

Assessment of wind energy potential for Tuvalu with accurate estimation of Weibull parameters

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Abstract

Wind resource assessments are carried out for two sites in Tuvalu: Funafuti and Nukufetau. The wind speeds at 34 and 20 m above ground level were recorded for approximately 12 months and analyzed. The averages of each site are computed as the overall, daily, monthly, annual, and seasonal averages. The overall average wind speeds for Funafuti and Nukufetau at 34 m above ground level were estimated to be 6.19 and 5.36 m/s, respectively. The turbulence intensities at the two sites were also analyzed. The turbulence intensity is also computed for windy and low-wind days. Wind shear analysis was carried out and correlated with temperature variation. Ten different methods: median and quartiles method, the empirical method of Lysen, the empirical method of Justus, the moments method, the least squares method, the maximum likelihood method, the modified maximum likelihood method, the energy pattern factor method, method of multi-objective moments, and the wind atlas analysis and application program method were used to find the Weibull parameters. From these methods, the best method is used to determine the wind power density for the site. The wind power density for Funafuti is 228.18 W/m² and for Nukufetau is 145.1 W/m². The site maps were digitized and with the WAsP software, five potential locations were selected for each site from the wind resource map. The annual energy production for the sites was computed using wind atlas analysis and application program to be 2921.34 and 1848.49 MWh. The payback periods of installing the turbines for each site are

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calculated by performing an economic analysis, which showed payback periods of between 3.13 and 4.21 years for Funafuti and between 4.83 to 6.72 years for Nukufetau.

Keywords

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

Introduction

Energy is one of the major requirements for the development of a nation. The use of accessible clean energy has now become a matter of paramount importance. This is because of the extensive use of non-renewable fossil fuels, which leads to the emission of harmful gases like carbon dioxide and carbon monoxide into the atmosphere, causing global warming which leads to sea level rise. These fossil fuels are not only causing pollution, but are also creating economic issues in the society and for the governments in Pacific Island Countries (PICs). Lots of expenses need to be directed for buying these fossils. Thus, by using clean renewable energy, the impacts of the fossil fuels like the greenhouse effect will reduce. Also, renewable energy resources are sustainable. According to Alrikabi (2014), the cost of retrieving/extracting the fossil fuels from the ground is very expensive and also these fossil fuels will eventually end. There are also very harmful gases like carbon dioxide, nitrogen oxides, sulfur dioxide, and mercury produced from burning these fossil fuels. According to Shahzad (2012) “these pollutants cause respiratory illnesses and even death in humans, produce acid rain that devastates buildings and destroys fragile ecosystems, and deplete the ozone layer through global warming”. According to Panwar et al. (2011), “renewable sources of energy are used to mitigate the greenhouse gas emissions and reduce global warming”. Xu et al. (2019, 2020b) have stated that regenerative coke method is one of the ways of energy saving and environment protection to overcome this energy crisis. In these articles, they also discussed methods to lower NO_x emissions so that less pollution can reduce the damage to the environment. One of the other ways is through the use of renewable sources of energy to minimize or eradicate pollution. Many countries have started to use the renewable sources of energy like hydro, wind and solar to overcome the problems arising from the use of fossil fuels. Thus, research on how to harvest the renewable energy will be an effective way to know when and where the energy can be harvested efficiently and effectively.

Wind resource is one of the important topics to study in renewable energy. This is due to the fact that the wind speeds differ from site to site. For accurate wind resource assessment, we need to find the best distribution of the available wind data. At most of the sites, the Weibull distribution has been found to fit the data best. Researchers have used different Weibull parameter estimation methods to find the accurate Weibull parameters. Keyhani et al. (2010) statistically analyzed 11 years of wind speed data for Tehran, Iran. From the results, it was noted that wind speeds for Tehran are mostly more than 3 m/s. The highest yearly averaged wind speed was recorded in 2004 and 2005 at 4.5 m/s. The yearly wind power density (WPD) levels show that the generated power would be adequate for off-grid applications. The predominant wind speed recorded was from west. Aukitino et al. (2017) performed a wind resource assessment for two sites in Kiribati. In their work, 13 and 14

months of wind speed data were used for Tarawa and Abaiang sites, respectively. Also, in this assessment, seven different methods were employed to compare and find the best Weibull approximation method for the sites. From their assessment, the moments method (MO) was the best method for both Tarawa and Abiang sites; the overall average wind speeds for the two sites were 5.35 and 5.45 m/s respectively. One major conclusion made was that Kiribati has good wind energy potential and utilization of this will reduce the cost of power generation. The payback period for installing the wind turbines at Kiribati's sites was estimated to be 8.74 years. Saleh et al. (2012) statistically analyzed one year of wind data for Zafarana wind farm in Suez Gulf, Egypt. The highest wind speeds were recorded in June, July, August, and September which are the summer months with the average speeds of 9, 9.6, 9.2, and 9.2 m/s, respectively while January, February, and April recorded the lowest wind speeds. In the study, five different methods of obtaining Weibull parameters were used. The recommended method from their study was the maximum likelihood (ML) method, based on only the root mean square error (RMSE) metric, which may not be accurate to make conclusion about the best Weibull approximation method. In the assessment done by Rocha et al. (2012), seven different methods of Weibull approximation were tested using 21 months of wind speed data at Camocim and Paracuru cities in Brazil and two different error analysis methods were used to obtain the best method of Weibull approximation. Equivalent energy method was found to be the best method. It was noted from the analysis that with a lower standard deviation of the wind speed data, the efficiency is increased. Fazelpour et al. (2017) statistically analyzed wind speed data for four locations in Iran. Based on the maximum annual average wind speeds at Zabol and Zahak of 5.59 and 5.48 m/s, respectively at 10 m above ground level (AGL), these were found to be the best sites. The highest WPD of 284.97 W/m^2 was also recorded in Zabol. In the study, the investigators used only the empirical method of Justus (EMJ) to compute the Weibull parameters which is incongruous.

Dabbaghiyan et al. (2015) statistically analyzed the wind speed data at 10, 30 and 40 m AGL for 12 months at four locations in Bushehr, Iran. From the results, it was concluded that out of the four sites, Borkhun is the best site for wind energy production since the annual mean power density for this site was between 115 and 175 W/m^2 . It was also concluded that *Proven 15* wind turbine is the most cost effective wind turbine for the site. Shoaib et al. (2019) analyzed the wind characteristics at Jhampir in Pakistan. The study was based on 10 years of data. In the analysis, three different methods were used. Using the error analysis, the best method for the site was found to be the ML method. It was also observed that the months of May to October recorded more winds than the other months. The predominant wind speed direction was from 250° . The total annual energy which can be harvested was estimated to be $10,054 \text{ kWh}$. The turbine and plant efficiencies were estimated to be 40% and 46% respectively.

Ozay and Celiktas (2016) statistically analyzed 5.5 years of wind data at 30, 50, and 70 m AGL for Alacati in Cesmir, Izmir situated in Turkey. The predominant wind direction was 340° and 350° which is North-North East and North East. In the analysis, using three methods, they concluded that Weibull distribution is a better fit than Rayleigh distribution for the measured wind data. Bassyouni et al. (2015) statistically analyzed 10 years of wind speed data for Jeddah, Saudi Arabia. The maximum wind power which can be harvested was found to be in March while February recorded the lowest wind speeds. One of the findings was that wind speeds during March to August are high. The WPD calculated for the region was between 42.86 and 83.78 W/m^2 which was low. These results indicated that

installing smaller wind turbines will be suitable for the site. Ahmad et al. (2003) in their study used three different Weibull approximation methods to calculate the k and A parameters for a site in Malaysia. To do the analysis, 12 months of wind speed data were used. From the analysis, it was found that the ML was the best method to find the Weibull parameters. One of the major findings was that during northeast monsoon season, the wind energy generation will be more efficient. In a study carried out by Azad et al. (2014), seven different methods were used to find the best method to compute the Weibull parameters for three sites in Bangladesh. They used six different performance analysis metrics to determine the best Weibull approximation method. From the analysis, the MO and the ML methods were found to be the most efficient methods.

Soulouknga et al. (2018) used 18 years of 10 m AGL wind speed data to find the cost effective turbines to be installed in Faya-Largeau, Chad. There were six different Weibull parameter estimation methods used in the analysis. One of the observations made was "The more it rains, the lower the wind speed". Another important observation made was that the standard deviation was low between May and September while it increases for the rest of the year. From their work, the calculated maximum power density was 48.27 W/m^2 while in August it was very low at 8.24 W/m^2 . It was recommended that Bonus 1 MW/54 wind turbine is the best turbine for the site since its capacity factor was estimated to be 26.61%. Shu et al. (2015) used three different Weibull approximation methods to analyze the wind resource for five sites in Hong Kong; two of which were on a hilltop. One of the findings was that the Weibull parameters differ from season to season. Tai Mo Shan weather station had the highest WPD of 915.23 W/m^2 ; however, the measurements were made at 966 m above sea level at this location. It was observed that wind speeds in September were the highest for all the five sites. In the study, they used only EMJ to determine the Weibull parameters.

