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► **To cite this version:**

Kunal Dayal, John Cater, Michael Kingan, Gilles Bellon, Rajnish Sharma. An analysis of the 10 MW Butoni wind farm in the Tropical Southwest Pacific Island of Fiji. *Wind Engineering*, 2022, 46 (4), pp.1264-1280. 10.1177/0309524X221075808. hal-03755668

**HAL Id: hal-03755668**

**<https://hal.science/hal-03755668v1>**

Submitted on 22 Aug 2022

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## An analysis of the Butoni wind farm in Fiji

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### Abstract

This study carries out an analysis of the Butoni wind farm in Fiji using 6 years of uninterrupted near-surface wind observations (2013 – 2018) from a nearby Automatic Weather Station (AWS). The standard wind-industry software, Wind Atlas Analysis and Application Program (WAsP) is used to analyse and evaluate the wind characteristics of the wind farm and the surrounding areas. In addition, the modelled and operational annual energy production (AEP) are discussed with the related economic analysis together with the main causes for the under-performance of the wind farm. The results revealed that the mean wind speed, power density and the AEP at the Butoni wind farm are 3.5 m/s, 68 W/m<sup>2</sup> and 130 MWh/year/turbine, which are below the utility-scale standard of 6.4 m/s, 300 W/m<sup>2</sup> and 500 MWh/year/turbine respectively, at 55 m above ground level (AGL). The main reason for the under-performance of the wind farm is that it was commissioned for a low mean wind speed regime of 3.1 m/s to 4.0 m/s. The wind farm has a lower than expected capacity factor of 5.4 % and a higher wind shear coefficient of 0.35. An economic analysis revealed that the payback time is 24.5 years and the cost of energy generation is FJD \$0.55/kWh.

**Key words:** Fiji, wind farm, wind characteristics, WAsP.

### 1. Introduction

Fiji is a small island developing state (SIDS) located in the tropical Southwest Pacific region between the latitudes of 12 °S - 22 °S and longitudes of 177 °E - 178 °W. The 332 islands in the country cover a total land area of 18,333 km<sup>2</sup> with 110 islands being inhabited. The two largest islands of Viti Levu and Vanua Levu occupy around 87 % of the total land area with 10,400 km<sup>2</sup> and 5,540 km<sup>2</sup> respectively. The islands are mountainous with a maximum peak of 1300 m above mean sea level and are of volcanic origin. The islands of Fiji experience a tropical marine climate, which consists of two climatic seasons, namely austral summer (wet

season) extending from November to April and austral winter (dry season) from May to October. The islands are also prone to tropical cyclones with a frequency of on average 2 tropical cyclones forecasted during austral summer for the Fijian waters [1].

Energy Fiji Limited (EFL) (formerly known as Fiji Electricity Authority - FEA) is responsible for the generation, transmission and distribution of grid electricity in Fiji. Electricity generation in Fiji is a mixture of renewable (hydro, biomass and wind) and conventional (industrial diesel and heavy fuel oil) power stations. In the year 2019, 1060 GWh of electricity was generated with 57.7 % (610.8 GWh) from renewable sources and 42.4 % (449.7 GWh) from conventional power plants. The renewable energy-based power plants contributed 52.7 % (559.3 GWh) from hydropower, 4.6 % (48.8 GWh) from biomass-based independent power producers and 0.25 % (2.7 GWh) from wind [2].

An assessment of the wind resources is required to determine the potential for wind power generation at any scale, whether for grid-connected or stand-alone systems. In addition, siting of wind turbines is important for the optimal utilization of the available wind resources and the viability of a wind power project [3, 4]. Several wind-resource assessment studies have been conducted in Fiji using the Wind Atlas Analysis and Application Program (WAsP) [5 – 12] and WindPRO [13], with mean wind speed, power density and Weibull  $A$  and  $k$  parameters ranging from 4.6 m/s – 6.5 m/s, 139 W/m<sup>2</sup> – 241 W/m<sup>2</sup>, 5.2 m/s – 7.35 m/s and 1.68 – 2.63, respectively at 10 m elevation, but none have led to developing new wind farms to support the electricity grid. However, a recent study identified three potential wind farm sites that can be further investigated for utility-scale wind power applications with each site capable of incorporating a minimum installed capacity of 10 MW using Vergnet 275-kW wind turbines [14].

Fiji has a grid-connected 10 MW wind farm situated in the Butoni hills of Sigatoka. The wind farm consists of 37 × 275 kW Vergnet wind turbines, which are connected to the EFL grid network. Table 1 presents the electricity generation statistics, contribution to grid and the capacity factor (CF) of the Butoni wind farm since its installation in 2007. The wind farm is operating below the operational capacity of current utility-scale wind farms around the world and in the Oceania region, which have capacity factors ranging from 0.20 – 0.54 and 0.31 – 0.48, respectively [15]. The power production ranges from a minimum of 2.1 GWh in 2017 to a maximum of 7.2 GWh in 2009 with a minimum and maximum contribution of 0.21 % and 0.93 % to the annual electricity generation within Fiji over a 13-year period, respectively. The Butoni wind farm in Fiji is reported to be under-performing due to a lack of analysis

prior to installation [16]. To date, no research has been carried out to analyse the wind resources and to determine the main causes for the under-performance of the wind farm.

Table 1. Butoni Wind Farm Operational Statistics

Year	Production (GWh)	Contribution to grid (%)	Capacity Factor (%)
2007	3.35	0.44	3.83
2008	4.60	0.60	5.26
2009	7.21	0.93	8.23
2010	6.42	0.77	7.33
2011	4.98	0.62	5.68
2012	6.81	0.85	7.77
2013	5.35	0.62	6.11
2014	4.27	0.50	4.87
2015	5.67	0.64	6.48
2016	3.63	0.39	4.15
2017	2.08	0.21	2.38
2018	2.56	0.26	2.92
2019	3.15	0.25	3.59

This study aims to carry out an analysis of the Butoni wind farm to evaluate the wind characteristics in terms of mean wind speed, dominant wind direction, mean power density, diurnal and annual wind speed patterns, capacity factor, average wind shear and the energy potential via resource mapping of a 275-kW Vergnet wind turbine using measured data from a nearby located Automatic Weather Station (AWS) in WAsP. In addition, the analysis compares simulated yearly results with actual operational production from the wind farm and discusses the related economic return together with the causes for the under-performance of the wind farm.

Section 2 of this work provides the background for the analysis, section 3 describes the methodology, and the results are presented in section 4 and then discussed in section 5. The conclusions are presented in section 6.

## 2. Background

The key wind resource parameters computed by WAsP [17] include the Weibull distribution, power and energy production from a wind turbine and the mean wind speed. The wind shear coefficient, capacity factor and the economic viability parameters are computed using the WAsP results.

### 2.1 Weibull Distribution

In most locations surface wind speed distribution is well approximated by a Weibull distribution [3, 4, 17]. Fitting the Weibull distribution is therefore the method most frequently used in wind energy studies to obtain a smooth distribution despite under-sampling of wind

speed due to limited observation periods. The Weibull distribution is a two-parameter function, mathematically represented by  $f(u)$  while the cumulative distribution function is represented by  $F(u)$ :

$$f(u) = \frac{k}{A} \left(\frac{u}{A}\right)^{k-1} e^{-\left(\frac{u}{A}\right)^k} \quad (1)$$

$$F(u) = 1 - e^{-\left(\frac{u}{A}\right)^k}, \quad (2)$$

where  $u$  is the reference wind speed at the height of measurement,  $k$  the non-dimensional shape parameter, and  $A$  the scale parameter whose dimensions coincide with that of  $u$  (m/s).  $k, A, u > 0$ . The Weibull shape parameter  $k$  indicates how peaked the distribution is, the Weibull  $A$  parameter indicates on average how windy the site is and the Weibull mean  $u$  indicates the long-term mean wind speed at the site. A higher Weibull  $A$  parameter ( $> 4$  m/s) also indicates an increase in the dispersion of the wind speed around the mean wind speed and a higher Weibull  $k$  parameter ( $> 2.5$ ) indicates that the variation of mean wind speed is small [3, 4].

