UPPSALA
UNIVERSITET

Design of Stand Alone Renewable Power Supply Systems on Futuna Island, Vanuatu

Katrine Berning

Arbetsgruppen för Tropisk Ekologi
Committee of Tropical Ecology
Uppsala University, Sweden

Minor Field Study 161
ISSN 1653-5634

Juni 2011 Uppsala

UPPSALA
UNIVERSITET

Design of Stand Alone Renewable Power Supply Systems on Futuna Island, Vanuatu

Katrine Berning

Supervisors:
Dr. Marcus Berg, Department of Engineering Sciences, Division of Electricity, Uppsala University, Sweden.
Mr. David Stein, VANREPA, Port Vila, Vanuatu.

Abstract

Design of Stand Alone Renewable Power Supply Systems on Futuna Island, Vanuatu

Katrine Berning

This Master's Degree project has been performed on behalf of *Vanuatu Renewable Energy and Power Association*. The purpose of the project was to suggest the design of stand-alone renewable power supply systems on Futuna Island in the Republic of Vanuatu. Futuna is the easternmost island in Vanuatu with a population of about 400 people. The island covers an area of just 13 km^2. The proposed sites for power production were the villages of *Mission Bay*, *Matangi*, *Herald Bay* and *Iahsoa*. In Mission Bay and Matangi the power should be produced by wind turbines and in Herald Bay and Iahsoa, solar modules are proposed.

The results of the study showed that some parts of Futuna Island can be suitable for wind power production and wind speeds in the order of 5-7 m/s are suggested. However, wind monitoring on the sites are required to estimate the exact potential. Furthermore, the study showed that there is less uncertainty involved with estimating the power output from the solar modules. In addition, solar power proved to be more reliable and less vulnerable to local variations in weather and topography. Solar modules are therefore considered more appropriate for small scale power production on the island, at least until the wind climate is better known.

The results of the study also showed that proper sizing of battery banks and cables are essential to increase the efficiency and lifetime of the systems. If there are insufficient financial resources in the project, it is therefore recommended in the report to use all resources available to properly size the systems in 1-2 villages rather than to inadequately size the systems in all the villages.

Populärvetenskaplig sammanfattning

Ögruppen Vanuatu är en självständig nation som består av mer än 83 bebodda öar av varierande storlek. Landet ligger mellan Fiji och Australien i Stilla havet och tillhör enligt FN världens fattigaste länder. Av landets befolkning på ungefär 200 000 människor är minst 80 procent självförsörjande bönder. Förutom på några av de större öarna där man byggt ut elnät till viss del finns det i princip ingen produktion av elektrisk energi i landet. Undantaget är några enstaka dieselaggregatsystem och solcellssystem som installerats med hjälp av privata medel och bistånd. Dock är många av dessa mikrosystem beroende av fossilt bränsle som måste importeras och därför är både dyrt och ofta en bristvara då transporten mellan öarna kan vara oberäknelig. Öarnas geografiska isolation och bristen på infrastruktur hindrar utvecklingen av storskalig energiproduktion i landet.

För att förbättra denna situation initierade frivilligorganisationen *Vanuatu Renewable Energy and Power Association* (VANREPA) år 2005 ett projekt med syftet att producera elektrisk energi på öarna Futuna och Aneityum med hjälp av förnybara energikällor. Landet har gott om förnybara energiresurser i form av hög solinstrålning, passadvindar, biobränslen och höga vulkanberg som även möjliggör produktion av vattenkraft. Landet har därför potential att producera relativt billig och miljövänlig energi med hjälp av lokala resurser. Projektet leds av VANREPA's grundare David Stein, ursprungligen från USA, och finansieras med hjälp av bidrag från EU.

Det här examensarbetet har utförts i samarbete med VANREPA, och med David Stein som handledare. Ämnesgranskare på Uppsala universitet har varit Marcus Berg och examinator har varit Kjell Pernestål. Examensarbetet har även utförts som en *Minor Field Study* i samarbete med Arbetsgruppen för tropisk ekologi (ATE) på Uppsala universitet och med stipendium från Styrelsen för internationellt utvecklingssamarbete (Sida). I tillägg har examensarbetet finansierats med hjälp av ett resestipendium ur Jacob A. Letterstedts resestipendiefond som förvaltas av Kungl. Vetenskapsakademien (KVA).

Syftet med examensarbetet har varit att föreslå lämplig design av de fyra förnybara kraftproduktionssystem som planeras i byarna Mission Bay, Matangi, Herald Bay och Iahsoa på Futuna. Den totala befolkningen på ön består av ungefär 400 människor. Det var önskvärt att kraftproduktionssystemen utformades så enkelt som möjligt. Detta för att underlätta att drift och underhåll ska kunna skötas av den lokala befolkningen på ön men även för att minimera projektets kostnader. Eftersom både efterfrågan och produktion av energi kommer att vara relativt låga var det även önskvärt att minimera alla förluster så mycket som möjligt. Dessutom var det önskvärt att systemen designades med möjlighet för expansion då detta endast anses vara ett första steg i att försörja Futuna med elektrisk energi. Komponenter som inkluderades i designen var vindturbiner, solpaneler, batterier och kablar.

Ett antal givna förutsättningar begränsade utförandet av examensarbetet. Dels var vindturbinerna och solpanelerna redan införskaffade vid den tidpunkt då författaren påbörjade examensarbetet. Detta innebar att det inte fanns möjlighet att påverka vare sig val av produktionsmetod eller antal produktionsenheter. Dessutom hade byggnaderna för batteribankerna i de fyra byarna redan byggts. Eftersom det var viktigt att hålla förlusterna och kostnaderna på en minimal nivå kunde därför inte heller placeringen av solpanelerna eller vindturbinerna påverkas, då dessa måste placeras så nära batteribankerna och konsumenterna som möjligt.

Utförandet av examensarbetet delades in i tre delar. I den första delen gjordes förberedande litteraturstudier i Sverige om småskaliga energisystem i allmänhet och förutsättningarna i Vanuatu i synnerhet. I den andra delen utfördes under sex veckor fältstudier på plats i Vanuatu. Under denna period genomfördes bland annat en fältresa till Futuna, där de fyra platserna föreslagna för kraftproduktion besöktes. Under fältresan samlades relevanta data in, såsom koordinater för platserna i behov av elektrisk energi och topografiska förutsättningarna för sol- och vindkraft på de fyra platserna. Dessutom intervjuades representanter för de fyra byarna för att kartlägga var och till vad elektrisk energi var önskvärd. Under den sista delen av examensarbetet analyserades materialet som samlats in under fältstudierna tillsammans med ämnesgranskaren på Uppsala universitet.

Den förväntade kraftproduktionen från solpanelen och vindturbinerna uppskattades med hjälp av data från NASA, då inga vind- eller solmätningar gjorts på plats per idag. På grund av den stora osäkerheten med att använda dessa data är den beräknade kraftproduktionen inte lika exakt som den annars kunnat vara. När den förväntade kraftproduktionen uppskattats beräknades den nödvändiga storleken på batteribankar och kablar. För att inte underdimensionera systemen inkluderades ett visst antal dagar som batteribanken skulle kunna försörja den givna lasten med elektrisk energi om vind eller sol skulle utebli. Dessutom dimensionerades batteribankerna för ett maximalt urladdningsdjup, detta för att förlänga batteriernas liv. Kablarna dimensionerades för att minimera spänningsfall och i gränsfall valdes därför alltid den större kabelstorleken. Både batteribankarna och kablarna dimensionerades även med hänsyn till övriga förluster i systemet.

Studien visade att vissa områden på Futuna kan vara lämpade för vindkraftsproduktion. Dock krävs vindmätningar på plats för att kunna uppskatta den exakta potentialen. Osäkerheten med kraftproduktion från solceller är mindre än för vindturbiner. Denna energikälla är också mindre känslig för lokala variationer och kräver mindre kunskap hos lokalbefolkningen för drift och underhåll. Solenergi anses därför vara en bättre lämpad energikälla för småskalig kraftproduktion på ön, åtminstone tills man fått en bättre uppfattning om det rådande vindklimatet.

Kostnaden för batterier är en känslig del av energisystemen som tyvärr inte går att komma undan, då kraftproduktionen är för instabil för att försörja lasten direkt. Det är mycket viktigt att batteribankernas kapacitet dimensioneras korrekt, för att undvika kortlivade system. Underdimensionerade batteribanker leder även till mindre effektiva system då en mindre andel av den producerade energin kan användas. Detsamma gäller för dimensioneringen av kablar, eftersom för högt spänningsfall kan leda till att den producerade energin inte når fram till konsumenten. Om tillräckliga finansiella resurser saknas för att slutföra projektet är det därför rekommenderat att snarare satsa på korrekt dimensionerade system i 1-2 byar än ofullständigt dimensionerade system i alla fyra byarna.

Preface

Vanuatu, a small archipelago in the South Pacific Ocean, is a country few people know much about. In fact, before I started the search for a place to carry out my Master's Degree project, I had never even heard about the country myself. So why did I choose to do my project in this very remote place, far away from civilization as we know it?

The idea that I wanted to do my project in a developing country came to me already during my first year at university, when a graduate student spoke about her Master's Degree project in Chile. Later in my studies, I learned about the possibility to do a *Minor Field Study* funded by *Swedish International Development Cooperation Agency* and I immediately knew that that was what I wanted to do. But where would I go?

During spring 2010 I studied at the University of Wollongong in Australia and I started to search for suitable projects in that region, not expecting much. I was surprised, however, to find that when I googled "renewable energy projects in the south pacific" I got lots of hits. It seemed that renewable energy was new and upcoming in the whole region, not strange at all knowing that the pacific islands are extremely vulnerable to climate change and fossil fuels are particularly expensive in the region.

Despite all the existing projects, it was not going to be easy to get in contact with the people "that mattered". I spent about 3-4 months emailing people involved with renewable energy projects without getting any replies, before I finally (!) got a response from a nice gentleman named Solomone Fifita, at the time being project manager of *Pacific Islands Greenhouse Gas Abatement through Renewable Energy Program* (PIGGAREP). At the same time, I got in touch with a forthcoming, helpful lady working for the Australian Clean Energy Council and the *Renewable Energy and Energy Efficiency Partnership* in the South Pacific region. With their knowledge about the region and whom to contact my search became a lot easier.

Not long afterwards, I stumbled upon an interesting organization in Vanuatu working with renewable energy; the *Vanuatu Renewable Energy and Power Association* (VANREPA) managed by David Stein, an environmental engineer and originally a peace corps volunteer from USA. It turned out VANREPA was in the midst of implementing a project called "The Answer is Blowing in the Wind: improving electricity access to energy services for the communities of Futuna and Aneityum Islands using wind technology". David invited me to participate in the project and I accepted.

I have never regretted this decision, or all the work I put into actualizing my dream of performing my project in a developing country. It has been a journey well worth traveling filled with hard work, frustration, setbacks and discouragements. But also joyful moments, the pleasure of getting to know the happiest people in the world (Vanuatu was the "winner" of *Happy Planet Index* in 2006) and a feeling of doing something important and of making a difference. Vanuatu is for sure an extraordinarily beautiful country with so much to offer. Without doubt, I would do it all over again if I could and I strongly encourage other people to do the same!

Acknowledgements

First of all, I would like to express my appreciation towards my supervisor David Stein, who invited me to participate in his project in Vanuatu, and to my reviewer Marcus Berg for giving me support, guidance and good advice all the way. Thanks also to my examiner Kjell Pernestål who gave his perspective on certain aspects.

There are so many persons I would like to thank in Vanuatu. My first and most special thanks go to my coworker Nini Tamasui, who treated me like a friend, introduced me to Vanuatu *kastom* and to his incredible island Futuna and who helped find a local family to stay with. *Tankyo tumas* Carl, Rose and your two wonderful children in Mele village for welcoming me into your family and treating me like your own. And of course; the communities of Futuna Island, who shared their thoughts with me, served me the most delicious food and were just so incredibly generous; tankyo tumas and I hope to meet you again in the future!

I would also like to thank Eric Kerres, one of the most competent guys around Port Vila who helped me although he did not have to and Nikunj Soni, for all the interesting conversations and evenings at the local *kava bars*. Big thanks also to Oliver Crowder for sharing your knowledge about renewable energy systems with me.

My next appreciations are directed towards two people who helped me a lot in my initial search of finding an appropriate project for my study. After months of trying to get in touch with people in the region, I finally got a reply from a gentleman named Solomone Fifita. Thank you for answering all my emails and sharing your knowledge about the region with me. Thank you also Eva Oberender, for being so forthcoming and offering your assistance, your advice helped me a lot!

Last but not least; I would like to thank Kerstin Edlund and *Committee of Tropical Ecology* for assisting me in all matters related to the Minor Field Scholarship and Thomas Malm, who gave me some really good advice prior to my fieldtrip. And of course; thanks to *Swedish International Development Cooperation Agency* (Sida) and *Royal Swedish Academy of Science* (KVA) for the financial support of my project; without these grants my study would not have been possible to carry out in the first place.

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Background

The Republic of Vanuatu is an archipelago consisting of 83 islands located between Fiji and Australia in the South Pacific Ocean. The country has a small population of around 200 000 people. Eighty percent of the population live in remote, rural parts of the country and are engaged in subsistence agriculture[1]. The country is listed among the least developed countries (LDCs) in the world by the United Nations[2].

The government of Vanuatu is increasingly recognizing the potential social and economic benefits of rural electrification. Even so, the majority of the rural population still has limited or no access to electric energy. Major barriers such as large distances between the islands and underdeveloped infrastructure make the deployment of a centralized power grid extremely difficult and thus hinder the development of large-scale power production.

For that reason, several small-scale energy-producing units have been installed around the islands. However, these are mainly powered by imported fossil fuels and are therefore both expensive and extremely vulnerable to price fluctuations and disruptions in supply. Moreover, the need for transportations between the islands for the supply of fuel, which often are operated at an irregular basis, means that shortage of fuel or fuel simply being out of stock is common.

The absence of continuous supply of electric energy in rural Vanuatu implies, amongst other things[3]:

- Hardship (no lighting, no refrigeration, no water pumping, etc.)
- Inadequate health facilities (no electrical health equipment, no vaccine refrigeration, etc.)
- Disadvantaged learning environment (no evening classes, no computers, etc.)
- Poor communications (no radios, no Internet, etc.)
- Fewer economic activities (no cool rooms, no electrical equipment, etc.)

In order to address these issues, the not-for-profit organization *Vanuatu Renewable Energy and Power Association* (VANREPA) has initiated a project aiming to provide the inhabitants on Futuna Island with electric energy based on renewable power production. The geographical and topographical conditions in Vanuatu result in an abundance of renewable resources being available such as hydro, solar, wind and biomass. Hence, the country has a potential to produce relatively inexpensive and environmentally friendly electric energy based on local, renewable resources.

Futuna is the easternmost island in Vanuatu with a population of about 400 people. The VANREPA project was initiated in 2006 on the island, and is funded by the European Commission (EU-ACP Energy Facility). The project is due to be completed by June 2011.

[1] European Commission, ACP-EC Energy Facility, Grant Application Form, p 1
[2] The United Nations Office of the High Representative for the Least Developed Countries (UN-OHRLLS)
[3] European Commission, ACP-EC Energy Facility, Grant Application Form, p 1

1.2. Organization

This Master's Degree project was performed on behalf of VANREPA with the founder of the organization, David Stein, as supervisor. In addition, the project was a *Minor Field Study* funded by Sida and KVA. The reviewer at Uppsala University was Marcus Berg, lecturer within wind power. The examiner was Kjell Pernestål.

1.3. Purpose

The purpose of this Master's Degree project was to suggest the design of renewable power supply systems at four sites on Futuna Island in the Republic of Vanuatu. The power supply systems are characterized as *Stand Alone Power Systems* (SAPS). The components included in this report are the major components in the designs: small scale wind turbines, solar modules, battery banks and cables. The following factors had to be estimated in order to make the designs:

- The power outputs from the existing solar modules and wind turbines
- The daily load at each site
- The required capacity of the battery banks at each site
- The required cable length and cable gauge at each site

It was required that the power systems will be easy to manage and maintain by the local communities on the island. In addition, as the generated power output will be extremely low, it was important to minimize losses and keep the system designs as simple as possible. Furthermore, due to financial constraints, it was important that the designs are economically sustainable.

1.4. Methodology

The execution of this Master's Degree project was divided into three sections. Initially, preparations and literature research in Sweden on stand-alone renewable power supply systems in general and on the conditions on Futuna Island in particular were made.

This part was followed by fieldwork in Vanuatu and meetings with the local project management teams. A field trip to Futuna was made for gathering necessary data in the projected area such as GPS coordinates for essential institutions at each site. Another important aspect of this visit was making daily energy use audits for the four sites. Power production, and therefore also consumption, is practically non-existent in Futuna at the moment. Because of this, the daily loads were estimated by interviewing local villagers at each site, to determine their requirements and needs.

Information about the power use of some existing appliances such as freezers, computers and lights were collected for the energy use audits during the fieldtrip. For non-existing appliances the power use in the energy use audits were based on well-known and widespread appliances available for purchase online. Information needed to calculate the estimated power outputs, such as wind conditions, topography and distances between key institutions were also gathered during the fieldwork in Vanuatu.

The last part of the project was carried out in Sweden in collaboration with the student's reviewer. During this part of the project the findings from the fieldwork were assembled and analyzed. In addition, necessary calculations for estimating the power outputs at the sites and sizing of the components were completed.

No long-term wind monitoring has ever been conducted on Futuna Island to this date. Because of this, wind- and solar data required for estimating the power outputs from the wind turbines and solar modules were obtained from NASA's databases. A wind assessment report performed on behalf of VANREPA by a volunteer and employee of the renewable energy consultancy *Garrad Hassan* was used to evaluate the accuracy of the data.

The most important literature source used in this report was *Stand Alone Power Supply Systems – Design and Installation,* a training manual by Global Sustainable Energy Solutions (GSES, Australia). Two other important sources were Paul Gipe's book *Wind Power – Renewable Energy for Home, Farm, and Business* (2004) and *Wind Energy Explained* (2009) published by John Wiley & Sons.

