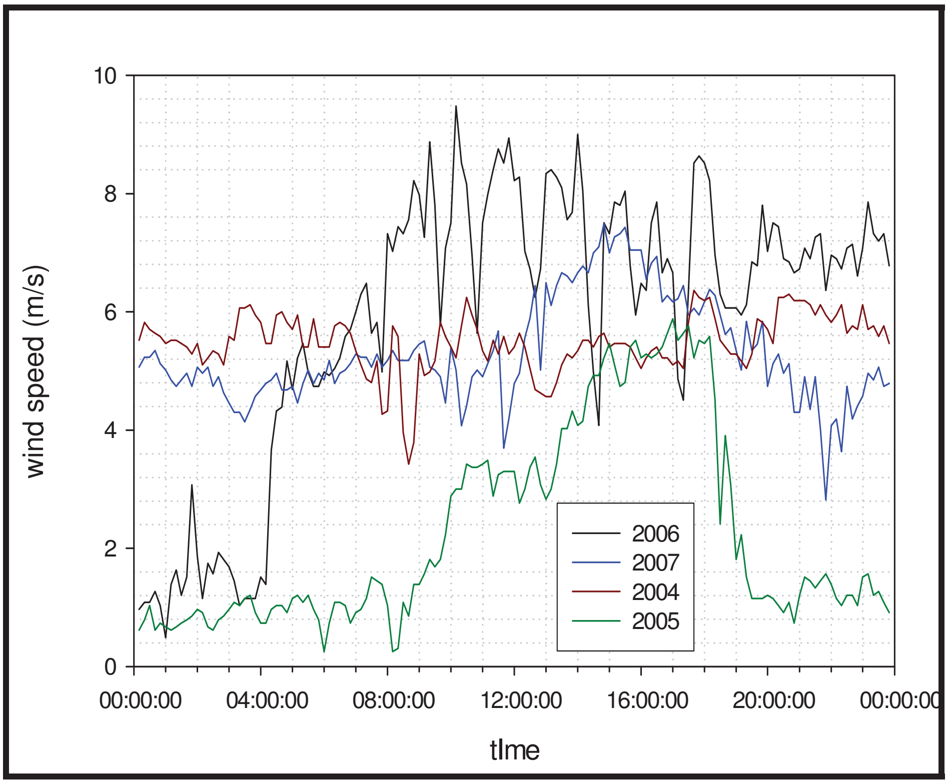


Figure 3.4 *Diurnal wind speed variation for Julian day 147 at the MSP site.*

3.5 Laucala Bay Site Analysis

3.5.1 Wind Resource Statistics

Wind speed and direction at the Laucala Bay (study site) was measured for 5 months. The simultaneous 10 minute average data for MSP site and Laucala Bay Site were correlated (Figure 3.5) to determine the relationship. A four year mean wind pattern for Laucala Bay was constructed using the coefficient derived from Figure 3.5.

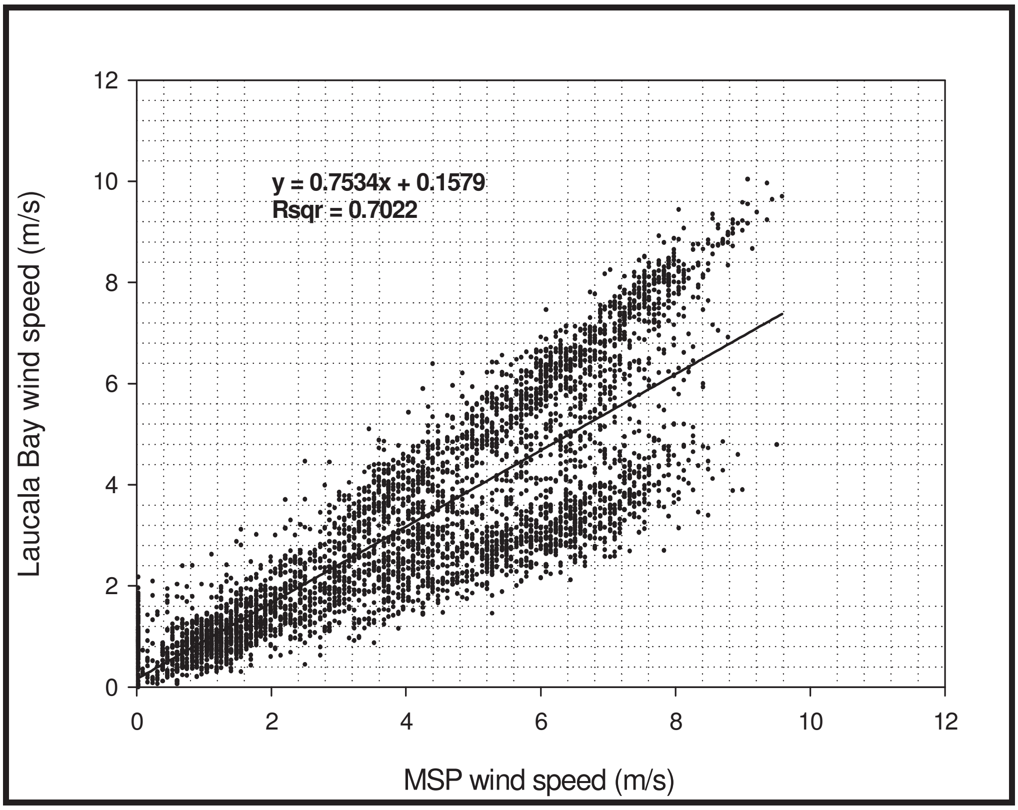


Figure 3.5 *Scatter plot for the Laucala Bay and MSP data.*

The annual mean wind speed, standard deviation and turbulence intensity (Table 3.2) were calculated for both MSP and Laucala Bay sites for the four years (2004-2007) at 15 m. The mean wind speed (Figure 3.6) shows the annual and inter-annual variation at the Laucala Bay (study site). A complete set of data is included in Appendix B (Table B3).

Table 3.2 *Annual wind characteristics at 15 m for Laucala Bay and MSP sites.*

	Laucala Bay site	**MSP site**
Mean wind speed (m/s)	3.88	4.60
Standard Deviation	2.01	2.51
Turbulence intensity	0.53	0.54

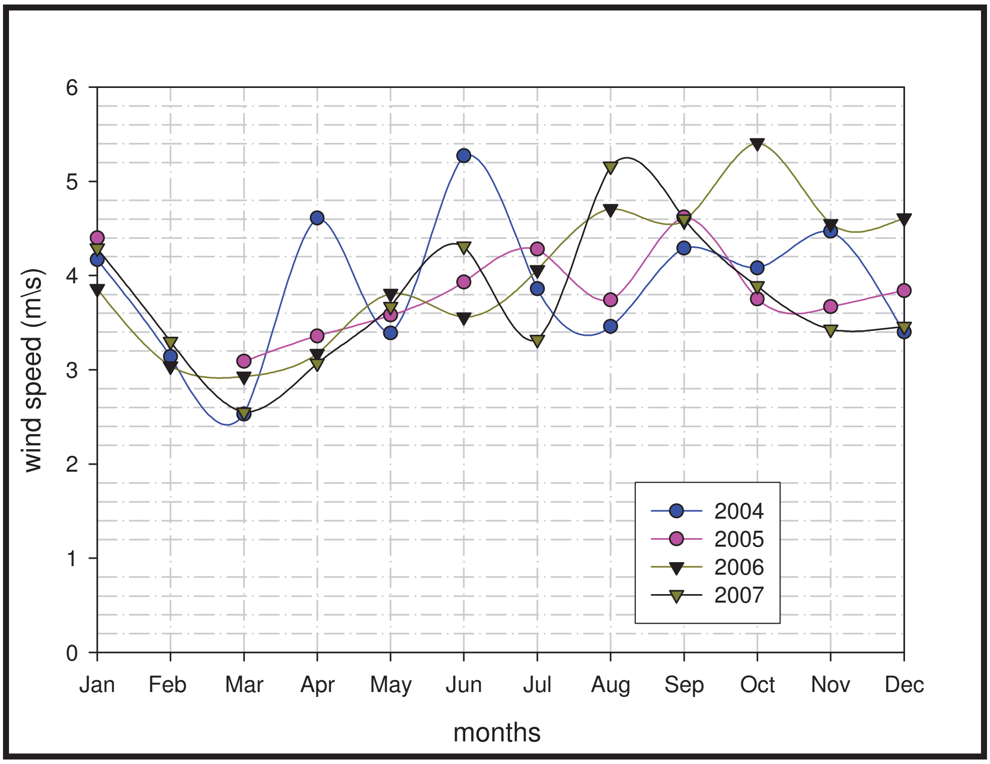


***Figure 3.6** Annual and inter-annual wind speed variation at the Laucala Bay site.*

3.5.2 Whisper 100 Turbine

The Whisper 100 turbine at Laucala Bay site was commissioned in September 2007. A continuous monitoring was carried out. In the first complete month of operation, it produced 59 kWh. The mean wind speed was 4.6 m/s during that month. It resulted in a capacity factor of 9.1 %.

3.5.3 WAsP Analysis

Several data files are required as the input to WAsP software to analyze the time-series of wind measurements to provide a statistical summary of the observed, site-specific wind climate. The wind data from the measuring sites were analyzed and converted into a regional wind climate or wind atlas data set. Data files of observed wind climate, vector map (including roughness parameter), turbine power curve, and obstacle groups are essential to WAsP predicting the wind climatology and resource grid. The construction of the above data files and their outputs are summarized in the following sections.

3.5.3.1 Observed Wind Climate

WAsP software was used to plot the wind rose and frequency distribution for the Laucala Bay site for the four years (2004-2007). OWC wizard as used to produce OWC files from the raw wind speed and direction measurements. The measurements were transformed into a table and analyzed by WAsP. It produced a time-independent summary (Figure 3.7) of the wind regime at the measuring site. It calculated the Weibull-A, Weibull-k parameters, mean wind speed and displayed the average annual wind direction.

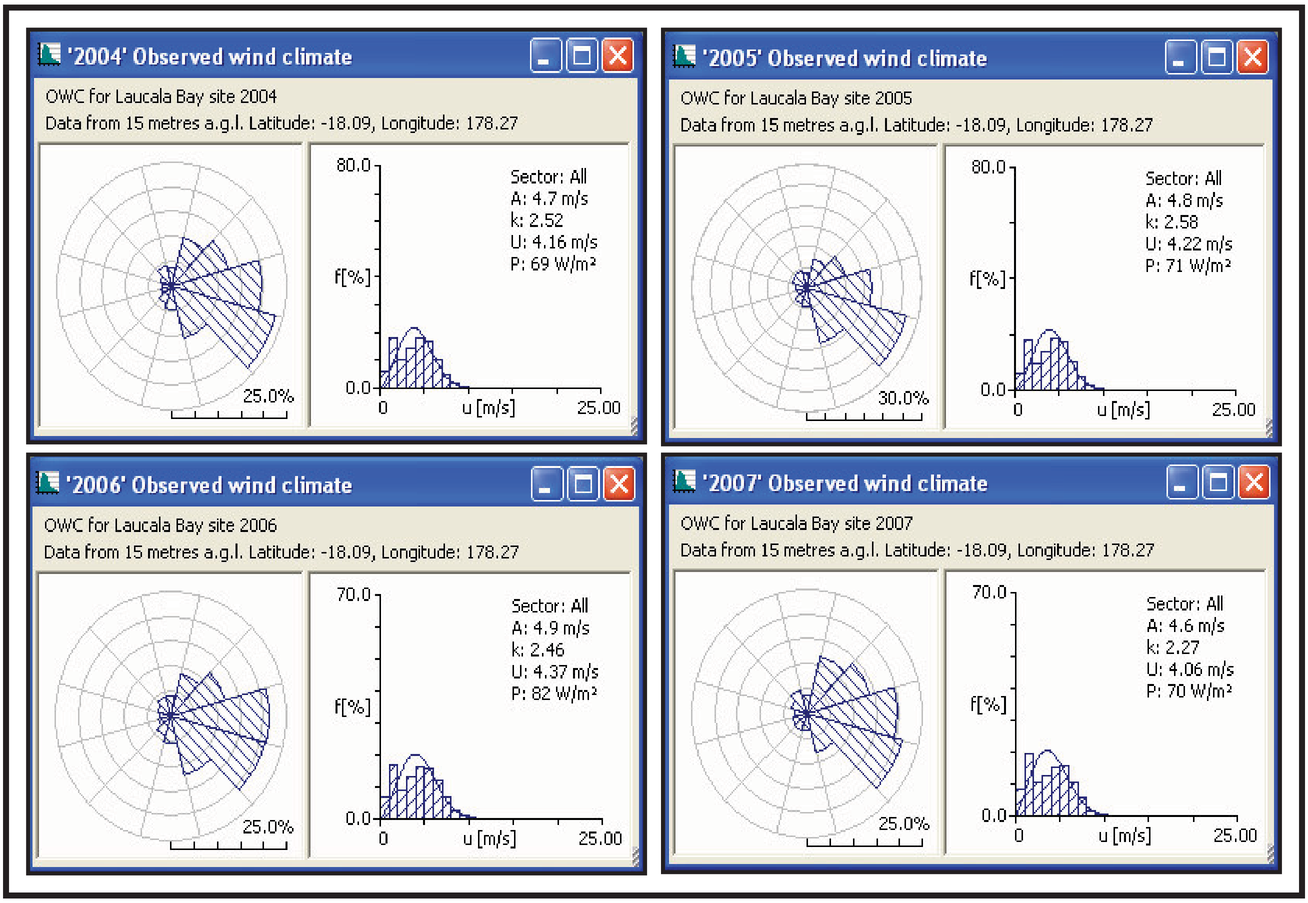


Figure 3.7 *Observed wind climate at the Laucala Bay site, (2004-2007).*

3.5.3.2 Vector Map

Vector map (Figure 3.8) used to describe the orography and the surface roughness of the surrounding area was digitized. The digitization process was carried out using the map editor version of the WAsP software. A background map for the Suva area was loaded on which the vector map was digitized. The map was digitized using the contour heights and estimated roughness values derived from European Wind Atlas. Detailed values are given in Appendix C.