## 2.2 Power and Energy Production from a Wind Turbine

The power production  $P$  (in units of  $W$ ) from a wind turbine is estimated using the wind turbine power curve  $p(u)$  and the probability density function of the wind speed at the hub height of the wind turbine as follows:

$$P = \int_0^{\infty} f(u) p(u) du. \quad (3)$$

The annual energy output from a wind turbine  $E$  (in units of Wh) is estimated using the following equation:

$$E = \eta TP, \quad (4)$$

where  $T$  is the number of hours in one year and  $\eta$  is the energy conversion efficiency of the wind turbine [17].

## 2.3 Wind Speed calculation using WAsP

WAsP is a linear wind simulation model, based on linear models of the fluid flow equations and considers the following fundamental factors when calculating wind speed:

1. The geostrophic balance, where the geostrophic drag law gives the geostrophic wind speed 'G':

$$G = \frac{U^*}{K} \sqrt{\left[ \ln \frac{U^*}{Fz_0} - \mathcal{A}(\mu) \right]^2 + B^2(\mu)}, \quad (5)$$

where  $\mathcal{A}$ ,  $B$  are dimensionless constants,  $U^*$  is the friction velocity,  $K$  is the dimensionless von Karman's constant (0.4),  $z_0$  is the surface roughness length and  $F$  is the Coriolis parameter.

2. The modified logarithmic wind profile.

$$u(z) = \frac{U^*}{k} \left[ \ln \frac{z}{z_0} - \psi \left( \frac{z}{L} \right) \right], \quad (6)$$

where  $u(z)$  is the wind speed at height  $z$ ,  $\psi$  is the stability dependent function which is positive for unstable and negative for stable conditions, and  $L$  is the Monin-Obukhov Length [17].

3. A specific (but uniform) stability, roughness variations and elevation variations from the topographical data.

#### 2.4 Vertical Profile of Wind Speed and Wind Shear

A power law is often used to describe the wind velocity profile near the surface and is commonly used to model the vertical profile of wind speed over regions of homogeneous, flat terrain and prairies. The power law is expressed as:

$$\frac{u(z)}{u(z_r)} = \left( \frac{z}{z_r} \right)^\alpha, \quad (7)$$

where  $u(z_r)$  is the reference wind speed at height  $z_r$  and  $\alpha$  is the power law exponent, which is the estimated wind shear coefficient at the site.

The wind shear is the vertical variation of wind speed with height. It results from the surface drag which slows down the wind at the surface. It depends on how the effect of this drag is transported upwards by turbulence, and on the surface roughness, which modulates turbulence. It is an important parameter not only for power production from wind turbines, but also for aerodynamic loadings on the wind turbine blades. The wind shear coefficient can be computed using known wind speeds at two elevations, as in equation (8):

$$\alpha = \frac{\ln \left( \frac{u(z_1)}{u(z_2)} \right)}{\ln \left( \frac{z_1}{z_2} \right)}. \quad (8)$$

Many researchers have used a one-seventh power law where  $\alpha = \frac{1}{7}$  for relatively flat terrain.

#### 2.5 Capacity Factor

The capacity factor (CF) is the ratio of the energy output ( $E_T$ ) produced by a wind power system to the output that would have been generated if the system operated at its rated power ( $P_R$ ) over a given time period ( $T$ ). The dimensionless value of CF is given by:

$$CF = \frac{E_T}{P_R T}. \quad (9)$$

## 2.6 Payback Period and Cost of Energy Generation

In a simple payback analysis, the revenue is compared with the costs and the length of time required for recovering the initial investment costs. The payback period in years equals to the total capital costs of the wind energy system divided by the annual revenue generated from the energy produced [3, 4]. The simple payback period is expressed as:

$$SP = \frac{C_c}{AAR} = \frac{C_c}{E \times P_e}, \quad (10)$$

where  $SP$  is the simple payback period,  $C_c$  is the total installation cost (\$),  $AAR$  is the average annual return (\$/year),  $E$  is the annual energy production (kWh/year) and  $P_e$  is the feed-in-tariff for electricity (\$/kWh).

The cost of energy ( $CoE$ ) generation is the unit cost required to produce energy in \$/kWh from a power generation system, it is expressed as:

$$CoE = \frac{Total\ Costs}{Energy\ produced} = \frac{[(C_c \times FCR) + C_{O\&M}]}{E}, \quad (11)$$

where  $C_{O\&M}$  is the average annual operation and maintenance cost (\$/year) and  $FCR$  is the fixed charge rate (\$/year), which refers to the value of interest one pays and or an average annual charge used to account for debt, equity costs and taxes etc.

## 3. Methodology

Fiji Meteorological Services (FMS) provided 6 years of wind data from 2013 to 2018 for the Sigatoka Automatic Weather Station (AWS) in Fiji since its installation. The average wind speed and wind direction dataset was recorded with a temporal resolution of 10 minutes using mechanical anemometers and wind vanes at a height of 10 m above ground level (AGL) as per the World Meteorological Organisation (WMO) requirements.

Table 2 shows the station details in terms of the latitude, longitude, altitude, observation period and the total number of observations and the data availability. The AWS site has a data availability of 95.4 % over the study period.

Table 2. Location and Data Records for the Sigatoka AWS

Station	Latitude	Longitude	Height	Elevation	Data	# of	Availability
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	(degrees)	(degrees)	(m)	(m)	Period	Records	
Sigatoka	-18.1422	177.5039	10 m	6.7 m	2013 – 2018	300855	95.4 %

Figure 1 shows the map of Fiji with the study area and an enlarged spatial map with the location of the Sigatoka AWS (denoted by X) and the wind farm site (bounded by the rectangular box). In the enlarged spatial map, the contours are at intervals of 10 m, the roughness is represented by polygonal shapes and the rectangular box outlines the location of the wind farm and the 37 Vergnet 275 kW wind turbines located on the Butoni hills.