1.5. Delimitations

As described above, this Master's Degree project was part of a project managed by VANREPA, a project which also includes the island of Aneityum. However, due to the time constraints of this Master's Degree project, the study was limited to the design of the power supply systems on Futuna Island only.

Furthermore, the study was limited by the state of the VANREPA project at the time the author participated. For instance, the wind turbines (three turbines rated 600 W each) and solar modules (eighteen modules rated 60 W each) had already been purchased. This implies that there was no possibility to influence the generated output, as the number and size of the wind turbines and solar modules had already been determined.

This was also true for the placement of the turbines and modules at the sites, as the powerhouses for the battery banks had already been built. Given that both the generated output and the demand will be extremely low it was desired to minimize the power loss as much as possible, and therefore the placement of the turbines and modules should be in vicinity to the battery banks.

Moreover, it was desired that the designs of the power supply systems were as cost-efficient as possible, as the project experienced financial difficulties. This affected the maximum battery capacity possible to include in the designs and also limited the possibility to design systems adapted for future expansion. However, due to time constraints, it was not possible in this report to compare several different system design options in order to find the most economical solution. Instead, the simplest design solution was sought after.

Last but not least; no wind monitoring has been conducted on Futuna Island to this date and instead both wind and solar data were obtained from NASA's databases. Because of this, the calculated energy outputs were not as accurate as otherwise would have been possible.

1.6. Report Layout

Initially, a chapter describing the conditions and topography of Futuna Island and the four sites are presented (chapter 2). This chapter is followed by a theory chapter describing the technologies included in the system designs (chapter 3). Chapters 4-7 are concerned with features affecting the designs.

In the subsequent chapters, the power outputs and the load requirements at the four sites are estimated. After that, the battery banks and cables at each site are sized to meet the estimated production, consumption and losses in the systems. In this chapter, component costs are also presented.

Finally, the suggested designs are presented in chapter 8, followed by a discussion (chapter 9) and conclusions (chapter 10). The suggested designs presented in chapter 8 also contain an estimate of the total system cost at each site. In the final chapter (chapter 11), recommendations for this and future projects based on the findings of this report are given.

2. Description of the Sites

In the following chapter, conditions and topography of Futuna Island in general and the four sites proposed for power production in particular are described in detail. The key institutions requiring power supply and the estimated power consumption on each site will be identified and discussed in chapter 6.

2.1. Futuna Island

Futuna Island is a small island located in the easternmost part of Vanuatu, covering an area of approximately 13 km^2. Figure 1 illustrates the Republic of Vanuatu with its islands, also showing the country's location relative to Australia. The circled islands are Efate, with the country's capital city Port Vila (1) and Futuna Island (2).

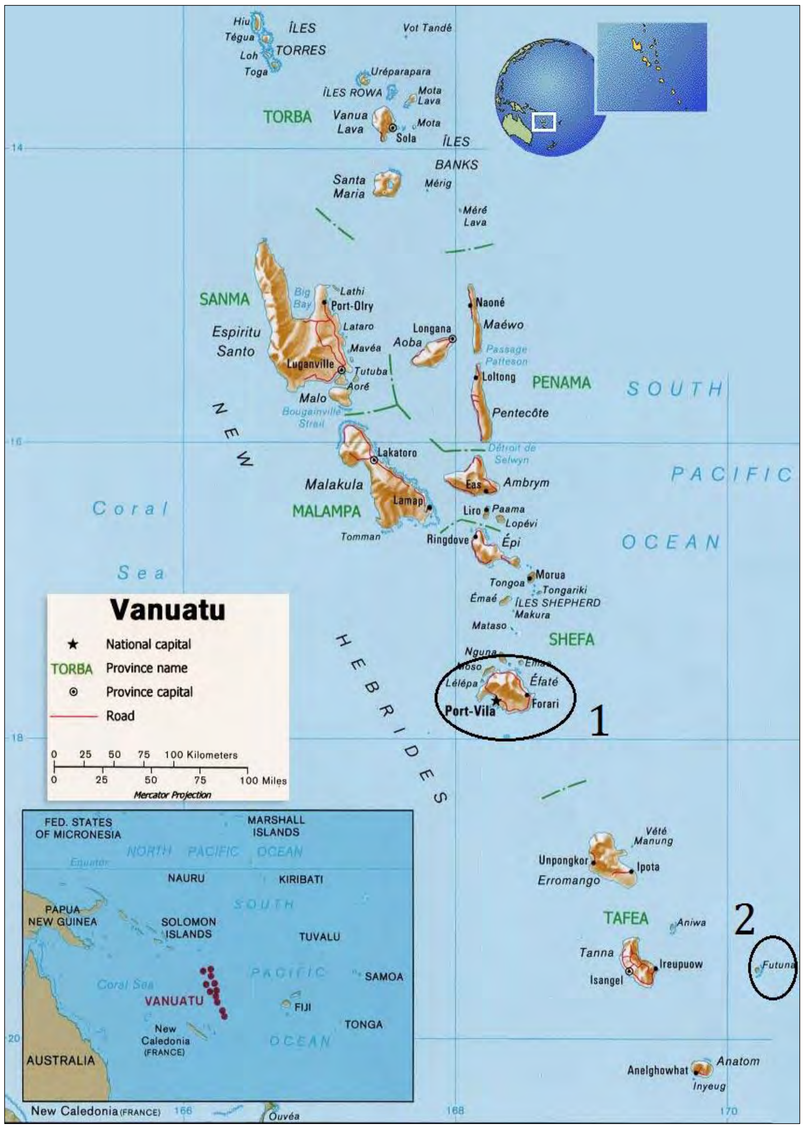


Figure 1: Map illustrating the Republic of Vanuatu. The circled islands are Efate, with the country's capital city Port Vila (1) and Futuna Island (2). (www.geographicguide.net/oceania/maps/vanuatu.jpg)

Futuna is made up of an extinct volcano with an altitude of 630 m above sea level. Very steep slopes characterize the landscape up from the coast, all around the island, into the dominating mountain in the center. The island is almost entirely covered by dense vegetation, apart from small cleared areas for farming and community spaces in the populated areas. There are a few flatter peninsulas around the coast, these being the populated areas of the island and therefore the desired locations of the wind turbines and solar modules.

The prevailing wind direction in the region is from southeast. This indicates that the part of the island facing towards southeast is likely to experience relatively undisturbed winds, as there are no other land areas in that direction for a tremendously long distance. However, due to the lack of open, clear areas and the steep slopes on the island, there are surprisingly few sites appropriate for wind generation. Furthermore, because of the dominating mountain in the middle of the island, the western part of the island is most likely not suitable for wind turbines as the wind experienced at this side would be much too turbulent.

In Figure 2, an overview map of Futuna showing the four sites proposed for the power supply systems is given. The sites chosen for wind power are *Mission Bay* and *Matangi*, both in good position of the prevailing wind direction, and *Herald Bay* and *Iahsoa*, facing west, where solar modules will generate the power.

Figure 2: Overview map of Futuna Island showing the four sites proposed for power supply systems. (Google Earth, date of picture 19-09-2005)

2.2. Mission Bay

The village of Mission Bay is located near the island's airstrip and is the administrative headquarter of the island. The village extends from the mountain slope toward the airstrip, the largest area of flat and cleared land on the island. There is a significant hill to the northeast of the airport. This area would be very suitable for wind power, except for the distance to the power users being too far away. Moreover, there are many trees scattered throughout the main village area acting as effective windbreaks, making this area less appropriate as well. The number of households in the village is approximately 20.

Two wind turbines rated 600 W each are proposed to be installed in the area. An overview map of the peninsula comprising Mission Bay together with a close-up map showing the village and the airport strip is displayed in Figure 3. The red dot illustrates the location of the powerhouse for the battery bank on the site. To minimize power loss, it is desirable to install the turbines as close to the powerhouse as possible.

Figure 3: Mission Bay overview and close-up maps. The red dot illustrates the location of the powerhouse for the battery bank on the site. (Google Earth, date of picture 19-09-2005)

The location chosen for the powerhouse is the flat, open terrain in the vicinity of the airport terminal building. This location is well exposed to the prevailing wind direction, is out of the shadow of the central mountain, is not located near any steep slopes and is easily accessed for both construction (close to airstrip) and use (close to village). As such, this site is most likely a good choice for the installation of wind turbines in the area. Figure 4 portrays the airport area also showing the powerhouse to the left.

Figure 4: Mission Bay powerhouse and airstrip.

2.3. Matangi

The area of Matangi is located in the southeastern part of the island. There are two small peninsulas here, one pointing south and one east on which clusters of villages are scattered. Most of the houses are located on the southern peninsula, where the villages of *Ileke*, *Inokoke* and *Imarae* are found. These villages consist of approximately 20 households in total. The coastline in the area is steep with rocky slopes and cliffs. The household clusters are generally surrounded by trees, particularly along the coastline, which act as windbreaks.

One 600 W turbine is proposed to be installed in the area. The powerhouse has been built near the village of Inokoke, on the southern peninsula. In Figure 5, a map of the southern peninsula together with a close-up map of the village is shown. The red dot in the close-up map indicates the location of the powerhouse for the battery bank on the site.

Figure 5: Matangi overview and close-up maps. The red dot indicates the location of the powerhouse for the battery bank on the site. (Google Earth, date of picture 19-09-2005)

The area chosen for the powerhouse is an open clearing of approximately 30x30 m. There are scattered 15-20 m tall palms in the easterly direction and a 15 m tall She-oak in the southeasterly direction, both in the prevailing wind direction. Thus, the trees will act as windbreaks, reducing the wind speed experienced at the site and increasing the level of turbulence. There is also a steep slope to the northeast of the site, which should have little effect on the wind regime, as winds from the northeast are rare. Figure 6 displays the Matangi powerhouse site and surroundings. Colored circles are used to identify identical objects on the three photos.

Figure 6: Matangi powerhouse site and surroundings. The colored circles are used to identify identical objects on the three photos.

2.4. Herald Bay

The village of Herald Bay is located on the northwestern side of the island and is the largest village with approximately 40 households. The prevailing winds in the area are being diverted around the central mountain, suggesting that the wind regime experienced in the region is turbulent and as such not suitable for wind power generation. Because of this, it has been decided that solar modules will be used instead of wind turbines to generate power in the village. It has been proposed that 12 modules of 60 W each will be installed on the site. Figure 7 displays an overview map of the Herald Bay area and a close-up map of the village. The red dot marks the location of the powerhouse built on the site.

Figure 7: Herald Bay overview and close-up maps. The red dot marks the location of the powerhouse built on the site. (Google Earth, date of picture 19-09-2005)

2.5. Iahsoa

Iahsoa is a small village of about 20 households located on the western peninsula. The mountain rises very steeply to the east of the village, located on a flat area of land on the top of a cliff about 40-50 m above the beach. As with Herald Bay, Iahsoa is sheltered from the prevailing wind direction by the central mountain, and therefore solar modules will be used instead of wind turbines to generate power. It has been proposed that 6 modules of 60 W each will be installed in the area. Figure 8 illustrates an overview map of the area together with a close-up view of the Iahsoa village. The red dot in the close-up map indicates the location of the powerhouse for the battery bank on the site.

Figure 8: Iahsoa overview and close-up maps. The red dot in the close-up map indicates the location of the powerhouse for the battery bank on the site. (Google Earth, date of picture 19-09-2005)

3. Theory

In this chapter, the technologies included in the renewable power system designs on Futuna Island will be discussed. The focus of the chapter will be on wind turbines, solar power, batteries and cables, as these are the main elements included in the designs.

3.1. Small Scale Wind Power

Historically, small-scale wind power is best known for pumping water and grinding grain. In addition, wind power has also gained a reputation for the ability to generate power off the grid at remote sites. This is particularly true at sites far from the main power grid. According to a general rule, if the distance to the closest power grid is more than 1 km, it will be cheaper to install an independent power system than connecting to the power grid[4].

Today, about three-fourths of all small-scale wind turbines are installed in stand-alone power systems at remote sites[5]. Small-scale wind turbines are defined as turbines with a power output in the range of 0.5-50 kW[6]. This section of the report deals with technical aspects of small-scale wind power and conditions associated with the power output of wind turbines.

3.1.1. Wind Power System Options

3.1.1.1. Grid Connected Wind Power Systems

Wind power systems directly connected to the power grid do not require batteries to store surplus electric energy. Instead, the electric energy produced in excess of demand will supply the grid. Conversely, when the turbines are inactive, electric energy is supplied by the grid.

Compared to off-grid wind power systems, grid-connected wind power systems are relatively simple. In addition, they are less expensive than systems including battery back-up and require less maintenance. A disadvantage of these systems is that they might be vulnerable to grid failure[7].

3.1.1.2. Off-grid Wind Power Systems

In off-grid systems, the power produced by the wind turbine will charge a battery or bank of batteries. Rectifiers convert the variable frequency produced by the turbine into direct current stored in the batteries. Thereafter, inverters are used to convert the low voltage electric energy from the battery bank into the voltage required by the household.

Off-grid systems powered by renewable energy sources are particularly vulnerable to shortfalls, due to the intermittent nature of the power sources. This can be avoided by the use of back-up diesel generators or by combining different power sources, such as hybrid systems including both wind and solar power.

[4] Gipe, P., 2004, p 13
[5] Gipe, P., 2004, p 13
[6] Wineur 2005
[7] Chiraz, D., 2010, p 46

Hybrid systems combining wind turbines with PV arrays are usually very successful due to the variability of the wind throughout the year. In many places, the sun and the wind complement each other and thus provide a more consistent year-round output than either of the systems would do by themselves[8].

These power systems are generally the most complex of all options. They are also generally the most costly wind energy systems, except when they are located a certain distance away from the nearest grid. In addition, they require more maintenance and are less efficient than grid-connected systems[9].

3.1.2. Factors Affecting the Power Output

Using the fundamental equation of kinetic energy, the power in the wind can be calculated[10]:

$$P = \frac{v^2}{2} \times \frac{dm}{dt} = \left[\!\left[\frac{dm}{dt} = \rho A v \right]\!\right] = \frac{\rho A v^3}{2} = \frac{\pi}{8} \times \rho \times D^2 \times v^3 \qquad [3.1.1]$$

P = power output of the turbine [W]
v^3 = wind speed [m/s]
ρ = air density [kg/m^3, 1.205 kg/m^3 for dry air at 20^{o}C]
A = swept area of the rotor [m^2]
D = diameter of the rotor [m]

The theoretical optimal power can only be obtained during best possible conditions, which is to say when all parameters involved act in favor of the generated output. However, several factors affect the maximum possible power output from a wind turbine. Some of these are listed below and will be further discussed in the following sections:

- Betz limit
- Wind speed
- Frequency distribution of the wind
- Friction and turbulence
- Spacing of several turbines at a site
- Rotor diameter
- Tower height

3.1.2.1. Betz Limit

According to fundamental laws of physics, it is not possible to capture all the power available in the wind. The theoretical limit of the power in the wind that is possible to capture by the rotor is called the Betz limit, named after the German aerodynamicist Albert Betz, who derived it. Betz demonstrated that the optimum between a rotor that completely stops the wind and one that

[8] Chiraz, D., 2010, pp 55-56
[9] Chiraz, D., 2010, p 55
[10] Wizelius, T., 2007, p 48

does not affect the wind at all is attained when the rotor reduces wind speed to one-third of the original volume[11].

However, most wind turbines operate at efficiencies much less than the Betz limit. The power coefficient C_P is used to characterize the efficiency of a turbine and is defined by the following expression[12]:

$$C_P = \frac{P}{\frac{1}{2}\rho v^3 A} = \frac{Rotor\ power}{Power\ in\ the\ wind} \qquad [3.1.2]$$

C_P = power coefficient of turbine [dimensionless]
P = rotor power [W]
v = wind speed [m/s]
ρ = air density [kg/m^3, 1.205 kg/m^3 for dry air at 20^{o}C]
A = swept area of the rotor [m^2]

Another expression for C_P is $C_P = 4a(1-a)^2$, where “a” is the so called *axial induction factor*, i.e. the relative reduction of the wind speed at the turbine. In this expression, substituting “a” by “1/3” gives the maximum theoretical value of the power coefficient[13]: $C_{P,max}$ = 16/27 ≈ 0.59

The maximum value of C_P differs between turbines and greatly depends on the chosen product design as well as on the wind speed. The typical maximum of C_P for small wind turbines is 0.25. In the equation below, the power coefficient has been added to equation [3.1.1]:

$$P = \frac{\pi}{8} \times \rho \times D^2 \times v^3 \times C_P \qquad [3.1.3]$$

P = power output of the turbine [W]
v^3 = wind speed [m/s]
ρ = air density [1.205 kg/m^3 for dry air at 20^{o}C]
D = diameter of the rotor [m]
C_P = power coefficient of wind turbine [dimensionless]

3.1.2.2. Wind Speed

Wind is created by differences in atmospheric pressure that in turn are caused by differences in air temperature[14]. According to equation [3.1.1], the power from the wind increases by a factor 4 as the diameter of the rotor doubles, and by a factor 8 as the wind speed doubles. Thus, in order to generate more electric energy it is important that a potential wind site has good winds, especially when small-scale wind turbines are used.

3.1.2.3. The Frequency Distribution of the Wind

Although two sites might have identical mean wind speed, the *energy content* of the wind at the same two sites may not be equal. The average of the cube of many different wind speeds will always be greater than the cube of the average speed, as it is the winds above the average that contribute most of the power[15].

[11] Manwell, J.F. et al, 2009, pp 92-93
[12] Manwell, J.F. et al, 2009, p 94
[13] Manwell, J.F. et al, 2009, p 95
[14] Wizelius, T., 2007, p 34
[15] Gipe, P., 2004, pp 35-36

Thus, in addition to knowing the mean wind speed at a certain site, it is also important to have an idea about the energy content of the wind at the same site. This can be calculated by knowing the duration of different wind speeds, also known as the *frequency distribution of the wind*. The frequency distribution of the wind is a way to illustrate the number of times winds occur at various speeds throughout the year. In general, the frequency distribution of the wind fits well with an asymmetric, bell-shaped curve called *the Weibull distribution*, as shown in Figure 9.