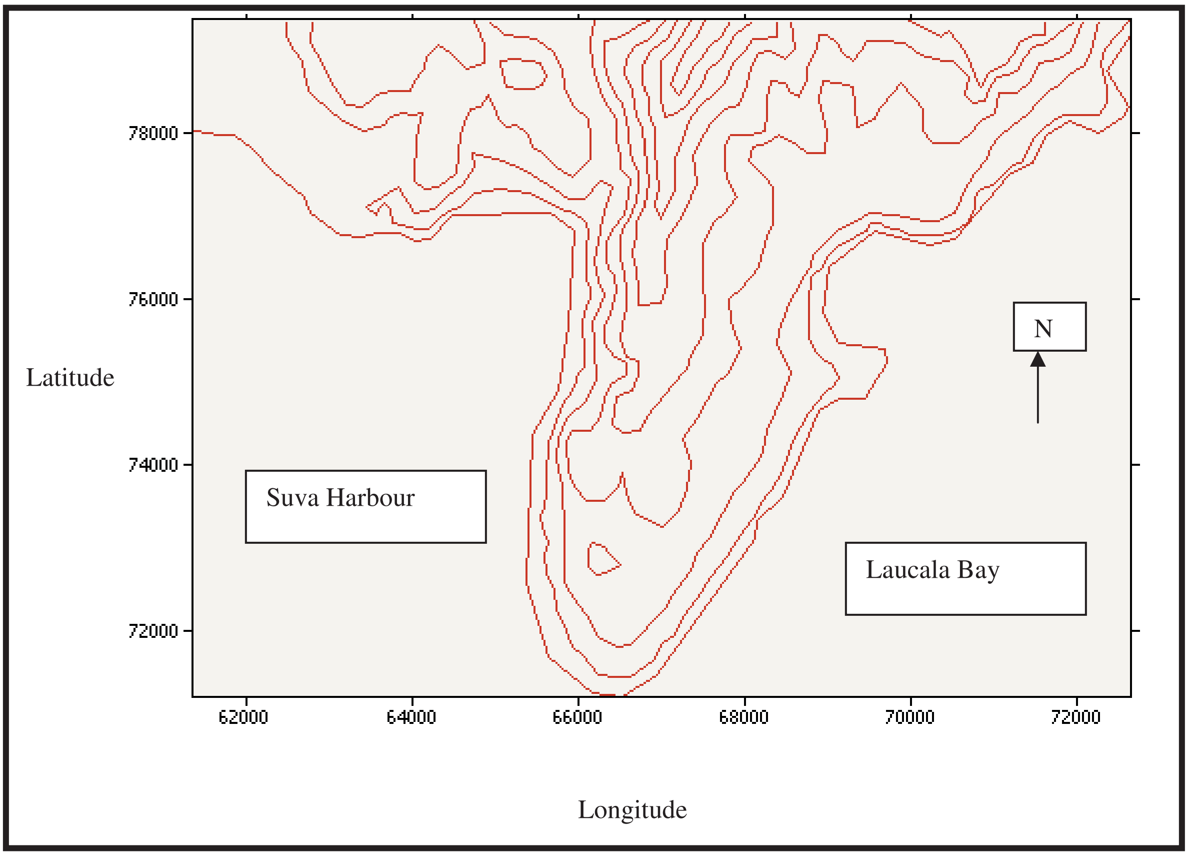


Figure 3.8 *Digitized vector map for greater Suva area. The numbers on the horizontal and vertical scale represents the easting and the northing distance in meters. The meridian of origin is 177 °E of the Greenwich and the equator is the latitude of origin. The false coordinate of origin is 500,000 m Easting and 10,000,000 m Northing.*

3.5.3.3 Turbine Power Curve

To establish the turbine power curve, WAsP turbine editor was used. A look up table containing the wind speed (m/s), power output (kW) and the thrust coefficient (C_t) with other relevant information were supplied to the editor. The workspace window (Figure 3.9) shows the information supplied to the turbine editor. The power curve was generated using the information supplied.

The power curve (Figure 3.10) with its thrust coefficient shows the power that would be produced by Whisper 100 turbine at the given wind speed.

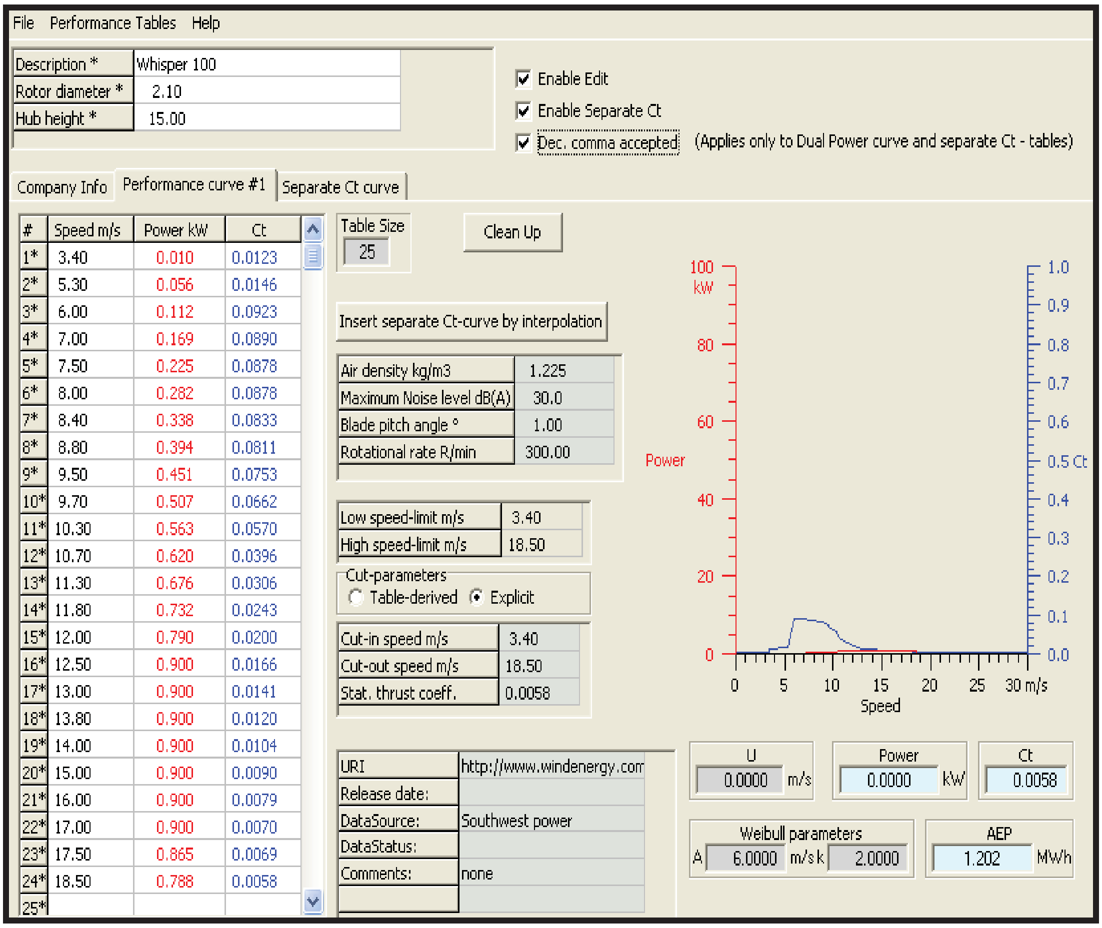
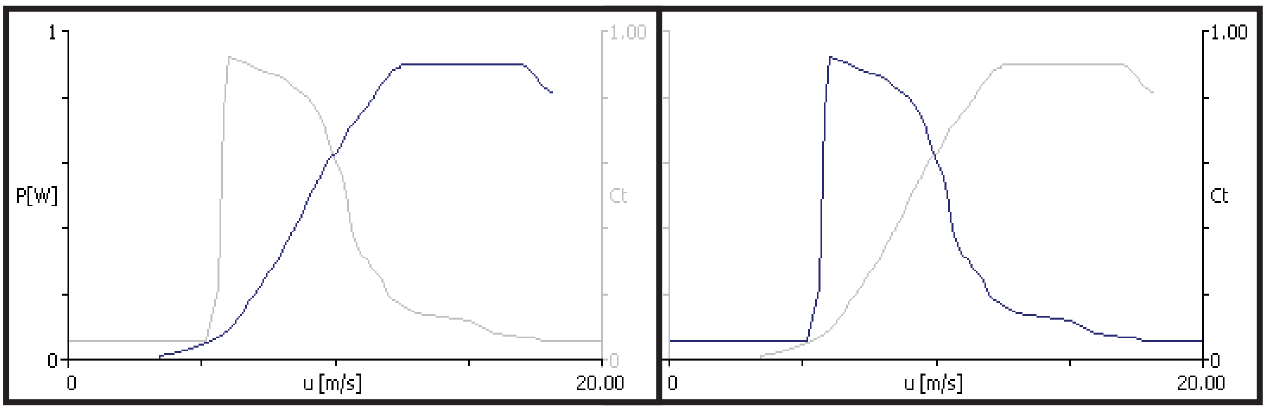


Figure 3.9 *Turbine editor window used to construct the power curve.*



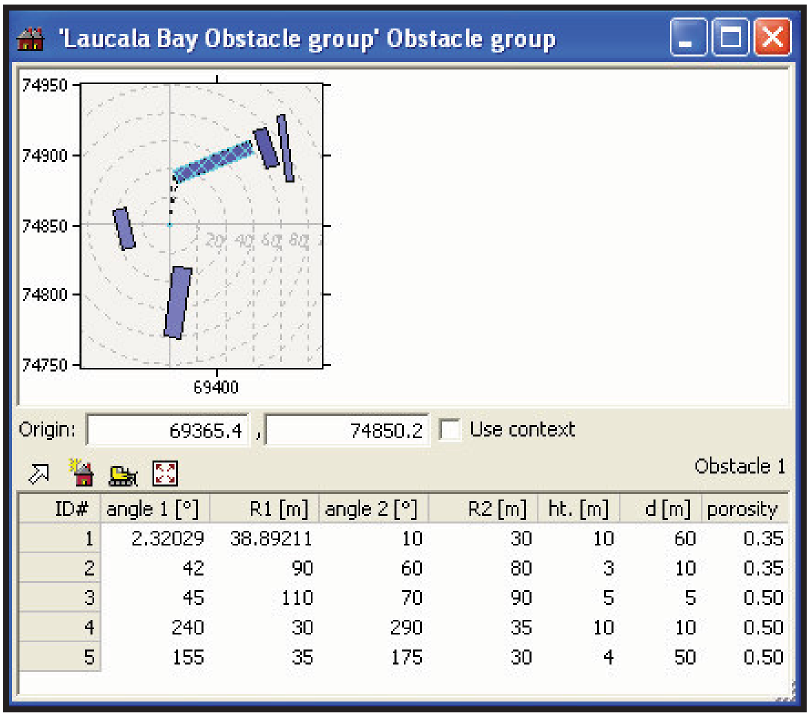
(a) Power curve

(b) Thrust coefficient curve

Figure 3.10 *The Power (a) and Thrust coefficient (b) curve for Whisper 100 wind turbine.*

3.5.3.4 Obstacle Group for the Laucala Bay site

At the Laucala Bay site, several buildings, and shelter trees were found in the vicinity of the anemometer mast. Obstacle group (Figure 3.11) was constructed by measuring, the distance from the obstacles to the anemometer, the height of the obstacle, the height of the point of interest (hub height), length of the obstacle and the porosity (the area of the windbreaks pores to its total area) of the obstacle. Mortensen et al. (2004) suggested likely values of porosity that were used for this study.



ID#	angle 1 [°]	R1 [m]	angle 2 [°]	R2 [m]	ht. [m]	d [m]	porosity
1	2.32029	38.89211	10	30	10	60	0.35
2	42	90	60	80	3	10	0.35
3	45	110	70	90	5	5	0.50
4	240	30	290	35	10	10	0.50
5	155	35	175	30	4	50	0.50

***Figure 3.11** Obstacle group for the Laucala Bay site.*

3.5.3.5 WAsP Report for the Study Area

Once all the input parameters were ready for the WAsP prediction, WAsP workspace was opened, a new project (Figure 3.12) was inserted, and the input parameters were added. Since the Whisper 100 turbine generator and the digitized map were common for the entire project it was added as the child of the project followed by the wind atlas. Next to this, the wind data (met. station) was added to the hierarchy followed by the OWC for the Laucala Bay site. The Laucala Bay obstacle group title was added to the project.

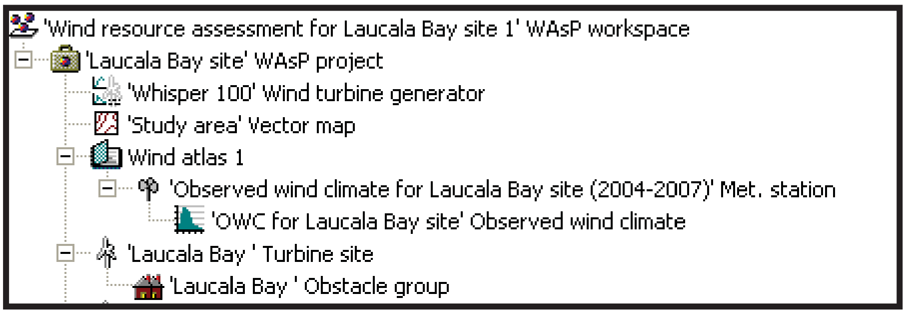
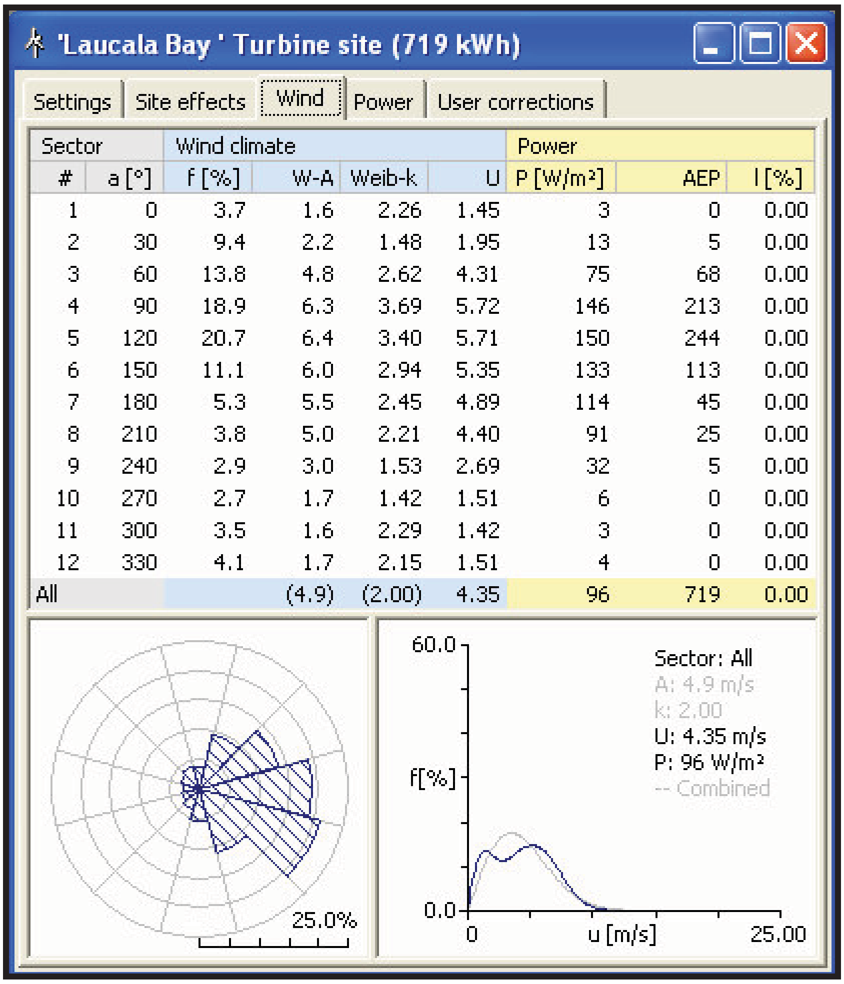


***Figure 3.12** WAsP workspace for the study site.*

Once the calculations were carried out WAsP report was generated. A detailed wind climate at the Laucala Bay site (Figure 3.13) obtained. The annual energy production (AEP) for the Laucala Bay site was calculated as 719 kWh, a power density of 96 W/m^2 and other details as shown.