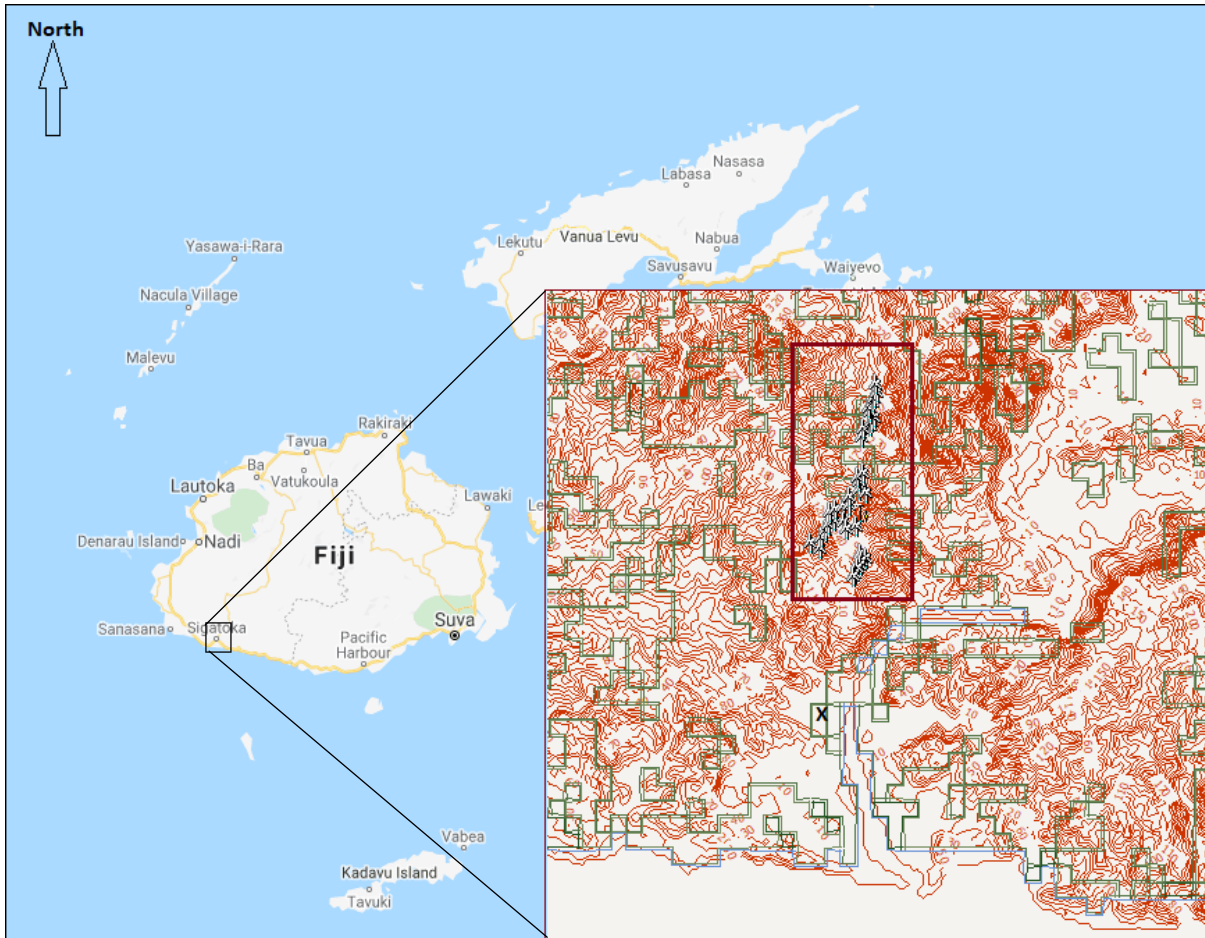


Figure 1. Map of Fiji showing the location of the AWS and the wind farm site (Original Map Source: Google Earth).

This study uses WAsP Climate Analyst 3.1 [17] with observed wind climatology as input, WAsP Map Editor 12.1 for topography and land roughness maps and WAsP 12.1 for mean wind speed, power density, and annual energy production analysis. WAsP is PC-based wind simulation software, developed and distributed by researchers within the Department of Wind Energy of the Denmark Technical University. It is a standard wind resource assessment, siting, and energy-yield calculation tool used in the wind-power industry and in scientific research. It produces spatial patterns of wind and mapping of wind resources by extrapolation



of wind data. The accuracy of the predictions are subject to the assumption that there is the same overall weather regime for the reference and predicted sites, the weather conditions are close to neutrally stable, the reference wind data is reliable, the surrounding terrain is sufficiently smooth, and the topographical inputs are adequate and reliable.

WAsP Climate Analyst 3.1 generated an estimate of the wind climatology for the Sigatoka AWS location using the raw data provided by Fiji Meteorological Services. The estimated wind is presented sector-wise in the form of a wind rose and a Weibull distribution function. The wind rose indicates the relative frequency of occurrence of wind direction grouped in 12 sectors. Equation (8), is used to compute the wind shear coefficient  $\alpha$  using the mean wind speeds at 10 m and 55 m above ground level (AGL) as the reference and calculation elevations for wind shear coefficient, respectively. These heights have been used because 10 m wind speed is available from the automatic weather station, while WAsP modelled the wind speed at 55 m AGL, and measurements are not available at any other heights.

The topography and the land roughness maps were imported from the GWA-Elevation Database and GWA-Roughness-Global-Cover Databases (<https://globalwindatlas.info/>) at a horizontal resolution of 3 arc seconds (approximately 90 m) and 10 arc seconds (approximately 300 m), respectively. Both the topography and the land roughness maps were joined into one map using the WAsP Map Editor 12.1.

WAsP 12.1 was then used to analyse the wind energy resource in terms of mean wind speed, power density, orography, and the AEP using a Vergnet 275-kW wind turbine on a resource grid of 14 km  $\times$  14 km at a height of 55 m AGL. The obstacles and sheltering effects from nearby vegetation and buildings were considered in the WAsP analysis. High-resolution micro-scale resource maps for the resource grid of 14 km  $\times$  14 km at 50 m horizontal resolution were developed for each resource parameter. A turbine cluster of 37  $\times$  275 kW Vergnet wind turbines were placed at the same locations as in the Butoni wind farm. Annual energy production (AEP) was computed using WAsP 12.1 and the wake losses were modelled using the Park 2 model [17].

The Vergnet 275-kW wind turbine has been used at the Butoni wind farm as these turbines can be lowered to the ground and secured in place during extreme wind conditions, such as tropical cyclones, which are not uncommon in Fiji. Vergnet wind turbines are in use at existing wind farms in other Southwest Pacific island countries prone to tropical cyclones

such as Samoa, Vanuatu and New Caledonia. Table 3 presents the specifications of the Vergnet 275-kW wind turbine.

Table 3. Vergnet 275-kW turbine specifications

Rotor Diameter	Hub Height	Cut-in speed	Cut-out speed	Rotation rate	Rated Power	Rated wind speed
32 m	55 m	3.5 m/s	25 m/s	31 rpm	275-kW	12 m/s

Figure 2 presents the elevation and the polygonal land roughness grid maps of Sigatoka with a contour interval of 10 m. The elevation varies from sea level to 380 m.

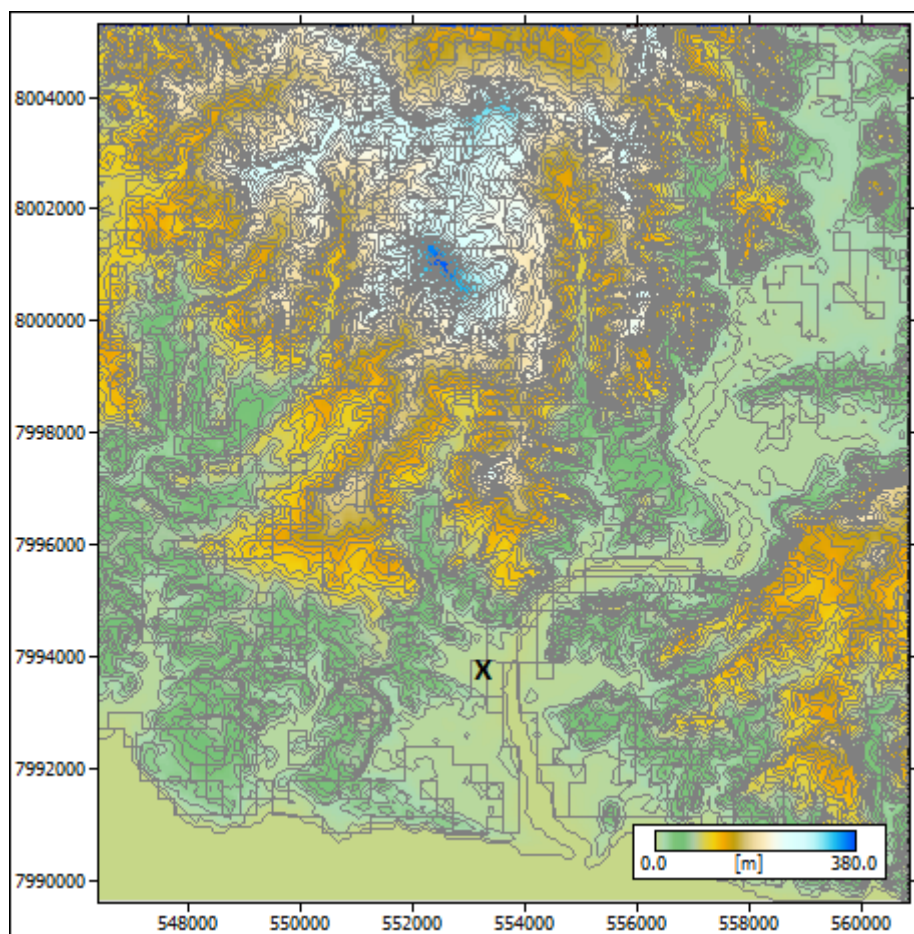


Figure 2. Elevation map of Sigatoka (x denotes the location of the AWS).

Table 4 presents details for the locations of the individual wind turbines in the Butoni wind farm. The information includes the wind turbine generator (WTG) number, the distance from the central meridian (X-location) and the distance from the equator (Y-location) and the elevation above mean sea level. All wind turbines have a standard hub-height of 55 m.

