Wind Power Potential at Benau, Savusavu, Vanua Levu, Fiji

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Abstract

Benau, Savusavu is located at 16.8°S and 179.6°E in the Fiji Islands Group. Benau, a rural settlement, has no grid connected electricity supply. It costs approximately USD 1.50/ℓ to generate electricity using a diesel generator. Wind resource assessment was carried out to determine the wind power potential at Benau. The wind assessment is based on 3 years wind speed and direction data provided by Fiji Department of Energy. The Wind energy potential was analyzed using Wind Atlas Analysis and Application Program (WAsP). It showed that Benau had a mean wind speed of 6.24 m/s and mean power density of 590 W/m^2 at 30 m above sea level. Hence, it is a reasonable candidate site for a wind farm. WAsP verified that a wind farm with 2 turbines would have a mean annual energy production (AEP) of 641 MWh. An economic analysis for a prospective wind power generation was carried out using Vesta V27 and Vergnet (GeV) 275 kW wind turbines. The economical analysis showed that Vergnet 275 kW wind turbine has the maximum annual energy production (AEP) for the integrated wind farm. The levelised cost of energy was $0.08/kWh with a cost to benefit ratio of 1.38 and internal rate of return (IRR) of 21.3%.

Keywords: *energy potential, WAsP, power density, resource grid, Vesta V27, Vergnet 275, AEP*

1. Introduction

World proven oil reserves in 2010 estimated by BP Global are sufficient to meet 46.2 years of global production [1]. Currently about 68% of the world's energy needs are met by fossil fuels (oil, natural gas, coal), 13% by nuclear power, 16.2% by large hydro with the remaining 3.3% met by various renewable energy resources [2]. The Pacific Islands countries are either coral atolls or volcanic islands and have no proven oil reserves. They import all their oil requirements and this imposes a substantial constraint on their foreign reserves and developments. The price votality and reliability is a major concern for these countries.

The annual electricity consumption for Fiji is estimated at 835 GWh in 2010 (FEA, 2010). Hydro power contributed the majority of this energy, with diesel generating approximately 236 GWh, with some energy generated from the Butoni wind farm and the remainder produced by Tropic Woods Ltd and Fiji Sugar Corporation Ltd. using biomass. However, this energy only reaches about 70% of Fiji's population since grid connected electricity is not available to the rural settlements on the major islands and on the outer islands. Diesel used for generator sets are expensive since mineral fuel prices have increased exponentially in the last few years and with added cost incurred for transporting out of the main centres. With a national budget of approximately two billion dollars, Fiji spends over half ($1.4 billion) of its total import on mineral fuel. The recently developed 40 MW Nadarivatu hydropower is expected to reduce the oil demand and lead Fiji towards attaining 90% renewable energy by 2015 [3].

Clean energy technologies generally require more labour per unit of energy produced than conventional energy technologies, thus creating more jobs. However, conventional energy technologies exploit concentrated energy resources in a capital-intensive manner and require the constant exploration for new sources of energy. In contrast, energy efficiency measures focus on maximizing the use of existing resources and harvest more dispersed, dilute energy resources. This generally requires more human intervention, either in applying the technology or in manufacturing and servicing the equipment. The additional cost of the labour required by clean energy technologies is offset by the lower cost of energy inputs [4]. Over the last decade, the wind power generation has become financially attractive and dramatically growing as a result of a gradual decrease in the investment cost and a promotion of green power generation [4]. Wind power has grown significantly over the past 15 years with capacity ranging from 6.1 GW in 1996 to 238 GW in 2011 [2]. Wind energy though capital intensive, has a small operation and maintenance costs. Although the wind is free and the generation site is quite environmental friendly, the unpredictable nature of the wind is a major disadvantage and becomes a critical factor on investment decision. Wind energy projects are financially risky due to the uncertainties in the wind resource assessment. The uncertainties in the wind speed measurement results in a high uncertainty in the energy production. In order to avoid financial disadvantage, investment decision on generation capacity of wind energy system need to be studied in detail. The potential of wind power for electricity generation has been investigated extensively at several locations and in many countries. The power of the wind in an area, *A*, perpendicular to wind direction is given by

$$P = \frac{1}{2}\rho A V^{3} \quad (1)$$

where, P is power in watts (W), ρ is the air density in kg/m^3, A is the swept rotor area in square meters (m^2), and V is the wind speed in meters per second (m/s). The fraction of the wind captured by a wind turbine is determined by the power coefficient, C_p, which has a theoretical maximum of 59.3% (Betz limit).