Sector		Wind climate				Power		
#	a [°]	f [%]	W-A	Weib-k	U	P [W/m²]	AEP	I [%]
1	0	3.7	1.6	2.26	1.45	3	0	0.00
2	30	9.4	2.2	1.48	1.95	13	5	0.00
3	60	13.8	4.8	2.62	4.31	75	68	0.00
4	90	18.9	6.3	3.69	5.72	146	213	0.00
5	120	20.7	6.4	3.40	5.71	150	244	0.00
6	150	11.1	6.0	2.94	5.35	133	113	0.00
7	180	5.3	5.5	2.45	4.89	114	45	0.00
8	210	3.8	5.0	2.21	4.40	91	25	0.00
9	240	2.9	3.0	1.53	2.69	32	5	0.00
10	270	2.7	1.7	1.42	1.51	6	0	0.00
11	300	3.5	1.6	2.29	1.42	3	0	0.00
12	330	4.1	1.7	2.15	1.51	4	0	0.00
All			(4.9)	(2.00)	4.35	96	719	0.00

***Figure 3.13** Wind climate for the Laucala Bay site.*

The summary (Table 3.3) generated by WAsP shows the parameters of interest for the Laucala Bay site

Table 3.3 *Wind climate details of the Whisper 100 turbine at the Laucala Bay site.*

Site	Location [m]	Turbine	Height [m]	Net AEP [kWh]	Wake loss [%]	Mean wind speed (m/s)	Mean power density (W/m²)
Laucala Bay	(69365.4,74850.2)	Whisper 100	15	719	0.00	4.35	96

3.6 Nabua Site Analysis

3.6.1 Wind Resource Statistics

To validate the WAsP predictions for the Nabua site, on-site wind data measurement was carried out. The available data was for 33 months which was sufficient to validate the predictions. These data are presented in Appendix B (Table B4).

3.6.2 Regional Wind Climate for Nabua using WAsP

Just by using the OWC wizard and the measured wind data at the Nabua site, a wind climate (Figure 3.14) at the Nabua site was generated using WAsP.

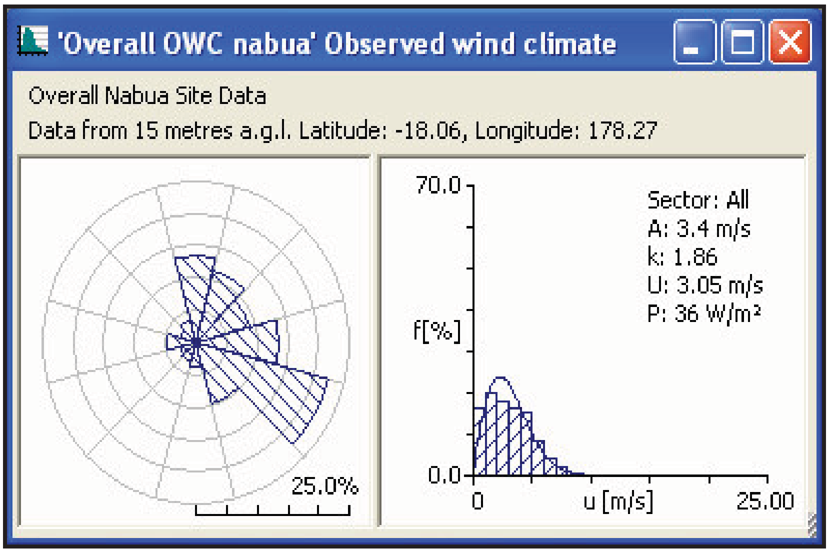
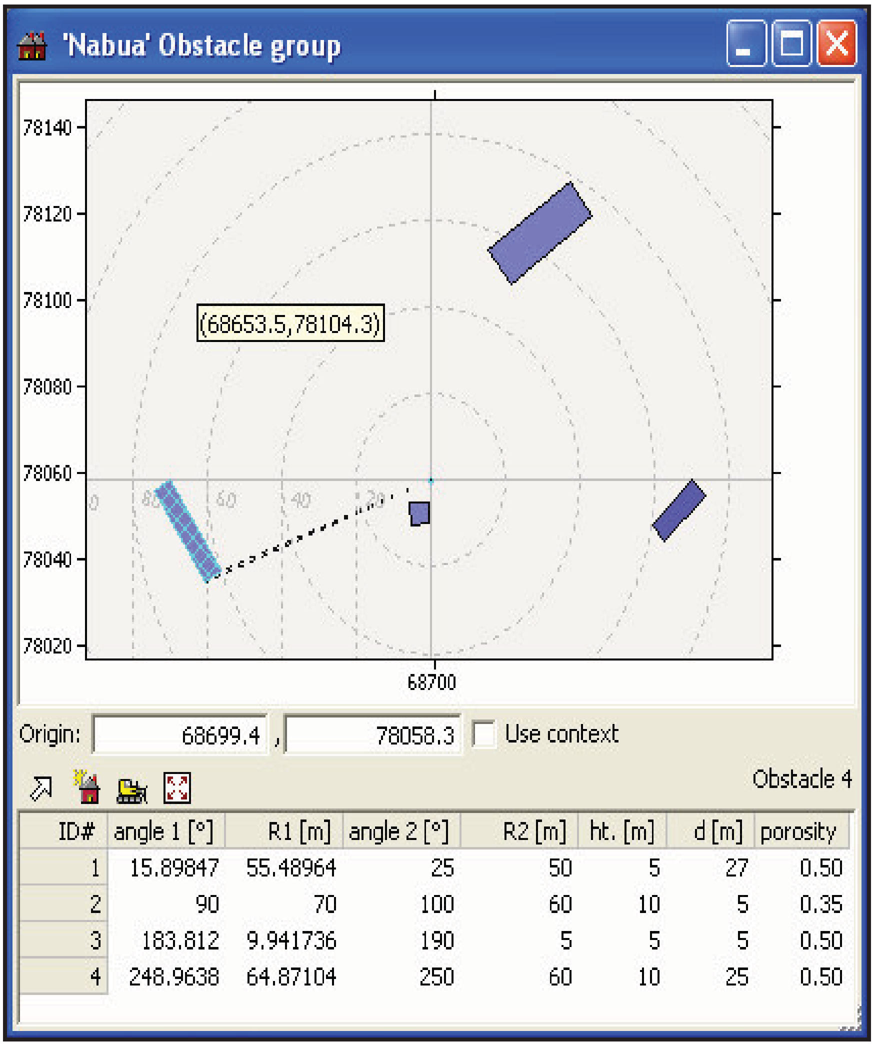


Figure 3.14 *Observed wind climate for Nabua site.*

3.6.3 Obstacle Group for the Nabua Site

Similar to Laucala Bay site, obstacle group for the Nabua site (Figure 3.15) was also created so that WAsP could predict accurate wind regime for the site.

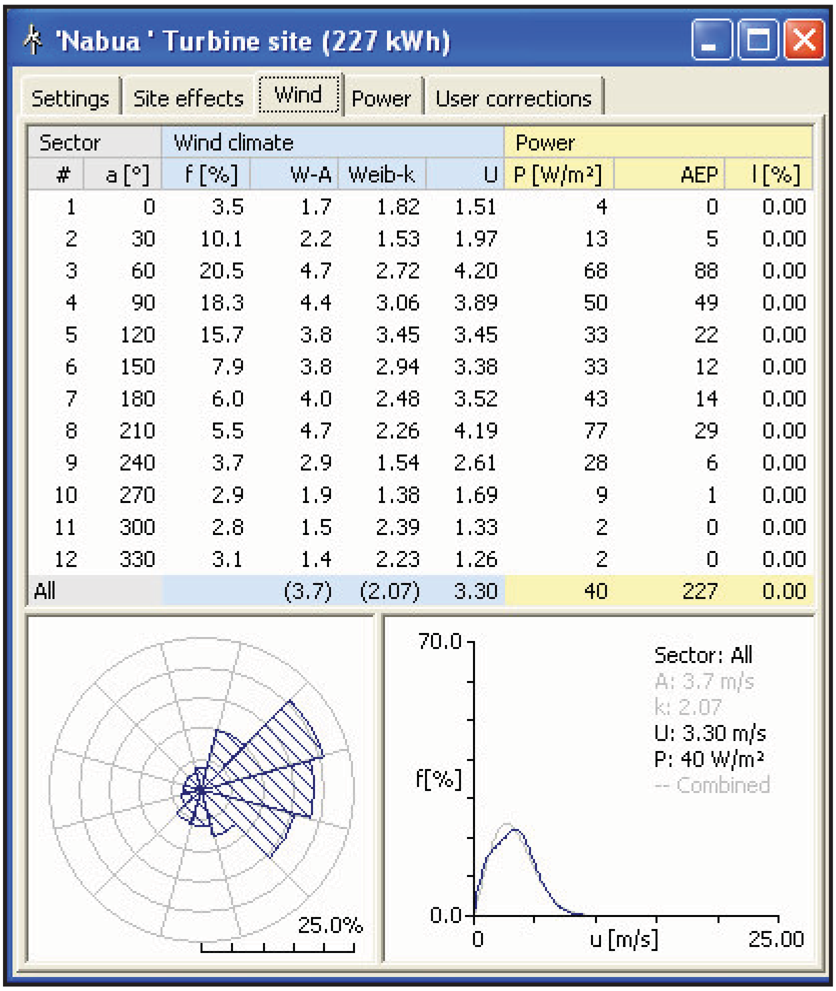


ID#	angle 1 [°]	R1 [m]	angle 2 [°]	R2 [m]	ht. [m]	d [m]	porosity
1	15.89847	55.48964	25	50	5	27	0.50
2	90	70	100	60	10	5	0.35
3	183.812	9.941736	190	5	5	5	0.50
4	248.9638	64.87104	250	60	10	25	0.50

Figure 3.15 *Obstacle group for the Nabua site.*

3.6.4 WAsP Output for the Nabua Site

In the WAsP workspace, obstacle group for the Nabua site, and Whisper 100 turbine was added to give a prediction of the possible wind regime that was present there. Following this, WAsP predicted (Figure 3.16) for the Whisper 100 turbine output at the Nabua site. The AEP for the Nabua site was calculated to be 227 kWh with a power density of 40 W/m^2. The summary (Table 3.4) shows all parameters of interest.



Sector		Wind climate				Power		
#	a [°]	f [%]	W-A	Weib-k	U	P [W/m²]	AEP	I [%]
1	0	3.5	1.7	1.82	1.51	4	0	0.00
2	30	10.1	2.2	1.53	1.97	13	5	0.00
3	60	20.5	4.7	2.72	4.20	68	88	0.00
4	90	18.3	4.4	3.06	3.89	50	49	0.00
5	120	15.7	3.8	3.45	3.45	33	22	0.00
6	150	7.9	3.8	2.94	3.38	33	12	0.00
7	180	6.0	4.0	2.48	3.52	43	14	0.00
8	210	5.5	4.7	2.26	4.19	77	29	0.00
9	240	3.7	2.9	1.54	2.61	28	6	0.00
10	270	2.9	1.9	1.38	1.69	9	1	0.00
11	300	2.8	1.5	2.39	1.33	2	0	0.00
12	330	3.1	1.4	2.23	1.26	2	0	0.00
All			(3.7)	(2.07)	3.30	40	227	0.00

Figure 3.16 *Predicted wind climate for the Nabua site.*

Table 3.4 *Wind climate details of the Whisper 100 turbine at the Nabua site.*

Site	**Location [m]**	**Turbine**	**Height [m]**	**Net AEP [kWh]**	**Wake loss [%]**	**Mean wind speed (m/s)**	**Mean power density (W/m²)**
Nabua	(68699.4,78058.3)	Whisper 100	15	227	0.00	3.30	40

3.7 WAsP Report and Resource Grid

After all the input parameters were ready WAsP was ready to predict the resource grid for the greater Suva area. Vector map, turbine generator, and obstacle groups were input into the software. The workspace (Figure 3.17) was then executed.

