Wind Energy Resource Assessment for Tokelau with Accurate Weibull Parameters

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***Abstract*—Wind energy resource assessment for two sites, Fakaofo and Atafu, in Tokelau is carried out with the help of a detailed statistical analysis of one year of measured wind data. The average wind speeds recorded for the sites were 3.81 m/s and 3.92 m/s for the Fakaofo and Atafu sites respectively at 34 m above ground level (AGL). The turbulence intensities (TI) for the two sites were also estimated. The wind shear coefficient correlated well with the temperature for both the sites. The best Weibull distribution method of approximation for the Fakaoko site was the WAsP method whereas it was the Empirical Method of Justus (EMJ) for the Atafu site from the 10 different methods that were used. The payback periods for installing the wind turbines were estimated to be 7.39 years and 7.85 years respectively for Fakaofo and Atafu.**

Keywords—Wind energy, Weibull distribution, wind shear coefficient, turbulence intensity, economic analysis, wind atlas analysis and application program

I. INTRODUCTION

Tokelau is a pacific island nation, a dependent territory of New Zealand which has three atolls and are situated near the equator. The total land area of Tokelau is 12 km^2. Currently Tokelau is fully powered by renewable energy (100% of solar energy). Since Tokelau is dependent heavily on solar energy, it is advisable to look for other alternatives such as wind which would also be available at night for having a hybrid system. Currently, they have the solar PV with batteries but if wind energy could also be used then the hybrid system will ensure continuous power supply as one resource will compensate if the other is lacking. For the placement of wind turbines, wind resource assessment must be carried out. Many previous researchers have not used different methods to estimate Weibull parameters. The present work focusses on using ten methods to estimate Weibull parameters and five goodness of fit estimation methods. The work also focusses on the detailed analysis of wind characteristics which involves estimation of diurnal variation of wind shear coefficient, diurnal variation of temperature as well as the correlating between the two for the two sites. The estimation of turbulence intensities were also done as well as finding the predominant wind direction. Finally, an economic analysis was carried out for finding the payback period based on the current electricity charges on both the atolls. Two similar works have been carried out using ten methods for two locations in the South Pacific. Singh et al. [1] carried out wind energy resource assessment for two sites in Vanuatu and found that the best Weibull method differed for both the sites. The moments method performed best for the Pentecost Island site whereas the median and quartiles method performed best for the Epi Island site. The mean wind speeds were 5.60 m/s and 5.86 m/s for the Pentecost and Epi sites respectively. The AEP was also estimated and economic analysis was carried out indicating a payback period of 4.85 years. Kutty et al. [2] carried out similar research for Suva in Fiji and concluded that the best method was the empirical method of Justus for estimating the Weibull parameters. The site in Suva has an average wind speed of 5.18 m/s. The economic analysis was also carried out indicating a payback period of 10.83 years.

Fakaofo is an atoll in the Tokelau group which was also known as Bowditch Island previously. The land area of Fakaofo is around 4 km^2 consisting of a few islets lying on a coral reef which surrounds a lagoon. The population of Fakaofo is around 480 with the main settlement being Fale located on the western side of the atoll [3].

Atafu is an atoll in the Tokelau group. The atoll is located 500 km north of Samoa with its land area being 3.5 km^2. Similar to Fakaofo, Atafu also surrounds a central lagoon but has 52 islets lying on a coral reef. The atoll lies in the pacific hurricane belt around 5 m above sea level and is almost triangular in shape [3].

II. METHOD

Two sites on different atolls were selected for the wind resource assessment. Two measurement towers were installed on each of the atolls mentioned in the Introduction. On these two atolls, the measurement equipment used were the NRG systems data logger and sensors. There were seven different sensors used to record the wind speed, temperature, pressure, rainfall, solar insolation, humidity and wind direction. The sensors were placed at different altitudes. There were two anemometers placed at 34 m AGL and one more at 20 m AGL. The wind vane was placed at 30 m AGL and aligned to the true North. The temperature, solar insolation, pressure and humidity sensors were all placed at 2 m AGL. The anemometers were made of 3 rugged Lexan cups moulded into one piece for better durability. The temperature sensor had a protective radiation shield to ensure correct measurement of ambient temperature.