Statistical analysis can be used to determine the wind energy potential of a given site and the wind statistics may be described using either Rayleigh or Weibull distribution [5] and mathematically represented using Equations (2)- (3)

1.1 Wind Statistics

Rayleigh distribution is the simplest velocity probability distribution function to represent the wind resource since it requires only knowledge of the mean wind speed, $\bar{u}$. The probability density function is given by

$$\varphi(u) = \frac{\pi}{2}\left(\frac{u}{\bar{u}^{2}}\right) \exp\left[-\frac{\pi}{4}\left(\frac{u}{\bar{u}}\right)^{2}\right] \quad (2)$$

However, Weibull probability distribution function requires the knowledge of two parameters shape factor *k* and scale factor *c*. Both of these parameters are functions of ū and standard deviation *σ*. The Weibull probability density function *φ (u)* is given by

$$\varphi(u)=\frac{k}{c}\left(\frac{u}{c}\right)^{k-1} exp\left[-\left(\frac{u}{c}\right)^{k}\right] \quad (3)$$

where *k* is defined as $\left[k=\left(\frac{\sigma_u}{\bar{u}}\right)^{-1.086}\right]$ and *c* is define as $\left[\frac{c}{\bar{u}}=\left(\frac{0.568+0.433}{k}\right)^{-\frac{1}{k}}\right]$

Since, variations and deviations of wind speeds are high, variable simulation of wind speed are very difficult but it can be described by Weibull distribution function. However for $k = 2$ it is reduced to Rayleigh distribution function, but in the case of $k =1$; exponential distribution function is effective. On the other hand, for $k = 3.6$, Weibull distribution function approximates Gaussian distribution. The Weibull distribution can be fitted to wind time series data by using the maximum likelihood method as suggested by Stevens and Smulders [6].

Economic analysis involves estimating costs and benefits over the entire time period of the project. The costs and benefits associated with a project may vary over time. An 'economic toolkit' is required to account for the decreasing value of money over time when comparing costs and benefits over the project lifetime [7]. Wind energy projects are investments lasting for 20 to 30 years. There are cash inflows and outflows during all these years in the form of benefits and costs related to the project. Thus, for getting the real picture of the project economics, costs and benefits over the entire life span of the project has to be considered. Wind power system is capital intensive hence it is imperative that a detailed economic analysis is carried out before installation. Sathyajith [7] outlined that future value of wind investment C made today as

$$A_1 = C(1+i), A_2 = C(1+i)^2, A_3 = C(1+i)^3, L, A_n = C(1+i)^n \quad (4)$$

where, A1, A_2, A_3, ---, A_n indicate the value in the 1st, 2nd, 3rd ,---, and nth year and L denotes the Principal or amount of loan. Here *i* is the interest rate or as more commonly termed, the discounting rate.

Thus the accumulated present value of all the payments put together is simplified as

$$PV(A)_{1-n} = A\left[\frac{(1-i)^n - 1}{i(1+i)^n}\right] \quad (5)$$

The discount rate corrected for inflation is termed as the real rate discount (*I)* which can be evaluated by

$$1+I=\frac{1+i}{1+r} \quad (6)$$

where, *r* is the rate of inflation.

The real rate of discount, adjusted for both the inflation and escalation is then given by

$$I=\frac{1+i}{1+e_a}-1 \quad (7)$$

where, the apparent rate e_a is combination of the escalation rate e with the inflation r which is given by

$$e_a = \{(1+e)(1+r)\} - 1 \tag{8}$$

Hence, the yearly cost of operation of the project is

$$NPV(C_A) = \frac{NPV(C_A)_{1-n}}{n} = \frac{C_I}{n}\left\{1+m\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]\right\} \tag{9}$$

where, C_I is the investment is the operation and maintenance cost as a % of initial investment and NPV $(C_A)_{1\text{-n}}$ is the accumulated net present value of all the cost is given by

$$NPV(C_A)_{1\text{-}n} = C_I\left\{1+m\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]\right\} \tag{10}$$