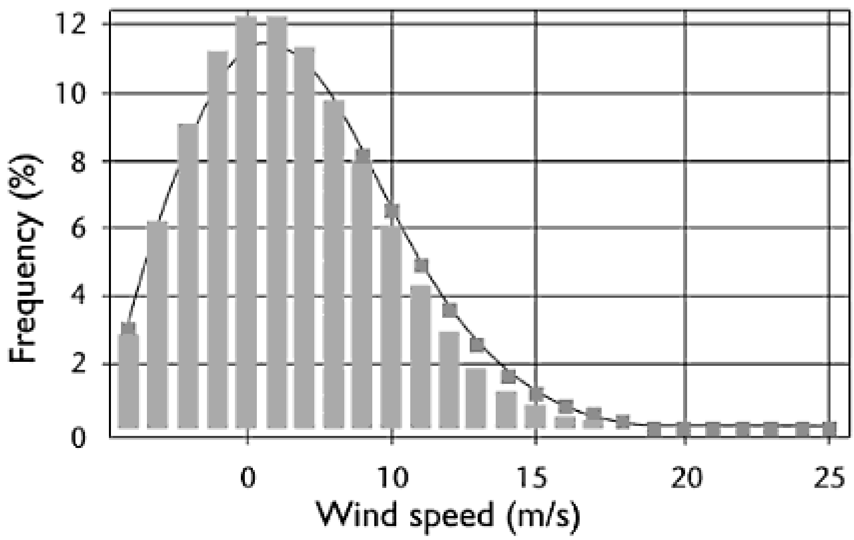


Figure 9: Weibull distribution.
(Wizelius, T 2007, p 50)

The shape of the *Weibull distribution*[16] is controlled by a variable called *shape factor* (k). High values of k correspond to a site with long periods of steady winds such as trade winds. A sheltered site generally has lower k values. In general, k tends to increase with increasing mean wind speed and height above ground level[17].

The *Rayleigh distribution*[18] is a special case of the Weibull distribution, with shape factor k=2. This relationship holds for many sites but might underestimate or overestimate the potential at other sites. Trade wind sites often have high average wind speeds. However, the winds are steady, and they have few occurrences of extremely high winds. At sites like these, the Rayleigh distribution will overestimate the potential power generation[19].

3.1.2.4. Friction and Turbulence

When wind flows across land or water, *friction* occurs due to the roughness of the surface. This reduces the speed at which air moves over a surface and is referred to as *ground drag*[20]. The

[16] GSES, p 149
[17] GSES, p 150
[18] Wizelius, T., 2007, p 50
[19] Gipe, P., 2004, p 36
[20] Chiraz, D., 2010, p 24

greatest effects of friction are encountered closest to the Earth's surface and can affect the wind speed considerably.

When the wind hits an obstacle, air whirls or waves are formed which force the wind to move in different directions around the prevailing wind direction. This creates short variations in wind speed, which is called *turbulence*. Turbulent wind flow causes stress on the turbine blades and can also reduce the generated power[21]. This is particularly true if the wind turbine does not react quickly enough to take advantage of the new wind direction.

According to a simple rule of thumb, an obstacle creates turbulence to *double the height of the obstacle, starts at a distance of twice the height in front of it and continues for 20 times the height behind it*, as illustrated in Figure 10.

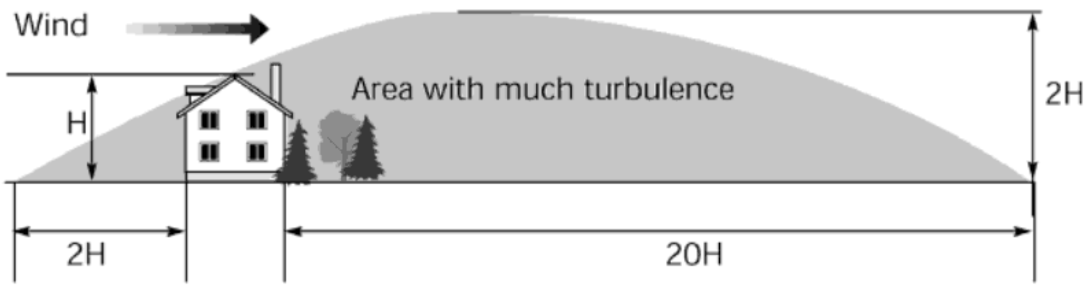


Figure 10: Turbulence from an obstacle.
(Wizelius, T 2007, p. 43)

Certain characteristics of an obstacle such as height, width and porosity, determine how much impact it will have on the wind[22]. Also, in general, gentle slopes enhance the wind speed and abrupt slopes cause turbulence[23].

3.1.2.5. Spacing of Several Turbines at a Site

When installing more than one turbine at the same site, the turbines should be separated by certain distances to avoid turbulence and minimize losses. In general, a separation distance of at least 8-10 rotor diameters apart in the prevailing downwind direction is recommended[24]. In the crosswind direction, at separation distance of at least 5 rotor diameters is recommended[25]. If shorter separation distances are used, more wind turbines can be installed at the site but each turbine will capture a smaller part of the energy available in the wind. Figure 11 illustrates the recommended set up of several turbines at a site with a dominating wind direction.

[21] Wineur 2005
[22] Wizelius, T., 2007, p 42
[23] GSES, p 154
[24] Manwell, J.F. et al, 2009, p 423
[25] Manwell, J.F. et al, 2009, p 423

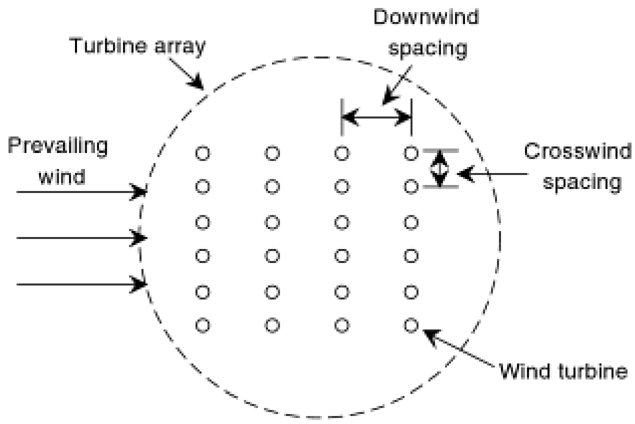


Figure 11: Recommended spacing of turbines.
(Manwell, J.F. et al 2009, p 422)

3.1.2.6. Rotor Diameter

For conventional, horizontal axis wind turbines, the swept area can be calculated as the area of a circle[26]:

$$A = \pi r^2 \qquad [3.1.4]$$

A = area of the rotor [m^2]
r = radius of the rotor [m]

According to this formula, even small increases in blade length produce a large increase in swept area; doubling the diameter increases the swept area four times. The rotor diameter, therefore, gives a good indication about how much power a certain wind turbine can generate.

3.1.2.7. Tower Height

Mounting a wind turbine on a tall tower maximizes the electrical output of the machine as wind speed increases with height above the ground. Not only does the wind speed increase with height, the turbulence decreases as well. Even a small increase in wind speed can result in a substantial increase in the amount of power that is available in the wind, and hence the amount of electric energy the wind generators can produce.

The change in wind speed with height is also referred to as *wind shear*[27]. The rate at which wind speed increases with height varies with the degree of surface roughness[28]. For instance, the benefit of mounting a turbine on a taller tower is greater when the turbine is sited in hilly terrain than in smooth terrain. Moreover, the change of wind speed with height is less pronounced and more erratic at low wind speeds. The *power law* equation can be used to calculate the increase in wind speed with height[29]:

[26] Gipe, P., 2004, p 32
[27] Gipe, P., 2004, p 40
[28] Gipe, P., 2004, p 40
[29] Gipe, P., 2004, p 41

$$V = \left(\frac{H}{H_o}^{\alpha}\right) \times V_o \qquad [3.1.5]$$

V = wind speed at the new height [m/s]
V_o = wind speed at the original height [m/s]
H = new height [m]
H_o = original height [m]
α = wind shear exponent [dimensionless]

Alternatively, a logarithmic profile, or the *log law*, can be used[30]:

$$\frac{U(z)}{U(z_r)} = \frac{ln\frac{z}{z_0}}{ln\frac{z_r}{z_0}} \qquad [3.1.6]$$

U(z) = wind speed at height z [m/s]
$U(z_r)$ = reference wind speed at height z_r [m/s]
z_0 = surface roughness length [m]

In Table 1, the approximate values of surface roughness length (z_0) and the wind shear exponent (α) for various types of terrain have been summarized:

Table 1: Surface roughness length (z_0) and wind shear exponent (α).

Terrain description	z_0 (mm)	α
Very smooth, ice or mud	0.01	0.07
Calm open sea	0.2	0.09
Blown sea	0.5	0.09
Snow surface	3	0.11
Lawn grass	8	0.12
Rough pasture	10	0.14
Fallow field	30	0.16
Crops	50	0.19
Few trees	100	0.21
Many trees, hedges, few buildings	250	0.24
Forest and woodlands	500	0.29
Suburbs	1500	0.31
Centers of cities with tall buildings	3000	0.43

Sources: Manwell, J.F. et al 2009 and Gipe, P 2004

Both methods above describe the average wind shear and require that the surface roughness, or wind shear exponent, is approximated. This might be challenging, as the exponent varies with the time of day, season, terrain and stability of the atmosphere[31]. Generally, shear is low where there is minimum surface roughness and high where there are several objects to disturb the flow[32].

[30] Manwell, J.F. et al, 2009, p 45
[31] Gipe, P., 2004, p 41
[32] Gipe, P., 2004, p 41

3.2. Solar Photovoltaic Power

The use of solar photovoltaic power is growing rapidly as a source of energy. This is particularly true in developing countries where the solar radiation levels are high and the power grids often are undeveloped. This was recognized on the 2002 United Nations *World Summit on Sustainable Development*, emphasizing that PV-modules and other renewable energy sources have the potential to meet the needs of the world's poorest people at an affordable price[33]. In this section of the report, the PV-technology and aspects associated with the power output of solar modules will be further discussed.

3.2.1. Solar Cells, Modules and Arrays

A *solar cell*, also called *photovoltaic cell*, converts the energy of the sunlight into electric energy by the photovoltaic effect. The majority of commercial solar cells are composed mainly of silicon. Basically, to produce electric energy the silicon absorbs the incoming photons in the sunlight, releasing an electron flow in the material.

In electrical systems powered by solar cells, *solar modules* can be arranged together to form an *array* with the particular voltage and current required by the system. Solar modules consist of solar cells joined physically and electrically. Connecting cells in series keeps the current the same, but the voltage of each cell is added. Connecting cells in parallel gives the opposite effect; the current of each cell is added but the voltage remains the same.

The same principle applies for connecting modules in series and parallel. Modules joined in series form a *string*, which can be wired in parallel to form a solar array, according to Figure 12.

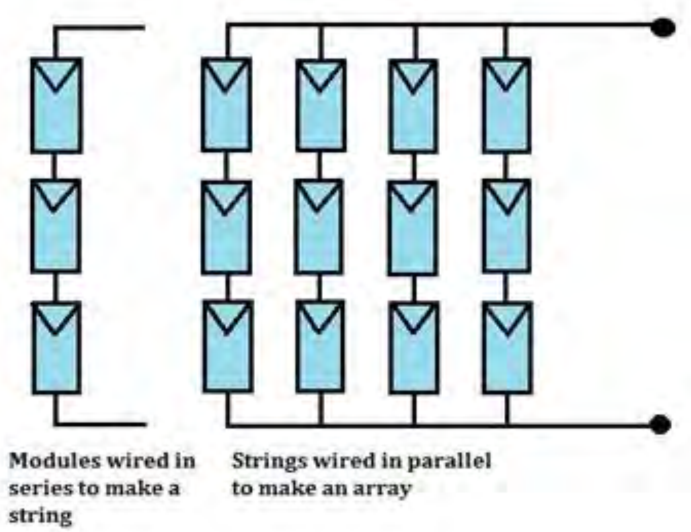


Figure 12: Modules wired to make strings and arrays.

It is required that the voltage generated by the array is equal to or higher than the nominal voltage level of the system, so that the battery bank can be charged from the array at varying levels of

[33] Boyle, G., 2004, p 85

irradiance[34]. Consequently, the voltage level of the modules connected in series should exceed the voltage level of the battery bank. Thus, the required number of modules in a string is given by[35]:

$$N_s \geq \frac{V_{dc}}{V_{mod}} \qquad [3.2.1]$$

N = number of modules in a string
V_{dc} = system voltage [V]
V_{mod} = nominal voltage of the module [V]

After determining the number of modules connected in series, the number of parallel strings can be determined according to the following relationship:

$$N_p = \frac{N}{N_s} \qquad [3.2.2]$$

N_P = number of parallel strings
N = total number of modules
N_S = number of modules in a string

3.2.2. Factors Affecting the Power Output

The average daily energy output of a PV-array, E_{PV}, is given by the following equation[36]:

$$E_{PV} = P_{mod} \times H_{tilt} \times N \qquad [3.2.3]$$

E_{PV} = the average daily energy output of a PV-array [Wh]
P_{mod} = derated output of the module [W]
H_{tilt} = daily irradiation in PSH for the specific tilt angle [hours]
N = number of modules in the array [dimensionless]

In the equation above, H_{tilt} equals the daily irradiation in *Peak Sun Hours*[37] (PSH) for the specific tilt angle. The number of daily peak sun hours is the equivalent number of hours per day when solar irradiance averages 1 kW/m^2.

Several aspects, both site specific and aspects associated with the solar modules, affect the maximum power output of the array. Some of these aspects are listed below and will be further discussed in the following sections:

- Solar irradiation
- Siting
- Maximum power point
- Derating factors

[34] GSES, p 69
[35] GSES, p 202
[36] GSES, p 204
[37] GSES, p 24

3.2.2.1. Solar Irradiation

The short circuit current, and thus also the power output, varies almost linearly with the solar irradiance[38]. *Solar irradiation* is defined as the total quantity of radiant solar energy per unit area received over a given period of time[39]. On a clear, sunny day at noon on the earth's surface at the equator, the solar irradiation is about 1 kW/m^2. *Solar trackers* are devices that can be used to ensure that modules are always facing the sun and thus obtain maximum power from the irradiance.

3.2.2.2. Siting

To obtain the optimal power output, the placement of a solar module should be in relation to the sun's altitude at *Solar Noon*, the sun's highest altitude, which typically occurs between 11 am and 1 pm. The module should be tilted so that the sun's rays are perpendicular towards the solar module. The optimal *tilt angle*[40] of a module is generally the latitude plus 5-15^o. For the latitudes between 15^o and 23.5^o, the module is generally tilted by 15^o to 20^o. A minimum recommended tilt angle of 10^o should be applied in order to allow for self-cleaning by rainwater[41].

3.2.2.3. Maximum Power Point

The power produced by a solar cell is the product of the voltage (V) and the current (I). As a consequence, the power output of a solar cell equals zero when either the current or the voltage equals zero. An IV-curve is used to illustrate this relation[42]. At maximum current, also called the *short circuit current* (I_{sc}), the voltage is zero. Oppositely, *open circuit voltage* (V_{oc}) is obtained when the electric current is zero. *Maximum power* (P_{mp}) is produced when the voltage equals V_{mp} and the current equals I_{mp} as illustrated in Figure 13 below. This point is also known as the *maximum power point* (MPP). It is important to make sure that solar cells operate at or close to the MPP.

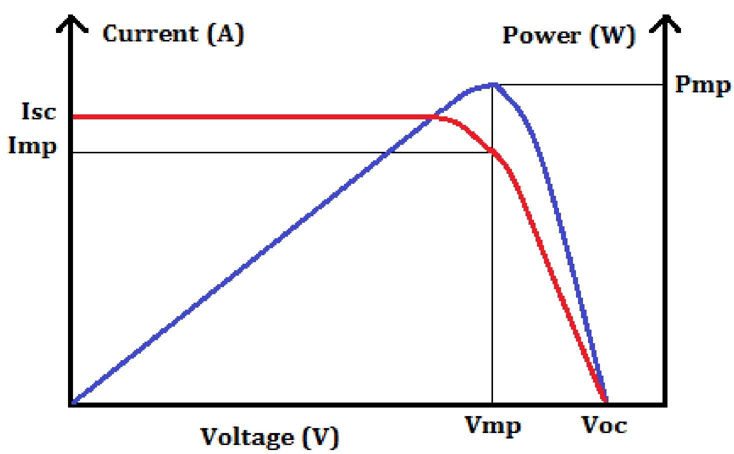


Figure 13: Graphical illustration of the Maximum Power Point. The red line equals current (A) and the blue line equals voltage (V). At the short circuit current, or maximum current (Isc), the voltage is zero. At the open circuit voltage, or maximum voltage (Voc) the current is zero. Maximum power (Pmp) is produced when the voltage equals Vmp and the current equals Imp.

[38] GSES, p 56
[39] GSES, p 23
[40] GSES, p 17
[41] GSES, p 200
[42] GSES, p 52

3.2.2.4. Derating Factors

Commonly available silicon cells have an average efficiency of about 14-17 %[43]. However, the life span and efficiency of solar cells are dependent on derating factors such as *manufacturer's tolerance*, *dirt* and *temperature*[44].

It is common that manufacturers derate their modules by a percentage or wattage. Unless tested, the modules should be derated by the percentage given by the manufacturers. Furthermore, dirt or salt building up on the array over a period of time is generally lowering the output by 0-10 %. This is especially true if the modules are located near the coast.

The power output of a solar module also decreases with increasing temperature. As a rule of thumb[45], the output power changes 0.5 % for every 1°C temperature change, decreasing for temperatures above 25°C and increasing for temperatures below 25°C. Therefore, to prevent overheating of modules, it is important to provide adequate ventilation by mounting the module on a tilted frame. Mounting a module flat on a roof makes it difficult for the heat to dissipate through convection[46].