Three wind resource parameters are considered important for determining the potential of the wind resource. Wind speed and wind power density in the range of Class 3 or higher (wind speed  $> 5.1$  m/s and  $6.4$  m/s and power density  $> 150$  W/m<sup>2</sup> and  $300$  W/m<sup>2</sup> at heights of  $10$  m and  $50$  m, respectively) and AEP of  $0.500$  GWh/year/turbine or higher are considered feasible for utility-scale wind power development [4, 18, 19].

Table 4. Details of the wind turbines in the Butoni wind farm

Site description	X-location [m]	Y-location [m]	Elevation a.s.l. [m]
WTG 1	553245.7	7996709	139.1
WTG 2	553066.1	7996809	150.1
WTG 3	553278.1	7996930	184.2
WTG 4	553352.5	7997063	213.7
WTG 5	553395.1	7997173	239.2
WTG 6	553501.1	7997239	238.7
WTG 7	553427.5	7997394	241.3
WTG 8	553533.4	7997461	213.6
WTG 9	553692.3	7997515	208.9
WTG 10	553787.6	7997548	200.7
WTG 11	553798.6	7997692	179.4
WTG 12	553989.4	7997824	199.4
WTG 13	554116.2	7997780	193.2
WTG 14	553979.2	7997979	188.6
WTG 15	553968.9	7998079	180.8
WTG 16	554053.8	7998156	170.8
WTG 17	554045.1	7998853	202.9
WTG 18	554077.3	7998997	224.2
WTG 19	554193.8	7999052	226.1
WTG 20	554236.4	7999129	219.9
WTG 21	554289.5	7999218	213.1
WTG 22	554205.1	7999317	218
WTG 23	554173.6	7999406	217.3
WTG 24	554248	7999517	229.8
WTG 25	554290.6	7999594	230
WTG 26	554343.8	7999704	221.7
WTG 27	554312.4	7999848	210.5
WTG 28	553691.5	7997217	204.6
WTG 29	553924	7997150	185.2
WTG 30	553754.6	7997095	193.9
WTG 31	554017.7	7996596	170.2
WTG 32	554112.7	7996518	153.9
WTG 33	554027.9	7996463	157
WTG 34	554017.1	7996386	148.3
WTG 35	553953.5	7996331	142.6
WTG 36	553910.9	7996242	134.5

The individual wind turbine and the overall wind farm capacity factor is calculated using Equation 9. The payback period and the cost of energy generation are computed using Equations 10 and 11, respectively.

#### 4. Results

This section presents the results as follows: wind speed frequency and wind direction analysis, diurnal and annual wind speed patterns, wind shear coefficient and resource maps of mean wind speed, wind power density and annual energy production (AEP). Also presented is a comparison between the AEP calculated using WASP and the actual AEP of the Butoni wind farm and the related wind farm economics.

##### 4.1 Wind Speed Frequency and Wind Direction

The wind speed frequency distribution provides information about the site-specific Weibull wind resource parameters ( $A$  and  $k$ ) and the average power density at the height of the measurement mast. Similarly, a wind rose provides site specific sector-wise wind direction information. Figure 3 presents the wind speed frequency distribution and the wind direction analysis of the Sigatoka AWS location.

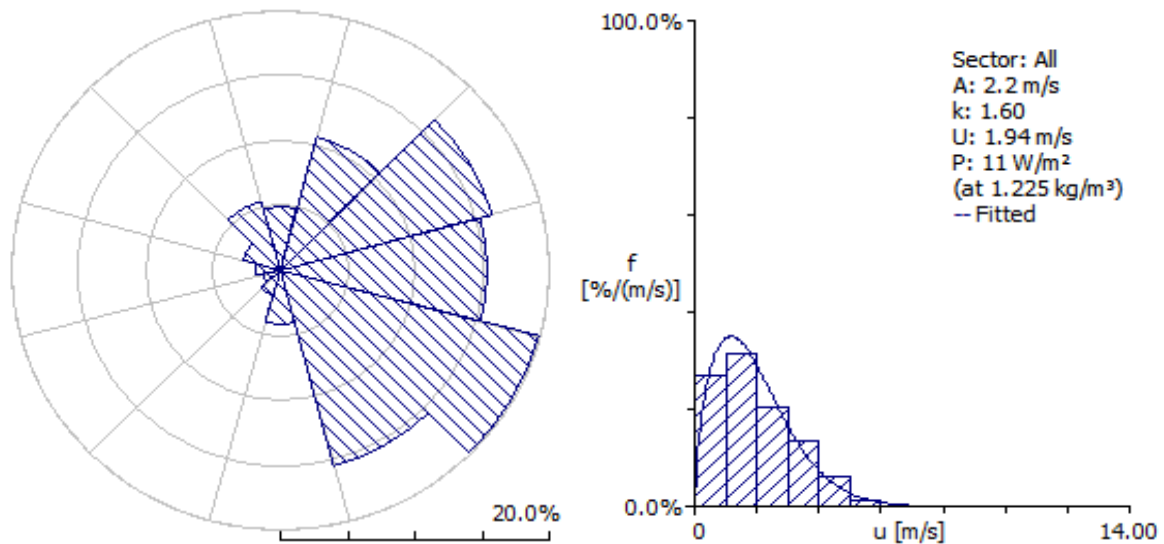


Figure 3. Wind rose and wind speed frequency distribution at Sigatoka AWS for 2013-2018 at 10 m AGL.

The wind speed varies from a minimum of 0 m/s to a maximum of 8.0 m/s with the majority (75 %) of the wind speed distribution being below 3 m/s. The average wind speed is 1.94 m/s with a power density of 11 W/m<sup>2</sup> at the height of 10 m AGL. Island-scale circulation and

sheltering effects from near obstacles shows the wind direction is spreading from the northeast to southeast with a dominant southeast wind direction. The Weibull  $A$  and  $k$  parameter values are 2.2 m/s and 1.60, respectively. The wind resource at the Sigatoka AWS can be classified as Wind Power Class 1 using the NREL standard classification at 10 m AGL [19]. The 10 m wind speed, power density and the Weibull  $A$  and  $k$  values at the Sigatoka AWS are less than those reported in the literature for wind energy studies in Fiji [5 – 14]. On average, the 10 m wind speed is lower by 192 %, power density is lower by 1654 %, the Weibull  $A$  parameter is lower by 190 % and the Weibull  $k$  parameter is lower by 36 % at the Sigatoka AWS in comparison with the wind energy studies reported in the literature [5 – 14]. The major reason for the larger differences observed between the Sigatoka AWS and other stations is the geographical location, as the wind resource parameters vary in space depending on the location, surrounding terrain and topography.

#### **4.2 Wind Speed Patterns**

The diurnal wind speed pattern represents the composite long-term averaged hourly variation of wind speed during a 24-hour period. The 6-year diurnal wind speed patterns and the average observed at the Sigatoka AWS location is presented in Figure 4. The average diurnal wind speed varies from a minimum of 1.1 m/s at midnight to a maximum of 3.4 m/s at 13:00 and 14:00 hours, at a height of 10 m. The diurnal variation of wind speed also falls in the category of Wind Power Class 1 [19]. The average diurnal wind speed pattern is similar to those reported in previous studies [5 – 14] in Fiji, but with lower magnitude. On average the minimum diurnal wind speed is lower by 272 %, while the maximum diurnal wind speed is lower by 91 % at the Sigatoka AWS in comparison with the other wind energy studies done in Fiji [5 – 14].