The energy generated by the turbine in a year is

$$E_I = 8760\, P_R C_F \tag{11}$$

where, P_R is the rated power and C_F is the capacity factor of the turbine

Hence, the cost of a unit (kWh) of wind-generated electricity is given by

$$c = \frac{NPV(C_A)}{E_I} = \frac{C_I}{8760\ n}\left(\frac{1}{P_R C_F}\right)\left\{1+m\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right]\right\} \tag{12}$$

Thus, the net present value is given by

$$NPV = NPV(B_A)_{1\text{-}n} - \{C_I + NPV(C_A)_{1-n}\} \tag{13}$$

where, the project delivers a benefit of B_A annually through electricity sales, then the accumulated present value of all benefits over the life of the project is

$$NPV(B_A)_{1\text{-}n} = B_A\left[\frac{(1+I)^n - 1}{I(1+I)^n}\right] \tag{14}$$

Benefit cost ratio (BCR) is the ratio of the accumulated present value of all the benefits to the accumulated present value of all costs, including the initial investment can then be calculated as

$$BCR = \frac{NPV(B_A)_{1-n}}{C_I + NPV(C_A)_{1-n}} \tag{15}$$

Payback period (PBP) is the year in which the net present value of all costs equals with the net present value of all benefits. Hence, PBP indicates the minimum period over which the investment for the project is recovered. Thus, the number of years, *n*, required to payback is determined by equating Eq. (13) to zero.

$$n = -\frac{ln\left(1 - \frac{I\,C_I}{B_A - mC_I}\right)}{ln(1+I\ )} \tag{16}$$

The internal rate of return (*IRR*) is the discount rate at which the accumulated present value of all the costs equals to that of the benefits. Hence, with *IRR* as the discount rate, the net present value of a project is zero. It is the maximum rate of interest that the investment can earn. *IRR* is the interest rate up to which we can afford to arrange the capital for the project. Thus equating Eq. 13 to zero and replacing *I* with *IRR*,

$$B_A \times \left[\frac{(1+IRR)^n - 1}{IRR(1+IRR)^n}\right] = C_I \times \left\{1 + m\left[\frac{(1+IRR)^n - 1}{IRR(1+IRR)^n}\right]\right\} \tag{17}$$

IRR can be solved by trial and error method or more, using numerical techniques.

The objective of this study is to analyse the wind regime at Benau, Savusavu and determine an appropriate wind turbine to harvest maximum energy and determine its economics.

2. Methodology

2.1 Description of Site of Study

The study site Benau is located at (16.8°S and 179.6°E) on Vanua Levu, Fiji. Benau (Figure 1) is covered with dense forests on one side and the other side with cultivation land and has a maximum altitude of 191 meters. There is no grid connected supply and people of Benau use standalone gen-set to meet their daily electrical power needs. The study site has a sea front and has a significant potential for future development.

The wind monitoring tower at Benau was installed on a flat ground facing the sea. The monitoring tower had a NRG type 40 anemometer and NRG type 200P wind vane mounted at 30 m above the ground level. The wind speed and the wind direction measurements were recorded continuously at every 10 minutes interval from 1st February 2002 to 30th November 2004. The data from the instruments were recorded in a data logger and managed by the Fiji Department of Energy (FDoE).