A. Data

The data logger recorded the measurements at an interval of 10 minutes. The measurements included the 10 minutes

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average, 10 minutes maximum, 10 minutes minimum and 10 minutes standard deviation from the data measured by seven different sensors described above. The data were recorded on an SD card and emailed to the server at the Japan ICT building at the University of the South Pacific. The raw data were then processed into excel formats to be analysed.

B. Estimation of Weibull Parameters

For the analysis of wind speed, it is not always best to use the normal distribution since wind speed is never negative and is also bound to one side thus the Weibull distribution is the best way to represent it. In the two-parameter Weibull distribution, the shape factor (k) and scale factor (A) need to be specified or determined. To determine the k and A values, different methods are used. From several methods, the best method for each site may be different. In this work, ten different methods were used from which the best method was selected using a number of performance parameters. The ten different methods used were: the median and quartiles method (MQ) [4], the moments method (MO) [5] , the empirical method of Justus (EMJ) [4], the empirical method of Lysen (EML) [4], the least squares method (LS) [6], the maximum likelihood method (ML) [4], the modified maximum likelihood method (MML) [4], the energy pattern factor method (EPF) [4], the WAsP method [6, 7] and new moments method (NMO) [8]. Table 1 lists the mathematical expressions for these methods:

Table 1: Several methods for determining Weibull parameters

Methods	Mathematical Expressions
MO	$\overline{U} = A\Gamma\left(1+\frac{1}{k}\right)$ (1) $\sigma = A\left[\Gamma(1+2/k) - \Gamma^2(1+1/k)\right]^{1/2}$ (2)
MQ	$k = \frac{\ln[\ln(0.25)/\ln(0.75)]}{\ln(U_{0.75})/U_{0.25}} \approx \frac{1.573}{\ln(U_{0.75})/U_{0.25})}$ (3) $A = \frac{U_m}{\ln(2)^{1/a}}$ (4)
EMJ	$k = \left[\sigma/\overline{U}\right]^{-1.086}$ (5) $A = \overline{U}/\Gamma(1+1/k)$ (6)
EML	$k = \left[\sigma/\overline{U}\right]^{-1.086}$ (7) $A = \overline{U}(0.568+0.433/k)^{-\frac{1}{k}}$ (8)
LS	$k = \frac{n\sum_{i=1}^{n} lnUxln\left[-\ln\{1-f(U)\}\right]\sum_{i=1}^{n} lnUx\sum_{i=1}^{n} ln\left[-\ln\{1-F(U)\}\right]}{\sum_{i=1}^{n}\ln U^2 - \{\sum_{i=1}^{n}\ln U\}^2}$ (9) $A = \frac{k\sum_{i=1}^{n} ln\ \mathrm{U} - \sum_{i=1}^{n} ln\left[-\ln\{1-F(U)\}\right]}{nk}$ (10)
ML	$k = \left[\frac{\sum_{i=1}^{n} U_i^k \ln U_i}{\sum_{i=1}^{n} U_i^k} - \frac{\sum_{i=1}^{n}\ln U_i}{n}\right]^{-1}$ (11) $A = \left[\frac{1}{n}\sum_{i=1}^{n}(U_i)^k\right]^{\frac{1}{k}}$ (12)
MML	$k = \left[\frac{\sum_{i=1}^{n} U_i^k \ln U_i f(U_i)}{\sum_{i=1}^{n} U_i^k} - \frac{\sum_{i=1}^{n}\ln U_i f(U_i)}{f(U \geq 0)}\right]^{-1}$ (13) $A = \left[\frac{1}{f(U \geq 0)}\sum_{i=1}^{n}(\mathrm{U}_i)^k f(U_i)\right]^{\frac{1}{k}}$ (14)
EPF	$k = 1 + \frac{3.69}{E_{pf}^2}$ (15) $A = \frac{\overline{U}}{\Gamma(1+1/k)}$ (16)
NMO	$\lambda_1\left(A\Gamma\left(1+\frac{1}{k}\right)-\overline{U}\right)^2 + \lambda_2\left(A^2\Gamma\left(1+\frac{2}{k}\right)-\overline{U^2}\right)^2 + \lambda_3\left(A^3\Gamma\left(1+\frac{3}{k}\right)-\overline{U^3}\right)^2$ (17) $\lambda_1 + \lambda_2 + \lambda_3 = 1$ (18) $\overline{U^r} = \sum_{i=1}^{n}\frac{U_i^r}{n}$ (19)