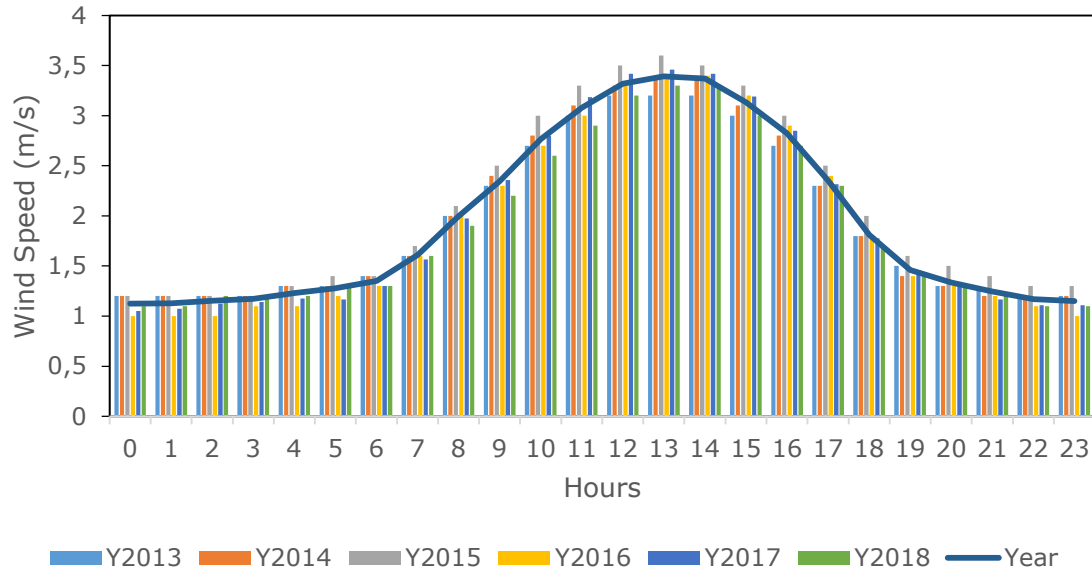


Figure 4. Diurnal wind speed patterns at 10 m AGL at Sigatoka AWS.

The monthly average wind speed during the annual long-term climatological cycle is representative of the annual wind speed pattern. Figure 5 presents the 6-year monthly averaged annual wind speed patterns observed at the Sigatoka AWS location. This varies from a minimum of 1.9 m/s to a maximum of 2.1 m/s. During austral summer the wind speed varies from 1.6 m/s to 1.9 m/s, and during austral winter from 1.8 m/s to 2.2 m/s at 10 m AGL. The annual variation of wind speed also falls in the Wind Power Class 1 category [19]. The magnitude of the annual wind speed variations at Sigatoka AWS are lower than those reported in previous studies [5 – 14], but similar behaviour is observed with higher wind speeds during austral winter (May – Oct) and lower wind speeds during austral summer (Nov – Apr). On average the minimum annual wind speed is lower by 100 % while the maximum wind speed is lower by 219 % at the Sigatoka AWS in comparison with wind energy studies done in Fiji [5 – 14].

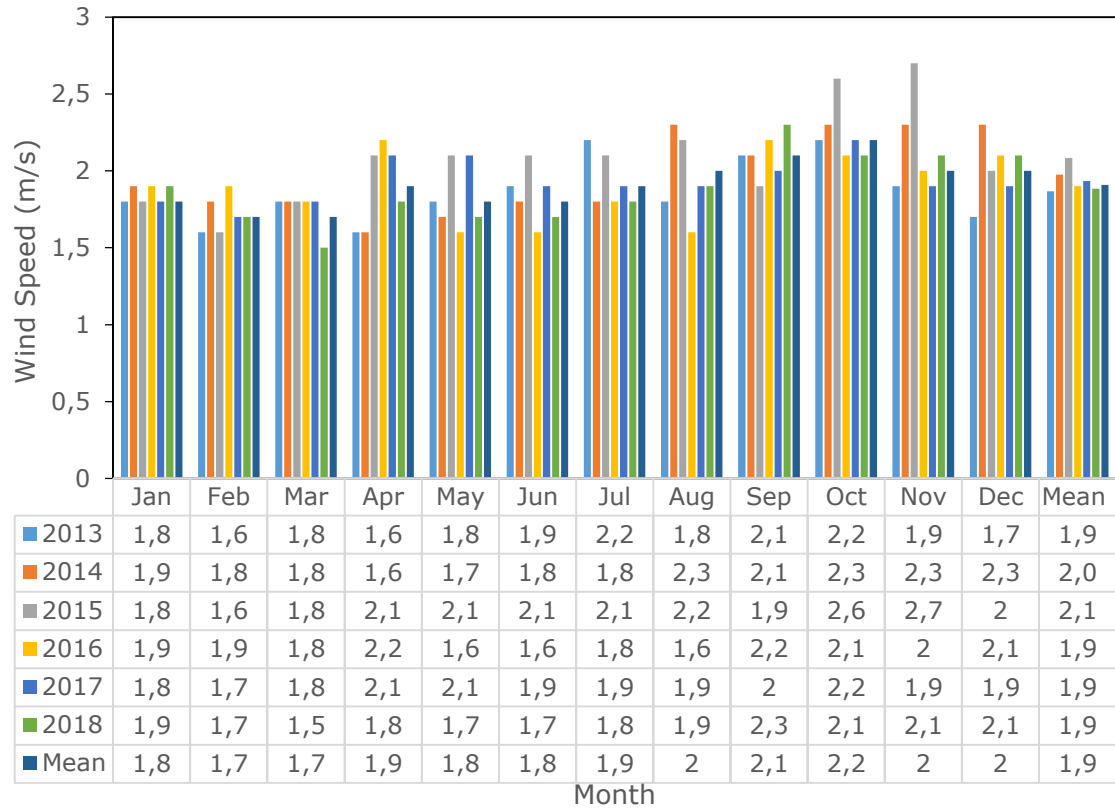


Figure 5. Annual wind speed patterns at 10 m AGL at Sigatoka AWS.

### 4.3 Wind Shear

The mean wind shear coefficient for the Sigatoka area is 0.35 as presented in Table 5. It represents a terrain type of a small town with few trees and shrubs [20]. For the normal wind turbine operation for all wind power classes, a wind shear coefficient of  $\alpha \leq 0.20$  is required [21], the Sigatoka wind shear coefficient is outside this range.

Table 5. Mean wind shear coefficient of Sigatoka area

Location	Wind speed @ 10 m [m/s]	Wind speed @ 55 m [m/s]	Mean wind shear coefficient [ $\alpha$ ]
Butoni	1.94	3.50	0.35

### 4.4 Wind Farm Statistics

Table 6 presents the WASP calculated average statistics of the individual wind turbines in the Butoni wind farm for the study period of 2013 – 2018. The net AEP varies from a minimum of 62.6 MWh for turbine 15 to a maximum of 215 MWh for turbine 6 with an average of 129.7 MWh for the 37 turbines in the wind farm. The wake losses vary from a minimum of 1.1 % (1.4 MWh) for turbine 37 to a maximum of 40 % (43.6 MWh) for turbine 23 with an average of 13.1 % (18.4 MWh) for the entire wind farm. The capacity factor of the wind

turbines varies from a minimum of 2.6 % for turbine 15 to a maximum of 8.9 % for turbine 6 with an average wind farm capacity factor of 5.4 %. The net AEP for the individual wind turbines is significantly below 500 MWh/year, which is considered feasible for utility-scale wind power applications [4, 18, 19]. The capacity factor is also below the operational capacity of current utility-scale wind farms around the world and in the Oceania region, which have capacity factors ranging from 0.20 – 0.54 and 0.31 – 0.48, respectively [15].