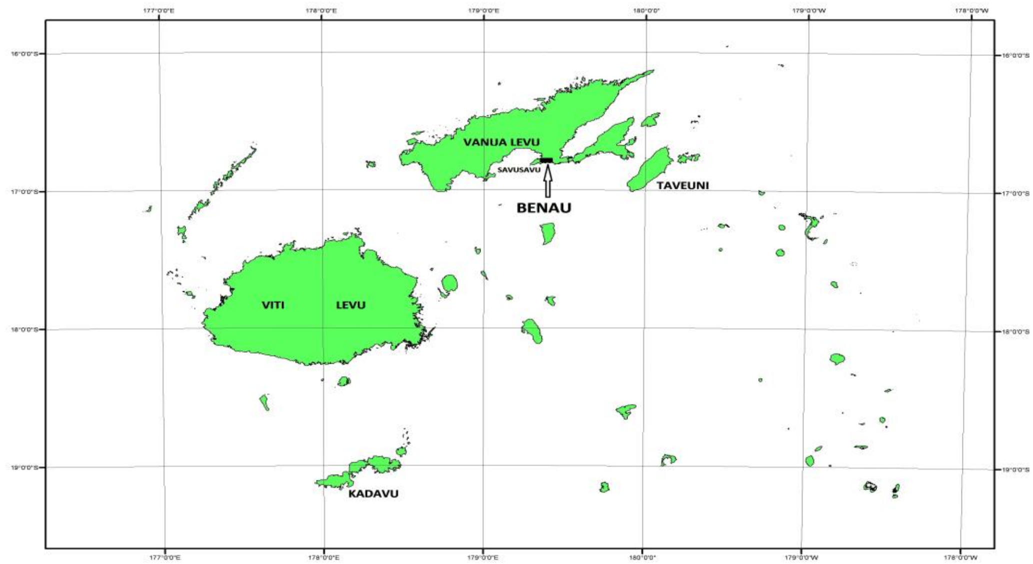

Figure 1. Map of Fiji Showing the Study Area (source: Government map shop, Department of Lands and Survey, Fiji)

The data were analyzed using Wind Atlas Analysis and Application Program (WAsP), software developed by the DTU wind energy, Denmark. Based on the expected electricity demand and the observed wind data, possible wind farms comprising of different wind turbines namely Vesta V27 and Vergnet 275 kW were analysed. A wind farm comprising of 4 turbines within 5 km radius of the monitoring station was estimated. The thrust coefficient curve, roughness parameter, vector map, Observed Wind Climate (OWC) and other hierarchal members were supplied to WAsP to estimate the annual energy production (AEP). The wind energy economics was determined based on the estimated or calculated, capital cost of individual turbines and other components of a wind farm.

The time-series of wind speed and direction data were transformed into a table which described a time-independent summary of the conditions found at the measuring site. The OWC report generated by WAsP provided the overall summary of the calculations carried. The Map of Benau was digitized using WAsP map editor with estimated elevation and roughness values. WAsP used vector maps, in which terrain surface elevation was represented by height contours and roughness lengths by roughness change lines [8]. The porosity of the obstacles was selected based on the characteristics of obstacles. The Annual Energy Production (AEP) of Vesta V27 and Vergnet 275 kW turbine were obtained from WAsP output. However, it could be determined using the swept area of the rotor method, the power curve method or using manufactures' estimates [9]. The economic analysis of the system was determined using Satyajith [7] to find the cost of energy, how long it would take to cover the initial investment, cost of one kWh of electricity, annual electricity return (R_A), Net Present Value (*NPV*), Benefit to Cost ratio (*BRC*), payback period (*n*), and Internal rate of return (*IRR*).

3. Results

Wind power density (WPD) is a calculation of the effective power of the wind at a particular location. The OWC Figure 2 suggests that it has a mean wind speed of 6.24 m s^{-1} and a mean power density of 590 Wm^{-2} at 30 m above ground level (a.g.l).

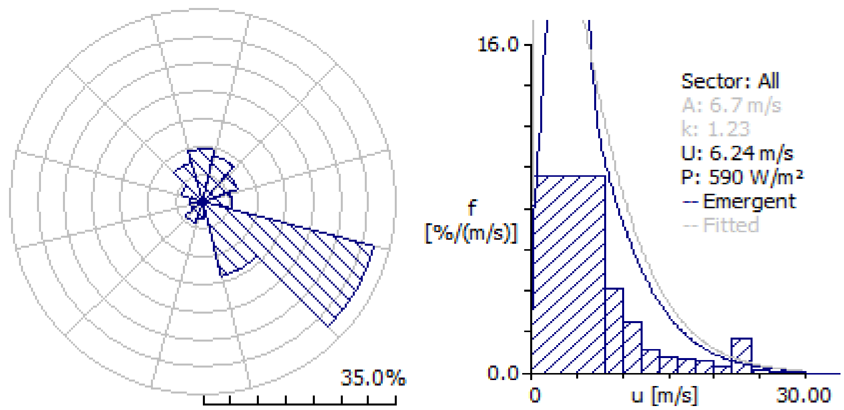

Figure 2. Observed Wind Climate at Benau, Savusavu

The wind atlas consists of the wind climate prediction for the whole area while taking the roughness and complexity of the terrain into consideration. WAsP uses the corrected wind climate data as one of its standard reference condition to predict the expected wind climate at every point in the terrain. The wind atlas obtained from WAsP contains results for 5 reference roughness lengths (0.000 m, 0.030 m, 0.100 m, 0.400 m, 1.500 m) and 5 reference heights (10 m, 25 m, 50 m, 100 m, 200 m) above ground level (a.g.l). However, for comparison only selected results (Table 1) are shown.