The power output of a solar module modified according to the derating factors discussed above, P_{mod}, is given by the following equation[47]:

$$P_{mod} = P_{STC} \times f_{man} \times f_{temp} \times f_{dirt} \qquad [3.2.4]$$

P_{mod} = derated output of the module [W]
P_{STC} = rated power output [W]
f_{man} = manufacturer's tolerance derating factor [dimensionless]
f_{temp} = temperature derating factor [dimensionless]
f_{dirt} = dirt derating factor [dimensionless]

3.3. Batteries

Because of the intermittent nature of most renewable energy sources and the shift in demand over the day, electric energy needs to be stored in order to match the production with the consumption. This is especially true for off-grid, small scale solar or wind powered systems. Battery storage is the most convenient and cost effective method of storage for most stand-alone power systems.

The most cost effective batteries for stand-alone power systems are vented (flooded) *lead acid* batteries. Batteries for SAPS need to have good cycling ability. *Deep cycle* batteries are generally used for this purpose[48]. This section of the report handles technical aspects of batteries used in renewable power systems, factors to consider when sizing a battery bank and factors associated with the battery capacity.

---

43 GSES, p 25
44 GSES, p 200
45 GSES, p 56
46 GSES, p 56
47 GSES, p 203
48 GSES, p 83

3.3.1. Battery Components

In most batteries, each individual cell produces a nominal voltage of 2 V. For higher voltages, some manufacturers sell two or three cells connected in one container. To obtain even higher voltages or currents the installer must connect the batteries in series and parallel strings. As with solar modules, connecting batteries in series adds the voltage of each battery whereas the current stays the same. Connecting batteries in parallel strings gives the opposite effect. It is important that the batteries connected are all of the same nominal voltage, current and of the same age. Also, batteries in a battery bank must be of identical capacity, model and from the same manufacturer[49].

3.3.2. Factors Affecting the Battery Bank Capacity

At least 10 years of useful life is reasonable to expect from a correctly sized, selected and maintained battery bank. However, several factors contribute to battery degradation over time, and thus affect the maximum capacity of the battery[50]. Some of these factors are listed below and will be further discussed:

- Discharge rate
- Depth of discharge (DOD)
- Battery temperature
- Self-discharging

3.3.2.1. Discharge Rate

When fully charged, every cell in a battery has the potential to produce a certain number of ampere hours. This capacity is generally specified for a given cell temperature and *discharge rate*, meaning the number of hours that a certain discharge current can be supplied by that battery[51]. The discharge rate is usually given as either C_{20} or C_{100}. For instance, if the battery capacity is stated as C_{20} = 100 Ah, it can provide 5 A continuously for 20 hours. However, a faster discharge rate means less capacity available. If the battery above would discharge at 10 A instead of 5 A, it would only last for 10 hours.

The battery bank capacity at a certain discharge rate, C_x, can be calculated by the following formula[52]:

$$C_x = \frac{E_{tot}}{V_{dc}} \times \frac{T_{aut}}{DOD_{max}} \qquad [3.3.1]$$

C_X = battery bank capacity at a certain discharge rate [Ah]
E_{tot}= total daily energy requirements [Wh]
V_{dc} = battery bank or system voltage [V]
T_{aut} = total number of days of autonomy [dimensionless]
DOD_{max} = maximum daily depth of discharge [dimensionless]

---

[49] GSES, p 97
[50] GSES, p 89
[51] GSES, p 87
[52] GSES, p 192

In the equation above, the total number of *days of autonomy* equals the maximum number of days that the batteries can supply the daily demand, assuming that there is no input from the energy source.

3.3.2.2. Depth of Discharge

The *depth of discharge* (DOD) is a measurement of how much of the total battery capacity that has been used. Generally, the maximum recommended depth of discharge is around 70 % and is specified by the manufacturer[53]. However, if the battery is regularly discharged to this depth it will affect the possible number of cycles for that battery and thus reduce the battery lifetime. Therefore, to increase battery life, the daily depth of discharge should be kept below 20 %[54].

3.3.2.3. Battery Temperature

The rate of chemical reactions in a battery is reduced during cold periods, which in turn results in a loss in battery capacity. Because of this, batteries should not be kept on the ground, as they will adopt the temperature of the material of the ground. A temperature interval of 20-25^{o}C is recommended for the battery environment[55]. Moreover, moisture should be kept away from batteries to prevent corrosion[56].

3.3.2.4. Self-discharging

Batteries lose capacity over time and are considered to be at the end of their lifetime when they cannot be charged to more than 80 % of their original capacity[57]. The rate of loss due to chemical reactions in battery cells even under no load is called *self-discharge rate*. This can be from 1 % to 3 % per month and as batteries age the discharge rate generally increases[58].

3.4. Cables

Small-scale renewable power systems are particularly vulnerable to power loss, as both the power sources and the load are relatively small. Power loss will reduce the system efficiency and life expectancy of most appliances and equipment. On the charging side, where too much voltage is lost, there may be insufficient voltage to charge the batteries[59].

Thus, it is especially important that cables used for power transmission in these systems are sized to keep the voltage drop to a minimum. Furthermore, if the cables are selected to carry only the maximum demand current in the installation, then there is no scope for extending the system without re-wiring[60]. The cables should therefore be oversized to allow for future expansion of the system. In this section, factors affecting the voltage drop in cables will be further discussed.

---

[53] GSES, p 88
[54] GSES, p 89
[55] GSES, p 95
[56] GSES, p 98
[57] GSES, p 88
[58] GSES, p 91
[59] GSES, p 259
[60] GSES, p 259

3.4.1. Factors Affecting the Voltage Drop

Cables from the renewable power source to the batteries should be fitted so that the voltage drop between the source and the batteries is less than 5 % of the system voltage. It is also recommended that the voltage drop between the batteries and any load should be limited to 5 %[61]. The voltage drop (V_d) in a cable can be determined by[62]:

$$V_d = \frac{2 \times L \times I \times \rho}{A} \qquad [3.4.1.]$$

2 x L = round trip length of conductor [m]
I = current [A]
ρ = resistivity of wire [$\Omega mm^2/m$]
A = cross sectional area of cable [mm^2]

Cable loss is a function of three parameters as listed below and each of these will be discussed in the following sections:

- Cross sectional area
- Cable length
- Current carrying capacity

3.4.1.1. Cross Sectional Area

From equation [3.4.1], it becomes obvious that the conductor's cross sectional area (CSA) affects the voltage drop. According to the equation, the greater the cross sectional area is, the less the voltage drop gets. It is desirable to reduce the voltage drop as much as possible and thus, when unsure, the larger cable size should always be selected[63]. Different sizing systems are used to determine the appropriate cable size. Cable sizes according to the international standard *IEC 60228* for conductors and insulated cables are given in Appendix G.

3.4.1.2. Cable Length

Voltage drop is the loss of voltage due to the resistance of the cable. The greater the cable length, the greater is its resistance to current flow[64]. To maximize the system efficiency and lifetime of most appliances and equipment, it is therefore important to avoid excessive cable runs.

3.4.1.3. Current Carrying Capacity

The maximum current capacity of a conductor is referred to as *Current Carrying Capacity* (CCC). A conductor's capacity to carry current increases as the diameter (cross sectional area) of the conductor increases. Other factors such as the environment in which the cable is installed and the type of circuit protection provided also affect the CCC. Insufficient CCC rating can result in overheating and, in turn, wasted energy and inefficiency[65]. Thus, it is always important to check the CCC rating for the selected cable.

---

[61] GSES, p 260
[62] GSES, p 260
[63] GSES, p 261
[64] GSES, p 259
[65] GSES, p 263

4. Design Procedure and Overall Design Considerations

As explained in the introducing chapter, the renewable power supply systems that will be designed in this report will be based on the existing power-producing equipment, i.e. eighteen 60 W solar modules and three 600 W wind turbines. The following design procedure will be applied:

1. The total energy output of the wind turbines and the solar modules at each site will be approximated.
2. The load requirements of the systems at each site will be based on energy use audits in each village.
3. The required size of the battery banks and cables at each site to balance the load and energy outputs including losses will be determined.

The basic goal of the design is to properly size the components to ensure that the loads will have close to constant power supply year-round. Furthermore, as this is only a first step towards electrification of Futuna Island, the systems should be designed to allow for future growth. Furthermore, because the project is experiencing financial constraints, the system designs should be as simple as possible, and losses should be kept to a minimum.

The following aspects will be considered in the system designs:

- The power outputs of the wind turbines will be estimated according to the average wind speed in Futuna (data from NASA) and corresponding power output of the given wind turbine (Ampair 600 test results).
- The power outputs of the solar modules will be estimated according to the average solar insolation in Futuna (data from NASA).
- The battery banks will be sized to allow for a certain amount of days of autonomy and a maximum depth of discharge, to increase battery lifetime.
- The battery banks will be sized according to the annual average power output of the wind turbines and solar modules OR the daily load, whichever is greater.
- All cable lengths will be kept to a minimum to reduce the total cost of the systems. However, the cross sectional areas of the cables will be properly sized to minimize voltage drops and thus the larger cable size will always be selected according to the standard cable sizes given in Appendix G.
- The cables from the wind turbines to the battery banks will be sized according to the maximum expected generated current from the turbines. This will be based on the maximum power output achieved according to the turbine test results in Appendix A.
- The cables from the solar modules to the battery banks will be sized according to the maximum expected generated current from the solar modules. This will be based on the module specifications given in Table 6.
- The cables from the battery bank to the load will be sized according to the maximum power consumption expected of the specific load. It will be assumed that the maximum power consumption occurs when all the appliances are used at the same time.

5. Energy Output at Each Site

5.1. Wind power

In this section, the daily energy output of the wind turbines at each site will be estimated. As mentioned in the theory section, the fundamental equation of kinetic energy can be used to calculate the power output. However, the design of the wind turbine and several site-specific aspects also affect the output. They will be examined more thoroughly in the following sections.

5.1.1. Selected Wind Turbine

The wind turbine selected by VANREPA for power production at the sites in Futuna is manufactured by Ampair in UK. The turbine is rated 600 W and has a three-bladed, upwind turbine[66]. All turbine materials are suitable for marine use, including seafront locations, according to the manufacturer. A picture of the turbine on a tilt-up tower is shown in Figure 14 and the specifications of the turbine are given in Table **2**.

Table 2: Turbine specifications.

SPECIFICATIONS*		
Rated power	600	W
Nominal voltage	24	V
Rotor diameter	1.7	m
Swept area	2.27	m^2
Tower height	12	m
Total weight	16	kg
Cut-in wind speed	3	m/s
Cut-out wind speed	N/A	

* Data from Ampair 600 Brochure

Figure 14: Ampair 600 W on a tilt-up mast. (Photo from Ampair 600 Brochure)

5.1.2. Power Coefficient

As explained in the theory chapter, the power coefficient of the generator differs between turbines and greatly depends on the chosen product design. However, a maximum value of $C_P = 0.25$ is typical for small wind turbines. In Appendix A, test data for Ampair 600 W performed by *New and Renewable Energy Centre* (NaREC) have been summarized. The test was performed in Great Britain over a period of 961 hours. The power curve and the power coefficient of the test data are given in Appendix B.

According to the test, the reference power at 11 m/s is 231 W, which equals a power coefficient of about 12 %. The maximal power coefficient obtained in the test is 24.7 %. However, this efficiency is only experienced for wind speeds around 5-6 m/s. For wind speeds lower or higher than this interval, the power coefficient is considerably lower.

[66] Ampair 600 Brochure

5.1.3. Wind Speed at the Sites

According to equation [3.1.1]: $P = \frac{\pi}{8} \times \rho \times D^2 \times v^3$, the power from the wind increases by a factor 8 as the wind speed doubles. Thus, in order to generate more electric energy it is important that a potential wind site has good winds, especially when small-scale wind turbines are used.

A description of the wind climate at a potential turbine site is most appropriately determined using wind data recorded at the site. However, no wind monitoring has been conducted on Futuna Island to date. Because of this, the calculation of the power output will instead be based on satellite data from NASA, together with the test data of the specific wind turbine.

In Table 3 below the monthly averaged wind speed at 10 m above ground level for Futuna Island has been summarized together with the corresponding power outputs, power coefficients and daily energy outputs of the specific turbine. The wind resource power in the table has been calculated according to equation [3.1.1]. The actual power and energy outputs of the given turbine have been obtained from Appendix A, assuming a linear relationship between the increase in wind speed and power.

Table 3: Monthly averaged wind speeds and power outputs for Futuna Island with given turbine.

Monthly Averaged wind speeds, Values Based on Wind Speed 10 m Above the Surface of the Earth for Terrain Similar to Airports							
Month	Jan	Feb	Mar	Apr	May	Jun	Jul
Wind speed (m/s)	5.28	5.08	5.57	6.61	6.55	5.96	6.20
Power output, wind resource (W)	201.30	179.28	236.33	394.96	384.30	289.52	325.93
Power output, turbine (W)	45.55	38.44	56.55	98.76	96.26	69.50	81.75
C_P, turbine	0.221	0.210	0.233	0.219	0.246	0.245	0.212
Energy output, turbine (kWh/day)	1.09	0.92	1.36	2.37	2.31	1.67	1.96
Month	Aug	Sep	Oct	Nov	Dec	Annual average	
Wind speed (m/s)	5.85	5.53	5.77	5.41	5.75	5.80	
Power output, theoretical (W)	273.79	231.27	262.71	216.54	259.99	266.83	
Power output, turbine (W)	67.46	55.03	64.20	50.48	63.38	65.42	
C_P, turbine	0.241	0.231	0.240	0.226	0.240	0.241	
Energy output, turbine (kWh/day)	1.62	1.32	1.54	1.21	1.52	1.57	

Sources: NASA, Surface meteorology and Solar Energy and NaREC,
Summary Test Report for Ampair 600/230 Mk 2.5

The wind speed data in Table 3 above were recorded by NASA satellites during a 10-year period from July 1983 to June 1993 for a one-by-one degree area comprising Futuna Island. According to the table, the average wind speed in the region is fairly constant throughout the year with a minimum of 5.08 m/s in February, a maximum of 6.61 m/s in April and an annual average wind speed of 5.80 m/s.

However, as the power is a product of the cube of the wind speed, the wind resource power that corresponds to the monthly averaged wind speeds varies considerably. For instance, the power output corresponding to the minimum wind speed of 5.08 m/s is 180 W and the power output corresponding to the maximum wind speed of 6.61 m/s is 395 W, more than twice as much.

Similarly, the daily energy output of the wind turbine corresponding to the given wind speeds varies significantly throughout the year, from around 0.92 kWh/day in February to 2.37 kWh/day in April, almost three times as much. However, most of the loads will be constant over the same period of time. This has to be taken into account when sizing the storage and transmission components of the systems.

As mentioned above, the wind speed data from NASA have been measured at 10 m above the surface, assuming the underlying terrain similar to that typical of airports. This description coincides with the site in Mission Bay and therefore an energy production close to that of Table 3 is reasonable to expect there. Matangi, on the other hand, is located at a different altitude and the surroundings do not agree with the description above. Therefore, estimating the wind speeds at the site becomes more complicated.

5.1.3.1. Wind Direction

In Table 4 below, the monthly averaged wind direction at 50 m above the surface of the earth has been given. The wind directions are measured clockwise from true north and show the direction from which the wind is coming.

Table 4: Monthly averaged wind direction at 50 m above ground level for Futuna Island.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Direction (degrees)	108	105	106	109	110	110	111	112	112	112	112	112

Source: NASA, Surface meteorology and Solar Energy

The information in the table above supports the assumption that the prevailing wind direction in the region is invariably from southeast throughout the year. The average wind direction based on the given data is 110 degrees.

5.1.3.2. Tower Height and Wind Shear

As mentioned in the theory chapter, mounting a wind turbine on a tall tower maximizes the power output of the turbine. This is due to the fact that wind speed increases with height but also because friction and turbulence tend to decrease with height. As stated in chapter 3, the less friction a surface has, the more vertical the wind profile becomes.

The towers that will be used for the turbines at Futuna Island are all 12 m high. Equation [3.1.6] from chapter 3 will now be used to calculate the wind speeds at the new height for the site in

Mission Bay. As mentioned above, the data from NASA have been measured at 10 m height assuming underlying terrain similar to that of airports, or rough grass. According to Table 1 in chapter 3, the surface roughness length equivalent to this terrain is that of *rough pasture*, defined as *a field covered with grass or herbage*. This terrain description corresponds to z_0 = 10 mm.

Based on the above assumptions, the log law gives the following values of the modified wind speed at the site in Mission Bay:

Min. wind speed: $$U(z) = \frac{ln\frac{z}{z_0}}{ln\frac{z_r}{z_0}} \times U(z_r) = \frac{ln\frac{12}{0.01}}{ln\frac{10}{0.01}} \times 5.08 = 5.21\, m/s \quad [5.1.1]$$

Max. wind speed: $$U(z) = \frac{ln\frac{z}{z_0}}{ln\frac{z_r}{z_0}} \times U(z_r) = \frac{ln\frac{12}{0.01}}{ln\frac{10}{0.01}} \times 6.61 = 6.78\, m/s \quad [5.1.2]$$

Ave. wind speed: $$U(z) = \frac{ln\frac{z}{z_0}}{ln\frac{z_r}{z_0}} \times U(z_r) = \frac{ln\frac{12}{0.01}}{ln\frac{10}{0.01}} \times 5.80 = 5.95\, m/s \quad [5.1.3]$$

As seen in the above equations, the modified wind speeds in Mission Bay are marginally higher than the reference wind speeds as the tower height is slightly higher than the reference height. In the equations presented below, it gets clear how much the wind speed increases with increasing tower height. The equations are all based on the minimum wind speed of 5.08 m/s:

Tower height = 18 m: $$U(z) = \frac{ln\frac{z}{z_0}}{ln\frac{z_r}{z_0}} \times U(z_r) = \frac{ln\frac{18}{0.01}}{ln\frac{10}{0.01}} \times 5.08 = 5.51\, m/s \quad [5.1.4]$$

Tower height = 24 m: $$U(z) = \frac{ln\frac{z}{z_0}}{ln\frac{z_r}{z_0}} \times U(z_r) = \frac{ln\frac{24}{0.01}}{ln\frac{10}{0.01}} \times 5.08 = 5.72\, m/s \quad [5.1.5]$$

According to the calculations above, increasing the tower height by 50 % will result in an increase in the wind speed of more than 8 %. Doubling the tower height will result in an increase in the wind speed by more than 12 %. This might seem like insignificant increases in the context, but as mentioned before, the power output is a function of the *cube* of the wind speed. The corresponding increases in power output will therefore be 27 % with a 50 % increase in tower height and 43 % with a double tower height at the given wind speed. Thus, taller towers should be considered as an alternative measure increasing the nominal power at the sites.