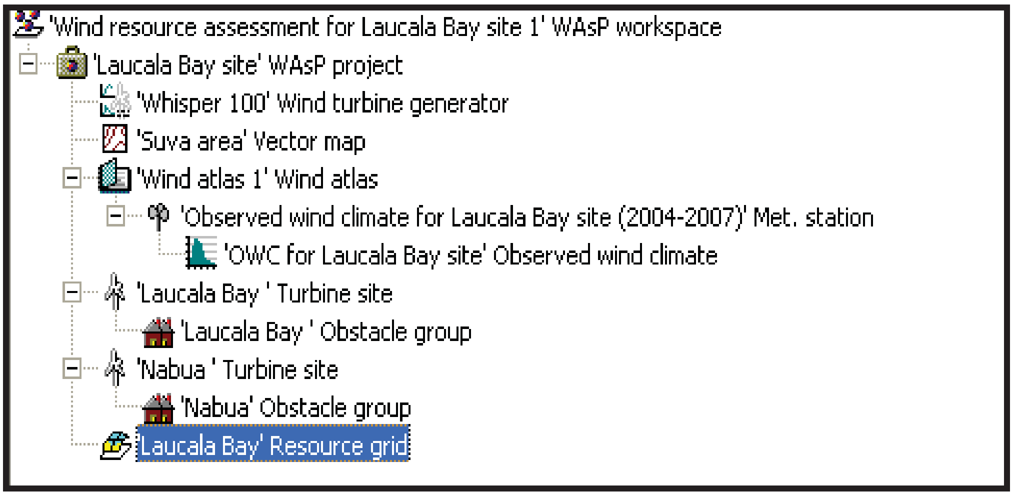
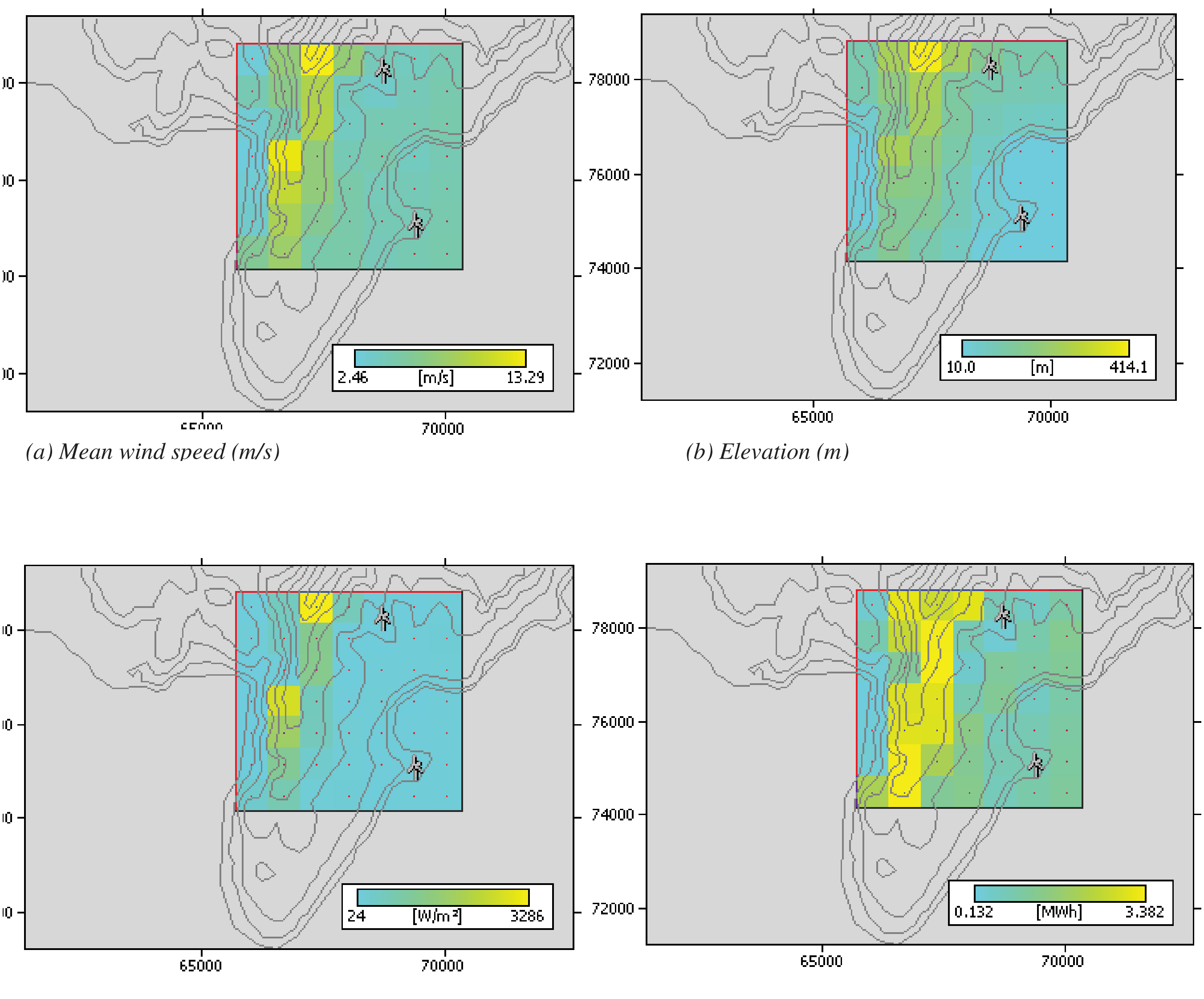


Figure 3.17 *WAsP workspace for the MSc project*

The resource grid (Figure 3.18) was analyzed for the designated grid area on the digitized map. The mean wind speed, power density, AEP, and elevation were output produced by WAsP.

The outputs on the resource grid were easily differentiated by the relative colour strength. The horizontal bar on the digitized map showed the areas of relative strengths on the resource grid.

The summary of the resource grid of the greater Suva area (Table 3.5) shows the minimum, maximum, and mean values of the mean wind speed, power density, annual energy production (AEP), and the elevation. The maximum AEP around greater Suva area is approximately 3 MWh, (area identified as Tamavua Heights) a value that could be further researched.



(a) Mean wind speed (m/s)

(b) Elevation (m)

(c) Power density (W/m^2)

(d) AEP (MWh)

Figure 3.18 *Resource grids analysis for the greater Suva area.*

Table 3.5 *Summary of the resource grid around Suva area.*

Variable	**Mean**	**Minimum**	**Maximum**
Weibull-A	6.3	2.7	14.9
Weibull-k	1.88	1.22	2.15
Mean speed (m/s)	5.60	2.46	13.29
Power density (W/m^2)	388	24	3286
AEP	1.435	0.132	3.382
Elevation	103.8	10.0	414.1

3.8 Validating WAsP Prediction

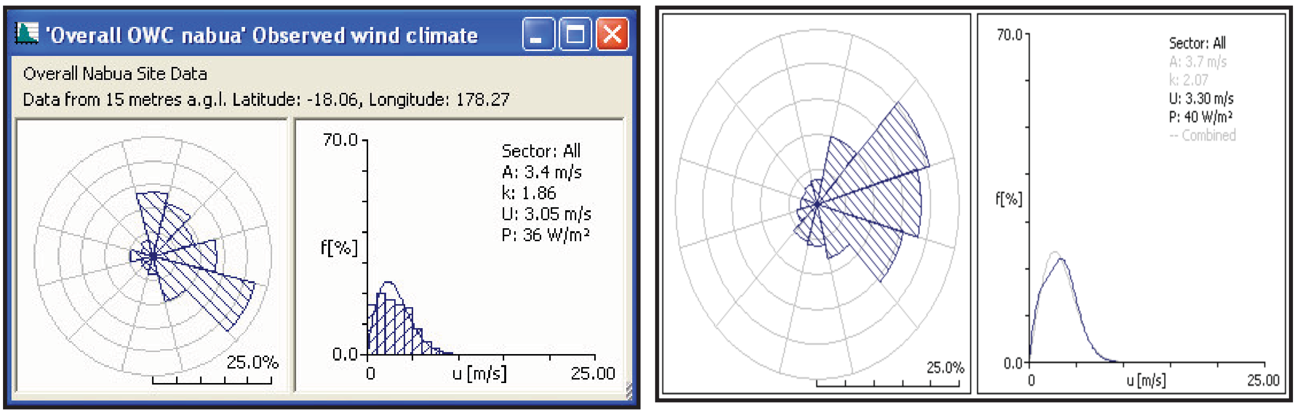
To validate the WAsP predictions, a comparison (Table 3.6) shows the values and the predicted and the empirical values for the Nabua site. The Weibull parameters of the wind statistics (mean wind speed and power density) were compared.

***Table 3.6** Comparison for wind regime predicted by WAsP with the actual measured data.*

	Measured Value	WAsP Prediction
Weibull A (m/s)	3.4	3.7
Weibull-k	1.86	2.07
Mean wind speed (m/s)	3.05	3.30
Power density (W/m^2)	36	40

AEP was not determined experimentally since it required the actual turbine to be installed at this site. However, WAsP has the capability to show the AEP for the Whisper 100 turbine at Nabua site.

It is evident from Figure 3.19 that the wind direction determined experimentally is different from that predicted by WAsP. However, it should be borne in mind that the experimental data is for only 5 months whereas WAsP makes an annual prediction.



(a) OWC from measured data *(b) OWC predicted by WAsP*

***Figure 3.19** Experimentally determined (a) and WAsP predicted (b) OWC at Nabua site.*

3.9 Relative Economic Benefits

It is crucially important to carry out an economic analysis of a project to determine its practicality before deploying funds. The long term benefit of the project output should be clearly established to determine its viability. To generate electricity using Whisper 100 turbine is a viable alternative to diesel power only if it is cost effective. The economic viability of a small wind power system depends to a large extent on the generating costs and the associated market value of wind energy (Manwell et al., 2004). Capital cost, financial cost, operating and maintenance costs, turbine availability, energy efficiency, life time of turbine, and site wind regime constitute the total generating costs.

3.9.1 Generating Cost Assessment

3.9.1.1 Availability

The availability of a turbine is the fraction of the time of the year that it is able to generate electricity. The unavailability times include shutdown time for periodic maintenance as well as unscheduled repairs. Availability figures are obtained from data on similar turbines in operation for many years. World energy council quotes availability of wind turbines in the 80's as 95 %. Manwell et al. (2004) stated that availability as high as 98 % has been achieved in recent times.

3.9.1.2 Lifetime of the System

Lifetime of the wind turbine system varies, but usually manufacturers estimate design lifetime of turbines used in economic assessment as the lifetime of the system. Danish Wind Industry Association's (2008) suggests a 20 year design lifetime as a useful economic compromise adopted by many as a guide for developers of components for wind turbines. However, American developers tend to use a 30 year design lifetime. In this work, a lifetime of 20 years was assumed for the Whisper 100 turbine.

3.9.1.3 Capital Cost

These are the costs expected (or total investment) before the beginning of operations. They include the cost of the wind turbine(s), and the cost of the remaining installations. Generally, wind turbine installed costs are normalized to cost per unit of rotor area or cost per rated kW.

3.9.1.4 Operation and Maintenance Costs

From time to time, regular maintenance operations have to be carried out to ensure the wind turbine systems are in good working condition and operating at the required level. In the early years the costs were between 1.5 % and 3 % of the turbine cost but increased with time as the turbines get older. A 'block' approach (Table 3.7) for operation and maintenance cost estimation has been used in this study.

Table 3.7 *Block approach for operation and maintenance cost of whisper 100 turbine*

Block	Years	Operation and Maintenance cost
1	1	2 % of the total turbine cost
2	2-5	2 % of the turbine cost + 1 % of the O & M cost for the previous year
3	6-10	2 % of the turbine cost + 2 % of the O & M cost for the previous year
4	11-15	2 % of the turbine cost + 3 % of the O & M cost for the previous year
5	16-20	2 % of the turbine cost + 4 % of the O & M cost for the previous year

3.9.1.5 Total Expenditure

Economic Appraisal Spreadsheet Model (Table 3.8) gives a detailed breakdown of the annual expenditure of the Whisper 100 turbine at Laucala Bay site. These values were used to calculate the total lifetime expenditure.

Table 3.8 *Economic evaluation of Whisper 100 turbine at the Laucala Bay site*

Year	Annual kWh generated	Operation and Maintenance Expense
1	719	200
2	719	202
3	719	202
4	719	202
5	719	202
6	719	204
7	719	204
8	719	204
9	719	204
10	719	204
11	719	206
12	719	206
13	719	206
14	719	206
15	719	206
16	719	208
17	719	208
18	719	208
19	719	208
20	719	208
Total		**$ 4098**

The initial capital cost for the Whisper 100 turbine including installation and labour was $FJ10, 000.

Therefore the total lifetime expenditure = Σ (annual O & M expenses + Capital cost)

= $FJ 4098 + $FJ 10,000

= $FJ 14,098

3.9.1.6 Cost of Energy from the Turbine

The total lifetime expenditure for the Whisper 100 turbine was calculated to be $FJ 14,098. The cost of energy/kWh for the Whisper 100 turbine at the Laucala Bay site is calculated as follows

$$\textit{Cost of Energy/kWh} = \frac{\textit{Total Lifetime Costs}}{\textit{Design Life of System x Annual Energy Output}} \tag{3.4}$$

$$\textit{Cost of Energy/kWh} = \frac{14{,}098}{20\ x\ 719}$$

= $0.98 /kWh.

Based on equation (3.4), the cost of energy produced (Table 3.9) was calculated for the Whisper 100 turbine if it was placed at the Nabua site, the mean AEP production site, and also on a site with maximum AEP.

Table 3.9 *Expected cost of energy produced by Whisper 100 turbine within the resource grid*

	Laucala Bay site	Nabua Site	Mean AEP site	Maximum AEP Site
AEP production (kWh)	719	213	1435	3382
Cost of Energy ($FJ /kWh)	0.98	3.31	0.49	0.21

3.9.1.6 Simple Payback Period Analysis

A payback calculation compares revenue with costs and determines the length of time required to recoup an initial investment. In its simplest form (simple payback (*SP*) period), it is expressed in equation form as:

$$SP = \frac{Total\,lifetime\,\cos t}{Cost\ of\ energy / kWh\ x\,Annual\ energy\ production} \tag{3.5}$$

In Fiji, the current electricity generation cost stands at $FJ 0.23/kWh. Hence, the simple payback period for Whisper 100 turbine at the Laucala Bay site is calculated as:

$$\text{SP} = \frac{14{,}098}{0.23 / kWh\ x\,719} = \mathbf{85\ years}$$

Based on the equation (3.5), the simple payback period (Table 3.10) was calculated for the Whisper 100 turbine if it was placed at the Nabua site, the mean AEP site, and also on a site, with maximum AEP.

Table 3.10 *Simple payback period for the Whisper 100 turbine at various sites within the resource grid generated by WAsP.*

	Laucala Bay site	**Nabua Site**	**Mean AEP site**	**Maximum AEP Site**
Simple payback period (yrs)	85	288	43	18

Chapter 4 Discussion

4.1 Overview

This chapter discusses the results obtained from the analysis carried out and presented in the previous chapter. It begins with a discussion of the wind resource data obtained at the MSP, Laucala Bay and Nabua site followed by the predictions made by WAsP and its validation with the actual measured data.