Table 1. Regional Wind Climate Summary at Benau

Height (m)	Parameter	Roughness		
10.0	Weibull (*A*) [m/s]	0.03m	0.10m	0.40
	Weibull (*k*)	4.89	4.25	2.29
	Mean speed [m/s]	0.93	0.93	0.93
	Power Density [W/m^2]	5.07	4.39	3.40
25	Weibull (*A*) [m/s]	5.83	5.22	4.31
	Weibull (*k*)	0.95	0.95	0.94
	Mean speed [m/s]	5.97	5.34	4.43
	Power Density [W/m^2]	900	636	372
50	Weibull (*A*) [m/s]	6.70	6.07	5.20
	Weibull (*k*)	0.98	0.97	0.97
	Mean speed [m/s]	6.76	6.14	5.27
	Power Density [W/m^2]	1200	908	580

The digitized map Figure 3 was based on the background map (R24 of Fiji Map Series). The roughness parameter and other pertinent features provided to WAsP are embedded in a vector map.

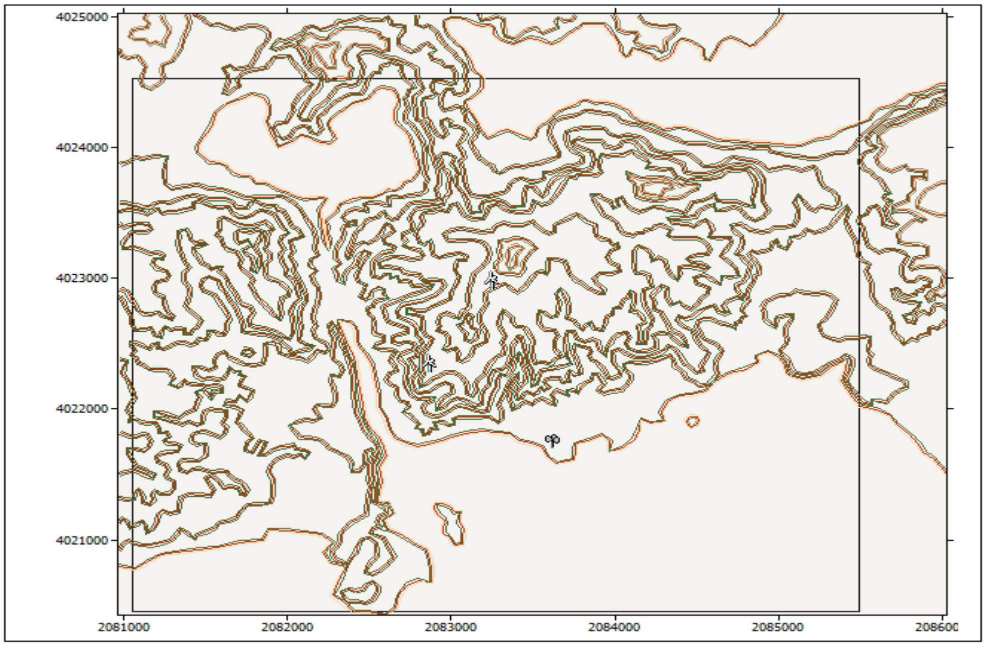

Figure 3. Vector Map of Benau Digitized using 1:50,000 Topographic Map (R 24)

To establish the turbine power curve, WAsP turbine editor was used. The power curve for Vesta was retrieved from the WAsP library however; Vergnet 275 kW power curve was derived from the data supplied by the manufacturer. The machine power curve predicts that at a wind speed of 7.0 m/s the power output from Vergnet is 64 kW and increases to 194 kW as the wind increases to 10 m/s.

WAsP generated report (Table 2) shows the wind turbine characteristics and the annual energy production (AEP) for the candidate site.

Table 2. Wind –turbine characteristics and annual energy production

Type	Cut-in speed (m/s)	Cut-out speed (m/s)	Rated power (kW)	AEP from Benau (MWh) (2 turbines)
Vesta V 27	4	25	225	611.83
Vergnet	3	20	275	768.57

The resource grid at 55 m above the ground Level (a.g.l) for Benau was generated using vector map, turbine generator, and obstacle groups within 5 km of the monitoring site. The resource grid Figure 4 shows the AEP differentials of Vergnet 275 kW wind turbine. However, mean wind speed, power density and elevation were also obtained but omitted for simplicity.