where:
A= scale factor in units of wind speed (m/s)
k = shape factor
Γ = gamma function
U_m = median wind velocity
$U_{0.25}$ = 25% wind velocity quartile
$U_{0.75}$ = 75% wind velocity quartile
$\overline{U}$ = mean wind speed
σ = standard deviation
λ = weights chosen
n = number of observations
U_i is the wind speed measured at the interval i
F(U) = the frequency for wind speed
f(U ≥ 0) is the probability for wind speed equal to or exceeding zero

Five performance parameters were used to find the best Weibull distribution: the root mean square error (RMSE) [5, 9, 10]. coefficient of determination (R^2) [9-11], mean absolute error (MAE) [5, 12], mean absolute percentage error (MAPE) [5, 9, 10, 13], and coefficient of efficiency (COE) [5, 14, 15]. By ranking the methods based on performance analysis, the best method was obtained.

The performance analysis determined the accuracy of the methods by the following rules:

- The lower the RMSE the better the Weibull method.
- The higher the R^2, the better the method.
- The lower the MAE, the better the accuracy.
- The lower the MAPE, the better the accuracy.
- The greater the COE, the better the accuracy of the method.

III. RESULTS

A. Wind Speed Analysis

The recorded wind speed data were analysed to determine the daily average and monthly average wind speeds. The daily average and monthly average wind speeds were calculated for the two sites. Equation (20) was used to determine the average wind speeds from the dataset.

$$\overline{U} = \frac{1}{n}\sum_{i=1}^{n} U_i \qquad (20)$$

where n is the number of recorded wind speeds and U_i is the wind speed recorded at different intervals.

Fig 1 and fig 2 represent the daily average wind speeds at 34 m and 20 m above ground level (AGL) for the entire period of measurements for the two sites in Tokelau. For the Fakaofo site, the highest wind speed was around 10.5 m/s recorded on 15th May, 2014 whereas the lowest wind speed was 0.6 m/s recorded on 15th July, 2014. For the Atafu site, the highest wind speed of around 10.7 m/s was recorded on 14th September, 2013 and the lowest wind speed of 0.5 m/s was recorded on 12th October, 2013.

It is noted for the two sites that the wind speed varies at different times of the year. The wind speeds were variable throughout the year. One of the reasons for having varying wind speed was the low pressure zone near the equator known as doldrums which causes variable winds due to the airflow towards the equator.

The other reason is due to the location of the atolls which is very close to the equator resulting in doldrums with frequent light breezes, showers and thunderstorms. The monthly averages of the wind speeds for the two sites were calculated and are presented in fig 3 and fig 4. It can be seen that the wind speeds at the two heights of 34 m and 20 m are generally not very high with the maximum monthly average wind speed close to 6 m/s.

The highest monthly average wind speeds were recorded during two different months for the two sites. The highest wind speeds were recorded in September followed by January at 34 m AGL for Fakaofo whereas for Atafu, the highest wind speeds were recorded in June followed by September. However the lowest average monthly wind speeds for both the atolls were recorded in April.