Table 6. Wind Turbines in the Butoni Wind Farm 2013 – 2018

Turbine Site	Gross AEP (MWh)	Net AEP [MWh]	Wake Loss (MWh)	Wake loss [%]	Capacity Factor (%)
WTG 1	97.0	94.7	2.3	2.4	3.9
WTG 2	142.8	139.0	3.9	2.7	5.8
WTG 3	153.2	140.0	13.2	8.6	5.8
WTG 4	186.6	175.7	10.8	5.8	7.3
WTG 5	232.1	210.7	21.4	9.2	8.8
WTG 6	228.5	215.0	13.5	5.9	8.9
WTG 7	227.8	177.3	50.5	22.2	7.4
WTG 8	198.9	169.5	29.4	14.8	7.0
WTG 9	189.8	168.9	20.8	11.0	7.0
WTG 10	167.4	152.3	15.1	9.0	6.3
WTG 11	127.7	108.8	18.8	14.8	4.5
WTG 12	161.3	149.2	12.0	7.5	6.1
WTG 13	178.8	172.9	5.9	3.3	7.1
WTG 14	100.4	76.7	23.7	23.6	3.2
WTG 15	92.2	62.6	29.7	32.2	2.6
WTG 16	98.5	87.0	11.6	11.7	3.6
WTG 17	118.5	110.3	8.1	6.9	4.6
WTG 18	158.3	137.5	20.8	13.2	5.7
WTG 19	155.6	146.5	9.2	5.9	6.1
WTG 20	131.9	119.4	12.6	9.5	5.0
WTG 21	114.1	105.8	8.4	7.3	4.4
WTG 22	103.4	69.8	33.6	32.5	2.9
WTG 23	109.4	65.8	43.6	39.8	2.7
WTG 24	138.5	110.0	28.6	20.6	4.6
WTG 25	155.7	132.9	22.8	14.6	5.5
WTG 26	138.1	123.8	14.3	10.4	5.1
WTG 27	94.7	63.7	31.0	32.7	2.6
WTG 28	168.9	141.6	27.3	16.2	5.9
WTG 29	146.7	135.3	11.5	7.8	5.6
WTG 30	151.2	140.0	11.2	7.4	5.8
WTG 31	160.2	109.2	51.0	31.8	4.5
WTG 32	157.9	154.6	3.3	2.1	6.4
WTG 33	154.6	115.6	39.0	25.2	4.8
WTG 34	149.8	145.0	4.8	3.2	6.0
WTG 35	138.9	131.4	7.5	5.4	5.5
WTG 36	128.9	119.2	9.7	7.5	5.0
WTG 37	121.7	120.3	1.4	1.1	5.0
Mean	148.1	129.7	18.4	13.1	5.4



Table 7 presents the WAsP average Weibull ( $A$  and  $k$ ) parameters, mean wind speed and the power density of individual wind turbines for the study period of 2013 – 2018 at the hub-height of 55 m AGL. The Weibull scale parameter  $A$  and the shape parameter  $k$  varies from a minimum to maximum of 3.4 m/s for turbine 1 to 4.5 m/s for turbine 5, and 1.42 for turbine 2 to 1.65 for turbine 14, with an average of 3.9 m/s and 1.51 for the entire wind farm, respectively. The mean wind speed and power density varies from a minimum to maximum of 3.1 m/s for turbine 1 to 4.04 m/s for turbine 5, 46 W/m<sup>2</sup> for turbine 1 to 106 W/m<sup>2</sup> for turbine 5, with an average of 3.51 m/s and 68 W/m<sup>2</sup> for the whole wind farm, respectively. The Weibull  $A$  parameter is less than 5 m/s, which indicates that the mean wind speed is lower at the wind farm site [3 – 14]. The Weibull  $k$  parameter is less than 2.0, which indicates a greater deviation from the mean wind speed. The mean wind speed and the power density are also less than 6.4 m/s and 300 W/m<sup>2</sup> (Wind Power Class 3), which are the minimum requirements for utility-scale wind power applications using the 50 m AGL reference from NREL [19].

Table 7. Wind Climate Statistics 2013 - 2018

Turbine Site	$A$ [m/s]	$k$	$U$ [m/s]	$P$ [W/m <sup>2</sup> ]
WTG 1	3.4	1.50	3.10	46
WTG 2	3.7	1.42	3.35	64
WTG 3	3.9	1.47	3.50	68
WTG 4	4.1	1.48	3.75	83
WTG 5	4.5	1.46	4.04	106
WTG 6	4.4	1.46	4.02	105
WTG 7	4.4	1.47	4.00	103
WTG 8	4.1	1.44	3.76	88
WTG 9	4.1	1.44	3.70	83
WTG 10	4.0	1.47	3.58	74
WTG 11	3.7	1.48	3.31	58
WTG 12	4.0	1.51	3.62	72
WTG 13	4.1	1.47	3.71	81
WTG 14	3.7	1.65	3.30	49
WTG 15	3.6	1.64	3.22	46
WTG 16	3.6	1.58	3.21	48
WTG 17	3.7	1.56	3.35	55
WTG 18	4.0	1.52	3.61	72
WTG 19	4.0	1.53	3.60	71
WTG 20	3.9	1.56	3.47	61
WTG 21	3.8	1.60	3.37	54
WTG 22	3.7	1.62	3.31	50
WTG 23	3.7	1.58	3.32	52
WTG 24	3.9	1.54	3.50	64
WTG 25	4.0	1.51	3.58	71
WTG 26	3.8	1.52	3.47	64
WTG 27	3.6	1.59	3.20	47
WTG 28	4.0	1.45	3.63	78
WTG 29	3.9	1.47	3.51	69

WTG 30	3.9	1.47	3.54	71
WTG 31	4.0	1.47	3.58	74
WTG 32	3.9	1.44	3.53	73
WTG 33	3.9	1.45	3.51	71
WTG 34	3.8	1.45	3.46	68
WTG 35	3.7	1.46	3.38	63
WTG 36	3.7	1.47	3.32	59
WTG 37	3.6	1.49	3.28	56
Average	3.9	1.51	3.51	68

#### 4.5 Resource Maps

Figures 6 – 8 present the high-resolution (50 m × 50 m) spatial distribution of the mean wind speed, wind power density and the AEP using the Vergnet 275-kW wind turbines, respectively. These are generated using WAsP on a 14 km × 14 km domain, surrounding the Sigatoka AWS and covering the Butoni wind farm and the greater Sigatoka area at 55 m AGL. The wind farm area is bounded by the rectangular box shown in Figure 6.

The mean wind speed, power density and the AEP in the Sigatoka area varies from 2.15 m/s – 4.14 m/s, 14 W/m<sup>2</sup> – 143 W/m<sup>2</sup> and 15.9 MWh – 308.2 MWh with an average of 3.1 m/s, 52 W/m<sup>2</sup> and 110.8 MWh respectively, at a height of 55 m. The Sigatoka area is Class 1 and is not suitable for utility-scale wind power applications but maybe applicable for rural electrification purposes [19].

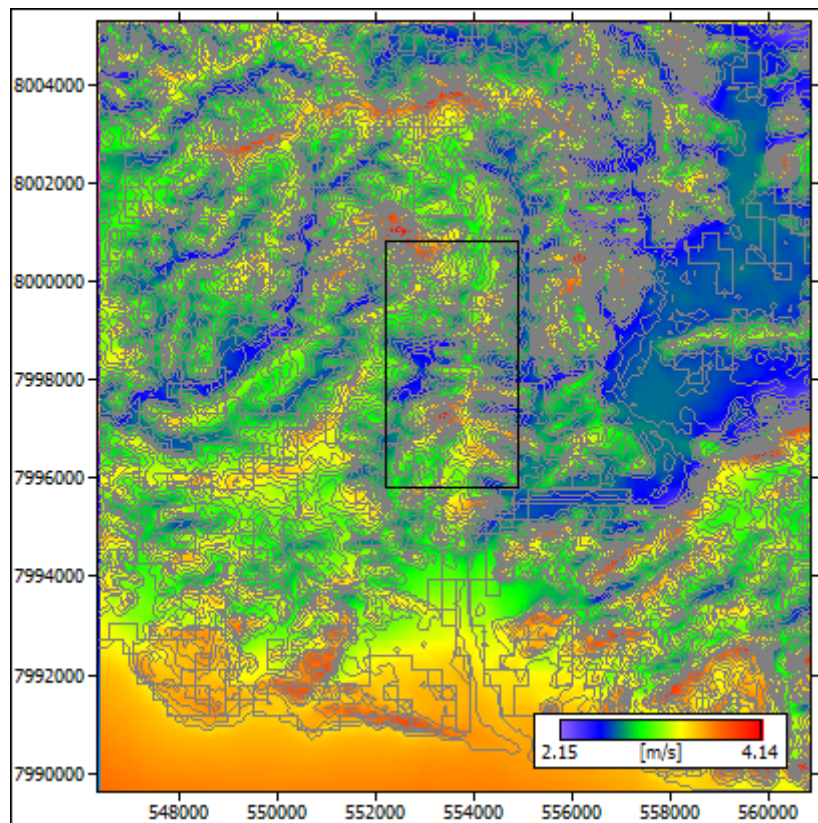


Figure 6. Mean wind speed map of the Sigatoka area at 55 m AGL.