In the present work, the wind characteristics and the energy potential for Tuvalu are statistically analyzed. Tuvalu is a small island country and it is feared that it will be among the first countries that will disappear due to rising sea level. Tuvalu consists of nine islands; five of them being coral atolls and the other four consist of land rising from the sea-bed. For a long time, the Tuvalu people are raising concerns about climate change and the risk the country is facing due to sea-level rise. With a total land area of 26 km^2 , the vulnerability of the country is easily comprehensible. The leaders of Tuvalu want to set an example by moving to 100% renewable power generation quickly. As the country is close to the equator (7° south), it is not expected to have strong winds. The present study thus provides valuable information to the energy planners of the country as well as to the international wind energy community whether the country can generate enough wind power. No detailed study of wind resource has been carried out in Tuvalu so far. This work also includes separate monthly and seasonal daytime and night time analysis of wind speed, WSC, and temperatures.

In this analysis, the wind speed averages (daily, monthly and diurnal), turbulence intensity (TI), and wind shear coefficient were calculated. The wind shear coefficient was then correlated with the temperature. Looking at the previous works discussed above, it would be prudent to compare different methods of Weibull approximation and find the best method. Ten different methods of Weibull approximation are used in the analysis to compute k and A parameters. Finally, estimation of annual energy production (AEP) and economic analysis are carried out to determine the payback period of installing the 275 kW Vergnet wind turbines, with five each on the two islands.

Data and methodology

The measurement towers for the assessment were installed in Funafuti and Nukufetau in Tuvalu. Tuvalu has six inhabited atolls which are Funafuti, Nanumea, Nui, Nukufetau, Nukulaelae, and Vaitupu, and also there are three inhabited reef islands which are Nanumanga, Niulakita, and Niutao. There are no rivers in Tuvalu; however, the dwellers use rainwater for drinking. It has good vegetation as Tuvalu receives very good rainfall and coconut palm trees are found in abundance in Tuvalu. Funafuti is the capital of Tuvalu and has the highest population of 6025. The geographic location of the site where the tower was installed is $8^{\circ} 29.64'$ south, $179^{\circ} 11.621'$ east and the measurement location is shown in Figure 1. Nukufetau on the other hand is a much smaller island and the geographic location of the site is $8^{\circ} 1.85'$ south, $178^{\circ} 19.05'$ east. The measurement location is shown in Figure 2. The measurement period was from July 2012 to August 2013 for both Funafuti and Nukufetau.

Method

NRG systems towers with a height of 34 m AGL were used in the present work; these towers are used globally for wind measurement campaigns. These towers are named Integrated Renewable Energy Resource Assessment Systems in this project. The data-logger used in the present work was the NRG *SymphoniePlus3* and was connected to seven different sensors installed on the tower. These sensors measure the wind speed, temperature, pressure, rainfall, solar insolation, humidity, and wind direction. The data-logger recorded the data on the SD card at every 10 min. The data can either be collected from the SD card in person or



Figure 1. Map of Funafuti showing the measurement location. Source: Google Maps.



Figure 2. Map of Nukufetau showing the measurement location. Source: Google Maps.

Table 1. Specifications of the measurement sensors (Aukitino et al., 2017).

Parameter	Sensor type	Range	Accuracy
Wind speed	NRG#40C anemometer	0.4–96.0 m/s	0.1 m/s
Wind direction	NRG 200P direction vane	0–360°	NA
Pressure	NRG BP-20 barometric pressure sensor	15–115 kPa	1.5 kPa
Temperature	NRG 110S	−40°C to 65°C	1.11°C

these can also be sent via the GSM based network to the data-bank which is located at the ICT center of the University of the South Pacific at the Laucala Campus. The anemometers (serial numbers 179500189054-57, 179500189089-90) have an accuracy of 0.1 m/s and have a range of 0.4–96 m/s. The wind vane is placed at 30 m AGL and aligned to true north. The specifications of each sensor are shown in Table 1.

There were some uncertainties which had to be taken into account. Some of the uncertainties were the calibration uncertainty, the terrain of the site that was used, and the dynamic over speeding, the error introduced due to wind shear and the inflow angle (Jain, 2016). The measurements in the present work were performed close to the shoreline at a flat terrain and the flow was in the horizontal plane, resulting in a lower uncertainty level. The calibration report for the anemometers used in the present work showed a maximum uncertainty of 0.6% for a wind speed range of 4–7 m/s, which reduced at higher wind speeds. The overall uncertainty in the estimation of wind speed is obtained by taking all the above uncertainties into account (Jain, 2016; Xu et al., 2020a) and using the relation in equation (1)

$$\varepsilon = \sqrt{\sum_{i=1}^N \varepsilon_i^2} \quad (1)$$

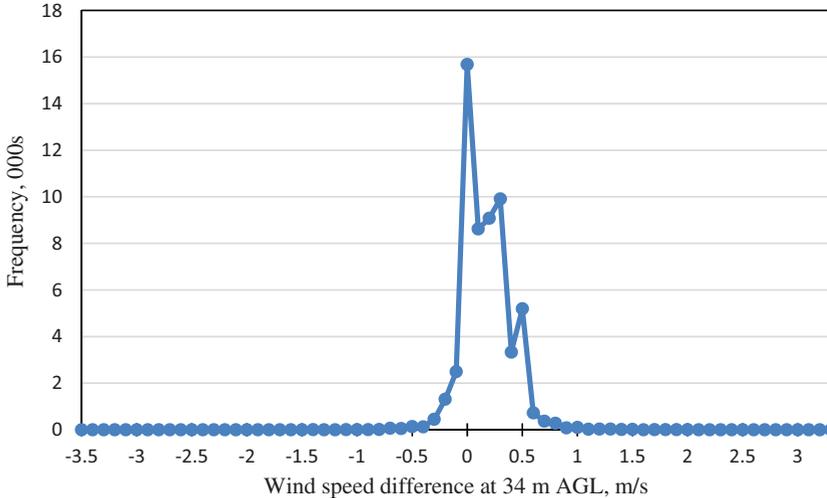


Figure 3. Comparison of wind speeds from the two anemometers installed at 34 m AGL in Funafuti.

where ε_i is each component of uncertainty and N is the number of components of uncertainty. The uncertainties were estimated at 95% confidence level. As per the IEC Standard IEC61400-12-1 (IEC, 2017), the uncertainty in the measurements was estimated to be 1.74%.

Data validation

The 12-month data for each site were validated first before processing. The range test was conducted on the obtained wind speed data, which need to be in the range of 0.4–96.0 m/s. The measured data for Funafuti ranged between 0.4 and 21.2 m/s at 34 m AGL while at 20 m AGL the wind speed was between 0.4 and 19.5 m/s. The data range for Nukufetau was between 0.4 and 17.5 m/s at 34 m AGL, while at 20 m AGL the wind speed was between 0.4 and 16.4 m/s. The maximum wind speed recorded at 34 m AGL was 25.3 and 24.1 m/s at 20 m AGL for Funafuti. The maximum wind speed recorded at 34 m AGL was 32.6 and 23.4 m/s at 20 m AGL for Nukufetau. The temperatures recorded at both the sites were in the acceptable range; the maximum temperatures for Funafuti and Nukufetau were 34.5°C and 35.3°C. There were two anemometers placed at 34 m AGL at both the locations at 22.5° and 202.5° and the wind speeds measured by the two are compared in Figures 3 and 4. At Funafuti, the average difference in the wind speeds recorded by the two anemometers was 4% while the average difference at the Nukufetau was 5.78%. Since the predominant wind direction was north-east, the results indicate that the error due to the wake of the tower is within 6%.

Results and discussion

Wind speed analysis

The results of the wind speed analysis for the sites in Tuvalu are presented in this section. The one year continuous data for Tuvalu were analyzed for hourly, daily, monthly, yearly,

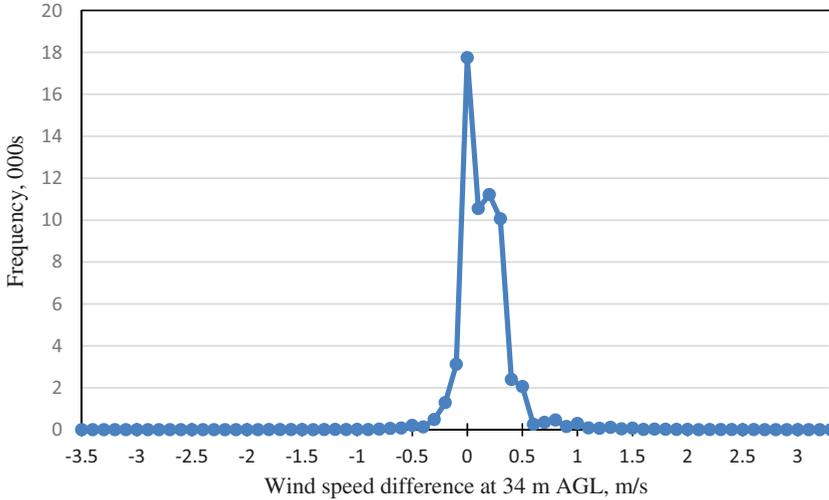


Figure 4. Comparison of wind speeds from the two anemometers installed at 34 m AGL in Nukufetau.