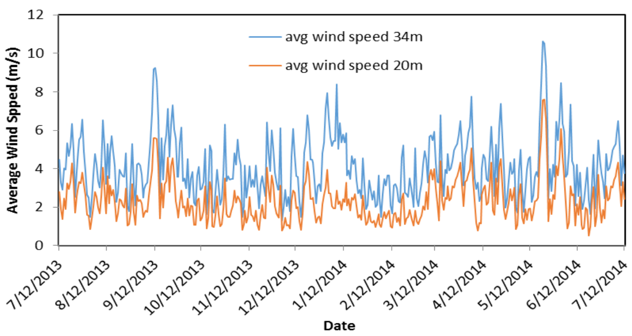

Fig 1: Daily average wind speeds for the entire measurement period recorded at 34 m and 20 m AGL for the Fakaofo site.

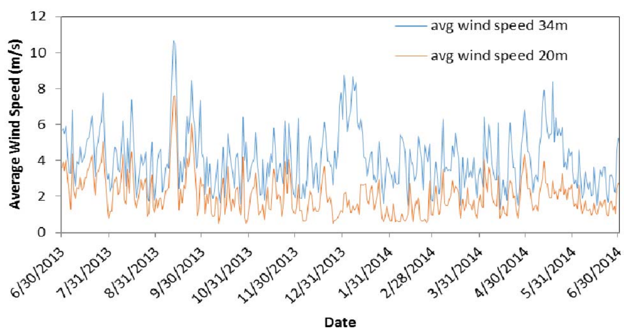

Fig 2: Daily average wind speeds for the entire measurement period recorded at 34 m and 20 m AGL for the Atafu site.

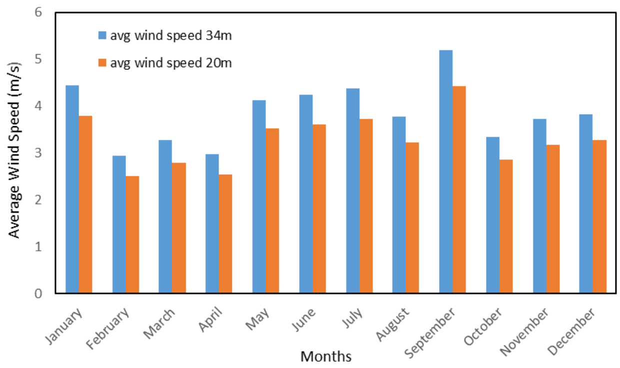

Fig 3: Monthly average wind speeds recorded at 34 m and 20 m AGL for the Fakaofo site.

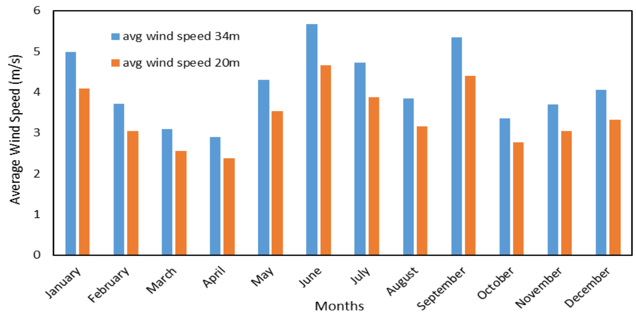

Fig 4: Monthly average wind speeds recorded at 34 m and 20 m AGL for the Atafu site.

B. *Wind Shear Analysis*

The wind shear coefficient (α) of the two sites was calculated using the power law which is shown by equation (21):

$$\alpha = \frac{\ln \bar{U}_2 / \bar{U}_1}{\ln h_2 / h_1} \tag{21}$$

From past works e.g. [16], it is noted that the wind shear coefficient (WSC) has an inverse relationship with the average temperature during the 24 hours. That means when the temperature increases the wind shear starts to decrease and vice versa. As seen from fig 5 and fig 6, the WSC is inversely proportional to the average temperature. From morning, the WSC tends to decrease while the temperature increases. At around mid-day, the WSC is the lowest and the temperature is the highest. After mid-day, the temperature decreases and the WSC increases. However, during the nights the temperatures tends to remain constant. It is interesting to note that the Atafu site showed a higher WSC as well as temperature compared to Fakaofo. This is different from the previous observations by [5].

