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RESEARCH ARTICLE

A comprehensive wind resource estimation and economic analysis for Rakiraki, Fiji

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Abstract: The wind resource assessment for three locations in Rakiraki, Fiji are carried out. The wind resources at Rokavukavu and Navolau has been analyzed along with the nearby Tuvavatu site. The annual diurnal wind speed, wind shear and turbulence intensity were analyzed. Rokavukavu, Navolau and Tuvavatu site has an average wind speed of 5.91 m/s, 8.94 m/s and 8.13 m/s respectively at 55 m above ground level (a.g.l). The wind direction for all the three sites is predominantly South-East. The diurnal wind speed pattern and the wind shear pattern for all the three sites were consistently similar. The turbulence intensity at Rokavukavu, Navolau and Tuvavatu were found to be 14.9%, 17.1% and 11.7% at 55 m a.g.l. The Weibull parameters and the wind power density were obtained for all the three sites by using the moment fitting method. A high resolution wind resource map for the three sites were obtained using Wind Atlas Analysis and Application Program (WAsP). The WAsP analysis indicates good wind potential at Navolau and Tuvavatu site for power production. The annual energy production (AEP) with six Vergnet 275 kW wind turbines for Navolau and Tuvavatu site is estimated and an economic analysis is performed, which exhibited a payback period of 5 and 6 years respectively.

Keywords: wind energy, WAsP Analysis, Weibull distribution, annual energy production, economic analysis, Rakiraki, Fiji

Nomenclature

AEP	annual energy production
i	Discount rate
AGL	above ground level
I	real rate of discount
BCR	benefit cost ratio
IRR	internal rate of return
c	cost
m	% of operation and maintenance cost
C_{om}	Operational maintenance/repair cost
n	Projects life span
C_p	Power Coefficient
NPV	Net present value
e	Escalation rate
P	Power
e_a	Apparent escalation rate
r	Inflation rate

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1 Introduction

To combat the effect of climate change more effort has been placed towards lowering the carbon dioxide emissions. The strategy that has extensively been used to reduce the emission is by reducing the carbon intensive electricity production in order to decrease the environmental dilapidation by making a transition towards harnessing the energy from renewable energy technologies. Amongst the many renewable energy sources, wind has been considered as one of the best identified renewables that are inexhaustible and are available everywhere on earth[1]. According to[2] wind is an excellent economical sources of electricity production. Due to its non-polluting characteristics, wind has been deliberated as an important source that is effective for power generation and for this reason it is dynamically pursued in voluminous and developing countries. Wind power is one of the fastest growing industries that contributes approximately 4.0% towards the world wide electricity and power supply diversification[3]. The total installed global wind power capacity by the end of 2017 was 539 GW from which 42.35% was installed in Asia, 33% in Europe, 19.51% in North America, 3.31% in Latin America and Caribbean, 0.96% in pacific region trailed by Middle East and Africa where the installed capacity was 0.84%[4]. In 2017, approximately 52.6 GW of wind power capacity was added which resulted in the increase in the global wind power capacity by 10.78%, however the gross addition in 2017 was 4.9% below than what was added in 2015 which exemplified the highest wind power capacity added till date[5]. In addition there are approximately 72 TW of available and exploitable form of wind energy globally that could be harnessed for generating electrical energy[6]. Harnessing of wind energy has been made possible through the use of modern wind turbines namely Horizontally Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). The wind turbines transfigures the winds kinetic energy into mechanical power which are then converted into electricity through the use of generators. The power available in the wind is directly proportional to the cube of the wind velocity and swept area of the turbine. In order to harness maximum power from the wind, it is important to select appropriate sites that are exposed to high wind speed by conducting comprehensive site surveys, so that the wind turbines can work efficiently for generating electricity. However, due to the intermittent nonlinear nature of the wind, it becomes extremely difficult to determine the feasible sites for setting up the wind turbines and the wind farms. Thus, to determine the viable sites for wind farms, researchers have adopted various techniques for developing the wind resource maps that are used for describing spatial wind distribution over a region. Wind resource maps are geographic information system (GIS) applications that are used in wind power development for supporting the auxiliary data exploration and for conducting comprehensive resource assessment. The selection of the sites for the construction of the wind farms without considering the use of wind resource map, generally lacks credibility in terms of available wind resources[7]. Wind resource map plays a major role in assessing and depicting the available wind resources that assists in the siting, development and in the successful operation of the wind farms. It permits the wind power developers and the policy makers with the unified illustrations of the expected wind speed at an altitude which corresponds to the hub height of the turbines. Thus, this study will focus on the construction of the wind resource map of Rakiraki, Fiji Island by using Wind Atlas Analysis and Application Program (WAsP). The wind speed map will be obtained and then the preeminent map will be determined that will describe the spatial wind distribution over Rakiraki, Fiji Island.