4.2 Wind Resource Data

Commercial wind power developers typically measure actual wind resource in order to determine the distribution of wind speeds for a complete year. However, because of time constraints, short time duration was used for this study. Since data dating back to 2004 were available for a nearby site, five months data collected at the experimental site was considered sufficient for the analysis and appraisal.

The amount of power that can be generated by a turbine depends to a large extent on the average wind speed at the proposed site. Because power output is proportional to the cube of the wind speed, any small change in wind speed affects the power output significantly. For this reason, it is important to measure the wind speed on any proposed site to facilitate a better estimation of how much power can be harnessed.

Where it is not practical for reasons such as cost or time constraint wind speed data from nearby meteorological stations are used. In this study data gathered were extrapolated to the proposed hub height of 15 m. Agbeko (2005) has successfully used this technique in his study towards Master of Science at Strathclyde University.

4.3 Marine Studies Programme (MSP) Site

As mentioned above, due to the limited time for this research, it was essential for the wind data from a nearby site to be corrected and utilized. Therefore, the MSP site was the original site at which the real time data monitoring was done. This data was later corrected to estimate the Laucala Bay data using the technique in Figure 3.1.

Four years of wind data was analyzed to see the wind regime at the MSP site. The mean wind speed, turbulence intensity, and wind direction were key interest features at this site. Rehman et al. (2005) stated that the annual mean wind speed provide basic information about the wind strength and consequently about the availability of wind power. The mean wind variation for the MSP site (Figure 3.3) was generally between 3 and 5 m/s over a period of 4 years. Higher values of wind speed occurred during the month from June to October. The annual mean wind speed values showed a cyclic pattern. For the same months, the wind speed was highest in 2004, while in 2005 it decreased and, peaked in 2006, and finally decreased in 2007. This inter-annual variation is difficult to model with 4 years data. Merzouk (2000) stated that, a larger period (≈ 10 years) data is required to make an accurate prediction.

The annual mean wind power density and annual mean wind speed (Table 3.1) shows a similar variation trend. This is because the annual mean wind power density is a product of air density and mean wind speed. The lowest value of 57 W/m^2 in 2005 corresponds to the lowest wind speed in the same year and the highest value of 67 W/m^2 in 2006 corresponds to the highest wind speed in that year. Manwell et al. (2004) stated that a power density < 100 W/m^2 is considered a poor candidate for a wind generation site, however it should be borne in mind that these data are for a height of 15 m whilst for most potential wind turbine site wind speed data at 50 m are normally considered. For this study, it was not necessary to calculate the power density at 50 m because these data were used for correction purposes only. However, an estimate wind pattern at 50 m showed a power density of 164 W/m^2. For similar height, of 15 m Merzouk (2000) reported that the power density in between 37 W/m^2 and 161 W/m^2 were possible. Other study by Akpinar and Akpinar (2006) affirmed values between 7 W/m^2 and 520 W/m^2 for all the regions (Maden, Agin, Elazig, and Keban) in Turkey.

Turbulence, the measure of turbulence intensity (*TI*), is the ratio of the standard deviation of the wind speed to the mean. For the MSP site it was between of 0.50 and 0.60. In general, the highest value of the turbulence intensities occurred at the lowest wind speeds. The lower limiting value at a given location depends on the specific terrain features and surface conditions at the site. Manwell et al. (2004) stated that turbulence intensity is frequently in the range of 0.1 and 0.4. For the MSP site higher values of turbulence intensities implies that the site is subjected to lower mean wind speed values. A study on the reduced mean wind speed and increased turbulence intensity downwind of large wind farms was reported by Christiansen and Hasager, (2005). In addition, (Petersen, et al., 1997) stated for complex terrain *TI* is generally 0.2 or more.

The diurnal variation for the Julian day 147 was investigated. This day was randomly chosen from the data set. It showed that during the morning the wind speed is lower compared to the wind speed in the evening because air near the land surface is heated by radiation and conduction, being lighter than the surrounding air, it expands and begins to rise To replace the rising air, cooler air is drawn in from the surface of the sea in the evening.

4.3 Laucala Bay Site

The Laucala Bay site was the experimental site and as mentioned in earlier chapters it had all the necessary wind monitoring equipment together with a Whisper 100 turbine. Once the MSP data was correlated with the Laucala Bay site data, a four year corrected data were built for the Laucala Bay site. The analyses were based on these data. As in the case of the MSP site, similar statistical analysis were carried out for this site and an annual and inter-annual wind speed variation graphs were plotted. It showed a similar trend in wind speed variation as that of the MSP site however, there was a reduced mean wind speed and it can be explained by noting that Laucala Bay site had obstacles such as buildings and trees which reduced the wind speed. Generally the mean wind speed at the Laucala Bay site varied from 2.5 - 4.5 m/s compared to that of the MSP site where the mean wind speed varied from 3 - 5 m/s because the latter had very few obstacles around the wind monitoring station.

4.3.1 WAsP Analysis

The hub height of the Whisper 100 turbine at the Laucala Bay site (experimental site) was 15 m and hence the MSP data were extrapolated to this height before it was analyzed by WAsP. Initially the OWC for four years were plotted which illustrated the wind rose and the frequency distribution for each year.

The mean wind speed was 4 m/s in all the four years, hence it can be stated that the Whisper 100 turbine would generate electricity as it has a cut-in wind speed of 3.4 m/s. However, the amount of power it would produce depends on the direction of the wind above 3.4 m/s (cut - in speed). The power density is less than 100 W/m^2 hence the Laucala Bay site is also a poor site for a wind turbine at a hub height of 15 m. However, at 50 m, the power density is 97 W/m^2 indicates that this site may be considered for wind power generation.

4.3.2 Vector Map

The essential part of WAsP analysis is the vector map that was digitized for the study area. Appropriate roughness values (Troen & Petersen 1989) derived roughness values, (Appendix C), were used in the digitization process. WAsP based its analysis on the digitized map supplied. The topographical terrain description used by the WAsP was contained in the digitized map.

Depending on the map projection, the units of the coordinates were chosen in meters. Two basic line types were used in WAsP map file and there were height (elevation) contour lines with the height above the sea level and roughness lines. The height contour lines represented the iso-heights on the map and optionally contained roughness information about the area of study. The roughness lines or more correctly roughness change lines denoted the boundaries between two roughness areas the Laucala Bay and the Mead Road urban area (Nabua Site).

Before the map was finalized a number of roughness conditions were met in order to have a consistent roughness description. The lines were checked for the cross points, they ended in a closed loop or end at a star-point (node) or ended at the map boundary to ensure that all roughness-lines facing the same coherent area had identical roughness lengths.

4.3.3 Turbine Editor

This facility of WAsP was used to develop the power curve and the thrust coefficient curve for the Whisper 100 turbine.

4.3.4 Obstacle Groups

The wind speed is often affected by the obstacles (buildings, trees) that are present near the monitoring site. At the Laucala Bay site, a number of buildings (Figure 3.11) were present together that obstructed the free flow in wind. These obstacles reduce the wind speed and were evident from the results obtained at the MSP site. The mean wind speed at MSP site was 4.60 m/s compared to the Laucala Bay site where the mean wind speed was 3.88 m/s at 15 m.

4.3.5 WAsP Analysis

The OWC, digitized map, and the obstacle groups were utilized by the WAsP software to determine the wind regime available at the Laucala Bay site. Considering the obstacle groups, the OWC, and the roughness of the area, Whisper 100 turbine would produce 719 kWh of energy per year. The site had mean power density of 96 W/m^2 and a mean wind speed of 4.35 m/s compared to the cut-in wind speed of 3.4 m/s. Generally, the Laucala Bay site is a potential site for a wind turbine. However, a hub height more than 15 m would give an acceptable annual energy value and thus, cheaper unit price. There was no wake loss since Whisper 100 turbine was the only turbine at the site.

4.4 Nabua site

To validate how well WAsP makes its prediction for the Nabua site, real time monitoring and statistical analysis were carried out. The OWC wizard used on the raw data at the Nabua site produced the wind rose and frequency distribution plots. These plots (Figure 3.16) supported the view that Nabua site is a poor site for a wind turbine or a wind farm since the mean wind speed is between 2.5 and 3 m/s. The annual power density of approximately 30 W/m^2 further reveals that Nabua is not a potential site for any wind power generation. Despite the site being at an elevation of 110 m above sea level (a.s.l) it is subjected to numerous obstacles groups and is located in a densely populated area with high roughness values contributing to its reduced and turbulent wind flows.

4.4.1 WAsP Analysis

The obstacle groups and roughness parameters for the Nabua site were used by WAsP to predict the wind regime at the Nabua site. The predictions were based using a Whisper 100 turbine generator. The WAsP report showed that Whisper 100 turbine would produce 227 kWh annually. It determined a power density of 40 W/m^2 and the mean wind of 3.30 m/s. This confirms that Nabua site is a poor wind turbine site. For a potential site the mean wind speed of 7.5 m/s is recommended to give a power density greater than 300 W/m^2 (Sahin, 2004).

4.5 WAsP Report and Resource Grid for the Study Area

Based on the OWC, digitized map (roughness parameters), obstacle groups, and the turbine generator WAsP produced a resource grid for the area of interest. Using different colour scales it showed varying wind speed, elevation, power density and the AEP for the region of interest. The grid showed that the mean wind speed for the greater area varied from 2.4 to 13.3 m/s. Areas with high elevation and low roughness values had higher wind speed contributing to higher power density that varied from 24 to 3286 W/m^2 whilst AEP for the selected area varied from 0.132 to 3.382 MWh annually. The maximum wind speed recorded for the grid area was 13.3 m/s, with a power density of 3286 W/m^2, and a maximum AEP of 3.382 MWh. This site was identified as Tamavua Heights. The mean wind speed for the grid area was 5.60 m/s, with a power density of 388 W/m^2, and a mean AEP of 1.435 MWh. Considering the resource grid the selected area has the potential for wind turbine site depending on the location at which the turbine is to be placed. Particularly, sites with higher elevation and fewer obstacles show promise for a turbine site. However, Suva being an urban area, it is difficult to put a wind turbine because of unavailability of suitable land and other siting and environmental concerns.

4.6 Validating WAsP Prediction

The central aim of the study was to assess the wind resources around Laucala Bay area however, it was not practical to measure at all potential locations because of instrument constraints. WAsP has been successfully used by Bowen & Mortensen 1996; 2004; Jimenez et al., 2006; Rathmann et al., 1996 to predict the wind regime in regions of difficult access and other constraints. In this study WAsP was used to predict the wind regime at Nabua based on the Laucala Bay site measurements. This prediction was based on the wind speed and direction data monitored at the Laucala Bay site and a digitized map for greater Suva area.

Comparison for wind regime predicted by WAsP with the actual measured data (Table 3.6) shows that WAsP prediction are slightly higher than those with the actual measured values at the site. It is important that a statistical analysis was carried out to determine whether the two mean wind speeds are significantly different. The difference between the two mean wind speeds at $\alpha = 0.10$ % reveals that the two means are not same. Therefore, the mean speed predicted by WAsP is greater than that experimentally determined. Rathmann et al. (1996) stated that in Northern Portugal WAsP over-predicted rugged sites when flat reference site were used. Similarly Nabua site was typically a rugged site whilst the reference site (Laucala Bay site) was a flat site. Hence, WAsPs' over prediction of mean wind speed at Nabua is consistent with Rathmann's study. At the reference site the prevailing wind blows persistently off the sea from the Southeast.

4.6.1 Accumulation of Prediction Errors

Accurately predicting wind at a meteorological site in spite of the availability of past data is difficult. However, it is even more difficult to predict with certainty elsewhere where no previous data is available. WAsP attempts to make such predictions. However, as we would expect there will be errors associated with its predictions.

Bowen and Mortensen (2004) suggested that the tendency for over-prediction by WAsP of rugged sites should hold equally well for the analysis and application procedures. Thus, for the application procedure,

$$U_A + (\Delta U_2 + E_2) = U_{pe} \tag{4.1}$$

Where U_{pe} are the mean wind speeds at the predicted site (Nabua Site) using measured U_{Rm} data at the reference site, (Laucala Bay Site), whilst ΔU_2 with its associated error, E_2 speed-up correction. Analysing the measured data, U_{Rm}, at the reference site to create the corrected speed in the Atlas file, U_A, a further accurate speed-up correction, ΔU_1, with its associated error, E_1, is involved. This Analysis procedure involves the orographic model in the opposite sense such that,

$$U_{Rm} - (\Delta U_1 + E_1) = U_A \tag{4.2}$$

Combining) equations (4.1) and (4.2) to eliminate U_A,

$$(U_{Rm} - \Delta U_1 + \Delta U_2) + (E_2 - E_1) = U_{pe} \tag{4.3}$$

The estimated speed at the predicted site, U_{Pe}, is made up of the correct (measured) speed, U_{Pm}, and the overall prediction error, which has accumulated from the two stages of the prediction process. The correct estimation at the predicted site is assumed to involve no errors and is made up of the following,

$$\begin{aligned} U_{Pm} &= U_{Rm} - \Delta U_1 + \Delta U_2 \\ \therefore U_{Pe} &= U_{Pm} + (E_2 - E_1) \end{aligned} \tag{4.4}$$

The overall prediction error in the WAsP prediction process is therefore (E_2 - E_1).
U_{Pe}, = 3.7 m/s whilst U_{Rm} = 3.4 m/s therefore the error (E_2 - E_1) for WAsP in this project is 0.3 m/s or 9 %. Further to this an error of 11 % was associated with the power density predication by WAsP. In Rathmann et al., (1996) study, the error associated with the mean wind speed and mean wind power density was between 5 to 20 % and 2 to 17 % respectively.

Maunsell et al. (2004) proposed that a one-year measurement campaign is sufficient to predict the long-term average wind speed to within 10 %, at a 90 % level of confidence, suggesting that the WAsP predicted wind speed might be inaccurate. However, it has its well-recognized limitations: the more complicated the situation is with respect to topography, climatology, or both, the more uncertain are the results from the calculations. Many of the procedures that constitute the method are strictly applicable only under an idealized and limited range of conditions. The most severe problems encountered are in mountainous terrain where large-scale effects render the model increasingly deficient because of the importance of dynamics which is at present not accounted for in the model (Petersen et al., 1997).

Several factors may have caused these errors of WAsP over-predicting the values. The two sites lay in the same wind regime hence errors associated with atmosphere may be neglected however error due to local strongly stable stratification, inversion layers, sea breeze or density driven flows may have caused the over-prediction at the Nabua site. Although the two sites lay in the same weather regime, but the prevailing atmospheric conditions were not stable.