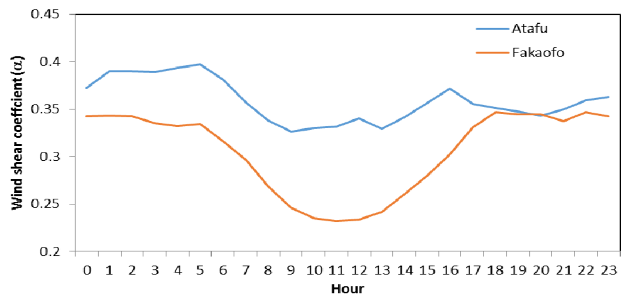

Fig 5: Diurnal variation of wind shear coefficient for Tokelau.

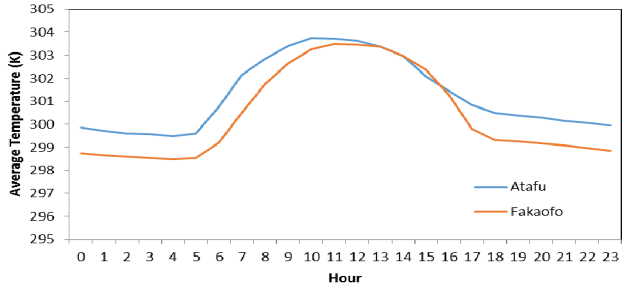

Fig 6: Diurnal variation of average temperature for Tokelau

C. *Turbulence Intensity*

The Turbulence Intensity (TI) for the overall period of measurements for the two sites at 34 m AGL is shown in fig 7. From the figure, it is clear that the TI for the Fakaofo site is higher than the Atafu site. The average overall TI for Fakaofo was 29% whereas for Atafu, the average overall TI was 23%.

Turbulence Intensity is the measure of the fluctuation in wind speed measured over a period of time. Continuously varying turbulence causes mechanical loading on the turbine which can lead to catastrophic structural damages. Very high turbulence levels ultimately cause the transformation of kinetic energy to thermal energy which are produced by the small eddies [5]. To calculate the TI, the following equation was used:

$$TI = \sigma / \overline{U} \tag{22}$$

Fig 8 shows the diurnal variations of the turbulence intensity on a very windy day of the year with the average wind speed around 11 m/s; for the Fakaofo site, the highest turbulence intensity was recorded to be 25% while the lowest was recorded to be 23%, whereas for the Atafu site, the highest and the lowest turbulence intensities were recorded at 17% and 11% respectively. Fig 9 shows the diurnal variations of the turbulence intensity on a less windy day of the year with the average wind speed around 3 m/s. For the Fakaofo site, the highest turbulence intensity recorded was 36% whereas the lowest recorded turbulence intensity was 21%. For the Atafu site, the highest turbulence intensity recorded was 43% whereas the lowest recorded turbulence intensity was 17%.

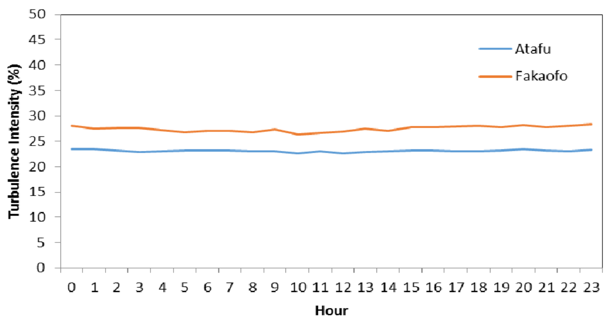

Fig 7: Diurnal variation of turbulence intensity for the whole year in Tokelau at 34 m AGL

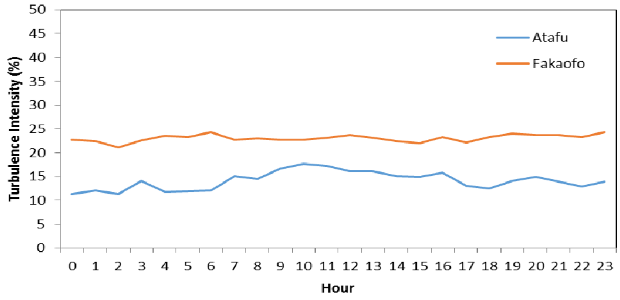

Fig 8: Diurnal variation of turbulence intensity on a windy day in Tokelau at 34 m AGL.