1.1 Background

Wind resource assessments are essential constituent that are necessary for the progression of the wind power project developments. It is mandatory for the wind energy experts to not only provide the potential resource assessment, but also to determine the accuracy through validation studies that will provide the comparison between the estimated wind energy assessment and the fully operational wind farm at a particular location. It should simply answer the question Does the wind farm produce what was predicted? The energy situation in Fiji is eminent for its high dependence on imported fossil fuels from foreign reserves. Fiji spends significant amount of money on importing fuels which accounts for the increasing energy demand and dwindling supplies. The continuous importation and usage of fossil fuel affects Fiji's economy and imposes harmful effects on the environment which will continue to upsurge in near future unless the country takes audacious steps to embrace the full benefits of having renewable energy sources that are clean and sustainable. In pursuance to sustain the energy security of Fiji, there is an absolute need to conduct research in the field of renewable energy in contemplation of finding alternative source of energy to overcome the turmoil of fossil fuel crisis. The National Energy Policy of Fiji (2013-2020), section (5.3) highlights that it is important to promote and to conduct research on renewable energy technologies in order to provide affordable and sustainable energy to the people of Fiji. The National Energy Policy also provides tax incentives for investing in renewable energy technologies and it also encourages and inspires all the tertiary institutes in Fiji to conduct and to extend their research facilities and programmes based on renewable energy[8]. The Pacific Island Countries generally lack credibility in terms of the available wind data which causes hindrance in the development of wind power projects. The wind farm developers hesitate to invest in any wind projects dreading that they might lose their capital. A similar situation occurred in Fiji, where the Butoni wind farm did not accomplish what was anticipated. The 34 million dollars wind farm was established in Butoni, Sigatoka which comprised of 37 wind turbines with each having the rated power of 275 kW was not very efficacious due to the lack of high wind speed[9]. Karan[9] also emphasized that the ineffectiveness of the wind farm was due to the lack of pre-feasibility study of the site before the implementation which resulted the project to become financially uneconomical. Likewise a preliminary study was conducted by[10] on Butoni wind farm which exhibited that the available wind speed was very marginal for producing the power. It was also established that the capacity factor was very low which was estimated to be 14-15% indicating an infeasible project. According to[11] if a wind farm has a capacity factor of 35% or higher than it can be considered as a feasible project. Due to the lack of knowledge, the wind power developers in Fiji have made mistakes when implementing projects resulting into massive capital loss. It is therefore imperative to conduct the comprehensive site surveys before the implementation of the project so that the same mistake does not happen again in the future. Numerous wind resource assessment has been conducted in Fiji. However, it has not always been successful since estimating the wind at a particular location is a challenging task as the wind speed and direction vary in time and space. A study conducted by[12] highlighted that Rakiraki, Fiji has significant wind resources that are available for wind power generation. Thus, this research concentrates on the identification of the potential wind resources that are available in Rakiraki, Fiji through the construction of wind resource maps. Since Rakiraki has abundance of idle hilly area which are not used commercially, these could be utilized for the development of wind farms once significant wind resources are determined. This initiative will enable Fiji to alleviate its energy crisis by generating its own clean and efficient wind powered electricity rather than fully depending on the imported fossil fuels. This project will also encourage and assist the wind power developers in Fiji to make appropriate decisions regarding the implementation of renewable energy projects such as the development of the wind farm.

1.2 Site selection

The preliminary phase of conducting wind resource assessment is the identification of candidate wind energy sites. The sites are selected through surveying relatively large areas where a huge consideration is placed on the wind resources by the estimated wind maps or by the available wind data[13]. Fiji has a good wind energy potential in the Western part of Viti Levu. According to[12] examine the prospects of wind energy potential in Fiji a wind resource assessment was conducted at Rokavukavu, Rakiraki site. The WAsP analysis assessment showed that the site had a good wind energy potential where the average wind speed at 30 m a.g.l and 50 m a.g.l was 6.7 m/s and 7.2 m/s respectively with predominant westerly winds. The three sites in Rakiraki namely, Rokavukavu, Navolau and Tuvavatu sites were selected to be the study site for this research due to the available wind resource present in these areas. The main reason for selecting these three site was to determine the wind regime in the neighborhood through the use of WAsP analysis. The other attributing factors that were considered during the site selection were as follows:

(1) Low population density around Rokavukavu, Navolau and Tuvavatu sites.

(2) Plateaus land that could be utilized for wind farm as there is significant evidence of the high wind density at all the three sites.

(3) Substantial saving in terms of money and risks due to the proximity of the transmission lines as the existing transmission grid are at a shorter distance.

(4) The land cover is conducive for wind farm development since it only has grass and small shrubs.

(5) Easy excess to the site due to good road condition and thus any kind of maintenance could be easily attended to in a short span of time.

1.3 Site description

Rakiraki is located approximately midway between Suva and Nadi. The data that has been used to examine the wind energy potential at Rakiraki was recoded at three anemometric stations. The direct distance between Rakiraki town and Rokavukavu, Navolau and Tuvavatu site is six, nine and three km respectively. Geographically, Rokavukavu, Navolau and Tuvavatu sites are located at (S 17.33^o, E 178.18^o), (S 17.36^o, E 178.18^o) and (S 17.36^o, E 178.28^o) respectively. All the three sites has been characterized as an agricultural land, however since the last site visit on 27th October 2017 it has been confirmed by the land owner that the Rokavukavu site is only used as grazing and pasture land. The vegetation at all the sites are small grass, shrubs and small tress. The terrain for the Rokavukavu site consists mostly of valleys and ridges with steady slopes. Navolau and Tuvavatu site has landforms that are mountainous in nature. Approximately 200 m from the Rokavukavu site there is a 240 V transmission grid while a substation is situated at about two km towards Rakiraki.

2 Description of WAsP software

WAsP is a graphical user interface (GUI) software that has been designed to facilitate in the vertical and horizontal extrapolation of the wind climate statistics. WAsP is a standardized software that has been used extensively for wind resource assessment, siting and the energy yield calculation of the wind turbines and wind farms. The WAsP suite has been used for carrying out the analysis at sites with all different kinds of terrain. The WAsP software has five phase method for performing the analysis which are known as the calculation blocks. The five phase method used for this research are as follows:

(1) Analysis of raw wind data. The analysis was performed in a separate software tool known as the WAsP Climate Analyst. The time series wind measurement data was analyzed and the statistical summary of the data was presented as observed wind climate (OWC) data. The OWC data consisted of wind speed distribution and wind direction distribution information for 12 different sectors.

(1) Generation of wind atlas data. In this process the OWC data has been transmuted into regionalized wind climate (wind atlas) data set. The wind observations were cleaned with reference to site specific situation. The regionalized wind climate data consisted of mean wind speed and wind power density for different standard classes which were categorized based on the height a.g.l and the roughness length.

(2) Wind Climate Estimation. After the regionalized wind climate data set was established the terrain description of the predicted sites were in-

troduced through the vector map into the software. The program then estimated the wind climate for the entire site for the height of 55 m a.g.l by using the inverse calculations to generate the wind atlas.

(3) Estimation of wind power potential. The energy output was calculated by using the mean wind speed. The Annual Energy Production (AEP) was also obtained by acquainting the program about the power curve of 275 kW Vergnet wind turbine.

(4) Calculation of wind farm production. The thrust coefficient and power curve for 275 kW Vergnet wind turbine were used for estimating the wake loss for each of the 4 wind turbines that were proposed for the wind farm. The net annual energy production was determined for each of the turbines together with the energy production of the entire wind farm was estimated by the WAsP software.

3 Statistics of wind energy

In wind energy the statistical analysis is used to determine the availability of the potential wind resources at a known site and to estimate the energy production from the wind turbines. The availability of the time series wind data for a specific site and height are frequently analyzed in terms of probability distribution and statistical techniques. When the measured wind data are projected between different locations it is an absolute need to use the analytical representation for the probability distribution of wind speed. The two probability distribution functions that are universally used in the wind data analysis are Weibull and Rayleigh distribution[14].