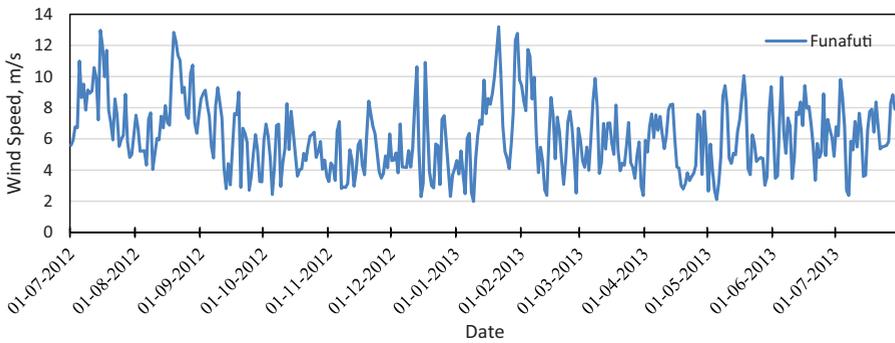


Figure 5. Daily average wind speed at Funafuti at 34 m AGL.

and seasonally averaged wind speeds. Zhang (2015) used equation (2) to find the mean wind speed

$$\bar{U} = \frac{1}{n} \sum_{i=1}^n U_i \tag{2}$$

where \bar{U} is the average wind speed and U_i is the wind speed recorded at constant intervals, i.e. 10 min averages for the data under study and n represents the number of observations and i is the interval at which the data were recorded. The overall average wind speed for 34 m AGL recorded over the assessment period was 5.18 m/s.

The daily average wind speeds for the Funafuti and Nukufetau sites are shown in Figures 5 and 6, respectively. For both the sites, the data were analyzed from July 2012 to July 2013. In Figures 5 and 6, the wind data were averaged on daily basis from the

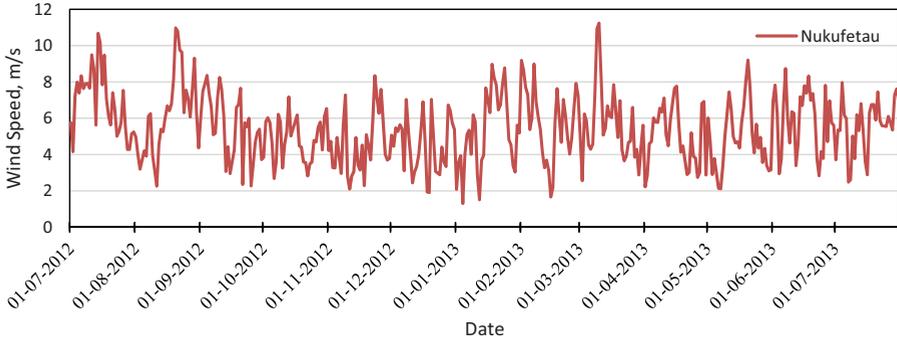


Figure 6. Daily average wind speed at Nukufetau at 34 m AGL.

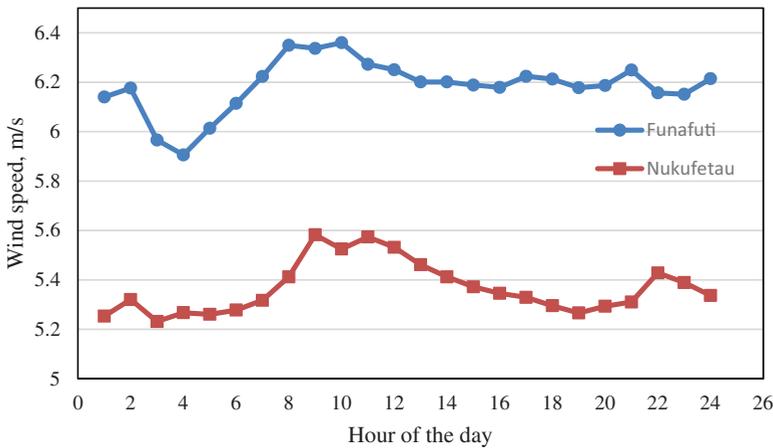


Figure 7. Diurnal variation of wind speeds at 34 m AGL for the entire measurement period.

computed 10 min mean wind speed. The daily average wind speed for Funafuti ranged between 1.98 and 13.19 m/s, while the daily averages were between 1.31 and 11.23 m/s at the Nukufetau site. The maximum wind speed recorded in Funafuti was 25.3 m/s at 34 m AGL while it was 24.1 m/s at 20 m AGL. The maximum speeds recorded for Nukufetau were slightly higher, with the speeds of 32.6 and 16.4 m/s at 34 and 20 m AGL, respectively.

In Figure 7, the diurnal variations of the wind speeds for the entire duration of measurements for the two sites are shown. The wind speed variations for both the sites have similar trends but the wind speeds for Funafuti are higher compared to Nukufetau. The trend that both Funafuti and Nukufetau follow is that the wind speed in daytime is higher compared to the wind speeds during the night.

In Figures 8 and 9, the average monthly wind speeds are presented for the two sites, which reveal that the wind speeds for the Funafuti site are slightly higher than the Nukufetau site. However, trends for the wind speeds for both the sites are same. The patterns of wind speeds for Funafuti as well as Nukufetau indicate higher wind speeds at the starting of the year and decrease till March; the wind speeds start to increase again reaching the peak in August and then decreases to the minimum by the end of the year.

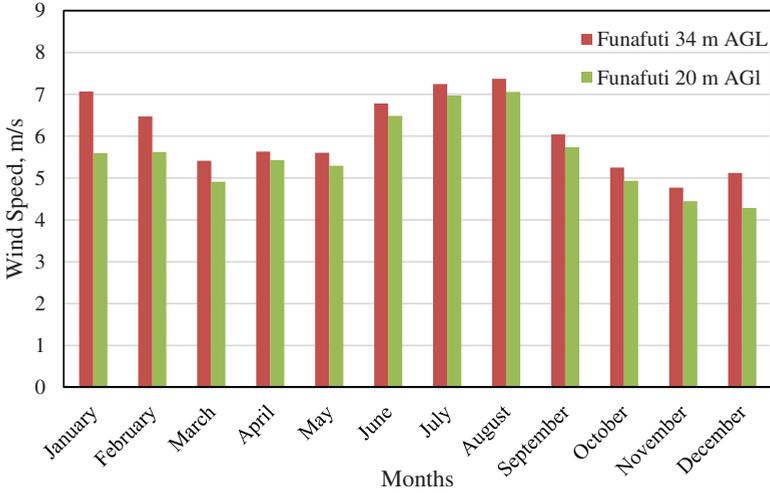


Figure 8. Monthly averaged wind speed for 34 m AGL and 20 m AGL for the summarized entire period.

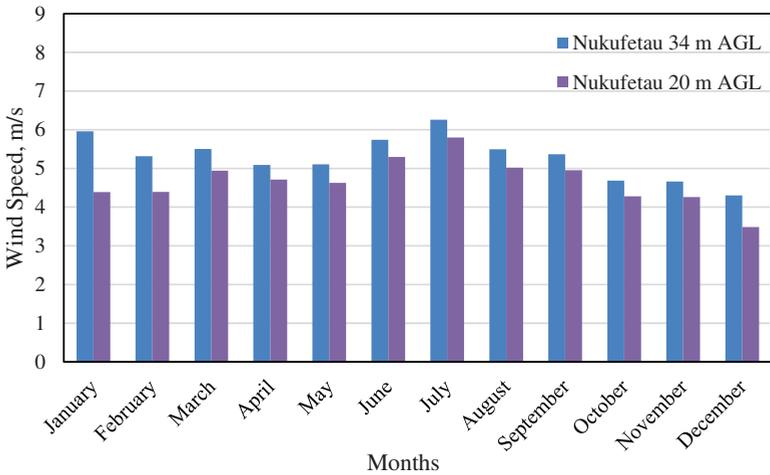


Figure 9. Monthly averaged wind speed for 34 m AGL and 20 m AGL for the summarized entire period.

The maximum averaged monthly wind speeds recorded for Funafuti are 7.37 and 7.07 m/s at 34 and 20 m AGL while the minimum are 4.77 and 4.44 m/s at 34 and 20 m AGL, respectively. The maximum average monthly wind speeds for Nukufetau are 6.25 and 5.27 m/s at 34 and 20 m AGL, respectively, while the minimum wind speeds are 4.3 and 3.48 m/s at 34 and 20 m AGL.

Tuvalu has two seasons, which are the dry and the wet seasons. The wet season, summer, occurs between November and April while the dry winter season is from October to March (although there is no real winter in Tuvalu as the temperatures vary very little throughout the year). It was observed that the site in Funafuti has higher wind speeds in summer

Table 2. Seasonal average wind speeds at 34 m AGL.

Season	34 m AGL	
	Funafuti	Nukufetau
Summer	5.746	5.139
Winter	4.753	5.442

AGL: above ground level.

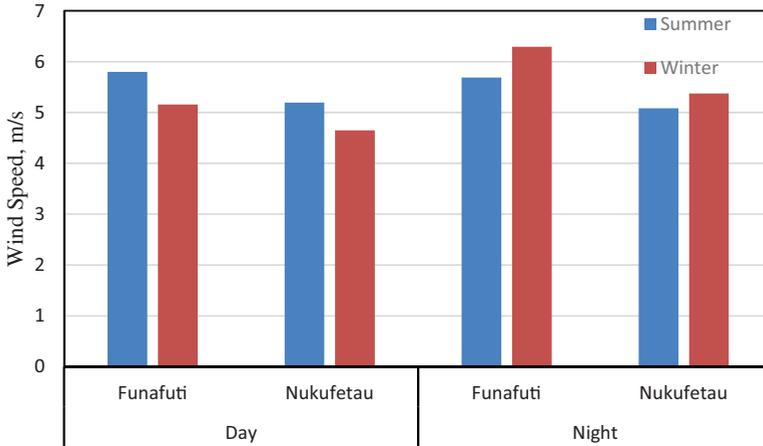


Figure 10. Seasonal average wind speeds at 34 m AGL.

compared to winter; while in Nukufetau, the wind speeds in winter were higher, as shown in Table 2.