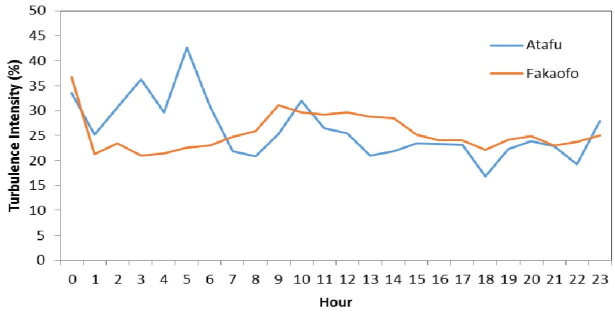

Fig 9: Diurnal variation of turbulence intensity for a less windy day in Tokelau at 34 m AGL.

D. *Wind Direction Analysis*

Fig 10 and fig 11 shows the wind rose plots for the Fakaofo and Atafu sites respectively. From both the sites, it is observed that the wind direction is mostly between 0-90°. However, the predominant wind directions for the two sites are not the same. The predominant wind direction for Fakaofo is East-North-East while it is East for Atafu. It is known that winds change direction near the Equator due to the Coriolis force which turns the winds to the left in the Southern Hemisphere. The predominant wind in the equatorial region are the prevailing westerlies which flow pole-wards in areas of higher pressure which are also known as the horse latitudes. The westerlies in the southern hemisphere can be strong since this region has less land in the middle latitudes. This can cause the flow pattern to amplify. The equatorial regions usually have calm winds but wind energy analysis is vital for determining the yield as most Islands in the South Pacific are isolated.

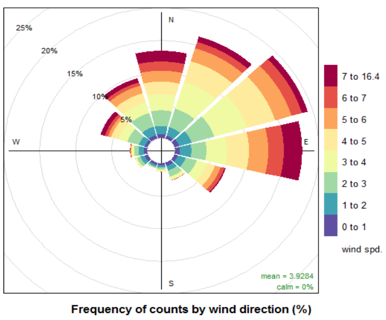

Fig 10: Wind rose plot of Fakaofo atoll in Tokelau showing frequency of winds received from all directions.

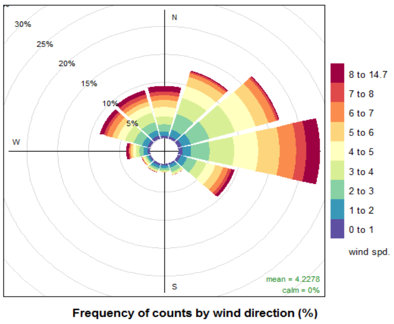

Fig 11: Wind rose plot of Atafu atoll in Tokelau showing frequency of winds received from all directions.

E. Estimation of Weibull Parameters

The wind data for Tokelau was analysed statistically using a program written in ‘R’ software to obtain the Weibull parameters. There were ten different methods of Weibull approximation to calculate the wind power density (WPD) and the Weibull parameters. The performance/error analysis was then carried out to find the best method of approximation for the two sites. Tables 2 and 3 show the 10 different approximation methods with the WPD and the Weibull parameters respectively for Fakaofo and Atafu. The best approximation method for Fakaofo site is EMJ while for Atafu, it is WAsP based on the performance parameters.

Table 2: Goodness of fit test error for Fakaofo, Tokelau.