3.1 Weibull probability distribution

The energy producibility of the turbine is dependent on the mean wind speed and the availability of the percentage duration that is the statistical frequency of occurrence of the wind speed for a defined time period must be known. To determine the wind energy conversion characteristics, Weibull probability distribution is used to statistically analyze the wind speed data. The anemological description of the site that is provided by the Weibull distribution is determined based on the two parameters, the shape parameter (k) and scale parameter (A). The scale parameter is univocally related to the mean speed and is expressed in m/s whereas the shape parameter is the Weibull slope and different values of it describes the behavior of the distribution. The scale and shape parameter are both the function of mean wind speed ($\overline{U}$) and standard deviation (σ_U)[14]. The Weibull probability density function is stated as $p(u) = \left(\frac{k}{A}\right)\left(\frac{U}{A}\right)^{k-1} e^{-\left(\frac{u}{A}\right)^k}$.

4 Economics of wind power

The selection of the optimum system for a specific site is not merely dependent on the technical feasibility or the efficiency but also dependent on the economic aspect of the system. For a wind farm to be viable and feasible contender for producing energy it needs to produce energy, survive in persisting with the regular operation and to be cost effective. The minimum conceivable cost per kWh generation optimizes the wind farm projects at the particular site. The economic viability of the wind project depends on the cost of generating energy and the monetary worth of the produced energy. The wind energy systems are deliberated as an asset that yields revenue, therefore economic analysis is essential to determine and to estimate the profitability of the wind power projects which could be used for making comparison with the alternative investments[14]. Since most of the cost is borne by the developer at the beginning, the purchase and the installations costs are financed by the banks and the investors where these lenders expect a return on their loan. Therefore, it is important to determine the energy produced by the wind farm in kWh and the time taken by the wind farm to pay back the financed amount to the lenders. The overall capital cost, financing cost, operations and maintenance cost of the system with other parameters are used in the economic analysis There are various economic analysis methods that can be used, however for this study the method outlined by[15] is used.

4.1 Accumulated present values of costs

The accumulated life cycle cost for n years of a wind energy project consists of the present values of the initial investment (C_I) and the operations and maintenance cost (C_{OM}). Mathematically, the accumulated net present value is expressed as

$$\mathrm{NPV}\left(\mathrm{C_A}\right) = \frac{\mathrm{NPV}\left(\mathrm{C_A}\right)_{1-n}}{\mathrm{n}} = \frac{\mathrm{C_1}}{\mathrm{n}}\left\{1+\mathrm{m}\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right]\right\} \tag{1}$$

where n is the life span of the project, C_A is the yearly cost of operation, m is percentage ratio of C_{OM}, C_I and I are the real discount rate which is normally stated as

$$I = \frac{1+i}{1+e_a} \tag{2}$$

where e_a , is the cost escalation rate and i is the real discount rate. The cost escalation rate is obtained by the relation

$$e_a = \{(1+e)(1+r)\} - 1 \tag{3}$$

where r is the rate of inflation and e is the rate of escalation.

The turbines rated power (P_R) and the capacity factor (C_F) could be used to determine the annual energy generated by the turbine. This is obtained by the relation

$$\mathrm{E_I} = 8760\mathrm{C_F}\mathrm{P_R} \tag{4}$$

Therefore, the cost (c) of electricity in (kWh) generated from the wind can be obtained from the relation

$$c = \frac{NPV\left(C_A\right)}{E_1} = \frac{c_1}{8760n}\left(\frac{1}{P_R C_F}\right)\left\{1+m\left[\frac{(1+I)^n-1}{I(1+I)^n}\right]\right\} \tag{5}$$

4.2 Accumulated net present value of benefits

The accumulated net present value of benefits refers to the merchandizing of the wind energy prices. The electricity generated from the wind are sold at a retail price to the energy market. Assuming that the wind farm delivers an annual benefit (B_A) by the electricity sales, the total accrued net present value of all the benefits during the entire life span of the project can be expressed by the relation

$$\mathrm{NPV}\left(\mathrm{B_A}\right)_{1-n} = B_A\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right] \tag{6}$$

4.3 Accumulated net present value

The accumulated net present value is the difference between the values of the present cash inflow and the cash outflow over the projects life span. The benefits represents all the income that is accumulated due to the electricity sales and the cash outflow constitutes the capital investments, monetary expenses values on the annual operations and the operations and maintenance costs. Therefore, the net present value can be expressed as

$$\mathrm{NPV} = \mathrm{NPV}\left(\mathrm{B_A}\right)_{1-n} - \mathrm{NPV}\left(\mathrm{C_A}\right)_{1-n} \tag{7}$$

Substituting $\mathrm{NPV}(B_A)_{1-n}$ and $\mathrm{NPV}(C_A)_{1-n}$ relations into the above expression yields

$$\mathrm{NPV} = \mathrm{B_A}\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right] - \mathrm{C_I}\left\{1+\mathrm{m}\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right]\right\} \tag{8}$$

The net present value greater than zero indicates that the project is economically satisfactory and will bring profits to the investors.

4.4 Benefit cost ratio

The Benefit cost ratio is used to determine the economic viability of the project. It is defined as the ratio of the accumulated present value of all the benefits to the accumulated present values of all the costs and the preliminary investments. Benefit cost ratio is expressed as

$$\mathrm{BCR} = \frac{\mathrm{NPV}\left(\mathrm{B_A}\right)_{1-n}}{\mathrm{C_I} + \mathrm{NPV}\left(\mathrm{C_A}\right)_{1-n}} \tag{9}$$

Thus, by substituting the expressions for $\mathrm{NPV}(B_A)_{1-n}$ and C_I + $\mathrm{NPV}(C_A)_{1-n}$, BCR can then be expressed as

$$\mathrm{BCR} = \frac{B_A\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right]}{\mathrm{C_I}\left\{1+\mathrm{m}\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right]\right\}} \tag{10}$$

The project is economically viable if and only if the benefit cost ratio is greater than 1.