Beside climate, the most significant category that may have affected the WAsP prediction was that associated with the terrain of both the Laucala Bay site and Nabua site. These errors could be influenced by individual site ruggedness, extensive flow separation, topographical features, and site elevation (Nabua site had an elevation of 110 m above the sea level). An important issue of the sensitivity of WAsP to map size has been addressed by Landberg and Mortensen (1993), who recommended a minimum area of atleast 6 by 6 km^2 depending on site complexity. In this study, an area of 4 x 5 km^2 was investigated on.

Differences between the complexity of the terrain at the reference and candidate sites can be a significant source of prediction error. A measure of the orographic complexity of terrain is the Ruggedness Index (RIX), described in detail by Bowen and Mortensen (1996). RIX describes the percentage of terrain with a slope greater than 0.3 and is thereby a coarse measure of the propensity for flow separation. A non-zero RIX is indicative of flow separation, a situation outside the performance envelope of WAsP. Differences between the RIX at the reference and target sites can lead to large prediction errors, while sites of similar complexity may experience more accurate predictions due to a cancellation of the prediction errors resulting from flow separation at each site.

The two sites have dissimilar complexity: the reference site is flat (Laucala Bay), with a RIX of zero, while the target site (Nabua) has RIX ranging from 0 % to 2.2 %, primarily due to the high elevation and steep slope.. Consequently a prediction error is expected. As the target site is more complex than the reference site, however, the sign of this error would be expected to be positive (i.e. over prediction of the wind resource). A study of Portuguese and French sites by Mortensen and Petersen (1997) suggested that the magnitude of the wind speed prediction error due to a RIX difference in the above range could be expected to be in the order of ± 5 %.

Other factors that may have caused variation in WAsP prediction includes wind speed records. In this study wind speed averaging time was 10 minutes. Bowen and Mortensen (2004) stated that longer averaging time say, 1 hour would be more appropriate as it would allow wind speeds to physically envelope the two sites. Wind direction may have also contributed to WAsP prediction error. The wind rose was normally divided into 12 equal direction sectors. Nabua site had steep, oblique ridges which may have affected the direction of the incident flow. This turning may have caused the wind direction to fall into adjacent direction sector, which was different to the observed one at the Laucala Bay site.

Dissimilarities between the wind direction frequencies derived from the short-term measurements at the candidate site, and those predicted by WAsP may indicate that WAsP has inaccurately modelled the flow. A comparison of the wind rose constructed from short term measurements at the candidate site (Figure 3.14), and the Wind Atlas rose derived from the long-term data from the reference site suggest that winds incident from the 30° and 120° sectors are being funnelled into the 120° sector at the candidate site, an effect not predicted by WAsP (Figure 3.19). Bowen and Mortensen (1996) attributed this effect to steep oblique ridges, although there are no prominent ridges in the terrain. A similar result was reported by Maunsell et al. (2004) in a study in Western Australia where the incident wind from 150° and 210° sectors were funnelled into 180° sector at the candidate site.

4.7 Economics

To make an informed discussion about a wind power prospect, a thorough economic analysis is necessary. The cost of wind energy is, as for all energy sources, difficult to generalize. The cost is related to many factors, including the wind speed distribution at the site, the size of the turbine, the wind farm project, and the proximity of grid connections. The financing package available is important because wind energy is highly capital intensive. Currently in Fiji, there is only one utility owned wind farm (Butoni farm), which is supplying electricity to about 8,000 residential customers (FEA, 2005). However, in remote islands and places wind projects tend to be privately owned.

In Fiji the current electricity price stands at $FJ 0.23 /kWh. Economic analysis carried out for the Whisper 100 turbine based on the resource grid generated by WAsP model, showed that at Laucala Bay site the cost of electricity generation would be $FJ 0.98 /kWh whilst at Nabua site it would be $FJ 3.31 /kWh which is not economically feasible compared to other generation technologies. However, within the resource grid and considering the mean AEP production, Whisper 100 turbine would generate electricity at a cost of $FJ 0.49 /kWh and at the site where maximum AEP (Tamavua Heights) is achieved the same wind turbine will generate at a cost of $FJ 0.21 /kWh which is comparable with the current electricity price.

In today's market the cost of electricity generation stands at $FJ 0.10 /kWh however Sahin (2004) stated that wind turbines installed at windy sites are already generating electricity at a cost less than $FJ 0.07 /kWh. In comparison to this study, the current market is cheaper, however, once again it must be considered that this analysis has been done for a single turbine whilst world market price for wind generated electricity are based on wind farms. Barthelmie (2007) stated that the cost of wind energy generation have been reduced due to increase in the size of individual wind turbines and wind farm projects together with engineering and design improvements to the blades, electronic controls and weight reduction of individual components that impacts their manufactured costs.

Whisper 100 turbines, has a life time of 20 years and simple payback analysis at the current electricity price showed that for Laucala Bay site it would take 85 years for the turbine to payback whilst at Nabua site it would take 288 years. Considering the lifetime of the turbine and its payback period for the both sites, it is certain that the turbine will never be able to payback of its investment. However, within the resource grid and at the maximum AEP production site the payback period is 18 years which is acceptable for an individual turbine. Whisper 100 turbine was installed at 15 m however, increasing the tower height to 50 m would mean a larger AEP. This would subsequently reduce the unit cost of energy production. This arrangement would increase the capital cost because of increased tower length but this cost can be easily offset by power produced at higher wind speed at 50 m.

Sahin (2004) stated that at current electricity prices, the cheapest wind plants are those with easy access and economically scaled to compete with other renewable sources and fossil fuels. He further sated that the cost of wind power generation falls as the average wind speed rises, and it is shown that an average site with a wind speed of 7.5 m/s and a cost per installed kilowatt of $US 700, wind can be cost competitive with gas. However, within the greater Suva area resource grid, a mean of

7.5 m/s is not available and in comparison currently the Whisper 100 turbine has been installed at cost of $US 7,000 which is not at all economically viable. However, it has to be taken in consideration that a single wind turbine costs higher compared to cost per turbine in a wind farm.

The need for a project is closely linked to the benefits derived from the proposals. Local financial gain is critical to the acceptance of new turbines in Fiji. If more people benefit directly from the turbines than there will be less opposition. Local financial gain, in the form of shares, reduced bills or local taxation, affects local participation as those who have a financial stake are inherently involved in the process. Devlin (2005) stated that if the plan will benefit the utility or an individual, financially, socially or culturally, than the utilities and individuals are more likely to be in favour. The erection of turbines can support those who own lands, especially land owning units and farmers. Fiji Electricity Authority (FEA) owns a wind farm. This means that the economic benefits are distributed among shareholders and employees. Barthelmie (2007) stated that the cost of wind energy is highly dependent on the financial package secured for the development of the wind farm.

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4.8 Social and Environment Impacts

According to the European Wind Energy Association (2003), there are currently 90,000 – 100,000 jobs in the wind energy sector worldwide. After construction, turbines and access roads occupy 1 – 3 % of the land surface, leaving up to 99 % for other uses (mainly agriculture). Wind energy can therefore provide valuable income for farmers, landowners and local communities. In Fiji, FEA developed a close relationship with the land owners and were granted a 99 year land lease for the Butoni project (FEA, 2005).

However, small wind turbines are suited for the greater Suva area as larger structures would present a problem as visual pollution. The public acceptance of their aesthetic appearance is a major issue. While more modern, attractive structures will undoubtedly be developed, the solution is probably to group such large structures in "farms" as mentioned earlier, location where they will be seen by a few people.

Devlin's (2005) study confirms that urban residents who own properties are less willing to accept turbine introduction due to visual pollution.

Land use is also a concern for wind farms as they would, in general occupy more land area than fossil fuelled plants, but the difference is not great especially for fuel storage. The nature of wind power generation is such that multiple use of the land, as for agriculture, would present fewer problems.

Most turbine noise is masked by the sound of the wind itself, and the turbines run only when the wind blows. Noise from wind turbines has diminished as the technology has improved. Early-model turbines were generally noisier than most new and larger models. As wind turbines have become more efficient, more of the wind is converted into rotational torque and less into acoustic noise. Under most conditions, modern turbines are quiet. The social cost of nuisance noise defined by Ehyaei and Bahadori (2006) is the additional cost to reduce the noise level at a receptor to an acceptable, non-nuisance value. The acceptable sound level is considered to be 35 dB. Whisper as its name suggests is a reasonable quiet wind turbine and generates sound at 30 dB, hence, there is no cost involved to reduce the sound level (Huskey & Meadors, 2001).

In Fiji, the ecological impact on migratory birds is a minimum. There are no primary migratory routes crossing the island.

The research carried out in this project was presented at the American Wind Energy Association conference (1st – 4th June) in Houston, Texas through a poster presentation. The poster is illustrated in Appendix D.

Chapter 5 Conclusions

5.1 Conclusions

In this study, assessments of wind characteristics and wind power potential around Laucala Bay, Suva were made. The specific aims of the research were attained by constructing OWC at the Laucala Bay and Nabua site, using a WAsP model to predict the regional wind climate at Nabua, and later verifying this using measured on-site data. In addition, a wind regime pattern over greater Suva area was also determined.

The OWC for the Laucala Bay site was constructed. The wind regime at Laucala Bay site was calculated using 4 year data (2004 - 2007) from the MSP site and measured data at the Laucala Bay site. The OWC obtained for the Laucala Bay site showed that power density was less than 100 W/m^2 at 15 m above ground level. This fulfilled the first objective of the study. A Whisper 100 turbine was installed at the Laucala Bay site (FIT maritime school compound). The AEP from this turbine was monitored. In spite, of unfavourable weather conditions (when the turbine was shut down) it produced 59 kWh per month. As the project has yet to complete its first 12 months of existence, its AEP is not yet determined. It has been forecast as 708 kWh. This concluded the second objective of the study.

A circuit for a dual light sensor lamp was constructed and tested in the laboratory. The circuit was built and enclosed in a weather proof box before it was connected to the resistive load bank of the turbine. This completed the third objective of the study.

The wind speed and direction at Nabua site was measured at 15 m above ground level. The mean wind speed at Nabua was 3.1 m/s and the majority of the time it was north easterly to south easterly wind. WAsP was used to carry out the statistical analysis and build its OWC. Thus, the fourth objective of the study was successfully executed.

Vector map is an integral component of WAsP application. It is necessary to provide WAsP with a digitized map for it to make predictions of AEP for a selected turbine at the desired location within the same wind regime. A contour map of greater Suva was digitized to produce the vector map for WAsP use. This digitized map labelled as "Suva area" and was used by WAsP to make prediction for Nabua site. Hence, the fifth objective of this study was accomplished. Based on the OWC of Laucala Bay, digitized map of greater Suva area, and Whisper 100 power curve, WAsP predicted the wind regime for Nabua site. It predicted a mean wind speed of 3.3 m/s and a predominant south easterly wind for Nabua. Further, it showed a power density of 40 W/m^2 and an AEP of 227 kWh for the Whisper 100 at Nabua site. These conclude the sixth objective of this study.

To verify WAsPs' prediction, wind speed and direction measurement at Nabua site was compared with measured on-site data. WAsP prediction of Nabua site was found to be similar to the measured values (Table 3.6) within experimental uncertainties. This confirms that WAsPs' predictions are valid within the same wind regime. Hence, WAsP could be used for predicting the wind regime and AEP for a selected turbine with an uncertainty of less than 10 %. This concluded the seventh objective.

A resource grid enclosing the measured (Laucala Bay) site and the predicted (Nabua) site was displayed by WAsP to show mean wind speed, power density and AEP for different locations within the grid. The mean wind speed for the greater Suva area at a height of 15 m above the ground level was measured as 5.6 m/s while the maximal value of the wind speed in the investigation was predicted as 13.3 m/s. Correspondingly, the mean AEP was calculated as 1.435 MWh and a maximum value of 3.382 MWh (for Tamavua Heights) was predicted for greater Suva area. This suggests that within the designated resource grid there are potential sites where wind turbines can be installed with economically viable power generation. Hence, the eighth objective of the study was successfully carried out.

A simple economic analysis was carried out for Whisper 100 wind turbine within the WAsP generated grid. It showed that Tamavua Heights was the best candidate for installation of a turbine in greater Suva area. The analysis revealed that it would take

18 years to payback at a generation cost of $FJ0.21 /kWh. Though it was a simple payback analysis, it gives an indication of the time required to payback such installations. These conclude the final objective of the study.

The greater Suva area has the potential for generating electricity from wind. However, landownership, environmental implications, public acceptance and other constraints should be studied in detail before any wind power generation project is installed.

5.2 Limitations and Suggestions for Future Work

5.2.1 Limitations

There were a couple of limitations and constraints encountered in the present work. Initially it was very difficult to get the land area to install the turbine. However, it was solved after the Head of School for the maritime FIT campus allowed the project to be built on its site. Secondly, the procurement of the turbine was a cumbersome and slow process. Even though it was bought locally, it required the paperwork to be completed by various agencies. Thirdly, after the turbine was installed, it was shut down on many occasions because of mechanical/electrical failures in the resistive load bank or by adverse weather conditions in late 2007 and early 2008. There were occasional theft but these were easily compensated.

The wind monitoring instruments (anemometer and wind vanes) were acquired from New Zealand and this consumed a lot of time. This delayed the start of the measurement process. Since there were two monitoring sites, it required a stringent coordination procedure to monitor, record, and retrieve data.

The manufacturer failed to provide the experimental power curve of the turbine which further delayed the project. However, this was overcome by resorting to the theoretically derived power curve. The WAsP software was learnt from scratch. The map digitizing was a slow and tedious process and required a great deal of time.

5.2.2 Suggestions for Future Work

Additional wind speed data at various locations around Fiji should be measured to determine further accuracy for WAsP predictions and its comparison. Further to this, it will provide a good reflection of seasonal variation of the wind speed. WAsP has given a relatively accurate prediction within the same wind regime however, considering the topography of Viti Levu with its rugged terrain, is expected to cause uncertainty in WAsPs' predictions. Wind speed measurement should be carried out at 50 m which is the recommended hub height for most wind turbines. In addition other capacity and configurations of turbines should be modelled to determine the most appropriate turbine for greater Suva area.

The importance of renewable energy and in particular wind power in the South Pacific region is gaining prominence. The results from this work may be used as a basis to understand the wind regime on the windward side of the main island. This study could be extended further to the leeward side for comparison.