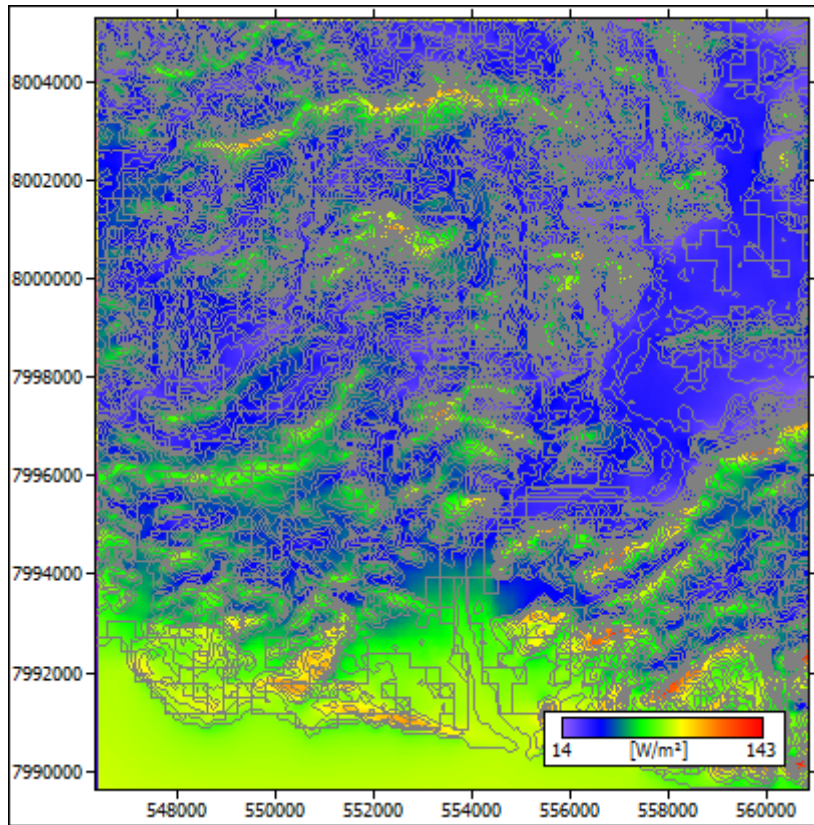


Figure 7. Wind-power density map of the Sigatoka area at 55 m AGL.

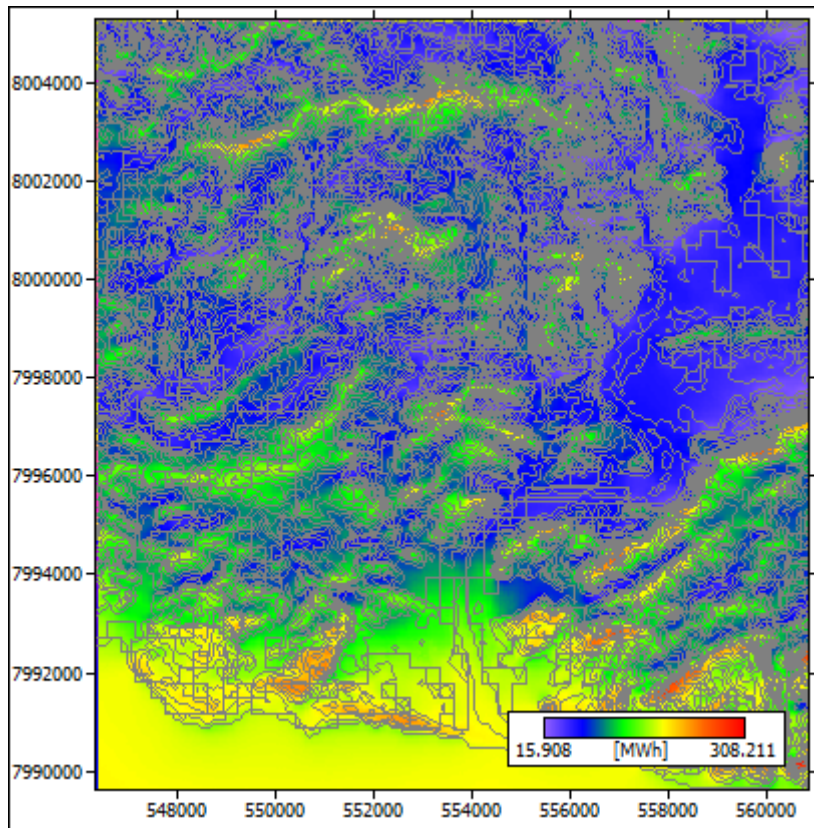


Figure 8. AEP map of the Sigatoka area at 55 m AGL.

It is concluded that the whole of Sigatoka and Butoni wind farm area are poor candidate sites to commission a utility-scale wind farm. Other sites that have used fewer wind turbines and target rural electrification have a higher wind resource potential than the current Butoni wind farm site [5 – 12]. Other work which has recommended utility-scale wind power applications also have a higher wind resource potential [13, 14].

### 3.6 Comparison of AEP

Figure 9 presents a graphical comparison of the measured AEP from the Butoni wind farm site to that computed with WAsP. Since measured wind data is only available from the years 2013 – 2018, the average of 6 years of WAsP AEP is used for the year 2019 for comparison.

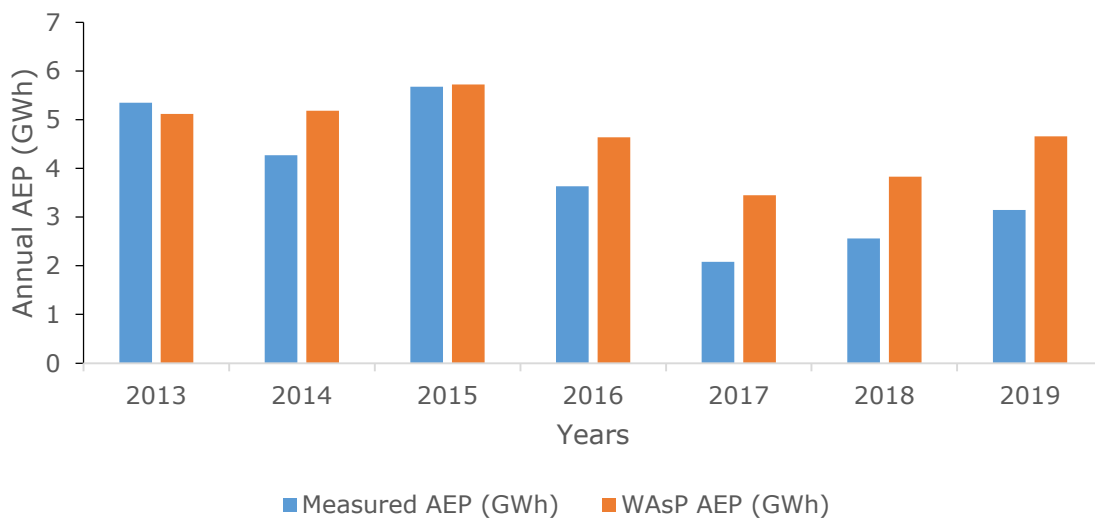


Figure 9. AEP comparison of the Butoni wind farm [EFL, 2019].

Table 8 presents a numerical comparison of the AEP from the Butoni wind farm to that calculated using WAsP from 2013 – 2018 with differences in AEP and possible explanations for the differences observed.