4.5 Payback period

The pay back period is the time in years when the accumulated present values of all the costs becomes equivalent with the accumulated present value of all the benefits. It is the minimum period required by the project to recover all the values that was invested from the beginning. Mathematically, the pay back period can be expressed as

$$B_A\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right] = \mathrm{C_I}\left\{1+\mathrm{m}\left[\frac{(1+\mathrm{I})^{\mathrm{n}}-1}{\mathrm{I}(1+\mathrm{I})^{\mathrm{n}}}\right]\right\} \tag{11}$$

To determine the payback period Equation (11) is solved for n years. Therefore, by reducing and rearranging the above relation it becomes

$$(1+\mathrm{I})^{\mathrm{n}} = \left(1-\frac{\mathrm{IC_I}}{\mathrm{B_A}-\mathrm{mC_I}}\right)^{-1} \tag{12}$$

Thus, by taking the natural logarithm on both the sides of Equation (12) and solving for n gives the expression

$$\mathrm{n} = -\mathrm{n}\frac{\left(1-\frac{\mathrm{IC_I}}{\mathrm{B_A}-\mathrm{mC_I}}\right)^{-1}}{\ln(1+\mathrm{I})} \tag{13}$$

The project that has the lower pay back period that is lower than the projects life span are normally preferred.

4.6 Internal rate of return

Internal rate of return is used to estimate the profitability of the investments and is generally considered as discount rate where the accumulated net present value of the project is zero[15]. That is the accumulated net present value of benefit equals the present value of costs which can be mathematically expressed as

$$\mathrm{NPV}\left(\mathrm{B_A}\right)_{1-\mathrm{n}} = \mathrm{C_I} + \mathrm{NPV}\left(\mathrm{C_A}\right)_{1-\mathrm{n}} \tag{14}$$

Thus, by substituting the expressions for $\mathrm{NPV}(\mathrm{B}_A)_{1-n}$ and C_I + $\mathrm{NPV}(\mathrm{C}_A)_{1-n}$ into Equation (14) yields

$$\mathrm{B_A}\left[\frac{(1+\mathrm{IRR})^{\mathrm{n}}-1}{\mathrm{IRR}(1+\mathrm{IRR})^{\mathrm{n}}}\right] = \mathrm{C_I}\left[1+m\left(\frac{(1+\mathrm{IRR})^{\mathrm{n}}-1}{\mathrm{IRR}(1+\mathrm{IRR})^{\mathrm{n}}}\right)\right] \tag{15}$$

Due to the nature of the formula Equation (14) it becomes very difficult to solve it analytically, therefore it is computed either by the trial and error method or through the use of programmed software's[15].

5 Results and discussion

5.1 Annual diurnal wind speed

The hourly annual wind speed variations at Rokavukavu, Navolau and at Tuvavatu were plotted as shown in Figure 1. This parameter was examined in order to determine the annual diurnal patterns of the maximum wind speeds at the three sites for the power production. It is evident from Figure 1 that the annual diurnal wind speed pattern for all the sites are similar however, the hourly wind speed values varied for each site. The result showed that for all the three sites the maximum wind speeds were perceived between (12:00 and 14:00) hours whereas the nominal wind speeds were observed during the morning and afternoon hours and were prolonged into the late evening hours. The maximum wind speed observed during the day time at Rokavukavu, Navolau and at Tuvavatu were 8.5 m/s, 11.3 m/s and 9.7 m/s receptively. Since at higher altitude there are high wind speeds during the day and less fluctuations and turbulence, this indicates that the wind turbines could be unremittingly utilized for power generations in order to meet the increased energy requirement.

5.2 Wind shear analysis

Wind shear coefficient is an important parameter that are essentially used for estimating the wind

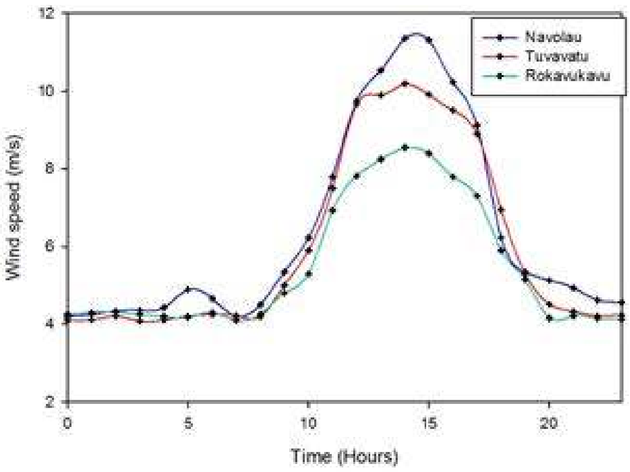

Figure 1 Wind speed with time

power production. To estimate the wind shear coefficient the mean wind speed at 50 and 55 m for Rokavukavu, Navolau and Tuvavatu site were used. It is evident from Figure 2 that the variation in the wind speeds are higher during the night time for Rokavukavu, Navolau and Tuvavatu sites. This happens as a result of nocturnal inversion effect (radiation inversion) where the temperature of the air mass increases and intensifies with the height and traps the cold and dense air near to the ground surface. The radiation inversions steadily weakens after the Sunrise once the cold air near to the ground surface gets heated up and rises upward resulting in the clustering of the horizontal wind streamlines aloft and consequently upsurges the wind speed directly above the previously confined air mass[16]. It is evident that for all the three sites, during the early hours of the day between 00:00 and 06:00 h, the wind shear coefficient values were higher and were persistent whereas from 06:00 h and thereafter once the ground surface and the air above it began to heat up the values started to decline until the minimum was achieved at approximately 09:00 h and remained nearly constant till 17:00 h. The wind shear coefficient values again increased from 17:00 h until the maximum value was achieved at around 22:00 h and exhibited a persistent pattern throughout the rest of night due to the continuous cooling of the ground surface.

The wind shear is a parameter that influences the power output of the wind turbine. According to[17] the increase in wind shear coefficient causes the reduction in the power output. Therefore, sites with lower wind shear is preferred for installing the turbines in order to maximize and optimize the power production at the desired sites.