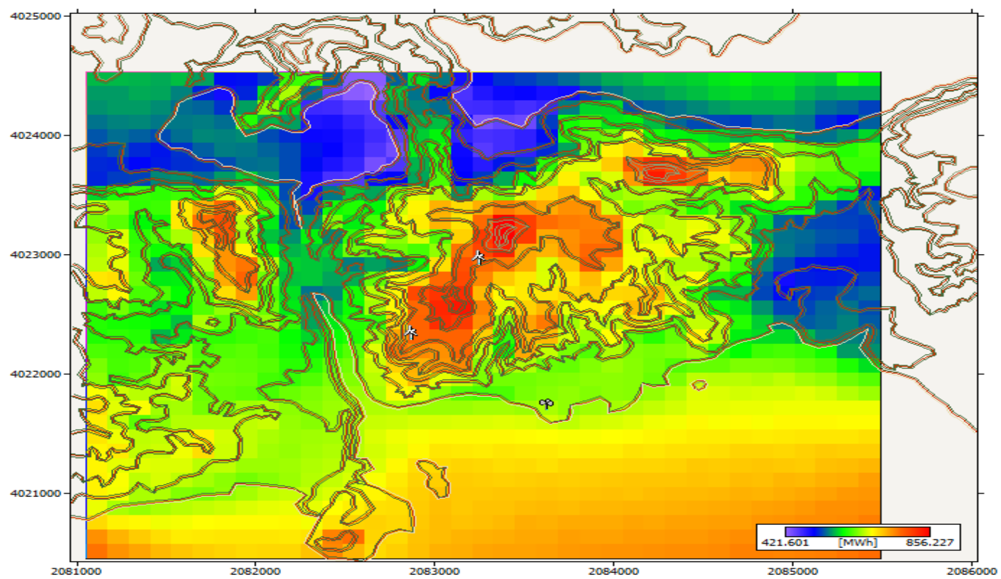

Figure 4. Resource Grids Analysis for Benau

The economic analysis of the proposed wind farm is based on the assumption that the capital cost of the individual wind turbine is estimated at $810, 000 for Vergnet 275 kW and $720,000 for Vesta V27 (based on the Butoni wind farm estimate) and the price of the turbine is approximately 68% of the total investment, Civil works, electrical infrastructure and power conditioning making up 23% of the total initial investment, legal fee including insurance and bank fees are approximated as 5%, and annual operation and maintenance (O&M) and land rent is 4% of the capital cost. The capacity factor is calculated using the AEP of the different turbine types. Also the life of the project is estimated at 20 years. The real rate of discount is assumed as 3.2%, interest rate at 10%, inflation rate at 4% and escalation rate at 2.5%. Presently FEA buys electricity from IPP's at $0.27 per kWh and the electricity price is $0.35 per kWh. Based on the above assumptions and Sathyajith [7] Table 3 shows the economics of the proposed wind farm using two different turbines (Vesta V27 and Vergnet 275 kW).

4. Discussions

Fiji with many islands scattered over a vast area of ocean has a considerable potential of diverse energy (solar, biomass, wind, coconut biofuel, and geothermal) sources that can reduce its dependence on imported fossil fuels. Yet, Fiji is highly dependent on imported fossil fuels to support its economy at a price compounded by the high cost of inter-island transportation. While high quality, reliable and affordable energy services is a key indicator for strong economic growth, the government of Fiji is considerably burdened by the escalating prices of the imported fuel. Hence, it is vital that a steady progress is made into harnessing renewable energy. Recently, IPPs have shown interest and have begun investing in biomass, solar, and hydro energies, however wind energy development is still lagging.

Table 3. Economics of 2 Turbines Wind Farm

Financial Parameters		Vergnet 275	Vesta V27
Capital cost	$	810,000	720,000
Cost of Turbines	$	550,800	489600
Annual Energy Production	(kWh)	768,566	611,817
Power coefficient	(C_p)	0.32	0.25
Annual Returns from Electricity Sales (B_A)	$	207,513	165,191
Net Present Value of Benefits ($NPV)B_A$	$	1,766,674	1,406,361
Annual O&M and land rent (C_A)	$	32,400	28,800
Net Present Value (O&M and land rent ($NPV)C_A$	$	473,793	421,060
Net Present Value of the project (*NPV*)	$	924,274	657,561
Benefit Cost Ratio (*BCR*)		1.38	1.23
Payback period (*n*) years		5.08 ~5	5.87 ~6
yearly cost of operation	$	64,185	57,053
Cost of kWh production	$	0.08	0.09
Internal Rate of Return (*IRR*)	%	21.3	18.3