To further understand the wind patterns, the wind speeds at 34 m AGL were divided into daytime and night time speeds as shown in Figure 10. The results indicate that in summer during day time the average wind speeds are higher compared to the wind speeds in winter. Compared to this, the night time wind speeds during winter are higher compared to summer. The land mass of both the islands is very small; the measurement location at Funafuti is very close to the shore while that at Nukufetau is 750 m from the shoreline. Due to this, the land gets heated up quickly in daytime, resulting in a stronger sea breeze, as can be seen from the figure. The consistent sea breeze results in higher wind speeds in the daytime both for summer and winter seasons. Considering the fact that the monthly average temperature changes by only 2 C during the entire year (as can be seen from Figures 13 and 14), this is expected. The opposite trend is seen at night time, when the land gets cooled quickly resulting in land breeze.

Wind shear analysis

The wind profile can be studied in detail using the wind shear analysis. “Wind profile enables us to deduce the mean wind speed from one height to another and tells us the wind speed

difference between two heights,” as stated by Zhang (2015). The log formula is used to compute the wind shear coefficient of a site as shown in equation (3)

$$WSC = \frac{\ln\left(\frac{U_2}{U_1}\right)}{\ln\left(\frac{h_2}{h_1}\right)} \tag{3}$$

where WSC is the wind shear coefficient, U_1 and h_1 are the average wind speed and the height, respectively, at 20 m AGL while U_2 and h_2 are the average wind speed and the height, respectively, at 34m AGL. The wind shear is very difficult to compute when only one anemometer is used, thus it is a common practice to use two anemometers at different heights for the computation of the WSC (Zhang, 2015). The logarithm formula can be utilized by having wind data at two different heights. The WSC at a location will never be constant due to the varying wind speed and direction and other conditions like the terrain, temperature, etc.

The WSC of a site is influenced by the heating and the cooling cycle also known as temperature inversion. It has been proved that the WSC of the site is higher at night while the wind shear is lower in the daytime (Aukitino et al., 2017; Firtın et al., 2011; Gualtieri and Secci, 2011; Rehman and Al-Abbadi, 2008). During the day, the ground and the air heats up causing upward movement of the air, thus the WSC is lower; while at night the cooling effect takes place.

The WSCs for the two sites are shown in Figure 11. As shown in the figure, the WSC for the sites from 12 midnight till morning 6 a.m. nearly remains constant and high. From 6 a. m. the WSC starts to decrease till 9 a.m. From 9 a.m. till 4 p.m., the WSC remains low. After 4 p.m. the WSC starts to increase till midnight and remains constant. To further study the heating and cooling effect, the diurnal temperature was analyzed as shown in Figure 12. The results showed that when the temperature increases, the wind shear decreases. The temperature normally peaks at 1.00 or 2.00 p.m. in the South Pacific region. After the peak, the temperature keeps dropping till morning 6.00 a.m., as can be seen from the figure. At this

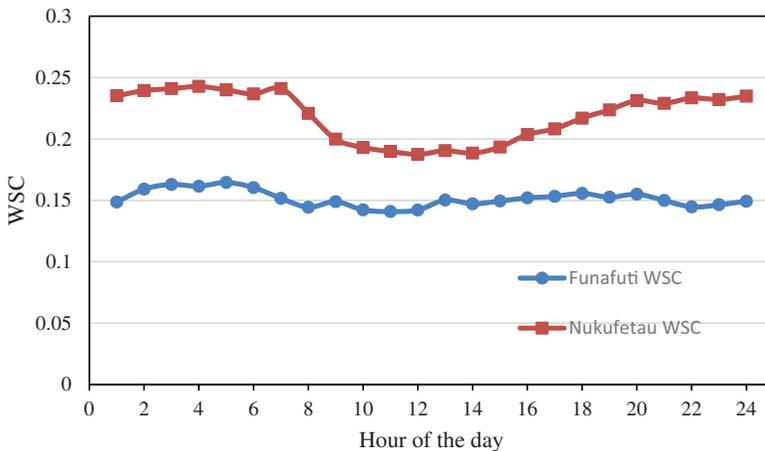


Figure 11. Average diurnal wind shear coefficient, α , for the entire measurement duration.

point in time, there is no upward flow of air and hence the wind shear coefficient is the maximum. The temperature inversion effect results in an increase in the temperature with height due to the cooler and denser air getting trapped close to the ground due to the movement of warm air above it. The temperature inversion effect is stronger in the morning, hence a higher WSC. As the air gets heated up after sunrise, the inversion effect disappears. Similar observations were made by Aukitino et al. (2017) and Kutty et al. (2019).

To further study the WSC, analysis of its monthly variation was carried out and is shown in Figures 13 and 14. A similar trend for both the sites can be seen with the coefficient increasing as summer approaches and decreasing as it progresses towards the dry season.

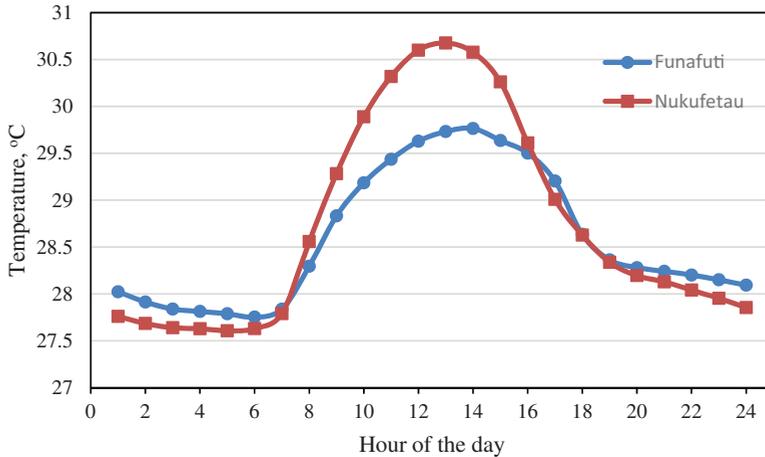


Figure 12. Average diurnal temperature variation for the entire measurement duration.

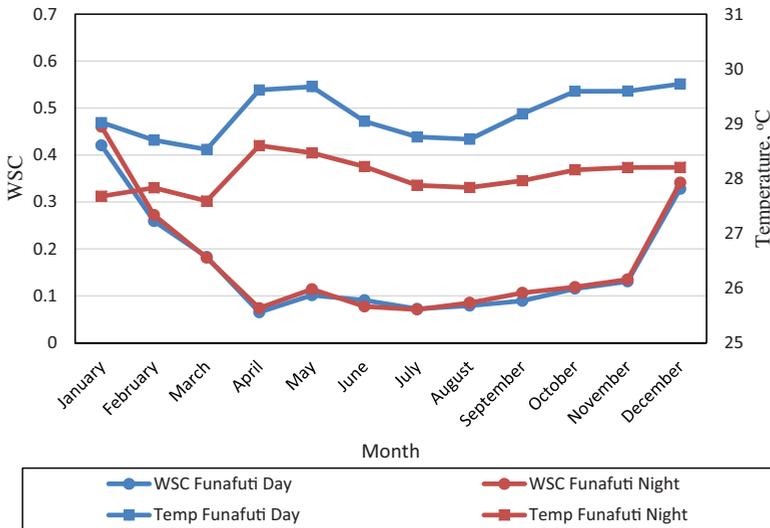


Figure 13. Monthly average WSC and temperature for Funafuti.

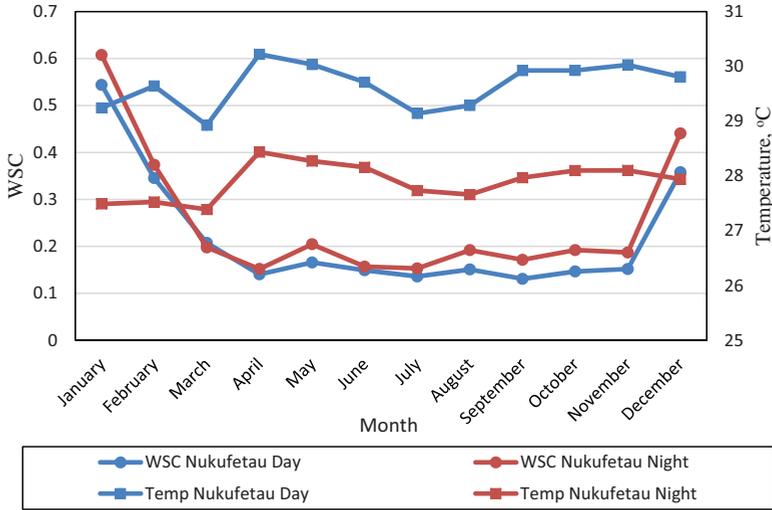


Figure 14. Monthly average WSC and temperature for Nukufetau.

The temperature difference at Funafuti during daytime and night time was small, resulting in similar values of WSC. Nukufetau has a higher WSC compared to Funafuti due to the larger difference between average daytime and night time temperatures. The highest WSC was 0.57 and 0.44 for Nukufetau and Funafuti, respectively, in the month of January. The rainfall in the months of December to February is normally higher, which affects the wind flow.