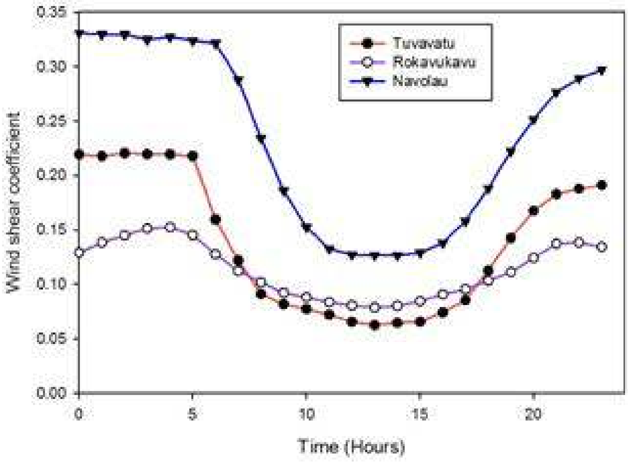

Figure 2 Wind shear coefficient with time

5.3 Turbulence

Turbulence is the fluctuation (spectral peaks) in the wind speed that comparatively occurs on a fast time scale. It is caused by the friction with the earth surface and due to the thermal effects[18]. Turbulent wind usually have the mean that persists over the time scale of an hour or more, however for the shorter time scale (minute or less) the mean is quite variable. Turbulence is determined by measuring its intensity. The turbulence intensity is defined by the relation that exists between the standard deviation of the wind speed and the mean wind speed. Mathematically the turbulence intensity is defined by $\mathrm{TI} = \frac{\sigma_{\mathrm{U}}}{\mathrm{U}}$, where $_U$ is the standard deviation and U is the average wind speed. Figure 3 shows the turbulence intensity at Rokavukavu, Navolau and Tuvavatu sites for an altitude of 55 m a.g.l. The overall average turbulence intensity at Rokavukavu, Navolau and at Tuvavatu sites were found to be 14.9%, 17.1% and 11.7%. The average turbulence intensity at Navolau was found to be higher than the other two sites due to the complexity of the mountainous terrain which is exposed to the open sea. However, at higher altitude there are less interference caused by the topographical features such as the surface roughness and the complexity of the terrain tends to have reduced effects on the wind speed and also the influence of thermal effect becomes diminutive. The turbulence intensity is an important parameter that needs to be determined since it affects the power extraction of the wind turbine. The high level of turbulence increases the drag on the turbine blades which tends to lower the power extraction and causes fatigue damage. Therefore, installing the wind turbine in an area that has high turbulence intensity would yield lower power extraction and would have progressive and localized structural damage.

However, for this study it was established that approximately 98% of the time the turbulence intensity at all the three sites were below 0.22. This indicated that the turbulence intensity at all the three sites are generally low and are within the permissible turbulence level of 19% for the wind speed of 10 m/s which has been set by the IEC61400-1 design standards for turbines[19].

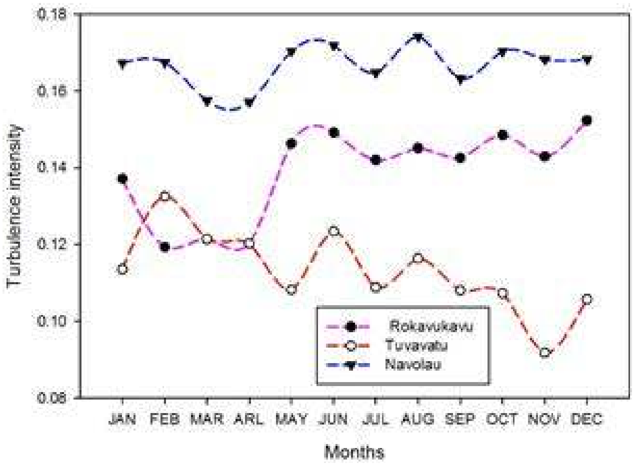

Figure 3 Turbulence intensity with months

The vector map Figure 4 represents the topographical data of Rokavukavu, Navolau and Tuvavatu sites in Rakiraki which contains information about the height that has the contour interval of 10 m and also the different surface roughness length values assigned according to the different land-use. The Cartesian map coordinate system contained information about the height and the geographical coordinates in meters. The datum system for the map projection was set to WGS84. The vector map was used to depict the true complexity of the land surface so that the wind resource can accurately be modelled by computational fluid dynamics using WAsP. The energy produced by the wind turbine is depended on the estimated wind speed which is influenced by the obstacles such as the topography, roughness length and land cover therefore, by not incorporating theses parameters would create uncertainties in estimating the energy generation at the desired sites[20].

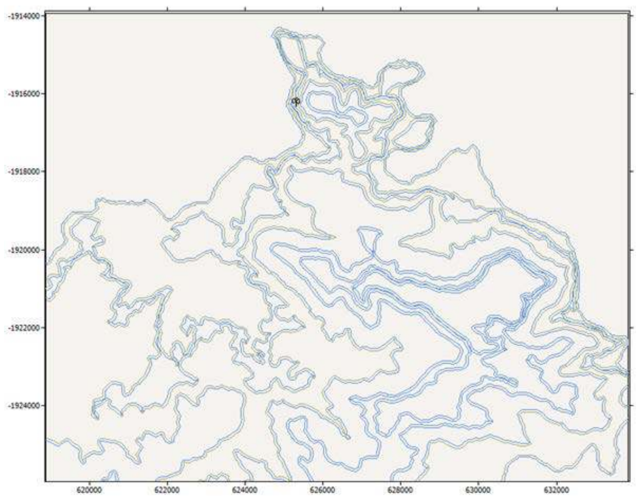

Figure 4 Elevation contours and roughness map

The calculation of the time series wind data for all the three sites were expediently performed with the utility of the WAsP Climate Analyst tool-pack. The 10 minutes average wind measurements and the information about the data discretisation was fed in graphical user interface (GUI) with the calm threshold value of 1 m/s was used to produce the statistical summary shown in Table 1, Table 2, Table 3 for site specific wind climate at Rokavukavu, Navolau and at Tuvavatu. For all the three sites the calculated OWC showed the long-term wind climate at the anemometer height where the out-