Method	k	A	U	WPD	R^2	COE	RMSE	MAE	MAPE
MQ	2.15	4.39	3.89	60.79	0.9984	1.1429	0.1701	0.081	2.6144
MO	2.03	4.43	3.93	66.16	0.9993	1.018	0.059	0.0233	1.3571
EMJ	2.04	4.43	3.92	65.79	0.9994	1.0344	0.0606	0.0175	1.1292
EML	2.04	4.44	3.93	65.89	0.9994	1.0333	0.0594	0.0169	1.1228
LS	1.93	4.4	3.90	68.03	0.9989	0.9465	0.0888	0.0664	2.5946
ML	2.01	4.43	3.93	66.61	0.9989	0.9967	0.069	0.0392	1.9507
MML	1.96	4.37	3.87	65.63	0.9989	0.9805	0.0816	0.0606	2.6443
EPF	2.03	4.43	3.93	66.20	0.9993	1.0175	0.0585	0.0232	1.3552
WAsP	1.96	4.3	3.81	62.65	0.9987	1.0062	0.1365	0.1226	4.3281
NMO	2.16	5.05	4.47	92.19	0.9981	0.916	0.5326	0.503	14.5368

Table 3: Goodness of fit test error for Atafu, Tokelau.

Method	k	A	U	WPD	R^2	COE	RMSE	MAE	MAPE
MQ	2.15	4.39	3.89	73.58	0.9964	1.2049	0.2873	0.1476	3.3812
MO	2.03	4.43	3.93	84.25	0.9976	1.0119	0.1107	0.0778	2.5273
EMJ	2.04	4.43	3.92	83.73	0.9973	1.0232	0.1197	0.0829	2.7066
EML	2.04	4.44	3.93	83.88	0.9973	1.0225	0.1186	0.0827	2.7043
LS	1.93	4.4	3.90	86.54	0.9982	0.9551	0.1086	0.0876	3.1014
ML	2.01	4.43	3.93	84.76	0.9978	1.0032	0.1054	0.0778	2.6237
MML	1.96	4.37	3.87	83.65	0.9981	0.9879	0.1139	0.0749	2.947
EPF	2.03	4.43	3.93	84.91	0.9978	1.0011	0.1044	0.0776	2.6235
WAsP	1.96	4.3	3.81	83.23	0.9982	0.9907	0.1168	0.078	3.0847
NMO	2.16	5.05	4.47	118.16	0.9958	0.9382	0.6202	0.5852	15.8218

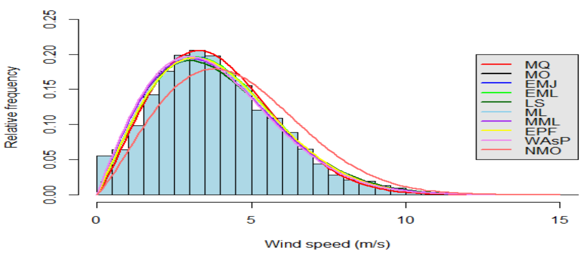

Fig 12: Wind frequency distribution and Weibull distribution curve for the Fakaofo site.

The EMJ is the best method for Fakaofo since from the performance analysis where the R^2 was the highest at 0.9994 and COE was the second highest. The WPD using the EMJ for Fakaofo was 65.79 W/m^2. The goodness of fit test error was also carried out for the Atafu site similarly and the results are shown in Table 2. It can be seen that the WAsP method performed the best. The WAsP method has a R^2 value of 0.9982 and the correct wind power density was 83.23 W/m^2. The results for both the sites aree plotted against the obtained results and are shown in fig 12 and fig 13 for the Fakaofo and the Atafu sites respectively.

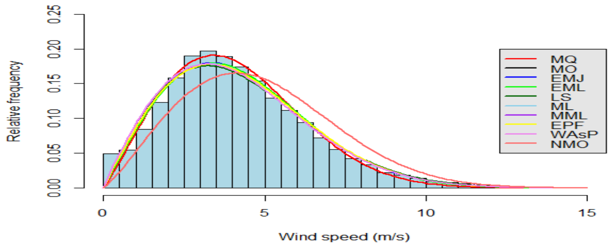

Fig 13: Wind frequency distribution and Weibull distribution curve for the Atafu site.