Turbulence intensity

Turbulence affects the major components of the wind turbine, causing fatigue loading on the major components (Zhang, 2015). In wind resource assessment, the TI is an important parameter which can help choose or design the right turbine for the particular location. According to Aukitino et al. (2017), the TI is a measure of the fluctuations in the wind speed and is the ratio of the standard deviation and mean wind speed. Equation (4) is used to compute the TI

$$TI = \frac{\sigma_u}{U} \tag{4}$$

Figures 15 and 16 show the diurnal variation of the TI for the entire period of measurements in Tuvalu. A similar trend is seen at both the sites, that is, the TI at 34m AGL is lower compared to the TI at 20 m AGL. Overall, it is clear that the TI tends to be higher at lower heights. The average TIs for Funafuti were 9.07% and 11.76% at 34 and 20 m AGL, respectively, while it was 11.34% and 13.5% at 34 and 20 m, respectively, at the Nukufetau site. According to IEC (2005) the allowable range for designing the wind turbines has a standard TI of 16% for 15 m/s wind speed and the present results are closer to the given TI.

The TIs for a low-wind day and a windy day were studied for both Funafuti and Nukufetau. The average wind speeds for the chosen windy days were 13.19 and 11.23 m/s

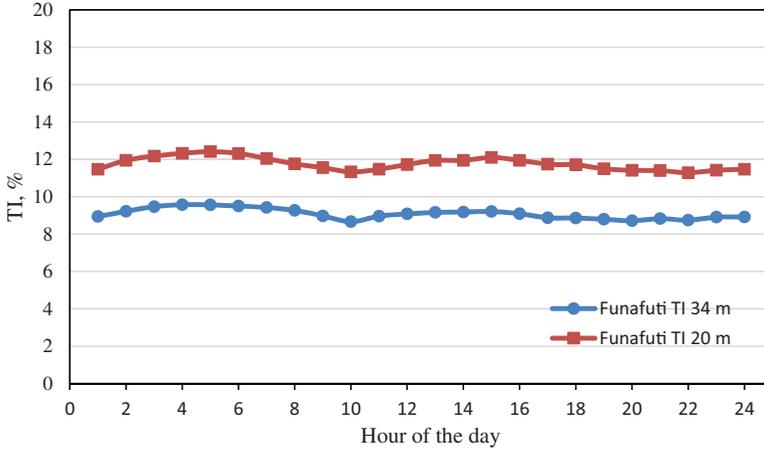


Figure 15. Diurnal variation of turbulence intensity for the measurement period at Funafuti site.

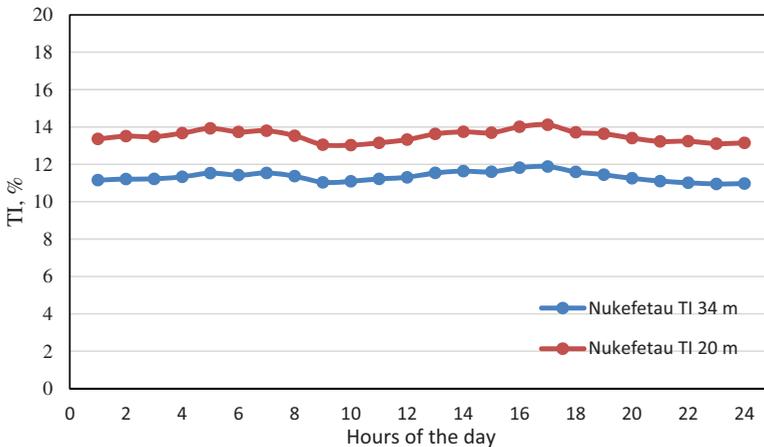


Figure 16. Diurnal variation of turbulence intensity for the measurement period at Nukufetau site.

for Funafuti and Nukufetau, respectively, at 34 m AGL. Figures 17 and 18 show the TI for the windy and low-wind day at the Funafuti and Nukufetau sites, respectively. The mean TIs at 34 m AGL were 7.98% and 7.34% for Funafuti and Nukufetau while the TI at 20 m AGL were 15.7% and 9.69%, respectively. According to the IEC61400-1 standards for wind turbines, obtained average TI should be lower than the standard value, therefore the standards are met for the sites, since for the windy day, the averages were lower.

Figures 19 and 20 show the TIs for low-wind days for Funafuti and Nukufetau, respectively. The average TIs for Funafuti were 18.59% and 21.57% at 34 and 20 m AGL, respectively, for average wind speed of 2.1 and 1.96 m/s, respectively. The average TIs for Funafuti were 13.41% and 15.67% at 34 and 20 m AGL, respectively, for average wind speed of 4.01 and 3.67 m/s, respectively.

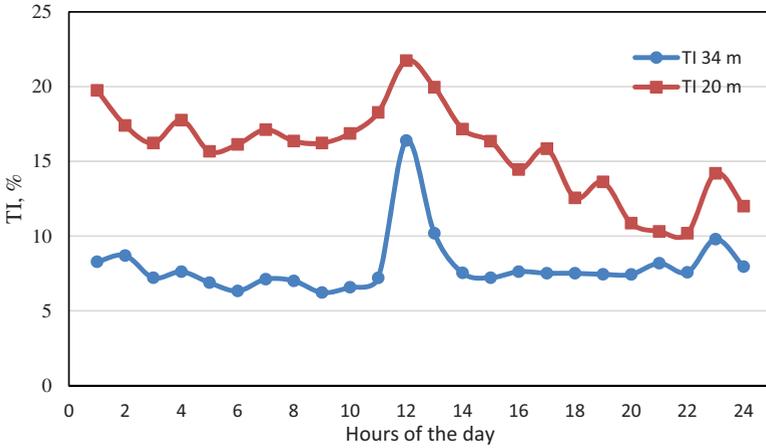


Figure 17. Diurnal variation of turbulence intensity on a windy day at Funafuti site.

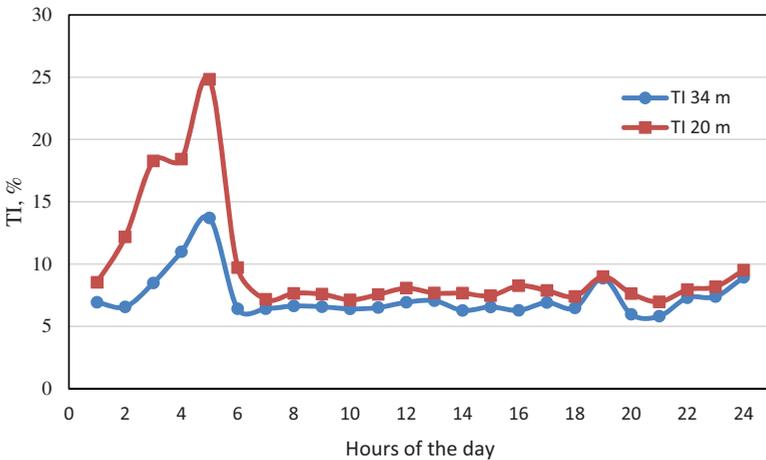


Figure 18. Diurnal variation of turbulence intensity on a windy day at Nukufetau site.

Wind direction analysis

The wind speed and wind speed directions are used to find the predominant wind direction for each site. The analysis also constitutes the availability of wind in the region. The global wind distribution plays the major role in the wind speed and direction at any location on the globe. One way to show the global wind direction is shown in Figure 21. As seen in Figure 21, Tuvalu is located very close to the equator and receives trade winds and also the doldrums.

In Tuvalu, the trade winds, the Hadley effect, and the walker circulation are all present. In walker circulation, the low-level winds blow from East to West across the Pacific region where the warm air moves to the western Pacific. The opposite effect is observed when the cold air returns from the west to east where the cold air sinks in the Eastern Pacific.

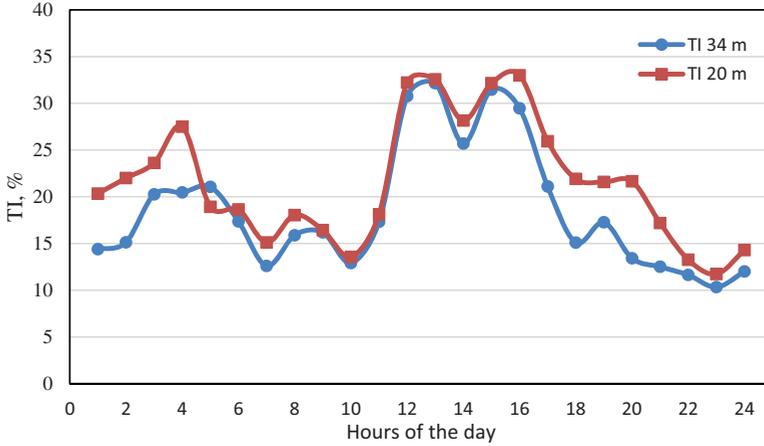


Figure 19. Diurnal variation of turbulence intensity on a low-wind day at Funafuti site.

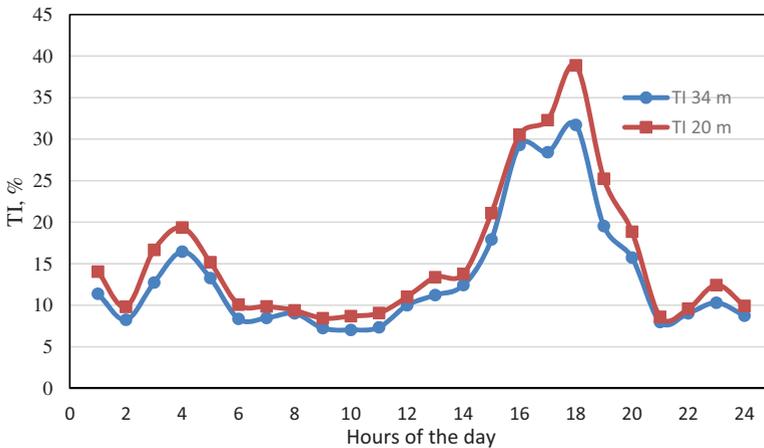


Figure 20. Diurnal variation of turbulence intensity on a low-wind day at Nukufetau site.