Table 1 Observed wind climate summary report for Rokavukavu site

Angle	Frequency	Weibull (A)	Weibull (k)	Mean speed	Power density	Speed Quality
^{o}	%	m/s	-	m/s	W/m^2	%
0	1.5	3.4	1.23	3.15	74	-1.494
30	4.3	3.7	2.93	3.30	31	4.522
60	14	4.3	3.47	3.83	45	0.644
90	31.8	5.7	2.62	5.08	123	-1.883
120	32.8	9.6	3.92	8.65	492	1.814
150	7.2	6.3	2.82	5.65	161	1.153
180	2.1	4.8	2.17	4.28	85	0.352
210	1.4	4.0	3.47	3.60	37	3.402
240	0.7	3.9	1.64	3.49	62	-1.272
270	0.5	3.6	1.44	3.30	63	-0.487
300	1.2	4.1	1.40	3.72	95	-2.852
330	2.3	4.7	1.73	4.15	98	2.799

put observed wind climate has been represented as the wind rose plot and wind speed distribution for each sector. The output for OWC at Rokavukavu, Navolau and at Tuvavatu sites are represented in Figure 6, 8, 10 respectively. The estimated OWC at 55 m a.g.l at Rokavukavu site showed an emergent wind speed of 5.91 m/s with the predominant south east wind direction. Similarly, the estimated OWC at 55 m a.g.l at Navolau and Tuvavatu site exhibited an emergent wind speed of 8.94 m/s and 8.13 m/s respectively with the predominant south east wind direction. Since, for all the three sites the Omni-directional wind speeds are from the south east the installed wind turbines will constantly be facing in this direction which will reduce the wake loss and the power loss due to less yaw movement and lower tower shadow for downwind turbines.

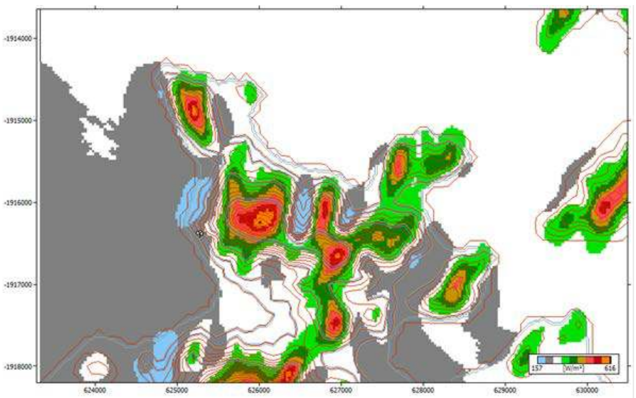

Figure 5 Power density map of Rokavukavu

The CFD technique was utilized to predict the mean wind speed at 55 m a.g.l at Rokavukavu, Navolau and Tuvavatu site. The WAsP simulation exhibited the variations in the mean wind speed by classifying the wind speed range with different colours that represented the different intensity level of wind speed. The mean wind speed at Rokavukavu mostly fell between 5.33 and 8.39 m/s whereas at Tuvavatu the wind speed fell between 4.72 and 10.10 m/s. The mean wind speed at Navolau has been classified as high that ranged between 4.13 and 10.70 m/s. It is also the elevated areas generally received high wind speed. The lower wind speed values has been obtained for areas with complex surface roughness and areas of low lands between hills. The magnitude of the spatial mean wind speed distribution over the study region showed that Navolau is potential wind resource site for power generation followed by Tuvavatu and Rokavukavu.

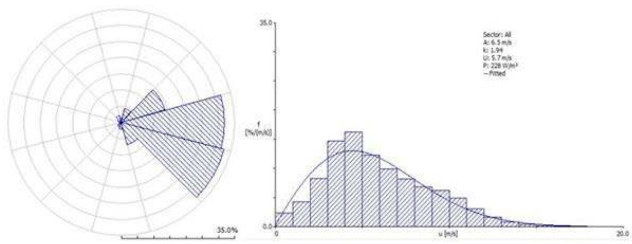

Figure 6 Wind rose and wind speed distribution at 55 m a.g.l at Rokavukavu site

The wind power density has been considered as an important parameter that is used to evaluate the available wind resources at a given site. It indicates the amount of energy that is available at the site that can be converted into electrical energy by

Table 2 Observed wind climate summary report for Navolau site

Angle	Frequency	Weibull (A)	Weibull (k)	Mean speed	Power density	Speed Quality
^{o}	%	m/s	-	m/s	W/m^2	%
0	0.6	2.9	1.37	2.68	37	-11.094
30	1.5	4.7	1.72	4.16	100	-1.745
60	20.5	11.2	2.99	10.02	867	-0.041
90	33.1	10.5	2.70	9.04	564	-0.004
120	36.2	10.0	3.89	9.35	749	-0.223
150	1.0	5.8	3.21	5.23	118	6.660
180	0.1	1.8	1.04	1.77	18	5.750
210	0.6	4.4	1.64	3.97	92	1.853
240	3.2	7.0	1.90	6.22	296	0.777
270	1.9	7.0	1.58	6.28	384	0.985
300	0.8	3.5	1.42	3.16	57	2.061
330	0.7	2.9	1.31	2.65	39	-2.574

the wind turbine. According to[21] the site that has the wind power class of 4 and above that is (wind power density greater than and equal to 400 W/m^2 at 55 m a.g.l) has been considered as an excellent site for the development of wind power projects. The power density map of Rokavukavu, Navolau and Tuvavatu region was established by the using of WAsP software. The power density values at Rokavukavu site, ranged between 157 and 616 W/m^2 whereas at Tuvavatu the value ranged between 97 and 979 W/m^2. Similarly, the power density at Navolau ranged between 77 and 1198 W/m^2. The areas with high wind power densities are considered as the potential sites for installing wind turbines for power generations. It is evident from the density map that as the elevation above the sea level increases the power density also increases. The low wind power densities between the range of 77 and 300 W/m^2 were obtained for the region of low lying areas whereas, high wind power densities ranging from 400 and 1198 W/m^2 were for the region of high elevations which has been indicated by the red color. It was also found that the wind power class at Rokavukavu is 6 whereas for Navolau and Tuvavatu site the wind power class is 7. This indicates that Navolau and Tuvavatu are the two best contending sites for developing the wind farm.