5.1.3.3. Wind Assessment Study

In 2008, a volunteer employed by Garrad Hassan performed a wind assessment[67] of Futuna Island on behalf of VANREPA. Due to the lack of suitable sources of long-term reference wind data in the region, the analysis was based upon satellite data recorded by NASA. A digital topographic map of Futuna Island was used together with the data from NASA to simulate the wind speeds across the island. The topographic map was partly manually generated and was considered to be a reasonable but not highly accurate representation of the terrain. The long-term wind speed

[67] Garrad Hassan, 2008

variation over the island was predicted using a computational wind flow model. The model was initiated assuming that the reference data are located on the airstrip.

The assessment resulted in a wind speed map for the entire island at a height of 10 m above ground level with a grid resolution of 200 m. It should be noted, however, that as there were several uncertainties involved with the making of this map, it should be used for feasibility purposes primarily. In Figure 15 below, the wind speed map of Futuna Island is presented.

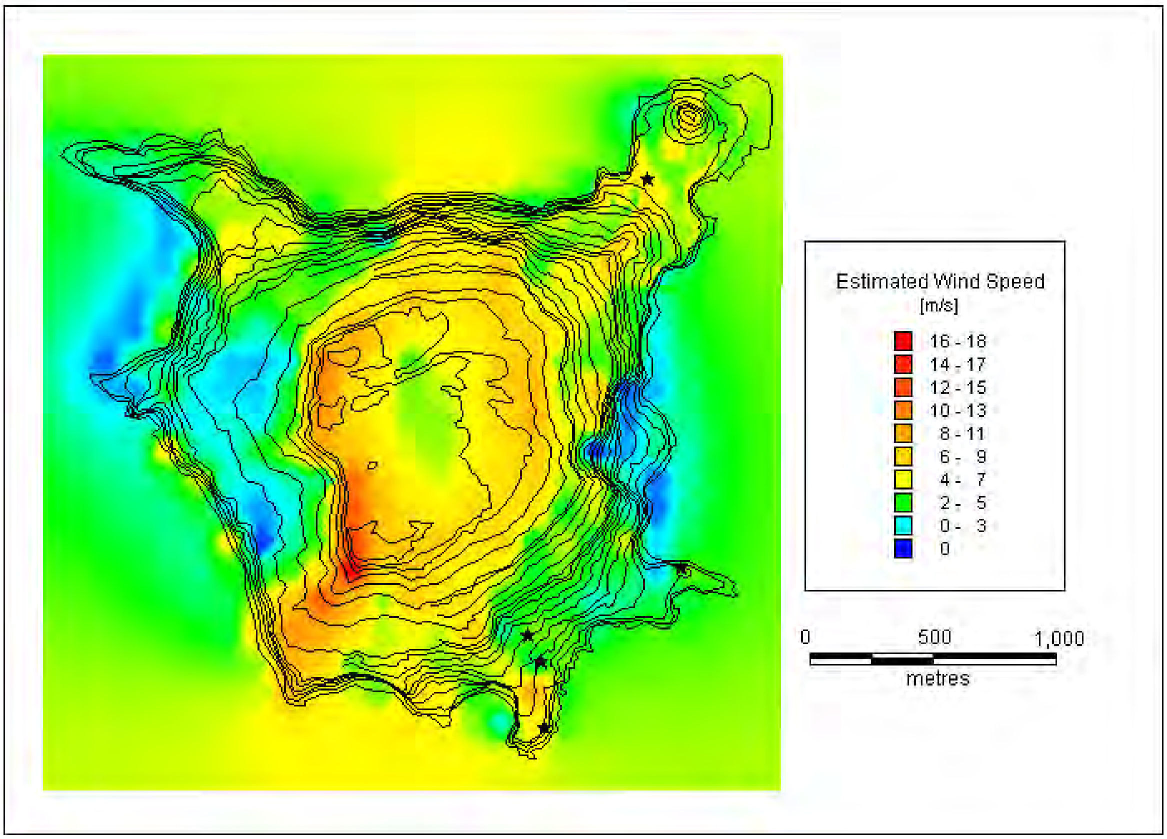


Figure 15: Wind speed map at 10 m above ground level for Futuna Island. The black star on the northern peninsula represents the location of the powerhouse in Mission Bay.
(Garrad Hassan, 2008)

The map suggests a wind speed interval of 4-7 m/s at the site, which coincides with the data retrieved from NASA in Table 3. The top star on the southern peninsula indicates the location of the powerhouse in Matangi. The map suggests a lower wind speed at this site than in Mission Bay, in the order of 2-5 m/s. A further analysis of this site in the report made by Garrad Hassan suggests a mean wind speed in the order of 4-6 m/s. However, the negative influence of the trees in the prevailing wind direction has been recognized in the report. Consequently, it has been presumed that a tower of at least 30 m and probably 40 m would be required for a turbine to experience undisturbed winds at the site.

According to Appendix A, the selected turbine will produce a negative power output for wind speeds equal to or less than 3.76 m/s. If the mean wind speed experienced at the site in Matangi is anything close to this value, the power output will be much less than the turbine is capable of producing. As a result, the efficiency of the system will be extremely low.

When sizing the battery banks and the cables at the site, an average wind speed of 5 m/s will be assumed. This is in the middle of the wind speed interval suggested in the study by Garrad Hassan. Unless a much taller mast or a more appropriate site can be considered, it is recommended that a majority of the trees in the prevailing wind direction should be cut down to maximize the wind speed at the site and for the turbines to experience undisturbed wind flow.

Mounting wind monitoring equipment at the site will reveal more information about the wind regime and wind shear profile necessary to judge whether the site is appropriate for wind power generation or not. In addition, this will give specific information about the most appropriate placement of a turbine at the site, and how many of the trees in the prevailing wind direction that need to be cut down in order to acquire undisturbed wind flow. The wind turbine installed at the site can be used for this purpose, if wind monitoring equipment is unavailable.

5.1.4. Calculated Power Output

In Table 5 below, the power output and daily energy output at the site in Mission Bay have been estimated.

Table 5: Monthly averaged wind speed, power and energy output for Mission Bay.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul
Wind speed (m/s)	5.42	5.21	5.72	6.78	6.72	6.12	6.36
Power output, turbine (W)	50.86	43.00	62.24	105.75	103.33	78.48	88.36
Energy output, turbine (kWh/day)	1.22	1.03	1.49	2.54	2.48	1.88	2.12
Month	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Annual average**	
Wind speed (m/s)	6.00	5.68	5.92	5.55	5.90	5.95	
Power output, turbine (W)	73.59	60.72	70.32	55.79	69.50	71.54	
Energy output, turbine (kWh/day)	1.77	1.46	1.69	1.34	1.67	1.72	

According to the table, the minimum daily energy output at the site will be approximately 1 kWh, the maximum daily energy output will be around 2.5 kWh and the annual average daily energy output will be in the order of 1.7 kWh. Two turbines are proposed for the site; this would give a total average energy output of 3.4 kWh/day.

In Matangi, assuming an average wind speed of 5 m/s, the average daily power output according to Appendix A will be 35.62 W giving a daily energy output of 0.85 kWh. This is only half of the expected output in Mission Bay. It is therefore recommended that a different location for the turbine will be considered.

5.2. Solar Power

In this section, the average daily energy output of the PV-modules at the sites in Futuna will be estimated, by applying equation [3.2.3] from chapter 3: $E_{PV} = P_{mod} \times H_{tilt} \times N$. In this equation, the derated output of the modules (P_{mod}) must be known, in addition to the daily insolation in peak sun hours for the specific tilt angle (H_{tilt}), and the number of modules in the array (N). Each of these parameters will now be estimated and discussed in relation to site-specific aspects and aspects associated with technical specifications of the selected PV-modules.

5.2.1. Selected PV Module

The PV-modules selected for power generation in Herald Bay and Iahsoa are the GSE 60 W modules manufactured by *Global Solar Energy*, see Figure 16. The modules have the technical specifications given in Table 6.

Table 6: Solar module specifications.

SPECIFICATIONS*		
Nominal voltage:	12	V
Peak Power Rating	60	W
Operating Voltage:	17.5	V
Current at Operating Voltage:	3.5	A
Open Circuit Voltage (Voc):	25	V
Short Circuit Current (Isc):	4.5	A
Length	1.18	m
Width	0.635	m

* Data at *Standard Test Conditions*, STC: Irradiance level 1000 W/m^2, spectrum AM 1.5 and cell temperature 25° C
Source: Global Solar Energy – 2008 Product Catalogue

Figure 16: GSE 60 W solar module.
(Global Solar Energy – 2008 Product Catalogue)

5.2.2. Derated Output of Modules

As stated in chapter 3, derating factors such as manufacturer's tolerance, dirt and temperature affect the maximum power output of the modules. The derated output of the modules can be calculated by equation [3.2.4]: $P_{mod} = P_{STC} \times f_{man} \times f_{temp} \times f_{dirt}$

As the modules will be located near the coast, there is a high probability of dirt or salt building up on the array over a period of time. How much this will lower the output is difficult to know but 0-10 % is commonly applied. Due to local conditions at the sites, a derating value close to the upper part of the given interval is reasonable to assume.

According to *Vanuatu Meteorological Services*, the average temperature in Vanuatu is fairly constant, in the interval 25-30°C. This is confirmed by the monthly averaged earth skin temperature data for Futuna Island obtained from NASA, given in Table 7 below. According to the table, the warmest month in Futuna is February, with an average temperature of 28.2°C, down to 24.2°C in August, the coldest month. The average temperature in Futuna is 26.1°C.

Table 7: Monthly averaged earth skin temperature in degrees Celsius for Futuna Island.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave
27.7	28.2	28.1	27.5	26.4	25.2	24.5	24.2	24.3	24.9	25.9	27.0	26.1

Source: NASA Surface meteorology and Solar Energy

As discussed in chapter 3, the power output of a solar module decreases by 0.5 % for every 1°C increase in temperature above 25°C. Consequently, the power output of the solar modules in Futuna will be affected by less than 1 % due to the influence of temperature.

The manufacturer's tolerance is an additional factor reducing the power output. However, it has not been possible to find any value presented by the manufacturer. Therefore, a commonly presented value of 3 % will be used instead.

In total, this gives a derating factor of 0.86. However, other derating factors such as shadowing obstacles might be present at the sites. Therefore, a total derating value of 0.8 will be applied to make sure all factors that might reduce the power output are accounted for. This gives the following modified power output of the solar modules: $P_{mod} = P_{STC} \times 0.8 = 60 \times 0.8 = 48\ W$

5.2.3. Solar Insolation

The monthly and annual average solar insolation data for Futuna Island are given in peak sun hours (PSH) in Table 8 with a maximum of 6.97 PSH in December, a minimum of 3.74 PSH in June and an annual average of 5.53 PSH.

Table 8: Monthly and annual averaged solar insolation data for Futuna Island

Monthly Averaged Insolation Incident on a Horizontal Surface (kWh/m²/day)													
Lat -19 Long 170 22-year Average	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual Average
	6.83	6.31	5.70	4.93	4.17	3.74	4.05	4.79	5.64	6.54	6.76	6.97	5.53

Source: NASA Surface meteorology and Solar Energy

According to the Vanuatu Meteorological Services, there are two main seasons in Vanuatu, the cold (dry) season from May to October and the hot (wet/cyclone) season from November to April. During the wet season, rainfall is particularly high on the windward side (southeast parts) of the bigger islands.

Differences in the amount of rainfall can also be observed between the northern and southern Vanuatu islands. The number of days with more than 0.1 mm of rainfall has been documented by the meteorological services over a ten-year period. According to this study, the northern islands have 219 days with more than 0.1 mm of rain per year, the middle islands have 148 days and the southern islands have 88 days.

The number of PSH on a rainy day can be estimated to be around 1-2.5 hours, based on site observations[68]. This is considerably lower than the average PSH for any of the months in the region, according to Table 8. However, the data obtained from NASA cover an area considerably larger than Futuna Island and thus local weather situations might differ. To account for this, the data from NASA will be weighted with the data from the local meteorological services in the country. A worst-case scenario of 88 rainy days with a PSH value of 1.0 hour will be assumed to ensure that the power outputs from the modules will not be overestimated. This gives the following value of the daily insolation in peak sun hours for the specific tilt angle: $H_{tilt} = \frac{(1.0 \times 88) + (5.53 \times 277)}{365} = 4.44$

To allow for efficient operation and make sure the optimal number of PSH above will be obtained, the modules have to be fixed with a proper tilt angle. As stated in chapter 3, the optimal power output from a solar module is obtained when the module is tilted to receive perpendicular solar insolation. For the latitudes between 15^{o} S and 23.5^{o} S, the module is generally tilted at 15^{o} to 20^{o}. Futuna is located at Lat 19^{o}, and thus the solar modules should be tilted at least 15^{o}, facing north.

5.2.4. Number of Modules in the Array

As stated in chapter 3, the voltage level of the modules connected in series should be equal to or exceed the voltage level of the battery bank. In Futuna, the voltage level of the battery banks, or the nominal system voltage V_{dc}, will be 24 V. Furthermore, according to Table 6, the nominal voltage of the modules, V_{mod}, is 12 V. Equation [3.2.2] then gives the total number of modules required in a string as $N_s = \frac{V_{dc}}{V_{mod}} = \frac{24}{12} = 2$

After determining the number of modules required in a string, the number of parallel strings, N_p, can be determined according to equation [3.2.3]. In the equation, N equals the total number of modules in the array. In Herald Bay, the total number of modules in the array will be 12, giving the number of parallel strings required as $N_p = \frac{N}{N_s} = \frac{12}{2} = 6$. In Iahsoa, the total number of modules in the array will be 6, and the number of parallel strings will therefore be 3.

5.2.5. Calculated Power Output

Based on the estimated parameters above, the power output of the solar modules at each site can now be predicted. Starting with Herald Bay, where 12 modules will be installed, the estimated power output will be equal to:

$$E_{PV} = P_{mod} \times H_{tilt} \times N = 48 \times 4.4 \times 12 = 2.53\ kWh/day$$

In Iahsoa, where 6 modules will be installed, the power output will be half of that in Herald Bay:

$$E_{PV} = 48 \times 4.4 \times 6 = 1.27\ kWh/day$$

[68] Chow, J., 2010, p 14

6. Load Requirements at Each Site

In this chapter, the load requirements at each site will be estimated. Futuna Island does not have any power production to speak of at present; the only exception being a couple of privately owned diesel generators and solar panels. Because of this, the estimated load requirements are based on what the villagers would wish to have power for. Of course, this wishing list would potentially be endless, only restricted by the amount of power available. It will therefore be necessary for the villagers to make priorities.

The energy use audits used for estimating the load requirements are given in Appendix C-F. The audits were obtained during a field trip to Futuna. During the visit, the author spoke with representatives of the four villages and discussed the essential needs and use of the power that will be available. It is emphasized that the energy use audits by no means are final lists of the total electric energy requirements in the villages, and as such should only be viewed as a first step towards electrification of Futuna Island.

The power use of the existing appliances is based on the actual power use of those appliances. The power use of non-existing appliances is based on common appliances available for purchase online.

The generated power will be stored in a battery bank centrally located in each village, and distributed to key institutions in need of power such as schools, churches and administrative buildings. For household lighting, the villagers will bring rechargeable lights to be charged by the powerhouse.

6.1. Mission Bay

As mentioned in chapter 2, Mission Bay is the administrative headquarter of the island. Currently, there are plans of building a community hall, and a province house for administrative use is under construction. These facilities have no means of obtaining electric energy at the moment. The island's main dispensary is also located in the village. The dispensary currently has 2x30 W solar panels installed powering one radio and a few light sources. More power is desirable in this facility, primarily for a fridge for vaccines and more light sources. The island's fishing co-operative is based in the village as well. This facility is self-sufficient at the moment but plans of expansion will require more power. The church has power points installed for lighting that is powered only when a privately owned diesel generator is available.

In Figure 17 below, the key institutions requiring power in Mission Bay have been indicated on the map. The distances between them are given in Table 9.

Figure 17: Key institutions Mission Bay.
(Google Earth, date of picture 19-09-2005)

Table 9: Distances between key institutions and the powerhouse, Mission Bay.

OBJECT	DISTANCE
Powerhouse – fishing co-op 1:	47 m
Powerhouse – fishing co-op 2:	45 m
Powerhouse – dispensary:	54 m
Powerhouse – church:	150 m
Powerhouse – community hall:	160 m
Powerhouse – province house:	227 m
Dispensary – airport:	50 m
Dispensary – fishing co-op 1:	48 m
Dispensary – fishing co-op 2:	29 m
Dispensary – church:	96 m
Dispensary – community hall:	108 m
Dispensary –province house:	137 m

In Appendix C, the Mission Bay energy use audit has been summarized. According to the audit, the total energy use in Mission Bay should be around 4.8 kWh/day. The total energy production will be in the order of 3.4 kWh/day, assuming that two turbines are to be installed at the site. Obviously, this will not be enough to supply all the loads in the energy use audit. Therefore, it will be necessary to evaluate which of the objects that should be prioritized at this first stage. If it is desirable that all of the objects in the audit are supplied by the system, more power producing units needs to be included, such as solar modules or diesel generators. To allow for future growth of the system, the battery bank and cables will be sized according to the total daily load in the energy use audit.

6.2. Matangi

The Matangi area consists of several small villages located on the two peninsulas pointing east and south. The largest communities are found on the eastern pointing peninsula where the villages of Ileke, Inokoke and Imarae are found. As mentioned in chapter 2, these villages consist of about 20 households in total and the powerhouse has been built near the village of Inokoke. The only facility requiring electric energy at the moment in this village is the church, which does not have any means of attaining electric energy at present. In addition, the village has plans of building a community hall and a community kitchen within the near future.