Table 8. Comparison of WAsP and Measured Production from the Butoni Wind Farm

Year	WAsP AEP (MWh)	Measured AEP (MWh)	Difference (MWh)	% Difference	Explanations
2013	5119.1	5348	-228.9	-4.3	5 WTG Partially down
2014	5182.9	4269	913.9	21.4	4 WTGs fully down and 5 Partially down
2015	5720.4	5674	46.4	0.81	8 WTGs fully down and 3 Partially down

2016	4640.1	3632	1008.1	27.8	8 WTGs fully down and 7 Partially down
2017	3450.4	2083	1367.4	65.6	12 WTGs fully down and 5 WTGs Partially down
2018	3832.6	2558	1274.6	49.8	12 WTGs fully down and 4 WTGs Partially down

For the years 2013 and 2015, the measured AEP from the Butoni wind farm are in good agreement with that modelled by WAsP with a difference of 229 MWh and 46 MWh, which is 4.3 % underestimated and 0.81 % overestimated by WAsP, respectively. For the other years 2014, 2016 – 2018, WAsP over-predicts the AEP from 913.9 MWh (21.4 %) to 1367.4 MWh (65.6 %). The overprediction in WAsP AEP is due to the partially down wind turbines being operational in the wind farm for the entire duration of the study period, but in the real wind farm there are of order 3 – 7 wind turbines, which were partially operational due to maintenance issues. The wind turbines that have been out of operation for the individual years have been excluded from the modeling work. The performance of the wind turbines in the wind farm has deteriorated over time as they face operation and maintenance issues whereas in the WAsP model all wind turbines considered are functioning ideally every year without problems. This is another reason for the overprediction in the WAsP AEP in comparison with the AEP from the Butoni wind farm for the individual years.

#### 4.6 Wind Farm Economics

Wind farm economics include important monetary information about the economic viability of a wind farm site or wind power project. Table 9 presents an approximate economic analysis of the Butoni wind farm in Fiji with all costs in Fijian Dollars (FJD). The total cost of the 10 MW Butoni wind farm was reported to be FJD \$34 M [16], the operational and maintenance (O&M) costs are adopted from operational wind farms in the Oceania region [15], the feed-in-tariff is the price set by the Fiji Commerce Commission [22] for renewable energy based power plants feeding the generated electricity to the national electricity grid network, which amounts to FJD \$0.30/kWh (fixed rate over the period) and a fixed charge rate (FCR) of 6.09 % (10-year average) is adopted from the Reserve Bank of Fiji [23]. The

AEP/year is taken as the average of the 13 years of operation of the wind farm which amounts to 4.621 GWh.

Table 9. Economic Analysis of the Butoni Wind Farm

Energy Economics Parameter	
Installed Capacity	10 MW
Cost per MW	\$3,400,000
O&M Costs per kWh	\$0.10
AEP in kWh/year	4621923
Feed-in-tariff / kWh	\$0.30
FCR	0.0609
Capital Costs	\$34,000,000
Annual Average Return	\$1,386,576.90
O&M Costs	\$462,192.30
Simple Payback Period	24.5
Cost of Energy per kWh	\$0.55

The cost of energy generation is calculated to be FJD \$0.55/kWh, which is higher than the cost of electricity generation from other sources of generation in Fiji (Hydro-power – FJD \$0.20/kWh, Oil-power – FJD \$0.39/kWh, Bagasse – FJD \$0.28/kWh and Biomass – FJD \$0.23/kWh) [24]. Using the wind farm capital costs, the average annual return from the wind farm and the feed-in-tariff, the payback period for the Butoni wind farm is computed to be 24.5 years, which is greater than the standard wind farm lifetime of 20 years. The cost of energy generation and the payback period in the current study is much higher in comparison with those computed in other wind energy studies in Fiji [5 – 14], which are of the order of less than FJD \$0.20/kWh and 10 years, respectively.

## 5. Discussion

The standard utility-scale wind farm application benchmarks from NREL [19] and the relevant literature [5 – 14], identifies that the Butoni wind farm is situated in a weak wind speed regime of Wind Power Class 1, which is not suitable for utility-scale wind power applications. No other sites in the greater Sigatoka area, analysed by WAsP using the 14 km × 14 km resource grid show potential wind resources that could be utilized for viable wind farm applications. Another problem is the higher wind shear coefficient of 0.35 at the Butoni wind farm, which is 75 % higher than the normal working standard (0.20) of wind turbines, and contributes towards the aerodynamic loadings on the wind turbine blades and may be one of the reasons for the higher turbine downtime reported earlier.



A recent 10-year (2009 – 2018) high-resolution mesoscale wind resource mapping study of the SIDS of Fiji using the Weather Research and Forecasting (WRF) model at a resolution of  $1 \text{ km} \times 1 \text{ km}$  [25], also indicates that the wind speed and the power density at the Butoni wind farm location ranges from 3.5 m/s to 4 m/s and  $50 \text{ W/m}^2$  to  $100 \text{ W/m}^2$ , respectively at 55 m elevation. The  $1 \text{ km} \times 1 \text{ km}$  mesoscale model results are similar to the overall results obtained with WAsP using 6 years of measured wind data from a nearby AWS, indicating that the wind resource falls in category of Wind Power Class 1.

The economics suggest that the Butoni wind farm project is not an economically viable wind power project in term of payback period ( $> 20$  years), capacity factor ( $> 0.20$ ) and the cost of energy generation exceeding other renewable and conventional power generations methods in Fiji.

It is recommended that EFL transfer the poorly operating wind turbines to other locations. Possible other sites have been identified as Rakiraki, Nabouwalu and Udu [14]. These three sites have been found to be potential wind farm sites with 5 – 6 years of wind data confirming the consistency of the potential of the wind resources [14]. This transfer is required to optimally utilize the wind turbines within their standard available lifetime of 20 years, out of which 7 years remain.

The main limitation of this work is that it is based on the measurements from a nearby AWS as no time series wind data measurements could be obtained from within the wind farm. For a further study, it would be interesting to use the 10 years of model simulation results at the Butoni wind farm location from the recent mesoscale wind resource mapping study for the three domains of  $15 \text{ km} \times 15 \text{ km}$ ,  $5 \text{ km} \times 5 \text{ km}$  and  $1 \text{ km} \times 1 \text{ km}$  and investigate how the wind resource parameters vary.

## **6. Conclusions**

This study completed an analysis of the Butoni wind farm in Fiji using 6 years of uninterrupted near-surface wind observations (2013 – 2018) from a nearby Automatic Weather Station (AWS). The standard wind-industry software, Wind Atlas Analysis and Application Program (WAsP) is used to analyse and evaluate the wind characteristics of the wind farm and the surrounding areas. In addition, the modelled and operational annual energy production (AEP) are discussed with the related economic analysis together with the main causes for the under-performance of the wind farm.

The results revealed that the average wind speed, power density and the AEP at the Butoni wind farm are 3.5 m/s, 68 W/m<sup>2</sup> and 129.7 MWh/year/turbine, respectively. These wind resource parameters are below the standard wind speed of 6.4 m/s, power density of 300 W/m<sup>2</sup> and AEP of 500 MWh/year/turbine for utility-scale wind power applications at 55 m AGL. The main reason for the under-performance of the wind farm is that it is commissioned for a weak mean wind speed regime of 3.1 m/s to 4.0 m/s. The wind farm has a low capacity factor of 5.38 % and a high wind shear coefficient of 0.35, which are also contributing factors to the wind farm underperformance. An approximate economic analysis revealed that the payback time for the Butoni wind farm is 24.5 years and the cost of energy generation is FJD \$0.55/kWh.

This research promotes the idea that wind farm project planning via wind resource and economic viability assessments are fundamental prior to the installation of a grid-connected wind farm project in the SIDSs of the Pacific, if they intend to optimally utilize the wind resources to ease its dependence on diesel-based power generation.

### **Acknowledgments**

This study is part of a PhD research project, for which the lead author is the recipient of scholarship funding from the New Zealand Ministry of Foreign Affairs and Trade (NZMFAT). The authors gratefully acknowledge the Fiji Meteorological Services for providing the ground-based wind data measurements, Mr. Om Dutt Sharma of Energy Fiji Limited (EFL) for providing production data from the Butoni wind farm and the Department of Wind Energy of the Denmark Technical University for providing a student license for the wind simulation software package WAsP.

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