These trade winds are normally constant on the surface of the earth as well as on the oceans due to Coriolis effects. Due to the Coriolis effects, there are different weather patterns. These effects also influence the wind direction. Since the earth rotates, the wind direction changes as seen in Figure 21. According to Johnson (1985), the wind speeds recorded in these regions are quite good and steady which makes them potential sites for harvesting wind energy. It is said that during the year, these regions have average wind speeds ranging between 8 and 14m/s. According to Johnson (1985) “These region should be the prime candidates for wind energy harvesting sites.” One of the causes of the tropical cyclones in the Pacific regions is the steering flow by the trade winds. These are caused by the atmospheric circulation known as the Hadley cell. The Hadley cell effect is due to the heating from the sun. The sun heats the air which rises and descends towards the sub-tropics and returns towards the equator which creates the trade winds (Quan et al., 2004).

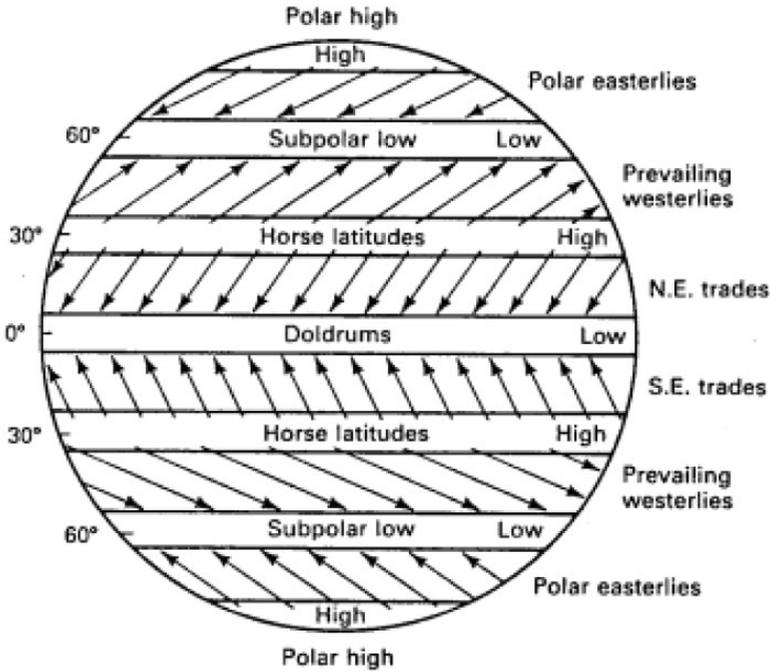


Figure 21. Global predominant wind directions (Johnson, 1985).

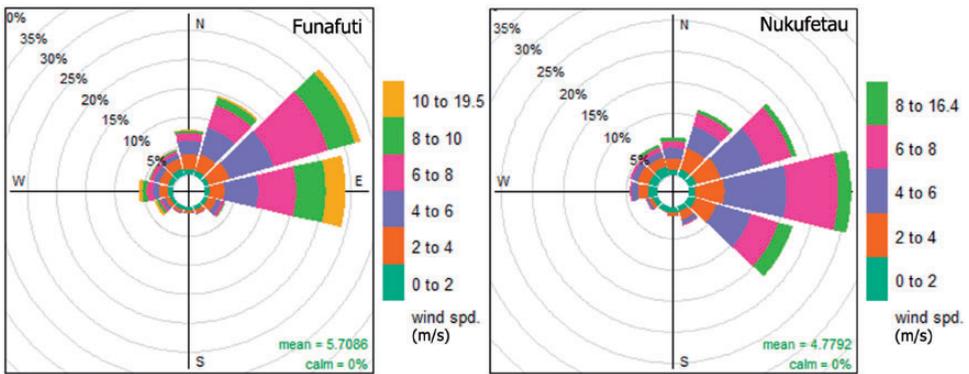


Figure 22. Wind rose plots for the overall duration of measurements.

The wind direction analysis is important as it gives the predominant wind direction from which the maximum amount of wind energy can be harnessed. The wind vane was placed at 30 m AGL. The wind rose plots were drawn in the form of 12 equal sectors of 30°. The data obtained were considered to be invariant with height and were recorded every 10 min. The overall wind directions for the Funafuti and Nukufetau sites are shown in Figure 22. For the Funafuti site, the North-easterly winds are predominant, while the Nukufetau site experiences mostly easterly winds, although it also receives winds from North-east and South-east.

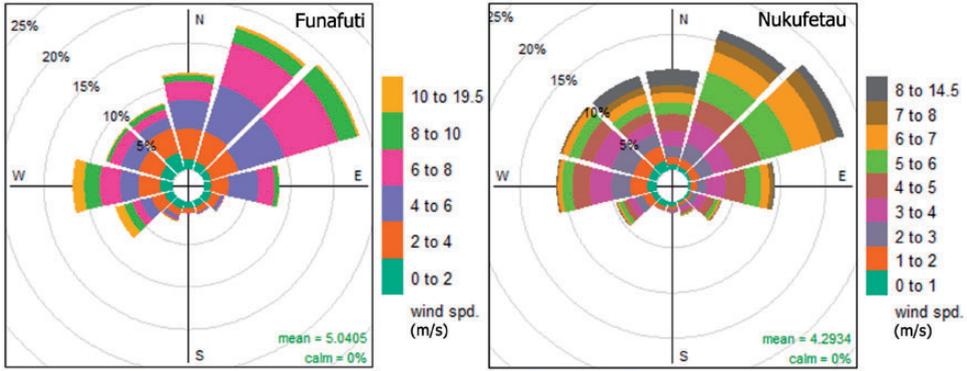


Figure 23. Wind rose plots for the summer season.

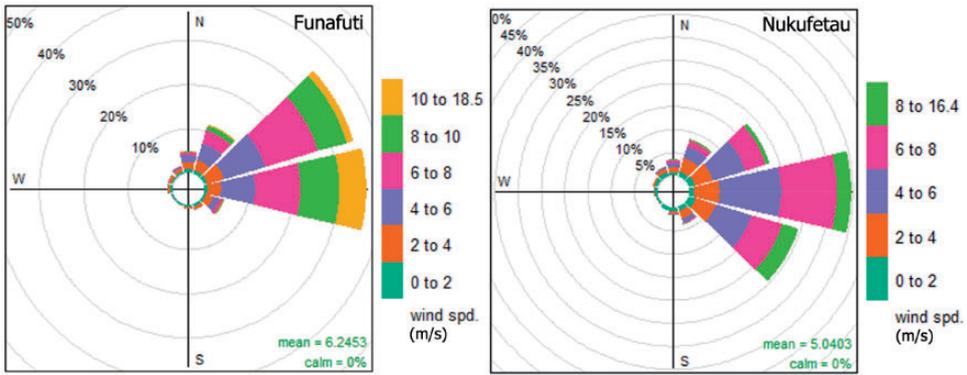


Figure 24. Wind rose plots for the winter season.

Funafuti and Nukufetau are located very close to the equator, which explains why it has more easterly and North-easterly winds. The summer wind speeds for both the sites were from the North-east direction as shown in Figure 23 while in winter, the predominant wind direction was from the East for both the sites, as shown in Figure 24.

Estimation of Weibull parameters

In wind speed analysis, the Weibull distribution is commonly used since the wind speed is bounded towards one side thus the normal distribution is not appropriate. As mentioned by Zhang (2015), the wind speeds are never negative and are also bounded to one side. In Weibull distribution, there are two parameters which need to be defined: the shape factor (*k*) and the scale factor (*A*). The equation for the Weibull probability density function is shown in equation (5) which uses the two parameters *k* and *A*

$$f(U) = \frac{k}{A} \left(\frac{U}{A}\right)^{k-1} e^{-\left(\frac{U}{A}\right)^k} \tag{5}$$

where U is the wind speed, k is the shape factor, and A is the scale factor. There are many methods to estimate these k and A values. In the present work, the Weibull parameters are found using 10 different methods: the median and quartiles method (MQ; Justus et al., 1978; Seguro and Lambert, 2000), the MO (Aukitino et al., 2017; Justus et al., 1978), the EMJ (Justus et al., 1978; Seguro and Lambert, 2000), the empirical method of Lysen (EML; Seguro and Lambert, 2000), the least squares method (LS; Chaurasiya et al., 2017, 2018), the ML method (Ahmad et al., 2003; Katinas et al., 2017; Mohammadi et al., 2016; Rocha et al., 2012; Seguro and Lambert, 2000), the modified maximum likelihood method (MML; Ahmad et al., 2003; Katinas et al., 2017; Lysen, 1982; Mohammadi et al., 2016; Rocha et al., 2012; Seguro and Lambert, 2000), the energy pattern factor method (EPF; Chaurasiya et al., 2017, 2018; Rocha et al., 2012; Seguro and Lambert, 2000; Zhang, 2015), the wind atlas analysis and application program (WASP) method (Aukitino et al., 2017; Bowen and Mortensen, 1996; Solyali et al., 2016) and method of multi-objective moments (MM; Usta et al., 2018).

The equations for finding k and A values using the 10 different methods are presented in Table 3. The detailed description of these methods can be found in Kutty et al. (2019).