In Figure 18 below, the key institutions requiring electric energy in the village of Inokoke have been indicated. The distances between these facilities and the powerhouse are given in Table 10.

Figure 18: Key institutions Matangi (Inokoke).
(Google Earth, date of picture 19-09-2005)

Table 10: Distances between key institutions and powerhouse, Matangi (Inokoke).

OBJECT	DISTANCE
Powerhouse – church:	32 m
Powerhouse – community hall:	< 10 m
Powerhouse – community kitchen:	< 10 m

In Appendix D, the energy use audit of Matangi has been summarized. According to the audit, the total energy consumption in Matangi should be approximately 0.7 kWh/day. However, the only existing institution in need of energy supply in the village is the church, in addition to the household light battery charging. Thus, the present need of electric energy at the site is less than 0.4 kWh/day. The estimated daily energy output of the wind turbine proposed for the site is 0.85 kWh. This might be enough to supply the total load, even including losses, depending on the actual wind speed at the site. The battery bank and cables will be sized according to the total load, to allow for future growth.

6.3. Herald Bay

The village of Herald Bay is the location of the island´s only school. Partly because of this, the village is by far the largest on the island with approximately 40 households. The school already has 4 solar panels of 60 W each installed. These panels are supplying one of the school buildings, indicated as "school building 2" in Figure 19 below, with enough electric energy for lighting, one computer and a printer. According to the school's principal, the output of the solar panels would be enough to power at least one more school building.

The powerhouse has been built close to both school building 1 and the church. School building 1 has light bulbs and power points installed and it would be preferable to make use of the existing appliances. The church has 1 solar panel of 60 watt installed powering a few lights and a keyboard. However, according to the villagers, more power is desired to be able to supply more appliances with electric energy at the same time.

The key institutions in Herald Bay are indicated in Figure 19 below and the distances between them are given in Table 11. Because of the distance to the powerhouse and the relatively low power demand, it is suggested that the girls' dormitory will not be prioritized in the system design at this stage.

Figure 19: Key institutions Herald Bay.
(Google Earth, date of picture 19-09-2005)

Table 11: Distances between key institutions and powerhouse, Herald Bay.

OBJECT	DISTANCE
Powerhouse – school building 1:	30 m
Powerhouse – church:	60 m
Powerhouse – girls' dormitory:	120 m

In Appendix E, the energy use audit of Herald Bay has been summarized. According to the audit, the total energy consumption in Herald Bay will be approximately 1.2 kWh/day. The calculated daily energy output given that 12 modules are to be installed at the site is 2.53 kWh/day. Most likely, the load requirements at the site will be more than covered for by the 12 modules proposed for the site, even including conversion and transmission losses.

6.4. Iahsoa

Located on the western peninsula, Iahsoa is a small village of approximately 20 households. There are two facilities currently in need of power here: the church and the Nakamal. The Nakamal is a place for chiefs to meet and make decisions and as such the basic need would be power for lighting. The church has lights, power points installed and a stereo, powered by a diesel generator when fuel is available.

The powerhouse has been built next to the church. The village has plans of building a community hall within the near future, which would be located close to the powerhouse. In Figure 20 below, the key institutions requiring energy in Iahsoa have been indicated. The distances between them are given in Table 12.

Figure 20: Key institutions Iahsoa.
(Google Earth, date of picture 19-09-2005)

Table 12: Distances between key institutions and powerhouse, Iahsoa.

OBJECT	DISTANCE
Powerhouse – church:	10 m
Powerhouse – Nakamal:	45 m
Powerhouse – community hall:	25 m
Church – Nakamal:	35 m

In Appendix F, the energy use audit of Iahsoa has been summarized. According to the audit, the energy consumption would be around 1 kWh/day. This load will most likely be covered for by the proposed 6 solar modules for the site, with an estimated power output of around 1.3 kWh/day, even including losses.

7. Sizing of Components

In this chapter, proper size of the battery banks and cables will be estimated to ensure that the loads will be supplied close to fulltime. An important aspect when sizing the components is to make sure that all losses are accounted for. Under-sizing of either of the components might result in system breakdown or wasted energy. Over-sizing of components will result in a more expensive system than required. Therefore, the components will be sized as close to the estimated power outputs and demands as possible.

7.1. Battery Bank

The energy demand in Futuna is currently non-existing. Therefore, the battery banks will be sized according to the estimated daily energy outputs OR the daily load according to the energy audits, whichever is greater. The battery bank capacity at a certain discharge rate, C_X, can be calculated by formula [3.3.1] from the theory chapter: $C_x = \frac{E_{tot}}{V_{dc}} \times \frac{T_{aut}}{DOD_{max}}$

An important aspect when sizing the battery banks is the maximum number of days that the batteries can supply the daily demand, assuming that there is no input from the energy source, also referred to as days of autonomy. As stated in the theory chapter, typically 3-5 days is recommended if a back-up generator is available or 5-10 days when a back-up generator is unavailable.

However, different methods are used to size battery storage. For instance, one international organization has required that all stand-alone medical equipment that it purchases must operate for 6 black or no-sun days in parts of the tropics[69]. In Table 13 below, the total number of no-sun or black days over the year for Futuna Island has been summarized. The numbers are based on a percentage of the total solar energy expected on that day.

Table 13: Number of no-sun or black days, Futuna Island.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1 day	0.95	0.89	0.96	0.96	0.91	0.96	0.96	0.94	0.96	0.91	0.95	0.88
3 days	2.45	2.08	2.69	2.49	2.18	2.09	2.23	2.36	1.92	2.27	2.24	2.21
7 days	3.00	3.71	3.82	4.31	3.86	3.87	3.14	3.85	3.30	3.46	3.29	4.02
14 days	4.59	5.05	5.05	6.15	4.38	4.61	3.19	6.05	5.03	4.00	4.54	4.16
21 days	4.14	6.61	4.99	8.35	5.81	5.37	3.79	6.13	6.14	4.24	5.40	5.54
1 month	4.17	7.24	5.48	2.78	5.09	5.28	3.67	6.55	6.25	3.95	4.27	4.93

Source: NASA, *Surface meteorology and Solar Energy*

According to the table, the highest number of no-sun or black days is found in April during a consecutive period of 21 days and equals 8.35. This implies that in order to have enough capacity to supply the loads fulltime over the year, the battery bank should be sized for 8.35 days of autonomy.

[69] NASA, *Surface meteorology and Solar Energy*

However, the cost of batteries is the most critical factor in the design of the power systems. The less financial capital available, the less storage capacity is possible to include. According to Table 13, the occurrence of more than 5 consecutive no-sun days is relatively uncommon. It is therefore recommended that the systems will be sized for *at least* 5 days of autonomy, the lowest number recommended for a system without a back-up generator. This means that for most of the year, the battery storage capacity will be much larger than the power production and demand. During the most critical month, in this case April, it is recommended to be cautious when using power consuming appliances to ensure that the battery bank will not exceed the maximum recommended depth of discharge. The sizing of the battery bank capacities will be based on the following:

- 5 days of autonomy.
- A maximum depth of discharge of 70 % to increase battery lifetime.
- A battery derating factor of 0.95 will be applied in the calculations to compensate for the negative influence of temperature.

7.1.1. Mission Bay

In Table 14, the required storage size of the battery bank in Mission Bay has been determined. The battery bank has been sized according to the total daily load given in Appendix C. According to the table, the required battery capacity in Mission Bay will be around 1500 Ah. The suggested battery for the battery bank is a Raylite 6 V, with a C_{100} rating of 1660 Ah. Four batteries are required to obtain the voltage level of 24 V. The cost of these batteries would be 12 000 AUD. To control the amount of charge into the battery bank, charge controllers connected to each wind turbine are required. The cost of each charge controller would be 2600 AUD giving a total battery bank cost of 14 600 AUD, including shipping.

Table 14: Sizing of battery bank Mission Bay.

Battery Bank Mission Bay		
Estimated daily load	4.71	kWh
at system voltage	24	V
Equals	196.3	Ah
Max depth of discharge	70	%
Days of autonomy	5	Days
Battery derating factor	0.95	
Required battery size	1476	Ah
Suggested battery	Raylite 4 V 1660 Ah*	MTE25S
Required number for 24 V	6	
Total battery cost	12000**	AUD
Suggested charge controller (1 for each turbine)	Ampair 24 V 600 W	600TS24
Total charge controller cost	2600***	AUD
Total battery bank cost	14600	AUD

* Recommended by *Energy Matters* (www.energymatters.com.au)
** Price according to Apollo Energy (www.apolloenergy.com.au)
*** Price according to Apollo Energy (www.apolloenergy.com.au)

7.1.2. Matangi

In Matangi, the estimated daily energy output of the wind turbine proposed for the site is 0.85 kWh. According to Table 15 below, a battery storage capacity of about 300 Ah is required. The suggested battery for the battery bank is Haze Battery Gel, with a C_{100} rating of 276 Ah. Two batteries are required to obtain a nominal voltage level of 24 V. The total cost of these batteries would be 2000 AUD. The total battery bank cost including a battery charge controller for the wind turbine would be 4700 AUD, including shipping.

Table 15: Sizing of battery bank Matangi.

Battery Bank Matangi		
Estimated daily energy production	0.85	kWh
at system voltage	24	V
equals	35.4	Ah
Max depth of discharge	70	%
Days of autonomy	5	Days
Battery derating factor	0.95	
Required battery size	266	Ah
Suggested battery	Haze Battery Gel 12 V 240 Ah	N200-GEL
Required number for 24 V	2	
Total battery cost	2100	AUD
Suggested charge controller	Ampair 24 V 600W	600TS24
Total charge controller cost	2600***	AUD
Estimated total battery bank cost	4700	AUD

* Recommended by *Energy Matters* (www.energymatters.com.au)
* Price according to Apollo Energy (www.apolloenergy.com.au)
*** Price according to Apollo Energy (www.apolloenergy.com.au)

7.1.3. Herald Bay

The estimated energy output in Herald Bay will be 2.53 kWh per day, assuming that 12 modules are to be installed, requiring a storage capacity in the order of 800 Ah, as given in Table 16 below. The suggested battery for the battery bank is Raylite 6V, with a C_{100} rating of 900 Ah. Four batteries are required to obtain the nominal voltage level of 24 V. The total cost of these batteries would be 7600 AUD. To ensure that the batteries are not overcharged and control the amount of charge from the solar array to the battery bank, a battery charge controller should be included. The total battery bank cost including a battery charge controller would be 7800 AUD, including shipping.

Table 16: Sizing of battery bank Herald Bay.

Battery Bank Herald Bay		
Estimated daily energy production	2.53	kWh
at system voltage	24	V
equals	105.4	Ah
Max depth of discharge	70	%
Days of autonomy	5	Days
Battery derating factor	0.95	
Required battery size	793	Ah
Suggested battery	Raylite 6 V 900 Ah*	MIL25S
Required number for 24 V	4	
Total battery cost	7600**	AUD
Battery controller	200***	AUD
Estimated total battery bank cost	7800	AUD

* Recommended by *Energy Matters* (www.energymatters.com.au)
** Price according to Apollo Energy (www.apolloenergy.com.au)
*** Price according to Apollo Energy (www.apolloenergy.com.au)

7.1.4. Iahsoa

In Iahsoa, 6 solar modules are proposed to be installed with an estimated energy output of 1.27 kWh per day. The total battery storage capacity required for this is about 400 Ah, according to Table 17 below. The suggested battery for the battery bank is Raylite 6 V, with a C_{100} rating of 600 Ah. Four batteries are required to obtain the nominal voltage level of 24 V. The total cost of these batteries would be 5800 AUD, including shipping. The total battery bank cost including a battery charge controller would be 6000 AUD.

Table 17: Sizing of battery bank Iahsoa.

Battery Bank Iahsoa		
Estimated daily energy production	1.27	kWh
at system voltage	24	V
equals	52.9	Ah
Max depth of discharge	70	%
Days of autonomy	5	Days
Battery derating factor	0.95	
Required battery size	398	Ah
Suggested battery	Raylite 6 V 600 Ah*	MIL17S
Required number for 24 V	4	
Total battery cost	5800**	AUD
Battery controller	200***	AUD
Estimated total battery bank cost	6000	AUD

* Recommended by *Energy Matters* (www.energymatters.com.au)
** Price according to Apollo Energy (www.apolloenergy.com.au)
*** Price according to Apollo Energy (www.apolloenergy.com.au)

7.2. Cables

As stated in chapter 3, the cables should be sized so that the voltage drop is less than 5 % of the system voltage. In this case, the system voltage is 24 V giving a maximum allowed voltage drop of 1.2 V. Equation [3.4.1] from the theory chapter can be applied to determine the cross sectional areas of the cables required not to exceed the maximum voltage drop: $A = \frac{2 \times L \times I \times \rho}{V_d}$

To minimize voltage drop and transmission losses, an inverter could be included in the designs. An inverter will convert the low-voltage DC power produced by the battery bank into higher voltage AC power (240 V). However, the inverter itself acts as a load and will lower the overall efficiency of the system. In addition, inverters are expensive and will considerably increase the total system cost. To keep the system losses and costs down, it is therefore recommended to wire the systems for 24 V DC only in all systems except for Mission Bay. The distances from the powerhouse to the key institutions in Mission Bay require larger cable section areas in order to keep the voltage drop down. In addition, many of the appliances already existing in Mission bay require 240 V AC to operate. Therefore, an inverter should be included in the design in Mission Bay despite the additional cost.

The round trip lengths of the conductor, the current level and the resistivity of the wire have to be identified to find the required CSA of the cables. These parameters will be identified based on the following:

- The round trip length of the conductor will be based on the distances between the key institutions at each site identified in chapter 6. As these are the air distances, an additional 10 % will be added to the distances to ensure the cables will be long enough.
- The maximum expected current from the wind turbines to the powerhouse will be based on the maximum power output of the turbine. The turbines will all be connected to a battery bank with a nominal voltage level of 24 V. According to the test results in Appendix A, the highest power output measured from the wind turbine is 267 W, at a wind speed of 17.72 m/s. This gives a maximum expected current from the turbines of 11 A.
- The maximum expected current from the solar modules equals the short circuit current given in Table 6. According to the table, I_{sc} equals 4.5 A. However, as stated in chapter 3, connecting modules in parallel adds the current of each module.
- The maximum expected current from the powerhouse to the load will be based on the maximum power according to the energy use audit of each site.
- The resistivity of the wire will be based on the resistivity of copper[70], a commonly used cable material, which is 0.0183 $\Omega mm^2/m$.

Based on the above assumptions, the length and required cross sectional area of each cable will know be determined.

[70] GSES, p 260

7.2.1. Mission Bay

The two turbines proposed for the site in Mission Bay should both be as close to the powerhouse as possible, to minimize cable length and power loss. Furthermore, according to Figure 11 in chapter 3, a separation distance of at least 5 turbine diameters is recommended in the crosswind direction for the turbines to experience undisturbed wind flows. With a turbine diameter of 1.7 m, this equals a separation distance of at least 8.5 m between the turbines. An illustration of how the turbines could be lined up toward the prevailing wind direction is given in Figure 21 below. According to the illustration, the required cable length to the turbines is 5 m. Including the tower lengths, the total required cable lengths are 17 m. The red dot in the figure marks the powerhouse, located on the downwind side of the turbines.

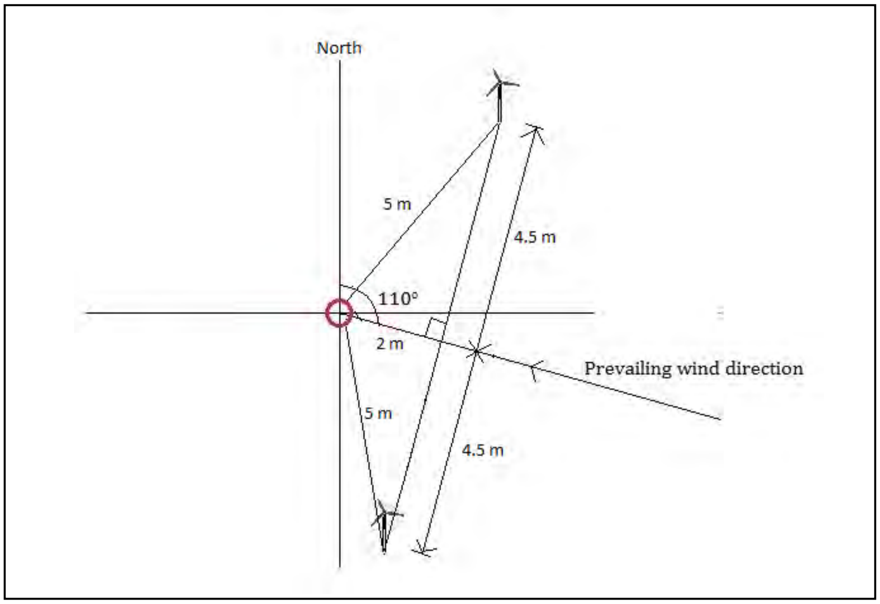


Figure 21: Suggestion of line-up of wind turbines, Mission Bay. The red dot in the figure marks the powerhouse, located on the downwind side of the turbines.

According to Table 9 in chapter 6, the powerhouse in Mission Bay has been built a fair distance from the key institutions requiring power in the village. It would therefore make sense to run several cables in the same conduit to a central location in the village. From there, the electric energy should be redirected to the different loads by a switchboard. Rectifiers connected to each wind turbine will convert the high-voltage AC power produced by the wind turbines into low-voltage DC power stored in the battery bank located in the powerhouse. Thereafter, an inverter connected to the battery bank will convert the DC power back into AC power distributed to the loads.

According to the energy use audit in Appendix C, the maximum power required by the load in Mission Bay is 1540 W. Splitting the loads by a switchboard located next to the dispensary requires a cable sized for the total load from the powerhouse to the dispensary. From the dispensary to the rest of the loads, each cable should be sized according to the maximum power of that particular load. Applying equation [3.3.3] gives the required cross sectional areas of the cables from the turbines to the powerhouse and from the powerhouse to the key institutions as listed in Table 18 below.

Table 18: Cable lengths and CSA's, Mission Bay.