Lack of wind statistics and detailed analysis of the wind regime has impeded utilizing wind energy technology in Fiji. The general criteria of investment in wind energy conversion systems are based on economic and financial analysis techniques considering meteorological data and technical specification of appropriate wind turbines [10]. Kongnam and Nuchprayoon [11] developed investment strategies exclusively for low wind speed area may be utilized for Benau where the mean wind speed at 25 m is less than 5 m/s for surface roughness of 0.4m. Wind speed and direction are highly variable and wind energy conversion systems are capital intensive. To account for the unpredictable nature of the wind, proper investment planning [12-14] is necessary to minimize economic risks. Konnam et.al [15], proposed a decision analysis technique to optimize capacity was partially used with Sathyajith [7] to evaluate the generation capacity and economics of a two turbine wind farm in a 25 km^2 area at Benau.

The statistics of the wind regime 30 m a.g.l at Benau Figure 2 shows a wind speed of 6.24 m/s corresponding to a power density of 590 W/m^2. The cut-in speed of Vergnet 275 is 3.5 m/s. At 50 m a.g.l (<55 m hub height), Sector-wise Weibull distributions table for roughness length 0.40 m revealed that 100 % of the time the wind speed is above the cut-in speed hence the turbine would produce power all the time. The minimum power density at 50 m is between 73 and 75 W/m^2 and this occurs for approximately 13% of the time. Vergnet 275 kW turbine has a rotor diameter of 32 m and this translates to 59 kW of wind power is available for harvest. Assuming a power coefficient of 0.2, the turbine would produce at least 103 MWh in that 13% of the time. However, Vesta V27 with a hub height of 32.5 m and rotor diameter of 27 m and a cut-in speed of 3.5 m/s would not produce any power for 16% of time. It should be borne in mind that the hub height of Vesta (32.5m) is lower than 55 m, knowing that wind speed increases with height and the power varies with cube of wind speed. It is desirable to have a turbine with higher hub height but optimizing the cost of energy produced. This led to a detailed economic analysis that crucial for an accurate determination of the preferred turbine for a given site. The capital cost for Vergnet is 12.5% more compared to Vesta but generates 25.5% more annual returns from sale of electricity.

Lifetime of the wind turbine system is assumed 20 years; however manufacturers estimate a life expectancy of between 20 and 25 years. Danish Wind Industry Association (2008) [16] suggests a 20 year design lifetime as a useful economic compromise adopted by many as a guide for developers of components for wind turbines. The determination of the capital (or total investment) costs_generally involves the cost of the wind turbine(s), and the cost of the remaining installation. Wind turbine costs can vary significantly. This may be due to differing tower height or rotor diameter. Generally, wind turbine installed costs are normalized to cost per unit of rotor area or cost per rated kW or per kWh of energy generated.

Based on Table 3 above Vergnet 275 kW wind turbine is the better option to choose. Vergnet 275 kW wind turbine has the lower levelised cost of energy with a payback time of 5 years and also has a better cost to benefit ratio.

Thus from the economic analysis it is evident that Vergnet 275kW wind turbine has a potential of maximizing the energy output from Benau. But for investment security further in depth analysis has to be carried out in order to determine the sensitivity for each of the wind turbine in different economic conditions.

5. Conclusion

The cost of energy production is approximately same for both turbines. However, Vergnet would produce more energy than Vesta V27. The candidate site (Benau) has sufficient wind to be considered a commercially viable site for a medium sized (275 kW) turbine. WAsP verified that a wind farm with 2 x Vergnet 275 kW turbines would produce 769 MWh annually at $0.08/kWh with a cost to benefit ratio of 1.38, payback period of 5 years, and internal rate of return (IRR) of 21.3%. This generation cost compared against FEA’s purchase price of $0.27/kWh, shows that investing in wind power generation at Benau is economically viable. However, the limiting factor at Benau appears to be the sea front which may be developed later for tourism industry would increase the obstacle and roughness parameters in the prevalent wind direction. Other factors such as permitting issues, noise and airspace issues, environmental permitting, and utility inter-connection are not a major concern for developing wind energy at Benau.

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