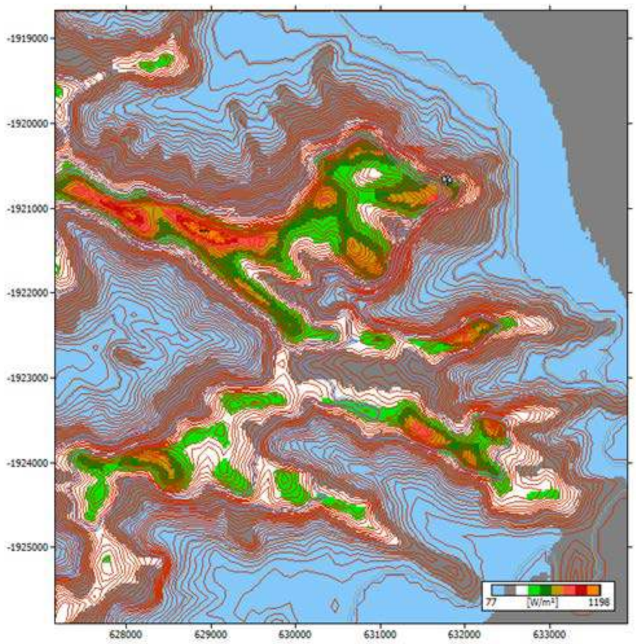

Figure 7 Power density map of Navolau

5.4 Annual energy production (AEP) estimation

An important consideration of wind resource assessment is the annual energy production (AEP) which is dependent on the power density of the site and the wind turbine characteristics[22]. The turbine characteristics have been incorporated through the use of power curve. The power curve is used to track the performance of the wind turbine which indicates the amount of electrical power that will be produced at a particular wind speed[23]. It is used to determine the output from the operational performance of the turbine. The site specific power and thrust coefficient curve shown in Figure 11 of Vergnet 275 kW wind turbine was established by using the manufacturer's specification. To estimate the amount of power produced by the each turbine the WAsP software requires the information about

Table 3 Observed wind climate summary report for Navolau site

Angle	Frequency	Weibull (A)	Weibull (k)	Mean speed	Power density	Speed Quality
^{o}	%	m/s	-	m/s	W/m^2	%
0	0.8	4.8	1.72	4.28	109	0.898
30	1.6	4.5	2.52	4.01	62	1.012
60	13.2	7.8	3.27	6.95	276	-0.067
90	27.8	8.3	3.47	7.43	328	-2.030
120	49.7	9.8	3.38	8.81	555	-3.221
150	4.3	10.0	3.98	9.06	563	-0.724
180	0.1	1.4	1.10	1.39	8	-8.102
210	0.1	1.8	1.62	1.58	6	2.372
240	0.3	4.7	1.91	4.17	89	-2.069
270	0.7	4.1	1.92	3.61	57	-0.250
300	0.7	3.3	2.13	2.94	28	2.471
330	0.6	4.3	1.87	7.94	70	4.597

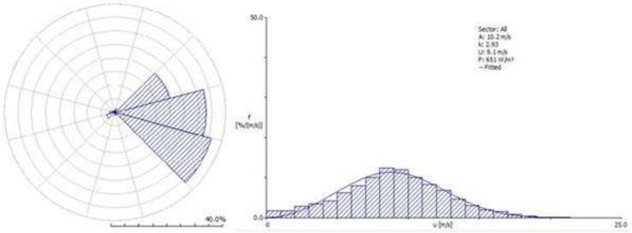

Figure 8 Wind rose and wind speed distribution at 55 m a.g.l at Navolau site

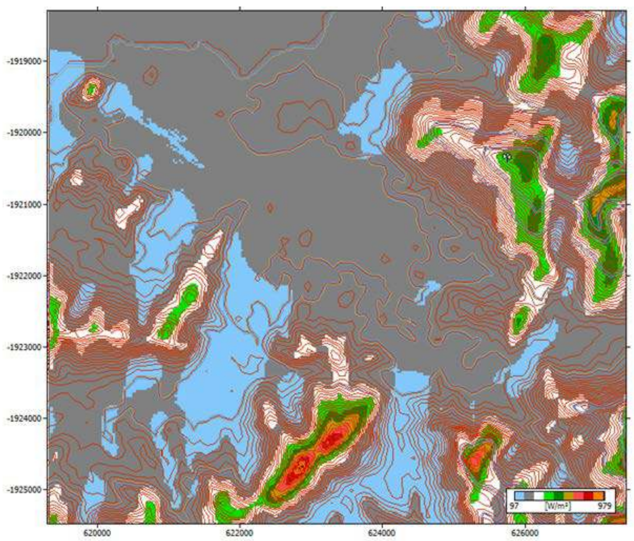

Figure 9 Power density map of Tuvavatu

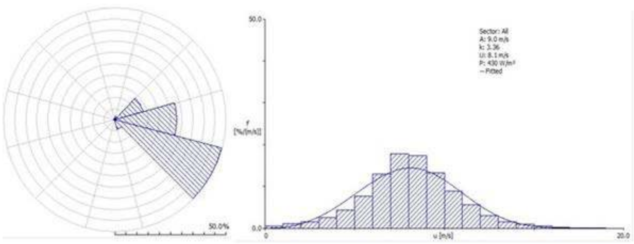

Figure 10 Wind rose and wind speed distribution at 55 m a.g.l at Tuvavatu site

the power production and thrust curve characteristics of the turbine. This information has been provided to WAsP by associating a wind turbine generator with the turbine site. The power curve shows that between the wind speed values of 0 and 3.5 m/s there is no power produced by the turbine whereas the wind speed values ranging from 3.5 m/s and onwards the turbine begins to generate power. The rated wind speed is 12 m/s and the cut out speed is 25 m/s. The specific thrust coefficient values of Vergnet 275 kW wind turbine were determined between the cut in and cut out wind speed values to estimate the wake loss by each turbines in the wind farm and thus, the net AEP of the proposed wind farm was determined.

The AEP obtained at Rokavukavu, Navolau and Tuvavatu varied from 0.401 to 1.097 GWh, 0.178 to 1.492 GWh and 0.237 to 1.420 GWh receptively. The areas (hilly areas) have the greatest AEP ranging between 1.00 and 1.420 GWh. The future prospects of developing the wind farm at Rakiraki should take place in an area that is confined within the red and orange colors in order to obtain the maximum outputs from the installed wind turbine. Thus, by observing the AEP map it can be established that Navolau site has the favourable wind resources that could be harnessed to generate electricity followed by Tuvavatu and Rokavukavu.