The Whisper 100 turbine installed during the project could be used in future by other interested researchers. The energy produced by this turbine should be continuously measured for at least another six months. The electricity generated could be used to light up the dark regions of the FIT complex and provide added security. The operation and performance of the turbine could be studied by postgraduate students using experimental power curve of the turbine, rather than the theoretical derived curve. In addition, hybrid systems i.e. wind and solar could be investigated on using battery storage.

WAsP has not been used in Fiji prior to this project. A detailed study of the software and its capabilities should be carried out by other interested researchers to develop a detailed wind map of the main islands of the Fiji group. A detailed evaluation of the noise and the environment impact should be carried out to determine the efficacy of such turbines for irrigation and lighting for small households. A detailed economic analysis based on the AEP is necessary to determine its effectiveness.

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Appendix

Appendix A
Execution Program for the data logger

```
;{ CR10}
; Programme to input wind speed and wind direction from Vector
; Instruments - A101M pulse output cup rotor anemometer and W200P/L
; Precision potentiometer wind vane respectively.
; Execution interval: 1 second
; Output processing interval: 10 minutes
; Pulse input channel used: 2
; SE channels used: 1, 2, 3
; 12Vdc output terminal used: 1
; Written for MSc student, Denise Chand - 29/10/2007
; Modified (comments inserted only): 15/08/2008

*Table 1 Program
 01: 1      Execution Interval (seconds)

; READ BATTERY VOLTAGE
1:  Batt Voltage (P10)
 1: 1       Loc [Battery]
; CHECK DATA LOGGER INTERNAL TEMPERATURE – INBUILT
 THERMISTOR
2:  Internal Temperature (P17)
 1: 2       Loc [Pinetop]
; READ IN COUNTS FROM A101M, AND CONVERT COUNT FREQUENCY
TO WINDSPEED (m/s)
; VIA MULTIPLIER (0.09792 m/s per Hz)
3:  Pulse (P3)
 1: 1       Reps
 2: 2       Pulse Input Channel
 3: 22      Switch Closure, Output Hz
 4: 3       Loc [Wind Speed]
 5: .09792  Mult
 6: 0.0     Offset
; READ IN VOLTAGES VIA GND REFERENCED SE MEASUREMENTS
FROM W200P/L
; POTENTIOMETER: V1, V2 & V3, WHERE V1 IS READING @ MAX. POT.
SETTING,
; V3 @ MIN. POT. SETTING AND V2 @ POINTER LOCATION
; READ IN V1
4:  Volt (SE) (P1)
 1: 1       Reps
 2: 35      2500 mV 50 Hz Rejection Range
 3: 4       SE Channel
 4: 5       Loc [CH1]
 5: 0.001   Mult
```

```
 6: 0.0      Offset
; READ IN V2
5:  Volt (SE) (P1)
 1: 1        Reps
 2: 35       2500 mV 50 Hz Rejection Range
 3: 5        SE Channel
 4: 6        Loc [CH2]
 5: 0.001    Mult
 6: 0.0      Offset
; BEGIN IF (THEN) LOOP 1: SET V2 TO MIN 0V (NEGATIVE VOLTAGES
INVALID)
6:  If (X<=>F) (P89)
 1: 6        X Loc [CH2]
 2: 4        <
 3: 0        F
 4: 30       Then Do

    7:  Z=F (P30)
     1: 0        F
     2: 0        Exponents of 10
     3: 6        Z Loc [CH2]
; END IF (THEN) LOOP 1
8:  End (P95)
; READ IN V3
9:  Volt (SE) (P1)
 1: 1        Reps
 2: 35       2500 mV 50 Hz Rejection Range
 3: 6        SE Channel
 4: 7        Loc [CH3]
 5: 0.001    Mult
 6: 0.0      Offset
; DETERMINE X-VALUE, WHERE: X= [(V2-V3)/ (V1-V3)]
; CALCULATE NUMERATOR OF X (V2-V3)
10:  Z=X-Y (P35)
 1: 6        X Loc [CH2]
 2: 7        Y Loc [CH3]
 3: 8        Z Loc [numer_X]
; CALCULATE DENOMINATOR OF X (V1-V3)
11:  Z=X-Y (P35)
 1: 5        X Loc [CH1]
 2: 7        Y Loc [CH3]
 3: 9        Z Loc [denom_X]
; CALCULATE X
12:  Z=X/Y (P38)
 1: 8        X Loc [numer_X]
 2: 9        Y Loc [denom_X]
 3: 10       Z Loc [X]
; CALCULATE SQUARE OF X
13:  Z=X*Y (P36)
 1: 10       X Loc [X]
```

2: 10 Y Loc [X]
3: 11 Z Loc [X squared]
; **STORE 'R' VALUE EQUAL TO 2 (FACTORY SPECIFICATION)**
14: Z=F (P30)
1: 2 F
2: 0 Exponent of 10
3: 12 Z Loc [R]
; **STORE 'R LOAD' VALUE (R LOAD = 488 OHMS - THE ACTUAL VALUE OF THE INSERTED RESISTOR)**
15: Z=F (P30)
1: 488 F
2: 0 Exponent of 10
3: 13 Z Loc [R_load]
; **CALCULATE (R)/ (R LOAD)**
16: Z=X/Y (P38)
1: 12 X Loc [R]
2: 13 Y Loc [R_load]
3: 14 Z Loc [RonR_load]
; **CALCULATE (X-X^2)**
17: Z=X-Y (P35)
1: 10 X Loc [X]
2: 11 Y Loc [Xsquared]
3: 15 Z Loc [XminusXX]
; **CALCULATE E=[(R)/(R LOAD)]*(X-X^2)**
18: Z=X*Y (P36)
1: 14 X Loc [RonR_load]
2: 15 Y Loc [XminusXX]
3: 16 Z Loc [l14_x_l15]
; **CALCULATE E+1**
19: Z=X+F (P34)
1: 16 X Loc [l14_x_l15]
2: 1 F
3: 17 Z Loc [l16plus1]
; **CALCULATE CORRECTED X: XC=[X*(E+1)]**
20: Z=X*Y (P36)
1: 10 X Loc [X]
2: 17 Y Loc [l16plus1]
3: 18 Z Loc [X_correct]
; **STORE CONSTANT D=5**
21: Z=F (P30)
1: 5 F
2: 0 Exponent of 10
3: 19 Z Loc [D]
; **CALCULATE (D/2)**
22: Z=X*F (P37)
1: 19 X Loc [D]
2: 0.5 F
3: 20 Z Loc [half_D]
; **STORE CONSTANT C=360**
23: Z=F (P30)

1: 360 F
2: 0 Exponent of 10
3: 21 Z Loc [three60]
; **CALCULATE F=C-D**
24: Z=X-Y (P35)
1: 21 X Loc [three60]
2: 19 Y Loc [D]
3: 22 Z Loc [Dfrom360]
; **CALCULATE G=F*XC**
25: Z=X*Y (P36)
1: 22 X Loc [Dfrom360]
2: 18 Y Loc [X_correct]
3: 23 Z Loc [l22_x_l18]
; **CALCULATE WIND DIRECTION (polar degrees): G+(D/2)**
26: Z=X+Y (P33)
1: 23 X Loc [l22_x_l18]
2: 20 Y Loc [half_D]
3: 4 Z Loc [WindDir]
; **SET OUTPUT AT START OF EACH 10 MINUTE INTERVAL**
27: If time is (P92)
1: 0 Minutes (Seconds --) into a
2: 10 Interval (same units as above)
3: 10 Set Output Flag High
; **ALLOCATE ACTIVE FINAL STORAGE AREA**
28: Set Active Storage Area (P80) ^12714
1: 1 Final Storage Area 1
2: 1 Array ID
; **INSERT TIMESTAMP DATA - YEAR, DAY, TIME (24 HOUR CLOCK - HHMM)**
; WITH EACH 10-MINUTE OUTPUT STREAM
29: Real Time (P77) ^7568
1: 1220 Year, Day, Hour/Minute (midnight = 2400)
; **OUTPUT AVERAGE WIND SPEED, AVERAGE WIND DIRECTION AND STANDARD**
; DEVIATION OF AVERAGE WIND DIRECTION
30: Wind Vector (P69) ^25483
1: 1 Reps
2: 60 Samples per Sub-Interval
3: 00 S, 01, & σ (01) Polar
4: 3 Wind Speed/East Loc [WindSpeed]
5: 4 Wind Direction/North Loc [WindDir]
; **ENABLE AUTOMATIC DATA TRANSFER TO PERIPHERAL STORAGE DEVICE**
31: Serial out (P96)
1: 71 Storage Module
*Table 2 Program
02: 0.0000 Execution Interval (seconds)
*Table 3 Subroutines

End Program

Appendix B

Table B1 *Wind speed, standard deviation and turbulence intensity for the MSP site*

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2004	**Mean (m/s)**	4.96	3.66	2.93	5.51	3.97	6.33	4.56	4.06	5.09	4.84	5.31	3.98
	STDEV	2.14	2.26	2.06	2.39	2.39	2.61	2.57	2.79	2.30	2.45	2.44	2.15
	TI	0.43	0.62	0.71	0.43	0.60	0.41	0.56	0.68	0.45	0.51	0.46	0.54
2005	**Mean (m/s)**	5.29	N/A	3.61	3.97	4.22	4.64	5.08	4.39	5.50	4.42	4.33	4.54
	STDEV	2.45	N/A	2.24	2.90	2.29	2.71	3.26	2.50	2.50	2.44	2.40	2.16
	TI	0.46	N/A	0.62	0.54	0.54	0.58	0.64	0.57	0.45	0.55	0.55	0.48
2006	**Mean (m/s)**	4.56	3.54	3.40	3.70	4.51	4.59	4.80	5.63	5.46	6.49	5.41	5.50
	STDEV	2.63	2.41	2.16	2.54	2.62	2.76	2.61	2.71	2.84	2.56	2.76	2.36
	TI	0.58	0.68	0.64	0.69	0.58	0.60	0.54	0.48	0.52	0.39	0.51	0.43
2007	**Mean (m/s)**	5.10	3.93	2.93	3.59	4.33	5.12	3.89	6.18	5.49	4.61	4.01	4.08
	STDEV	2.31	2.99	2.15	2.48	2.50	2.51	2.31	2.43	3.19	2.78	2.39	2.52
	TI	0.45	0.76	0.73	0.69	0.58	0.49	0.59	0.39	0.58	0.60	0.60	0.62

Table B2 *Mean Wind Direction and standard deviation for the MSP site*

	2004		2005		2006		2007	
	Mean	**STDEV**	**Mean**	**STDEV**	**Mean**	**STDEV**	**Mean**	**STDEV**
Jan	138.22	66.37	160.7	81.38	131.56	93.74	121.08	80.23
Feb	127.31	122.85	N/A	N/A	184.95	106.73	168.89	105.71
Mar	180.17	114.1	149.85	119.84	153.2	117.08	166.77	121.61
Apr	144.4	69.83	163.66	105.6	167.23	115.83	175.72	108.25
May	180.32	97.22	154.41	107.76	156.07	94.67	157.01	97.51
Jun	117.26	67.99	158.47	86.29	164.31	97.85	119.95	83.16
Jul	134.24	105.57	156.96	98.08	173.59	85.51	149.44	111.72
Aug	163.21	100.12	160.54	90.26	134.69	83.16	118.93	68.93
Sept	133.15	82.21	125.79	71.15	135.21	80.99	123.79	87.57
Oct	129.63	84.94	141.27	93.23	120.89	59.44	151.41	90.84
Nov	116.38	73.24	153.52	86.94	118.42	90.64	154.22	99.2
Dec	141.81	96.71	143.68	84.67	128	64.84	136.39	107.24

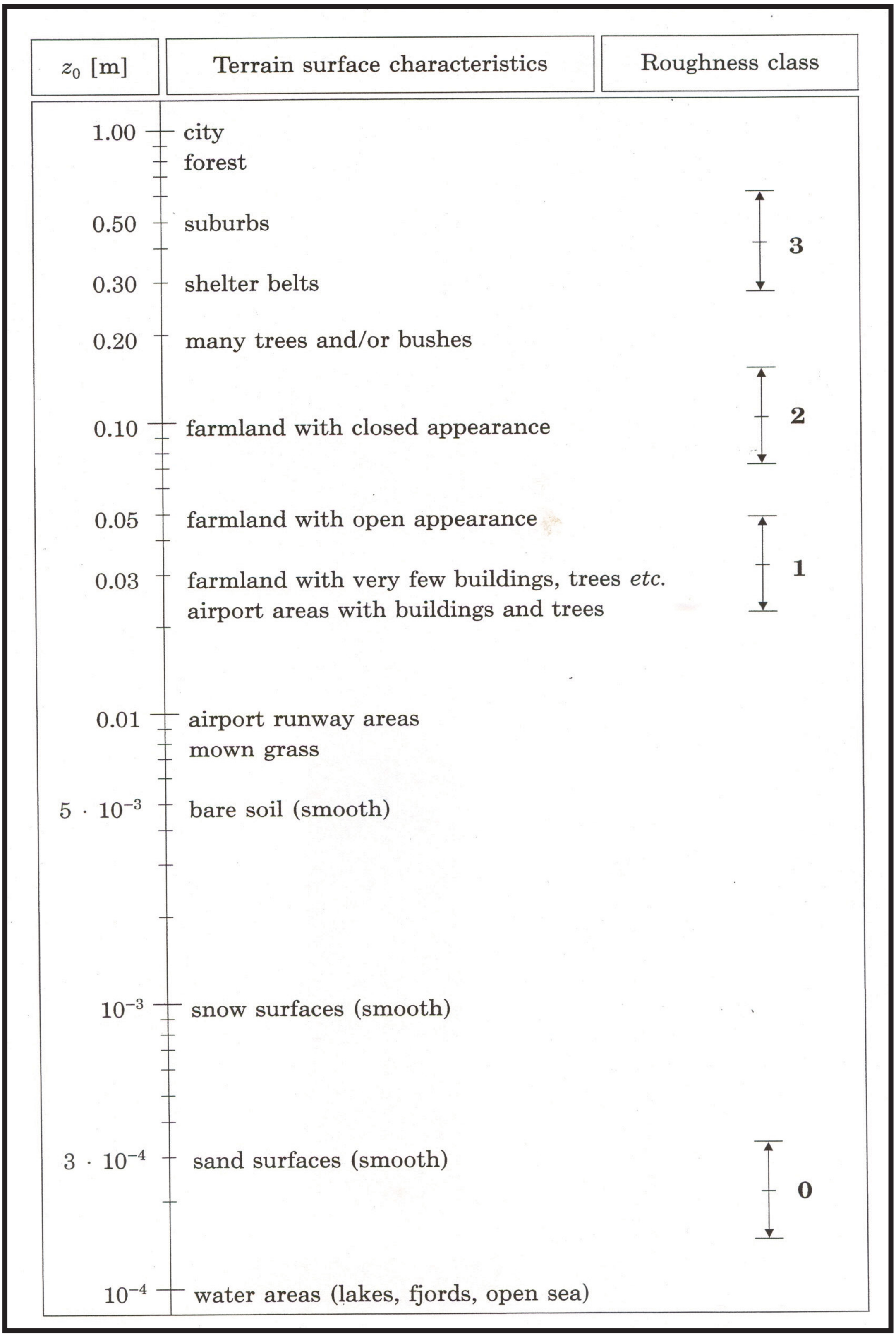
Table B3 *Mean wind speed, standard deviation and turbulence intensity for the Laucala Bay site*