Object from – to [m]	Cable length [m]	Max. current [A]	Required CSA of cable [mm^2]	Equivalent standard cable size at 240 V [mm^2]	Approx. Cable cost [AUD]*
Wind turbine 1 – Powerhouse	17	11	5.70	6	53
Wind turbine 2 – Powerhouse	17	11	5.70	6	53
Powerhouse – Dispensary	60	7	1.28	1.5	74
Dispensary – airport radio	50	0.5	0.07	0.5	32
Dispensary – fishing co-op 1	53	2	0.32	0.5	30
Dispensary – fishing co-op 2	32	2	0.20	0.5	18
Dispensary – Church	106	1	0.32	0.5	58
Dispensary – community centre	119	1	0.36	0.5	66
Dispensary – province house	151	1	0.46	0.5	83
			Approximate total cable cost		467
Suggested inverter model: Latronics Sinewave Inverter 1800 W 24 V (LS1824)					
				Inverter cost	1919**
				Approximate total cost	**2400**

* All prices according to Screwfix (www.screwfix.com)
** Price according to Apollo Energy (www.apolloenergy.com.au)

According to Table 18 above, the approximate total cost of the cables including an inverter is 2400 AUD. The cost per meter cable generally decreases when buying larger quantities of cables. Therefore, the cable cost above has been calculated assuming that all cables of the same size will be bought at the same time. A table giving the total cost and amount of cables needed at all sites is presented at the end of this chapter.

7.2.2. Matangi

In Matangi, the one wind turbine proposed for the site should be installed as close to the powerhouse as possible, requiring a maximum cable length of 17 m. The maximum power of the loads is obtained from the Matangi energy use audit in Appendix D. The cable lengths, maximum currents and required cross sectional areas of the cables in Matangi are given in Table 19 below. According to the table, the approximate total cable cost of the system is 190 AUD.

Table 19: Cable lengths and CSA's, Matangi.

Object from – to [m]	Cable length [m]	Max. current [A]	Required CSA of cable [mm^2]	Equivalent standard cable size at 24 V [mm^2]	Approx. cable cost [AUD]*
Wind turbine – powerhouse	17	11	5.70	6	53
Powerhouse – Church	35	4	4.27	6	109
Powerhouse – community hall	11	5	1.68	2.5	14
Powerhouse – community kitchen	11	1	0.34	0.5	6
		Approximate total cable cost			**190**

* All prices according to Screwfix (www.screwfix.com)

7.2.3. Herald Bay

The powerhouse in Herald Bay has been built in vicinity of an open clearing big enough to install the 12 solar modules proposed for the site. Thus, the cable length between the solar array and the powerhouse should not exceed 5 m and the modules measure 0.635x1.18 m. Thus, a total of 15 m of cable is required to connect the 12 modules in an array.

The solar module selected for the site has a maximum current rating of 4.5 A, according to Table 6. Of the 12 modules proposed for the site in Herald Bay, 6 will be connected in parallel, giving a total current of 27 A. The maximum currents of the loads are obtained from the Herald Bay energy use audit in Appendix E. In Table 20 below, the cable lengths, currents and required cross sectional areas of the cables needed in Herald Bay have been summarized. According to the table, the approximate total cost of the cables is 500 AUD.

Table 20: Cable lengths and CSA's, Herald Bay.

Object from –to [m]	Cable length [m]	Max. current [A]	Required CSA of cable [mm^2]	Equivalent standard cable size at 24 V [mm^2]	Approx. cable cost [AUD]*
Solar array – Powerhouse	20	27	15.65	16	111
Powerhouse – school building 1	33	14	14.09	16	183
Powerhouse – Church	66	2	4.03	6	205
			Approximate total cable cost		**500**

* All prices according to Screwfix (www.screwfix.com)

7.2.4. Iahsoa

In Iahsoa, the total number of modules suggested for the site is 6. Of these, 3 will be connected in parallel giving a total current close to 14 A. The maximum currents of the loads are obtained from the Iahsoa energy use audit in Appendix F. The cable lengths, currents and required cross sectional areas of the cables in Iahsoa are given in Table 21 below. The approximate total cost of the cables according to the cable is 300 AUD.

Table 21: Cable lengths and CSA's, Iahsoa.

Object from – to [m]	Cable length [m]	Max. current [A]	Required CSA of cable [mm^2]	Equivalent standard cable size at 24 V [mm^2]	Approx. cable cost [AUD]*
Solar array – Powerhouse	12	14	5.12	6	38
Powerhouse– Church	11	5	1.68	2.5	14
Powerhouse – Nakamal	50	5	7.63	10	230
Powerhouse – community hall	28	1	0.85	1	16
			Approximate total cable cost		**300**

***** All prices according to Screwfix (www.screwfix.com)

7.2.5. Cable cost summarized

In Table 22 below, the total cable cost for each cable size and length has been summarized. The prices in the table are according to Screwfix homepage including shipping. In the "required cable length" column, all cable lengths within the listed cable size interval have been added. The cable cost has been based on the corresponding wholesale cable length available online.

Table 22: Cable cost reference table.

Cable size [mm^2]	Required cable length [m]	Cable cost [AUD]	Corresponding wholesale cable length [m]
0.5 – 1.0	50	32	50
0.5 – 1.0	500	275	5*100
1.5 – 2.5	82	100	100
6.0	164	510	2*100
10.0	50	230	50
16.0	52	295	3*25

8. Suggested System Designs

8.1. Mission Bay

Wind Turbines		
Estimated daily energy output	3.4 kWh	• The turbines should be installed at least 5 turbine diameters (8.5 m) apart in the crosswind direction, as illustrated in Figure 21.
Load Requirements		
Estimated daily load	4.7 kWh alt. 2.2 kWh	• The daily load according to the energy use audit in Appendix C exceeds the expected daily energy output. As such, a priority of the most essential loads must be done. • A suggestion is to exclude the fishing cooperatives at this stage as these institutions already are partly powered by privately owned solar modules. This would give the alternative daily load given in the left column.
Battery Bank		
Required battery capacity	1500 Ah alt. 700 Ah	• The battery storage capacity has been sized according to a daily load of 4.7 kWh. • Excluding the fishing cooperatives from the design would give the alternative required battery capacity in the left column.
Cables		
Required cable lengths and CSA's	**Dispensary – Airport radio, Dispensary – Fishing co-op 1, Dispensary – Fishing co-op 2, Dispensary – Church, Dispensary – Community centre and Dispensary – Province house:** 151 m 0.5 mm^2 **Powerhouse – Dispensary:** 60 m 1.5 mm^2 **Wind turbines – Powerhouse:** 34 m 6 mm^2	• The cables should be run from the powerhouse to a central location in the village, for instance the dispensary. A switchboard should be included in the design to redirect the electric energy from this location to the loads. • An inverter should be included in the design to convert the power from the battery bank from 24 V DC to 240 V AC.
Total System Cost		
17 000 AUD		

8.3. Matangi

Wind Turbine		
Estimated daily energy output	0.85 kWh	• A more appropriate site should be considered. • A taller tower should be considered. • Unless a much taller mast or a more appropriate site can be considered, it is recommended that a majority of the trees in the prevailing wind direction should be cut down to maximize the wind speed at the site and for the turbines to experience undisturbed wind flow.
Load Requirements		
Estimated daily load	0.7 kWh	• The present load is less than 0.4 kWh per day. Care should be taken when increasing the load, depending on the actual power output of the wind turbine at the site.
Battery Bank		
Required battery capacity	300 Ah	• The battery storage capacity has been sized according to an estimated daily power output of 0.85 kWh.
Cables		
Required cable lengths and CSA's	**Powerhouse – Community kitchen:** 11 m 0.5 mm^2 **Powerhouse – Community hall:** 11 m 2.5 mm^2 **Wind turbine – Powerhouse and Powerhouse – Church:** 52 m 6 mm^2	
Total System Cost		
4 900 AUD		

8.4. Herald Bay

Solar Modules		
Estimated daily energy output	2.5 kWh	• The number of modules in a string should be 2 and the number of parallel strings 6 to obtain the desired voltage level of 24 V.
Load Requirements		
Estimated daily load	1.8 kWh	• A small, currently non-existing fridge for vaccines has been included in the daily load. This should be located as close to the powerhouse as possible, for instance in school building 1. It is important that an energy efficient fridge is selected.
Battery Bank		
Required battery capacity	800 Ah	• The battery storage capacity has been sized according to an estimated daily power output of 2.5 kWh.
Cables		
Required cable lengths and CSA's	**Powerhouse – Church:** 66 m 6 mm^2 **Solar array – Powerhouse and** **Powerhouse – School building 1:** 53 m 16 mm^2	• The girls' dormitory has been excluded in the design as the distance from the powerhouse is considered to be too far given the low demand.
Total System Cost		
8 300 AUD		

8.5. Iahsoa

Solar Modules		
Estimated daily energy output	1.3 kWh	• The number of modules in a string should be 2 and the number of parallel strings 3 to obtain the desired voltage level of 24 V.
Load Requirements		
Estimated daily load	1 kWh	
Battery Bank		
Required battery capacity	400 Ah	• The battery storage capacity has been sized according to an estimated daily power output of 1.3 kWh.
Cables		
Required cable lengths and CSA's	**Powerhouse – Community hall:** 28 m 1 mm^2 **Powerhouse – Church:** 11 m 2.5 mm^2 **Solar array – Powerhouse:** 12 m 6 mm^2 **Powerhouse – Nakamal:** 50 m 10 mm^2	
Total System Cost		
6 300 AUD		

9. Discussion

System Design

Generally, when designing a stand-alone power supply system, first the load should be determined, and then the required battery storage capacity to support the load should be sized. Next, power-producing units properly sized to ensure that the batteries are effectively charged to meet the system loads should be selected. In Futuna, the power demand is currently non-existing and the solar modules and wind turbines were selected before any energy use audits were conducted. What is more, there have been no feasibility studies of the chosen sites for power production. If the project procedure had been the other way around, it would have been possible to design less expensive and more efficient power supply systems.

As discussed in this report, off-grid renewable power systems are particularly vulnerable to shortfalls due to the intermittent nature of renewable energy sources. Moreover, a constant load demand over the year supplied by unpredictable power sources means the systems should be sized according to the worst month if constant supply year-round is desired. Consequently, the power systems will be less efficient as a smaller part of the power resource will actually be available to the consumers.

These problems can be avoided by the use of back-up diesel generators or by combining different power sources, such as hybrid systems including both wind and solar power. Hybrid systems are very successful due to the variability of the wind throughout the year. In many places, the sun and the wind complement each other and thus provide a more consistent year-round output than either of the systems would do by themselves. It would therefore have been preferable to design the systems for more than one power source.

Voltage Level

A component not discussed in this report that should be considered to be included in the system designs, is an inverter. Inverters are normally included in small scale power supply systems to convert low-voltage direct current (DC) produced by solar modules and battery banks into higher voltage alternating current (AC) used in many appliances. In this report, because of the need to keep the system costs down and minimize losses, a nominal voltage level of 24 V DC has been presumed at all sites except Mission Bay.

An advantage of including an inverter in the system design is that a higher system voltage will keep the transmission losses down. Also, the required cross sectional areas of the cables to keep the voltage drop below the accepted level will be much less and thus the cost of cables will decrease. Moreover, if the distance from the powerhouse to the loads is too long, higher voltages may be necessary to be able to transmit any power at all, given the extremely low power outputs. AC-powered appliances are also generally more widespread, cheaper and can be more reliable.

However, inverters are relatively expensive and will considerably increase the total system cost. Moreover, failing to include a properly sized inverter in the system will limit the number and size of appliances that can be run at once. In addition, the inverter itself acts as a load due to conversion efficiency losses and thus affects the total efficiency of the system. Depending on the distances from the powerhouse to the loads and on the appliances available, it should therefore be closely considered if the system should be wired for DC or AC, or maybe both. Even though many appliances today require 240 V AC to operate, special DC-powered appliances are available and these are often more energy efficient as well. Some of these appliances are more expensive but as they use less energy the total system cost will be reduced in the long run.

In Mission Bay, where the distance from the powerhouse to the loads is long, it makes sense to include an inverter in the design to keep the cable size down and to make sure there will be enough power available. Another reason to include an inverter in the design in Mission Bay is that it is desired to power several freezers, which have already been purchased and require 240 V AC to operate. In the other villages, the distances from the powerhouse to the loads are shorter and the power will mainly be used for smaller loads such as lighting. For this purpose 24 V DC is considered to be sufficient.

System Cost

According to the calculations made in chapter 7, the total system cost for all four sites will be in the order of 36 500 AUD or around 27 000 euro. The estimated total cost includes all major components such as batteries, cables, battery charge controllers and an inverter for the site in Mission Bay. It does not include safety equipment such as fuses and breakers. However, the cost of these components is minimal in comparison.

If there are not enough financial resources available, it is recommended that all resources are used to properly size the systems at 1-2 sites rather than sizing the systems inappropriately at all four sites. Prioritizing Mission Bay (as it is the administrative headquarter of the island) and Herald Bay (as it is the location of the island’s only school) would give a total system cost of approximately 25 500 AUD. Leaving out the fishing cooperatives of the design in Mission Bay would reduce the total system cost even further. As given in the results in chapter 8, the total battery capacity in Mission Bay excluding the fishing cooperatives would be 700 Ah, requiring a total battery storage capacity similar to Herald Bay. The total system cost would then be around 18 500 AUD.

Wind Turbines

The results in this study showed that even though Futuna Island might have good wind resources, more information about the predominating wind regime at the sites is necessary in order to evaluate the exact potential for small-scale wind power production. Data from NASA suggest relatively stable wind speeds in the order of 5-7 m/s. Given that the test results of the selected wind turbine suggested the highest power coefficient for winds speeds around 5-7 m/s, the selected wind turbine might be suitable for small-scale power production in Futuna. However, this assumption depends on the accuracy of the wind speed data obtained from NASA. Moreover, the cut-in wind speed should preferably have been somewhat lower than the 4 m/s obtained in the test results, to obtain higher efficiencies at lower wind speeds.

There are several uncertainties involved with the estimated power output of the wind turbines in this report. First of all, the data obtained from NASA cover an area of one-by-one degree containing Futuna Island and as such *could* be representative for the wind regime on the island. However, this has not been possible to confirm. Moreover, the topography and surface roughness on the sites will have a definite, but uncertain influence on the local wind resource. In addition, it is the winds above the average that contribute most of the power, and therefore the yearly energy content of the wind might differ between two sites with identical mean wind speed. As the estimated power outputs in this report have been based on the monthly averaged wind speeds, the actual power outputs at the sites might be greater depending on the actual energy content of the wind at the sites.

The statistical distribution of wind speeds varies from place to place around the globe, depending on local climate conditions, the topography and surface roughness. It is therefore highly recommended that wind-monitoring equipment be mounted at the sites. As the wind speeds in the area seem to be relatively stable, it may be sufficient to monitor the wind a couple of weeks at each site and each season. One set of wind-monitoring equipment could then be moved around to monitor the wind speeds at all the potential sites. The collected wind data could then be used to produce a wind speed frequency distribution diagram. Multiplying the power of each wind speed with the probability of each wind speed from the frequency distribution graph will give the distribution of wind energy at different wind speeds at the sites.

Solar Modules

The estimated power output of the solar modules is considered to be more accurate than the estimated power output of the wind turbines, mainly because solar modules are less sensitive to small variations in the available resource. A total of 88 rainy days with a PSH value of 1 hour has been assumed when estimating the power outputs. If the actual number of no-sun days is more (or less) than this, the power output over the year will differ from the estimated result in this report. To maximize the power output of the modules, it is essential that the modules are installed correctly, with a proper tilt angle and direction. It is also important to prevent overheating of the modules by allowing the air to circulate freely around them. This is done by installing the modules on a tilted frame rather than directly on a roof.

Battery Banks

The battery banks should be sized to allow for a certain number of days of autonomy and a maximum depth of discharge. Failing to do so will result in shorter battery life and thus the total cost of the system will be higher. In the designs in this report a maximum depth of discharge of 70 % and 5 days of autonomy have been assumed. A maximum depth of discharge of 50 % and 3 days of autonomy would give similar storage capacity. The most important thing is that the battery bank is oversized to ensure that the system is not overused during the worst months. This is especially important considering the uncertainties involved with the estimated power outputs in this report. It is also important that the powerhouses are sufficiently ventilated to prevent overheating of the batteries.

Organizational Issues and Human Error

The success of this project may not only depend on how well planned and thought of everything is. In many projects conducted in developing countries, the technical solutions are the easy part. The difficulties usually arise when administering the project after the installations have been done. An important factor is each individual's (or the community's) operational understanding, desire and ability to carry out maintenance and manage the systems properly.

The author's experience of these issues from the field studies in Vanuatu is that the most common problem that makes projects fail is the *sense of responsibility*. Hardly ever has maintenance and repairs been included in the projects and quite often there is confusion about who is responsible when anything breaks down. The villagers on the islands usually do not have the financial funds required to manage the projects after the power systems have been installed, and so, when something fails, the systems are left non-functioning.

This is especially true for projects funded by aid programs. A common procedure by the countries that give aid is sending a competent person down to make the installations. This person then leaves everything with the locals, who by no means have the knowledge or funds required to maintain the systems. Even worse; sometimes the technical articles given by the aid program are sent directly to the local communities without any instructions about how to make proper installations.

These problems are difficult to resolve as both cultural aspects and fundamental organizational shortcomings are present. The best thing to do would be to offer training and education of the locals so that they will be able to solve any problems that arise with the installed systems by themselves. Moreover, it is crucial that follow-ups or at least some kind of evaluation of implemented projects are done by the initiator of the project.

10. Conclusions

The purpose of this Master's Degree project was to suggest the designs of stand-alone renewable power supply systems at four sites on Futuna Island in the Republic of Vanuatu. The system designs included estimating the power outputs of the selected wind turbines and solar modules at the sites in addition to properly size the required battery banks and cables.

The suggested design should be of power systems easy to manage and maintain by the local communities. Also, because of the relatively low demand and power output of the selected wind turbines and solar modules, it was important to minimize system losses and keep the designs simple. This was also important from an economical perspective as the project is experiencing financial constraints.