5.5 Economics analysis

The optimum projects are selected and are implemented not only on the basis of their technical

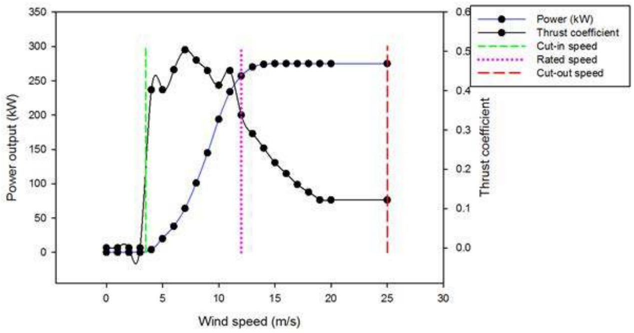

Figure 11 Power curve

feasibility and efficiency but are also based on their economic viability. It is essential that for a wind farm to be a feasible contender it needs to yield energy, must persist to withstand with the regular operation and to be cost effective. Conducting the economics of the wind farm assists in making the informed decision about the estimated revenue and the profitability of the wind farm during the lifespan of the project. The economic analysis was carried out by using the method that was specified by[15]. The on-shore wind farm at Navolau and Tuvavatu site has 6 X 275 kW Vergnet wind turbines each with the total installed capacity of 1650 kW. Several assumptions were made before the economics analysis was performed. The interest rate, inflation rate and escalation rate were assumed to be 1%, 4% and 25% respectively. The cost for each turbine were assumed to be FJD 810,000 hence, the total capital investment for the proposed wind farm was FJD 7,147,059. The overall operation and maintenance cost was considered to be 3% of the total capital investment as was stated by[14]. The retailed price of 27 cents/kWh was used to perform the economic analysis. The proposed onshore wind farm at Navolau and Tuvavatu will produce the net AEP of 7.858 and 6.590 GWh respectively. The net present value (NPV), benefit cost ratio (BCR), payback period and the cost of energy for the Navolau wind farm were found to be FJD 10002411.46, 1.54, 4.41 years and $0.07/kWh respectively. Thus, the payback period was approximated to nearly 5 years. The internal rate of return was determined to be 15.30%. Furthermore, NPV, BCR, payback period and the cost of energy for the Tuvavatu wind farm were found to be FJD 7715242.57, 1.34, 5.28 years and $0.09/kWh respectively. Thus, the payback period was approximated to nearly 6 years. The internal rate of return was determined to be 12.91%.The economic analysis of the on-shore wind farm showed that it is feasible to develop a wind farm at Navolau and at Tuvavatu site.

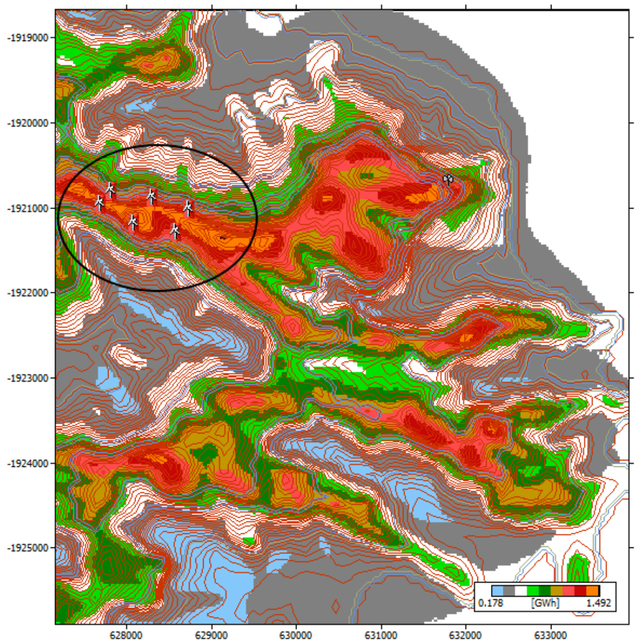

Figure 12 Wind farm layout at Navolau

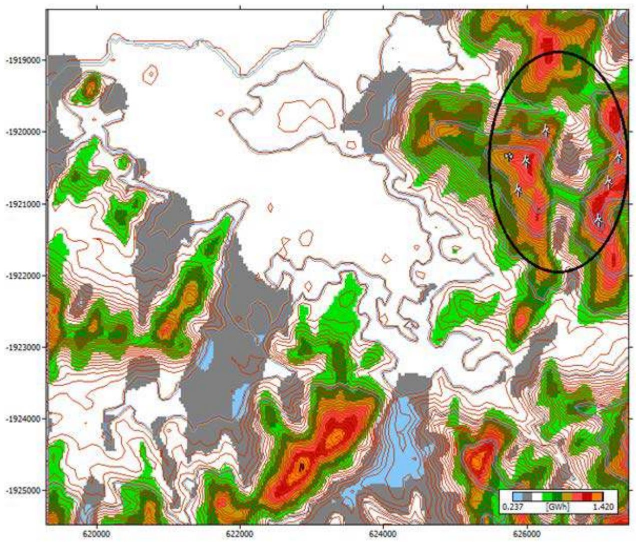

Figure 13 Wind farm layout at Tuvavatu

Table 4 Economical analysis of on-shore wind farms

Parameters of Economical Analysis	Navolau	Tuvavatu
Project life span (years)	20	20
Capital cost (FJD)	7,147,059.00	7,147,059.00
Retailed price of electricity (FJD)	0.27	0.27
Annual electricity production (kWh)	7,585,000.00	6,590,000.00
Annual return from electricity sales (FJD)	2,047,950.00	1,779,300
Accumulated net present value of benefits (FJD)	17,435,352.82	15,184,183.93
Operations and maintenance costs (FJD)	285,882.35	285,882.35
Accumulated present value of costs (FJD)	4,179,639.72	4,179,639.72
Accumulated net present value (FJD)	10,002,411.46	7,715,242.57
Benefit cost ratio	1.54	1.34
Payback period (years)	4.41-5.00	5.28-6.00
Internal rate of return (%)	15.3	12.91

6 Conclusion

The consumption of fossil fuel can be reduced by initiating the implementation of the correct technologies to meet the energy needs. Wind turbine technology has been considered as one of the favorable preferences which the decision makers could use to provide the clean energy. The wind resource assessment of three sites in Rakiraki, Fiji has been carried out. The investigation shows that the average wind speed at Rokavukavu, Navolau and Tuvavatu are 5.91 m/s, 8.94 m/s and 8.13 m/s respectively at 55 m a.g.l with the predominant South-East wind direction. The wind speed at Rokavukavu is quiet low, however at Navolau and Tuvavatu it is reasonably good. By using the moment fitting method, the average wind power density for Rokavukavu, Navolau and Tuvavatu sites are found to be 227 W/m^2, 651 W/m^2 and 430 W/m^2 respectively. The economics analysis of a proposed wind farm at Navolau and Tuvavatu site showed a convincing payback period of 5 and 6 years respectively.

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