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2004	**Mean (m/s)**	4.17	3.14	2.53	4.61	3.39	5.27	3.86	3.46	4.29	4.08	4.47	3.40
	STDEV	1.72	1.82	1.62	1.92	1.90	2.10	2.06	2.25	1.85	1.97	1.96	1.73
	TI	0.41	0.58	0.64	0.42	0.56	0.40	0.53	0.65	0.43	0.48	0.44	0.51
2005	**Mean (m/s)**	4.44	N/A	3.09	3.36	3.58	3.93	4.28	3.74	4.62	3.75	3.67	3.84
	STDEV	1.96	N/A	1.79	2.33	1.84	2.18	2.62	1.81	2.10	1.96	1.92	1.74
	TI	0.44	N/A	0.58	0.69	0.51	0.55	0.61	0.48	0.45	0.52	0.52	0.45
2006	**Mean (m/s)**	3.86	3.04	2.93	3.17	3.81	3.56	4.06	4.71	4.58	5.41	4.55	4.61
	STDEV	2.12	1.94	1.73	2.04	2.11	2.22	2.1	2.24	2.28	2.05	2.21	1.89
	TI	0.55	0.64	0.59	0.64	0.55	0.62	0.52	0.48	0.50	0.38	0.49	0.41
2007	**Mean (m/s)**	4.29	3.30	2.55	3.07	3.67	4.31	3.32	5.16	4.60	3.89	3.43	3.46
	STDEV	1.85	2.35	1.73	2.00	2.01	2.02	1.86	1.95	2.56	2.24	1.92	2.02
	TI	0.43	0.71	0.68	0.65	0.55	0.47	0.56	0.38	0.56	0.58	0.56	0.58

***Table B4** Mean wind speed, standard deviation and turbulence intensity for the Nabua site.*

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
2004	**Mean (m/s)**	N/A	N/A	1.55	3.22	2.36	3.52	2.61	2.36	3.11	3.70	3.36	3.23
	STDEV	N/A	N/A	1.27	1.72	1.42	1.68	1.48	1.71	1.49	1.62	1.71	1.71
	TI	N/A	N/A	0.82	0.53	0.60	0.48	0.57	0.72	0.47	0.44	0.51	0.53
2005	**Mean (m/s)**	2.41	3.47	2.55	2.69	2.44	2.67	3.09	2.82	3.11	2.79	2.61	2.83
	STDEV	1.51	1.76	1.68	1.92	1.37	1.62	1.98	1.55	1.63	1.62	1.71	1.63
	TI	0.63	0.51	0.66	0.71	0.56	0.61	0.64	0.55	0.52	0.58	0.66	0.58
2006	**Mean (m/s)**	3.51	2.19	2.13	2.84	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	STDEV	1.72	1.27	1.30	1.86	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	TI	0.50	0.58	0.56	0.65	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2007	**Mean (m/s)**	N/A	N/A	N/A	N/A	2.49	3.11	N/A	2.73	3.01	2.88	2.99	2.96
	STDEV	N/A	N/A	N/A	N/A	1.33	1.60	N/A	1.56	1.61	1.59	1.45	1.66
	TI	N/A	N/A	N/A	N/A	0.53	0.51	N/A	0.57	0.53	0.55	0.48	0.56

Appendix C



Appendix C *Roughness length, surface characteristics and roughness class. The roughness classes are indicated by vertical bars. The central points give the reference values and the length of the bars indicates the typical range of uncertainty in roughness assessments.*

Appendix D

Wind Characteristics and Resource Assessment Around Laucala Bay Area Suva, Fiji Islands

Denise Chand, The University of the South Pacific, Suva, Fiji Islands

Introduction

Renewable electricity generation capacity reached an estimated 240 GW worldwide in 2007, an increase of 50 % over 2004. The largest component of renewable generation was wind power, which grew by 28 % worldwide in 2007 (1).Today, wind energy is widely used to produce electricity in Germany, Spain, US, India and Denmark. Wind power installed capacity as at the end of 2007 was 93,849 MW, up from 77,223 MW (figure 1) in 2006 (2).The importance of renewable energy as an alternative source of energy has been realized in the South Pacific countries. Fiji located at 15 S to 22 S and 177 W to 175 E (figure 2) has recently ventured in wind energy projects. At Butoni in Fiji, the local utility has set up a wind farm (figure 3) consisting of 37 x 275 kW Vergnet turbines with 10 MW capacity expecting to produce 11.5 GWh annually. In the neighboring South Pacific countries New Caledonia has an installed capacity of 6 MW, Vanuatu has 3 x 275 kW, and Cook Islands has 2 x 20 kW Vergnet turbines installed.

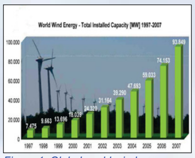


Figure 1. Global world wind energy Total installed capacity (MW) 1997-2007

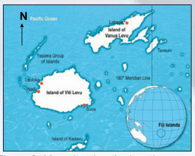


Figure 2. Map showing the location for Fiji

Figure 3. Description of the Butoni Farm In Fiji

Wind Atlas Analysis and Application Program (WAsP)

WAsP (8.3) is licensed software supplied by the Wind Energy and Atmospheric Physics Department at RisØ National Laboratory of Denmark. WAsP is a PC program for predicting wind climates and power productions from wind turbines and wind farms (3). The predictions are based on wind data measured at stations in the same wind region. The program includes a complex terrain flow model, a roughness change model and a model for sheltering obstacles . WAsP modeling involves:

- analyzing observed wind data to calculate regional wind climate (wind atlases)
- applying wind atlas to a particular turbine site to calculate an estimated wind climate and power output.

Flow diagram (figure 4) shows the intermediate steps required by WAsP software.

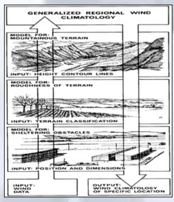


Figure 4 The Wind atlas methodology of WAsP. Meteorological Models that was used to calculate the regional wind climatologies from the raw data. In the reverse process the application of wind atlas data — the wind climate at any specific site may be calculated from the regional climatology

Aim of the Research

The purpose of this study is to investigate wind characteristics and resource assessment around Laucala Bay, Suva and the objective of the study was to analyze. The time series of wind speed and direction at Laucala Bay and Nabua site. Also to validate the WAsP prediction for Nabua site with measured data.

Methodology

For this study, wind resources were determined for three wind monitoring sites. The wind monitoring sites (figure 5) were confined to a radius of 3 km. Initially the local wind climate at Laucala Bay site was built by series of measurement and correlation with archived data of the Marine Study Program (MSP) site. The Laucala Bay wind climate was used with WAsP to predict the regional wind climate at Nabua. To validate the WAsP prediction, a on-site measurement is being carried out at Nabua.

A whisper 100 turbine (figure 6) was installed at the Laucala Bay site to determine the annual energy produced and its power coefficient, *Cp,* of such a turbine. Nabua site was chosen as the WAsP prediction site because after the crash of the 10/20 Vergnet turbine at the site, (figure7) it was vitally important to estimate the wind climate to recommend a appropriate replacement turbine.

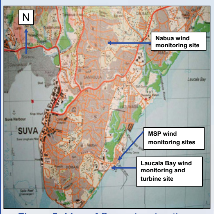


Figure 5. Map of Suva showing the study sites. Scale 1:50000

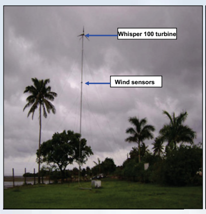


Figure 6. Whisper 100 wind turbine set-up at Laucala Bay site

Figure 7. The crushed wind turbine at the Nabua site

Results

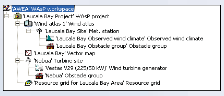


Figure 8. Work space hierarchy Utilized by WAsP to develop the resource grid

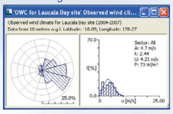


Figure 9. Generalized Observed Wind Climate (OWC) For the Laucala Bay site

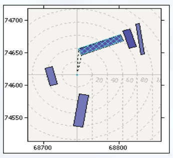


Figure 10 Obstacle group at the Laucala Bay site

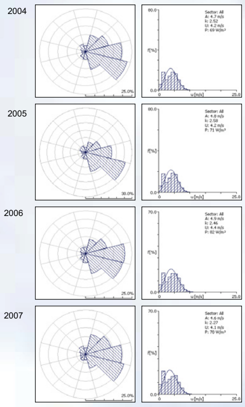


Figure 11 OWC for Laucala Bay site for past four years (2004-2007)

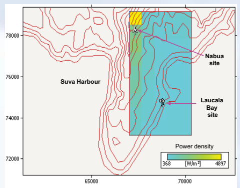


Figure 12. Illustrated is the vector map on which the wind resource assessment has been carried out for the study site.

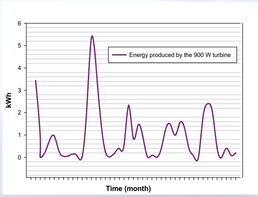


Figure 13. Daily energy produced by the 900 W turbine located at the Laucala Bay site

Analysis

To represent a wider variety of wind regime, Weibull distribution (4) is used in wind data analysis

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

Where k is the shape factor and c, a scale factor

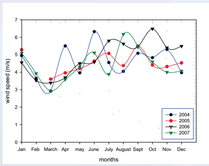
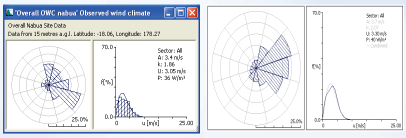
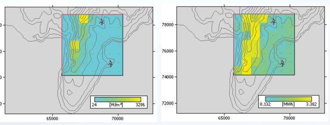


Figure 14. Wind speed frequency distribution at the Laucala Bay site for years (2004-2007)



(a) OWC from measured data (b) OWC predicted by WAsP

Figure 15. Experimentally determined (a) and WAsP predicted (b) OWC at Nabua site.



(a) Power density W/m²) (b) AEP (MWh)

Figure 16. Resource grids analysis for the greater Suva area

Table 1. Regional wind climate summary. The wind atlas contains data for 4 reference roughness lengths (0.000 m, 0.030 m, 0.100 m, 0.400 m) and 5 reference heights (10 m, 25 m, 50 m, 100 m, 200 m) above ground level

Height	Parameter	0.00 m	0.03 m	0.10 m	0.40 m
10.0 m	Weibull A [m/s]	12.36	8.72	7.55	5.89
	Weibull k	2.29	2.15	2.16	2.16
	Mean speed U [m/s]	10.95	7.72	6.69	5.21
	Power density E [W/m²]	1355	503	326	154
25.0 m	Weibull A [m/s]	13.45	10.21	9.15	7.63
	Weibull k	2.31	2.20	2.21	2.20
	Mean speed U [m/s]	11.92	9.04	8.10	6.76
	Power density E [W/m²]	1734	790	568	330
50.0 m	Weibull A [m/s]	14.31	11.45	10.45	9.02
	Weibull k	2.34	2.28	2.27	2.26
	Mean speed U [m/s]	12.68	10.14	9.26	7.99
	Power density E [W/m²]	2073	1084	825	533
100.0 m	Weibull A [m/s]	15.26	12.89	11.91	10.53
	Weibull k	2.35	2.41	2.40	2.36
	Mean speed U [m/s]	13.52	11.43	10.56	9.33
	Power density E [W/m²]	2509	1482	1175	820
200.0 m	Weibull A [m/s]	16.37	14.76	13.72	12.26
	Weibull k	2.32	2.41	2.42	2.42
	Mean speed U [m/s]	14.50	13.08	12.16	10.87
	Power density E [W/m²]	3118	2222	1779	1270

Table 2. Statistical resource grid for Laucala Bay area

Variable	Mean	Minimum	Maximum
Weibull-A	6.3	2.7	14.9
Weibull-k	1.88	1.22	2.15
Mean speed (m/s)	5.60	2.46	13.29
Power density (W/m²)	388	24	3286
AEP	1.435	0.132	3.382
Elevation	103.8	10.0	414.1

Table 3. Economics of Whisper 100 turbine

	Laucala Bay site	Nabua Site	Mean AEP site	Maximum AEP Site
AEP production (kWh)	719	213	1435	3382
Cost of Energy (FJ/kWh)	0.98	3.31	0.49	0.21
Simple payback period (yrs)	85	288	43	18

Conclusion

The average density measured at Laucala site is 73 W/m^2 compared to 36 W/m^2 measured at the Nabua site. The WAsP predicted for Nabua site was 40 W/m^2. Manwell et.al (2004) states that P/A < 100 W/m^2 is considered as a poor site. Even though, the power density at Laucala Bay site is low, the AEP of the 900 W turbine indicates a pay back time of ~18 years at the current electricity price.

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(1) Renewables 2007 Global Status Report (REN), (2007), available at www.ren21.net

(2) Global Wind 2006 Report. (2007). Global Wind Energy Outlook 2007 (GWEC).

(3) Mortensen, N, G., Heathfield, D, N., Myllerup, L., Landberg, L., & Rathmann, O. (2004). Getting started with WAsP 8, Riso National Laboratory, Roslilde. Denmark.mm .

(4) Manwell, J., McGowan, J., & Rogers, A., (2002). *Wind energy explained, theory, design and application*. University of Massachusetts, Amberst, USA. British library.

Acknowledgement

The author would like to thank the following people and organization for their support in making and presenting this poster. Firstly thanks goes to the supervisors, Dr. A Kumar, Dr. A Singh and Mr. R Mario. Thanks also goes to South Pacific Applied Geoscience Commission (SOPAC) for providing the travel funds from Fiji to Huston, Texas and also to University of the South Pacific for providing accommodation costs. Finally thanks goes to American Wind Energy Association for having confidence in the abstract and accepting it for the presentation.

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