Performance analysis of different methods

To assess the accuracy of the 10 different methods of Weibull approximation, a quantitative assessment of the performance of each method is done. There are five different methods used in this analysis and are tabulated in Table 4: the RMSE (Aukitino et al., 2017; Chaurasiya et al., 2017, 2018; Mohammadi et al., 2016), coefficient of determination (R^2 ; Chaurasiya et al., 2017, 2018; Mohammadi et al., 2016), mean absolute error (MAE; Aukitino et al., 2017; Willmott and Matsuura, 2005), mean absolute percentage error (MAPE; Aukitino et al., 2017; Chaurasiya et al., 2017, 2018; Tofallis, 2015) and coefficient of efficiency (COE; Aukitino et al., 2017; Kaldellis and Zafirakis, 2011; Rocha et al., 2012). The details of these methods can be found in Kutty et al. (2019).

Weibull parameters from different methods

Using the 10 different methods of Weibull approximation, k and A values for the Funafuti site were found. Tables 5 and 6 present the estimated k and A values, the WPD from each method and values of the five goodness of fit parameters. The R^2 and COE values should be high while the other three values should be low for the method to be more accurate. From the results, it can be said that WASP and MQ methods both are best for presenting the wind speed distribution in Funafuti. But from the overall ranking, WASP proved to be the best method of approximation since it gave the best results for four parameters except for RMSE (WASP was second). The new moments method (MM) had results which are not suitable compared to other methods.

The same 10 methods were also used for computing the best method of approximation for Nukufetau in Table 7. It can be observed that EMJ, EPF, EML, and MO all have the same k and A , thus all four methods are appropriate for this site. However, from the ranking of the error analysis presented in Table 8, the best method of approximation is EMJ since it has the lowest RMSE, second lowest MAPE and third highest COE and R^2 , which makes EMJ the best method of approximation. MM is not the suitable method for this site also as it ranked last. It can be seen that both the sites have similar values of the Weibull

Table 3. Methods of finding Weibull parameters.

Method	Equations for finding Weibull parameters	Equation number
MO	$\bar{U} = A\Gamma\left(1 + \frac{1}{k}\right)$	(6)
	$\sigma = A\left[\Gamma\left(1 + \frac{2}{k}\right) - \Gamma^2\left(1 + \frac{1}{k}\right)\right]^{1/2}$	(7)
MQ	$k = \frac{\ln[\ln(0.25)/\ln(0.75)]}{\ln(U_{0.75})/U_{0.25}} \approx \frac{1.573}{\ln(U_{0.75})/U_{0.25}}$	(8)
	$A = \frac{U_m}{\ln(2)^{1/\sigma}}$	(9)
EMJ	$k = \left[\frac{\sigma}{\bar{U}}\right]^{-1.086}$	(10)
	$A = \bar{U}/\Gamma(1 + 1/k)$	(11)
EML	$k = \left[\frac{\sigma}{\bar{U}}\right]^{-1.086}$	(12)
	$A = \bar{U}(0.568 + 0.433/k)^{-1/k}$	(13)
LS	$k = \frac{n \sum_{i=1}^n \ln U_i \ln [-\ln\{1-f(U_i)\}] \sum_{i=1}^n \ln U_i \sum_{i=1}^n \ln [-\ln\{1-F(U_i)\}]}{\sum_{i=1}^n \ln U_i^2 - \left\{ \sum_{i=1}^n \ln U_i \right\}^2}$	(14)
	$A = \exp \left\{ \frac{k \sum_{i=1}^n \ln U_i - \sum_{i=1}^n \ln [-\ln\{1-F(U_i)\}]}{nk} \right\}$	(15)
ML	$k = \left[\frac{\sum_{i=1}^n U_i^k \ln U_i}{\sum_{i=1}^n U_i^k} - \frac{\sum_{i=1}^n \ln U_i}{n} \right]^{-1}$	(16)
	$A = \left[\frac{1}{n} \sum_{i=1}^n (U_i)^k \right]^{1/k}$	(17)
MML	$k = \left[\frac{\sum_{i=1}^n U_i^k \ln U_i f(U_i)}{\sum_{i=1}^n U_i^k} - \frac{\sum_{i=1}^n \ln U_i f(U_i)}{f(U \geq 0)} \right]^{-1}$	(18)
	$A = \left[\frac{1}{f(U \geq 0)} \sum_{i=1}^n (U_i)^k f(U_i) \right]^{1/k}$	(19)
EPF	$k = 1 + \frac{3.69}{E_{pr}^2}$	(20)
	$A = \frac{\bar{U}}{\Gamma(1+1/k)}$	(21)
MM	$\lambda_1 \left(A\Gamma\left(1 + \frac{1}{k}\right) - \bar{U} \right)^2 + \lambda_2 \left(A^2\Gamma\left(1 + \frac{2}{k}\right) - \bar{U}^2 \right)^2 + \lambda_3 \left(A^3\Gamma\left(1 + \frac{3}{k}\right) - \bar{U}^3 \right)^2$	(22)
	$\lambda_1 + \lambda_2 + \lambda_3 = 1$	(23)
	$\bar{U}r = \sum_{i=1}^n \frac{U_i^r}{n}$	(24)
WAsP	$U = \sqrt{\frac{\sum_{i=1}^n U_i^3}{N\Gamma\left(\frac{3}{k}+1\right)}}$	(25)

EMJ: empirical method of Justus; EML: empirical method of Lysen; EPF: energy pattern factor method; LS: least squares method; ML: maximum likelihood method; MM: method of multi-objective moments; MML: modified maximum likelihood method; MO: moments method; MQ: median and quartiles method; WAsP: wind atlas analysis and application program.

Table 4. Methods of error/goodness of fit analysis.

Method	Formula	Order of performance	Equation number
RMSE	$RMSE = \sqrt{\frac{1}{n} \sum_{t=1}^n (\hat{U}_t - U_t)^2}$	The lower the RMSE, the better the Weibull method	(26)
R ²	$R^2 = \frac{\sum_{t=1}^n U_t - \hat{U}_t }{\sum_{t=1}^n U_t - \bar{U}_t }$	The higher the R ² , the better the Weibull method	(27)
MAE	$MAE = \frac{1}{n} \sum_{t=1}^n \hat{U}_t - U_t $	The lower the MAE, the better the accuracy of the Weibull method.	(28)
MAPE	$MAPE = \frac{1}{n} \sum_{t=1}^n \left \frac{\hat{U}_t - U_t}{U_t} \right \times 100$	The lower the MAPE, the better the accuracy of the Weibull method.	(29)
COE	$COE = \frac{\sum_{t=1}^n (\hat{U}_t - \bar{U})^2}{\sum_{t=1}^n (U - \bar{U})^2}$	The greater the COE, the better the accuracy of the method	(30)

COE: coefficient of efficiency; MAE: mean absolute error; MAPE: mean absolute percentage error; RMSE: root mean square error.

Table 5. Methods of estimating Weibull parameters, the *k* and *A* values, mean wind speed, and WPD and goodness of fit test/errors for the Funafuti site.

	k	A (m/s)	U (m/s)	WPD (W/m ²)	R ²	COE	RMSE	MAE	MAPE
MQ	2.35	7.01	6.21203	229.8545	0.9992	1.036	0.1027	0.0517	2.2885
MO	2.31	6.98	6.18400	230.5354	0.9987	1.0058	0.1034	0.073	2.3687
EMJ	2.32	6.98	6.18433	229.7069	0.9987	1.0126	0.1049	0.0711	2.4141
EML	2.32	6.98	6.18433	229.9264	0.9987	1.0114	0.1051	0.0715	2.4141
LS	2.12	6.74	5.96925	222.8722	0.997	0.9367	0.2809	0.2468	5.6148
ML	2.28	6.97	6.17425	231.4056	0.9987	0.9915	0.1043	0.0794	2.3679
MML	2.23	6.91	6.12003	228.8074	0.9983	0.9748	0.143	0.1205	3.1169
EPF	2.31	6.98	6.18400	229.8793	0.9987	1.0116	0.1056	0.0723	2.4274
WAsP	2.36	7	6.20358	228.1789	0.9994	1.0496	0.1034	0.0461	2.2502
MM	2.16	7.65	6.7748	319.59	0.9969	0.7977	0.6266	0.4952	7.7616

COE: coefficient of efficiency; EMJ: empirical method of Justus; EML: empirical method of Lysen; EPF: energy pattern factor method; LS: least squares method; MAE: mean absolute error; MAPE: mean absolute percentage error; ML: maximum likelihood method; MM: method of multi-objective moments; MML: modified maximum likelihood method; MO: moments method; MQ: median and quartiles method; RMSE: root mean square error; WAsP: wind atlas analysis and application program; WPD: wind power density.

parameters. The WPD for the Funafuti site was 153.4 W/m² while that for the Nukufetau site was 145.1 W/m².