F. Estimation of Annual Energy Production (AEP)

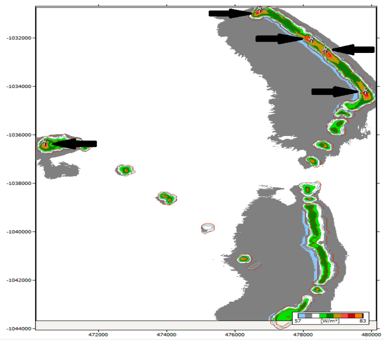

Fig 14: Wind power density map of Fakaofo atoll, Tokelau showing the location of five wind turbines.

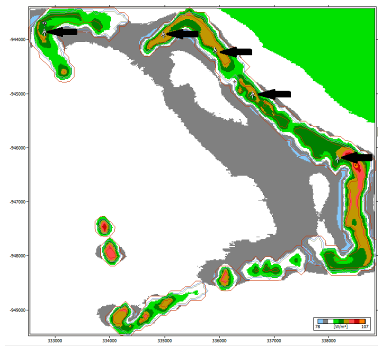

Fig 15: Wind power density map of Atafu atoll, Tokelau showing the location of five wind turbines.

The annual energy production with five Vergnet 275 kW turbines was estimated for the two sites. The specifications of the Vergnet 275 kW wind turbine are very important for consideration in the calculation. The hub height of the turbine used is 34 m, the rotor diameter is 32 m, the cut in wind speed is 3.56 m/s, the rated wind speed of the turbine is 12.2 m/s at a density of 1.16 kg/m^3 and the cut-out wind speed is 25 m/s. Wake loss is assumed to be 0%. There were five locations on the wind map where the turbines were placed and the AEPs were calculated. The wind resource maps for the sites are shown in fig 14 and fig 15. The total AEP for Fakaofo was calculated to be 934.46 MWh with an average AEP of 186.89 MWh per turbine. The total AEP for Atafu was calculated to be 1109.98 MWh with an average AEP of 222 MWh per turbine. The capacity factor calculated for Fakaofo was 7% while for Atafu, it was 9%. It is noted that the WPD of the Atafu atoll is almost similar to that for the Fakaofo atoll. The reason for a low wind power density could be the cause of low winds near the equator.

G. Economic Analysis

The economic analysis for the two sites in Tokelau were carried out separately. Using equation (22) for the present values of costs (PVC), the payback period was calculated for the turbines at both the sites.

$$PVC = I + C_{omr}\left[\frac{1+i}{r-i}\right]\left[1-\left(\frac{1+i}{1+r}\right)^{T}\right] - S\left(\frac{1+i}{1+r}\right)^{T} \quad (22)$$

where: Lifetime (T) of turbine is 20 years; Interest rate (r) = 12%; Inflation rate (i) is 3%; Operation, maintenance and repair works is 25% of the annual cost of turbine (machine price/lifetime); Scrap value is 10% of the cost of turbine and civil work; and Investment (i) = cost of the turbine + cartage cost + grid integration cost + civil work cost which comes to US$660,000.The cost of electricity in Fakaofo is $0.72 and that in Atafu is $0.58. The total profit per turbine per annum for Fakaofo and Atafu is $98,243.90 and $92,440.78 respectively. The payback periods calculated were 7.39 years and 7.85 years for Fakaofo and Atafu respectively.

IV. Conclusion

The wind resource assessments for the two sites were carried out for Fakaofo and Atafu atolls in Tokelau. The wind rose plot indicated that the predominant wind direction was East-North-East for the Fakaofo site and East for the Atafu site. There were 10 different methods used from which the best method was selected upon performance analysis to calculate the WPD and the Weibull parameters. EMJ was the best method selected for the Fakaofo while WAsP method was the best for Atafu. The total AEP calculated was 934.46 MWh and 1109.98 MWh for Fakaofo and Atafu atolls. Finally, the payback periods were calculated for the two atolls to be 7.39 years and 7.85 years respectively which is still a good investment. Normally, turbines are not installed at greater heights in such small PICs due to frequent cyclones and the logistics issues.

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