This study has shown:

- The total system cost of all four sites will be in the order of 36 000 AUD or 26 000 euro including batteries, cables, battery charge controllers and one inverter at the site in Mission Bay.
- Undersized battery banks will result in less efficient and short-lived systems. Undersized cables will result in too much voltage drop and less or no power available to the load. Therefore, if there are not enough financial resources available, it is recommended to use all the resources available to correctly size the systems in 1-2 villages rather than inadequately size the systems in all the villages.
- Prioritizing Mission Bay and Herald Bay at this stage gives a total system cost of around 25 500 AUD. Excluding the fishing cooperatives from the design in Mission Bay gives a total system cost of 18 500 AUD.
- Some parts of Futuna Island can be suitable for wind power production. However, wind-monitoring on the sites is required to estimate the exact potential.
- In the case of Matangi, it is recommended that the turbine is relocated to a nearby site with better winds. Unless a more appropriate site can be considered, a taller mast will be required to eliminate turbulent wind flow. Alternatively a majority of the trees in the prevailing wind direction should be cut down to maximize the wind speed at the site.
- There is less uncertainty involved with estimating the power output from the solar modules as they are less vulnerable to local variations. In addition, solar modules are easier to manage and maintain by the local communities on the island. Solar modules are therefore considered more appropriate for small scale power production on the island, at least until the wind climate is better known.
- The most preferable system design option in Futuna would be to combine wind turbines with solar modules or back-up diesel generators.
- If a diesel generator is too expensive, certain measures should be considered to maximize the power output of the wind turbines such as higher towers and minimizing the amount of obstacles in the prevailing wind direction.

11. Recommendations

The following recommendations should be considered when installing the power supply systems on Futuna Island:

General System Design

- If there is a shortage of financial resources, 1-2 villages should be prioritized for correctly sized power systems rather than sizing insufficient systems in all the villages. It is suggested in this report that Mission Bay and Herald Bay should be prioritized at this stage.
- A back-up diesel generator or combining other renewable energy sources should be considered in the designs if financial resources are available, as this would make the systems more reliable and efficient.

Wind Turbines

- It is recommended that wind monitoring equipment should be installed at the sites. As the wind speeds in the region are relatively consistent, one set of wind-monitoring equipment to be moved around the sites may be sufficient.
- If more than one turbine is to be installed at a site, the turbines should be installed *at least* 5 turbine diameters (8.5 m) apart in the crosswind direction.
- Turbulence should be reduced as much as possible by using taller towers or cutting down trees in the prevailing wind direction, especially at the site in Matangi.

Solar Modules

- The modules should be tilted so that the sun's rays are perpendicular towards the solar module, facing true north.
- To prevent overheating of the modules, it is important to provide adequate ventilation by mounting the module on a tilted frame, so that air can circulate freely under the module.
- For Futuna Island, located at latitude 19° S, the module should be tilted at 15° to 20°. A *minimum* tilt angle of 10° should be applied to allow for self-cleaning of modules.
- A derating factor of 0.8 should be included in the design to compensate for losses.
- The solar array should be installed as close to the powerhouse as possible, in order to limit cable length.
- It is very important that the solar array is out of the way of shadowing obstacles such as trees, as this would otherwise limit the power output considerably.

Battery bank

- It is recommended to allow for as much storage capacity as one can reasonably afford. A minimum of 5 days of autonomy and a maximum depth of discharge of 70 % have been recommended in this report.
- It is important that the batteries connected are all of the same nominal voltage and of the same age. Also, batteries in a battery bank must be of identical capacity and of the same model.

- It is recommended to include a battery charge controller in the system design to ensure that the maximum depth of discharge is never exceeded.
- It is important that the powerhouses are sufficiently ventilated to prevent overheating of the batteries.
- It can be a good idea to measure the voltage level of the batteries at a regular basis, to create awareness of the importance of battery health and make sure the systems are not overused. If the maximum depth of discharge is approached, the villagers should make sure that appliances are turned off.

Cables

- The cables from the renewable power source to the batteries should be fitted so that the voltage drop between the source and the batteries is less than 5 % of the system voltage.
- It is also recommended that the voltage drop between the batteries and any load should be limited to 5 %. This should be done to minimize the system losses and prevent system breakdown.
- It should be considered to include an inverter in the system design to minimize voltage drop, especially if power is needed far from the powerhouses.

Recommendations for further research

- As argued in the discussion, wind monitoring studies should be conducted in Futuna (and also elsewhere in the country). This would not only be valuable to this project, but to future projects as well, as the estimated power output of installed wind turbines could be more accurately determined.
- An evaluative study of implemented small scale renewable power projects on the islands would have been interesting. This would also be of value for future projects, as mistakes made in previous projects could be avoided.

References

Brochures

Ampair 600 Brochure, date of publication 15/04/2006,
www.ampair.com

Global Solar Energy – 2008 Product Catalogue, accessed on 18/01/2011,
http://www.stringerenergygroup.com/uploads/2008_Global_Solar_catalog.pdf

Literature

Ackermann, T., 2005, *Wind Power in Power Systems*, John Wiley & Sons

Boyle, G., 2004, *Renewable Energy – Power for a Sustainable Future*, second edition, The Open University, United Kingdom

Chiraz, D., 2010, *Wind Power Basics – a green energy guide*, New Society Publishers, Canada

Gipe, P., 2004, *Wind Power – Renewable Energy for Home, Farm, and Business*, Chelsea Green Publishing Company, Vermont

Global Sustainable Energy Solutions (GSES), *Stand Alone Power Supply Systems – Design and Installation*, Training Manual, 7th Edition

Harewood, J., 2009, *Vanuatu & New Caledonia*, Lonely Planet, 6th edition

Manwell, J.F. et al, 2009, *Wind Energy Explained*, John Wiley & Sons, UK

Wizelius, T., 2007, *Developing Wind Power Projects*, Earthscan, UK

Reports

Chow, J., 2010, *Assessment of Solar Home Systems (SHS) for Isolated Rural Communities in Vanuatu Using Project Lifecycle/Sustainability Framework*, Michigan Technological University

European Commission, ACP-EC Energy Facility, *Grant Application Form applied by VANREPA on behalf of the project The Answer is Blowing in the Wind*, 9th European Development Fund

Garrad Hassan 2008, *Assessment of the wind potential at various sites on Futuna Island, Vanuatu*, 2008/08/06, by Nalini Blacker on behalf of VANREPA

New and Renewable Energy Centre, *Summary Test Report for Ampair 600/230 Mk 2.5*, 27/05/2009, Version 2.0

VANREPA, Narrative progress report for: *The Answer is Blowing in the Wind – Improving access to energy services for the communities of Futuna & Aneityum Islands*

Wineur 2005, *Wind Energy Integration in the Urban Environment – Technology inventory report*, supported by the European Commission under the Intelligent Energy – Europe Programme

Websites

Government of South Australia – Department for Transport, Energy and Infrastructure, *Average appliance energy use*, accessed on 07/01/2011,
http://www.dtei.sa.gov.au/energy/be_energy_smart/appliance_energy_use

NASA Surface meteorology and Solar Energy release 6.0, *Meteorology and Solar Energy Tables for Lat-19.517, Long-170.2*, accessed on 18/01/2011,
http://eosweb.larc.nasa.gov/sse/

The United Nations Office of the High Representative for the Least Developed Countries (UN-OHRLLS), accessed on 19/08/2010,
http://www.unohrlls.org/en/ldc/related/62/

UN Department of Economic and Social Affairs – Division for Sustainable Development, SIDS Members, accessed on 19/08/2010,
http://www.un.org/esa/dsd/dsd_aofw_sids/sids_members.shtml

VANREPA, accessed on 15-08-2010, http://www.vanrepa.org/index.htm

Vanuatu Government - Vanuatu Meteorological Services, accessed on 03/03/2011,
http://www.meteo.gov.vu/VanuatuClimate/tabid/196/Default.aspx

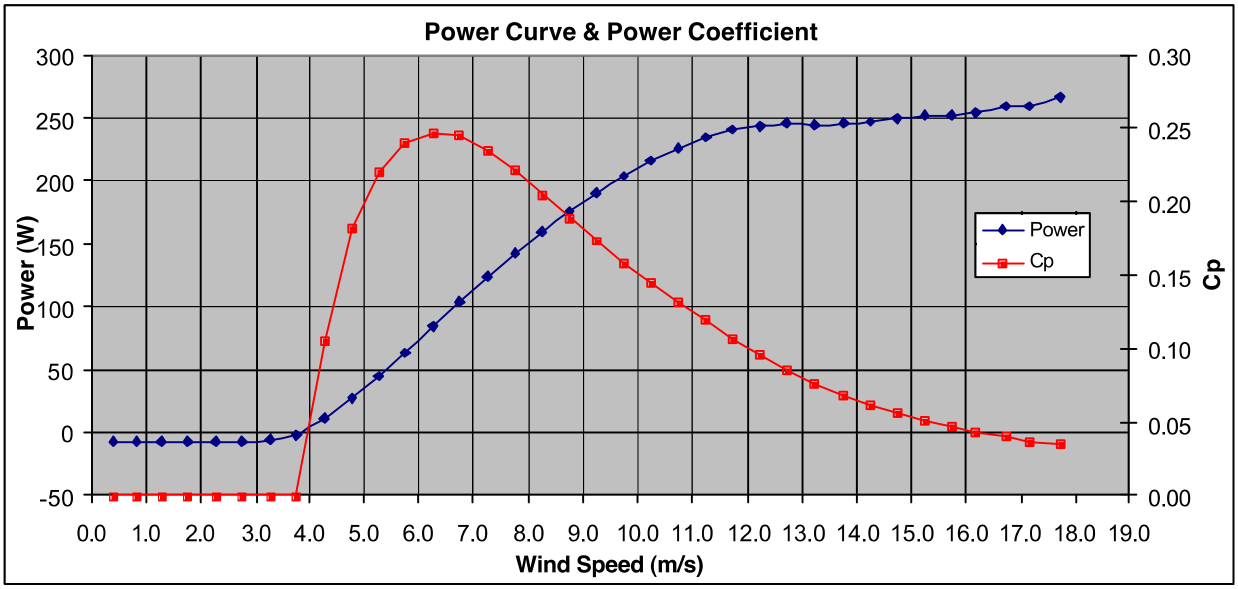
Appendix

Appendix A: Test data of Ampair 600, table of average power output

Average Wind Speed m/s	Average Power (W)	Data Points	Cp
0.40	-6.52	58	
0.81	-6.45	382	
1.27	-6.56	977	
1.76	-6.65	1258	
2.27	-6.60	1929	
2.76	-6.61	2542	
3.25	-6.20	3094	
3.76	-1.39	3492	
4.25	11.18	3653	0.105
4.76	27.19	3992	0.181
5.25	44.41	4768	0.220
5.75	63.38	5012	0.240
6.25	83.79	4906	0.247
6.74	104.16	4403	0.245
7.24	124.09	3635	0.235
7.74	142.82	2939	0.221
8.24	159.98	2314	0.205
8.74	176.12	1856	0.189
9.24	190.38	1616	0.174
9.75	204.28	1276	0.158
10.24	216.15	986	0.145
10.74	226.19	784	0.131
11.23	234.67	633	0.119
11.74	240.95	392	0.107
12.23	243.26	292	0.096
12.73	245.43	175	0.086
13.25	244.43	98	0.076
13.78	245.60	67	0.067
14.26	247.38	41	0.061
14.75	249.21	24	0.056
15.24	251.45	18	0.051
15.74	252.29	20	0.047
16.18	254.45	11	0.043
16.74	258.84	7	0.040
17.16	258.88	3	0.037
17.72	267.06	1	0.034

Source: NaREC, *Summary Test Report for Ampair 600/230 Mk 2.5*

Appendix B: Power curve and power coefficient of Ampair 600 W



Source: NaREC, *Summary Test Report for Ampair 600/230 Mk 2.5*

Appendix C: Mission Bay energy use audit

W = rated power [W], Q = quantity [dimensionless]

OBJECT	W	Q	Hrs/ day	Wh/ day	COMMENTS
Fishing co-op 1					3x90 W solar panels installed, powering freezer 1
Freezer 1	58	1	24	(820*)	Existing: DC, COSO202, 58W
Freezer 2	58	1	24	820	Not existing, want one more of the same model as freezer 1
Freezer 3	276	1	24	1000**	Existing, AC, 1.2A/230V
Lights	11	8	3	264	Lights installed with power point
Fishing co-op 2					Part of Putongi Project for processing fish, has 2x62 W solar panels installed, powering freezer 4
Freezer 4	225	1	24	(440***)	Existing: Sun Danzer, SDR225/C225
Freezer 5	225	1	24	440	Not existing, want one more same as freezer 4
Church					
Lights	11	8	2	176****	Lights installed with power point
Stereo	60	1	1	60	Not existing, estimated value
Dispensary					Has 2x30 W solar panels powering radio plus 4 light sources
Refrigerator	360	1	24	700*****	Not existing
Lights	18	8	4	576	Have 4 lights installed, need more
Airport Terminal					
Radio	100	1	1/7	15	½ hour 2days/week
Community centre					Not built yet
Lights	18	3	3	162	Not existing, estimated value
Province house					Not completed
Lights	18	5	3	270	Not existing, estimated value
Laptop	50	1	3	150	Not existing, estimated value
Printer	50	1	1	50	Not existing, estimated value
Household light battery charging					Approximately 20 households, 2 rechargeable lights per household
	1.3	20	1	26	Each light charged every second day
TOTAL	1540 W			4709 Wh/day	

* 790 Wh/24 hrs if 25°C, 980 Wh/24 hrs if 32°C, mean temperature in Futuna = 26°C

** Estimated value, unsure about actual wattage

*** 360 Wh/24 hrs if 21.1°C, 532 Wh/24 hrs if 32.2°C

**** Estimated value, unsure about actual wattage

***** Estimated value, based on small-size refrigerators

Appendix D: Matangi energy use audit

W = rated power [W], Q = quantity [dimensionless]

OBJECT	W	Q	Hrs/ day	Wh/ day	COMMENTS
Church					
Lights	11	6	2	132	**5 existing, need 1 more**
Lights	18	3	2	108	**Not existing, estimated value**
Stereo	60	1	2	120	**Not existing, estimated value**
Community centre					**Not built yet**
Lights	18	3	2	108	**Not existing, estimated value**
TV	80	1	1	80	**Not existing, estimated value**
DVD	15	1	1	15	**Not existing, estimated value**
Kitchen					**Not built yet**
Lights	18	2	2	72	**Not existing, estimated value**
Household light battery charging					**Approximately 20 households, 2 rechargeable lights per household**
	1.3	20	1	26	**Each light charged every second day**
TOTAL	**230**	**W**		**700**	**Wh/day**

Appendix E: Herald Bay energy use audit

W = rated power [W], Q = quantity [dimensionless]

OBJECT	W	Q	Hrs/ day	Wh/ day	COMMENTS
School					**One building has 4x60 W solar panels installed, powering lights and one computer**
Lights, room 1	18	3	2	108	**Lights installed with power point**
Lights, room 2	18	4	2	144	**Lights installed with power point**
Lights, office	11	2	5	110	**Lights installed with power point**
DVD	25	1	1	25	**Existing**
TV	100	1	1	100	**Existing**
Laptop	50	2	3	300	**Not existing, estimated value**
Printer	50	1	0,5	25	**Not existing, estimated value**
Fridge	65	1	24	168*	**For the aid post, not existing**
Girls' dorm	(11)	(2)	(4)	(88)	**Not existing, estimated value**
Church					**Has 1x60 W solar panel installed**
Lights	11	3	2	66	**Lights installed with power point**
Stereo	30	1	2	60	**Existing**
Fishing co-op					**Self supplied: has 2x90 W solar panels powering the freezer**
Freezer	?	1	?	?	
Household light battery charging					**Approximately 40 households, 2 rechargeable lights per household**
	1.3	40	1	52	**Each light charged every second day**
TOTAL	**321**	**W**		**1158**	**Wh/day**

* Suggested model: Sundanzer DCR165 DC powered fridge (http://www.eco-fridge.com/dcfridge.html)

Appendix F: Iahsoa energy use audit

W = rated power [W], Q = quantity [dimensionless]

OBJECT	W	Q	Hrs/ day	Wh/ day	COMMENTS
Church					
Lights	11	11	2	242	Lights installed with power point
Lights	36	3	1	108	Lights installed with power point
Stereo	60	1	2	120	Existing
Community centre					Not built yet
Lights	18	3	3	162	Not existing, estimated value
TV	80	1	1	80	Existing
DVD	15	1	1	15	Existing
Nakamal					
Lights	18	3	3	162	Existing
Household light battery charging					Approximately 20 households, 2 rechargeable lights per household
	1.3	20	1	26	Each light charged every second day
TOTAL	240	W		1000	Wh/day

Appendix G: Cable sizes – International standard IEC 60228

International standard wire sizes (IEC 60228)					
0.5 mm^2	0.75 mm^2	1 mm^2	1.5 mm^2	2.5 mm^2	4 mm^2
6 mm^2	10 mm^2	16 mm^2	25 mm^2	35 mm^2	50 mm^2
70 mm^2	95 mm^2	120 mm^2	150 mm^2	185 mm^2	240 mm^2
300 mm^2	400 mm^2	500 mm^2	630 mm^2	800 mm^2	1000 mm^2

Source: International Standard IEC 60228, Third Edition 2004-11, *Conductors of Insolated Cables*, Reference number IEC 60228:2004(E)

Appendix H: Pictures from the field trip to Futuna Island

Mission Bay powerhouse

Matangi powerhouse

Herald Bay powerhouse

Iahsoa powerhouse (church behind)

People hanging out by the airport terminal, Mission Bay

Arrival of an airplane, Mission Bay

Children outside one of the school buildings, Herald Bay

Ocean view, Herald Bay

Part of the walking track between Matangi and Mission Bay

Church, Mission Bay

Nakamal kitchen, Iahsoa

Satellite phone

Antenna powered by a privately owned solar power system

Dispensary, Mission Bay

Growing crops, Matangi

Sunset ocean view, Matangi

Children playing volleyball, Mission Bay

Weaving mats made of palm leafs, Matangi

Outdoor shower and traditional house in the background, Mission Bay