Wind speed frequency distribution

Figures 25 and 26 show the histograms of the wind speeds for the Funafuti and Nukufetau sites, respectively. The figures also include the different Weibull distributions obtained using different methods. Both the figures show nearly the same trends of wind speed. The wind

Table 6. Ranking by performance evaluation for the Funafuti site.

	k	A (m/s)	U (m/s)	WPD (W/m ²)	R ²	COE	RMSE	MAE	MAPE	Rank
WAsP	2.36	7	6.20358	228.1789	1	1	2	1	1	1
MQ	2.35	7.01	6.21203	229.8545	2	2	1	2	2	2
EMJ	2.32	6.98	6.18433	229.7069	3	3	5	3	5	3
MO	2.31	6.98	6.18400	230.5354	3	6	2	6	4	4
EML	2.32	6.98	6.18433	229.9264	3	5	6	4	5	5
ML	2.28	6.97	6.17425	231.4056	3	7	4	7	3	6
EPF	2.31	6.98	6.18400	229.8793	3	4	7	5	7	7
MML	2.23	6.91	6.12003	228.8074	8	8	8	8	8	8
LS	2.12	6.74	5.96925	222.8722	9	9	9	9	9	9
MM	2.16	7.65	6.77487	319.59	10	10	10	10	10	10

COE: coefficient of efficiency; EMJ: empirical method of Justus; EML: empirical method of Lysen; EPF: energy pattern factor method; LS: least squares method; MAE: mean absolute error; MAPE: mean absolute percentage error; ML: maximum likelihood method; MM: method of multi-objective moments; MML: modified maximum likelihood method; MO: moments method; MQ: median and quartiles method; RMSE: root mean square error; WAsP: wind atlas analysis and application program; WPD: wind power density.

Table 7. Methods of estimating Weibull parameters, the k and A values, mean wind speed and WPD and goodness of fit test/errors Nukufetau.

	k	A (m/s)	U (m/s)	WPD (W/m ²)	R ²	COE	RMSE	MAE	MAPE
MQ	2.42	6.17	5.47046	153.4117	0.9977	0.9822	0.1534	0.0994	3.1418
MO	2.41	6.05	5.36363	145.5391	0.9975	1.0061	0.1206	0.0901	2.9996
EMJ	2.41	6.05	5.36363	145.1001	0.9975	1.0137	0.1198	0.0864	2.9948
EML	2.41	6.05	5.36363	145.2058	0.9975	1.0128	0.1203	0.0876	3.0104
LS	2.2	5.81	5.14548	138.0362	0.9944	0.9412	0.294	0.2616	6.4799
ML	2.38	6.04	5.35355	145.7241	0.997	0.9896	0.1303	0.0995	2.9744
MML	2.33	5.98	5.29863	143.8129	0.9964	0.9748	0.1594	0.1367	3.6601
EPF	2.42	6.05	5.36407	145.037	0.9975	1.0144	0.1199	0.0867	2.9978
WAsP	2.57	6.1	5.41626	142.5374	0.9984	1.1109	0.1677	0.1012	4.1849
MM	2.16	6.55	5.80070	201.0823	0.9926	0.7642	0.5062	0.336	5.4251

COE: coefficient of efficiency; EMJ: empirical method of Justus; EML: empirical method of Lysen; EPF: energy pattern factor method; LS: least squares method; MAE: mean absolute error; MAPE: mean absolute percentage error; ML: maximum likelihood method; MM: method of multi-objective moments; MML: modified maximum likelihood method; MO: moments method; MQ: median and quartiles method; RMSE: root mean square error; WAsP: wind atlas analysis and application program; WPD: wind power density.

speeds are mostly between 0 and 10m/s. The peaks in the wind speed histograms were mostly between 4 and 7m/s. The near-perfect fit of the WAsP distribution can be seen for Funafuti.

Resource grid

The resource grids showing the WPDs for the measurement sites were plotted using the WAsP software. The resource map is drawn on the basis of the resolution of the map which

Table 8. Ranking by performance evaluation for Nukufetau.

	k	A (m/s)	U (m/s)	WPD (W/m^2)	R ²	COE	RMSE	MAE	MAPE	Rank
EMJ	2.41	6.05	5.36363	145.1001	3	3	1	1	2	1
EPF	2.42	6.05	5.36407	145.037	3	2	2	2	3	2
EML	2.41	6.05	5.36363	145.2058	3	4	3	3	5	3
MO	2.41	6.05	5.36363	145.5391	3	5	4	4	4	4
ML	2.38	6.04	5.35355	145.7241	7	6	5	6	1	5
WAsP	2.57	6.1	5.41626	142.5374	1	1	8	7	8	6
MQ	2.42	6.17	5.47046	153.4117	2	7	6	5	6	7
MML	2.33	5.98	5.29863	143.8129	8	8	7	8	7	8
LS	2.2	5.81	5.14548	138.0362	9	9	9	9	10	9
MM	2.16	6.55	5.80071	201.0823	10	10	10	10	9	10

COE: coefficient of efficiency; EMJ: empirical method of Justus; EML: empirical method of Lysen; EPF: energy pattern factor method; LS: least squares method; MAE: mean absolute error; MAPE: mean absolute percentage error; ML: maximum likelihood method; MM: method of multi-objective moments; MML: modified maximum likelihood method; MO: moments method; MQ: median and quartiles method; RMSE: root mean square error; WAsP: wind atlas analysis and application program; WPD: wind power density.

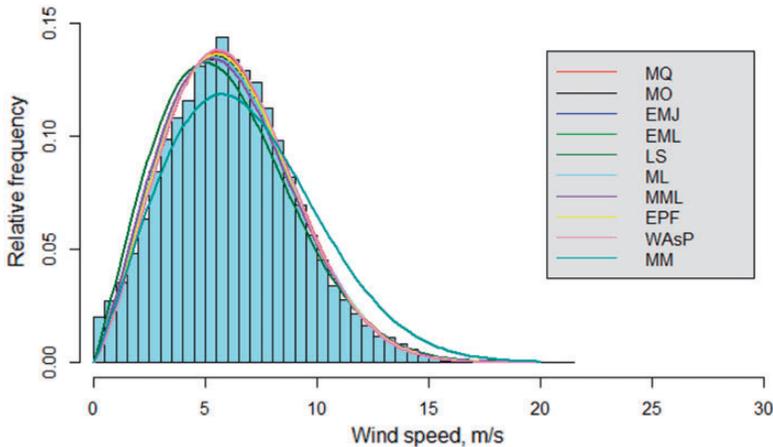


Figure 25. Wind frequency distribution and Weibull distributions from the 10 different methods for the overall measurement period for Funafuti.

is the rectangular sets of points on the map. Using the rows and columns, the rectangular sets of points are evenly spaced. The generalized wind climate needs to be calculated before a resource grid is obtained. To obtain a resource grid, the vector map must be digitized in which the roughness levels are determined as well as the terrains of the location. The final step is the calculations. Some of these calculations include WPD, wind speed, and Weibull parameters.

The wind resource maps of Funafuti and Nukufetau are shown in Figures 27 and 28, respectively, with the distances in meters. A vast area of the resource grid shows the ocean with a WPD lying in the middle range. Both sites do not have high-rise buildings but have thick vegetation. The WPD for Funafuti is mostly between 203 and 277 W/m^2 while for

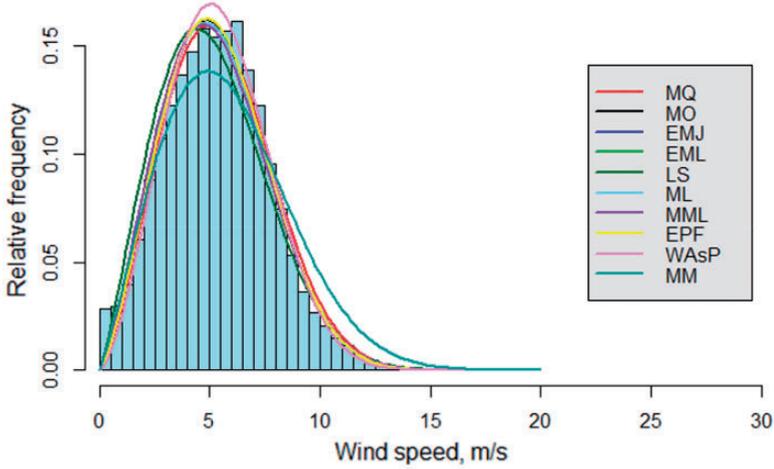


Figure 26. Wind frequency distribution and Weibull distributions from the 10 different methods for the overall measurement period for Nukufetau.

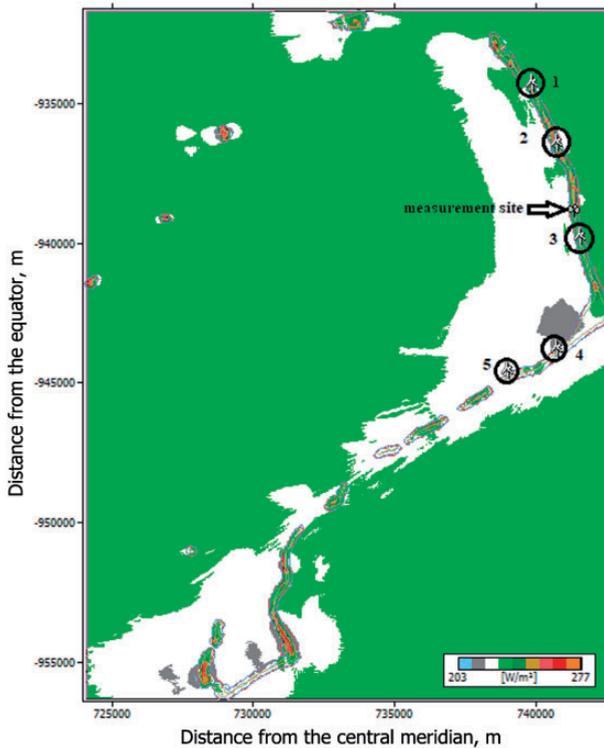


Figure 27. High resolution wind power density map of Funafuti site. The circles indicate the location of preferred installation sites for the turbines.

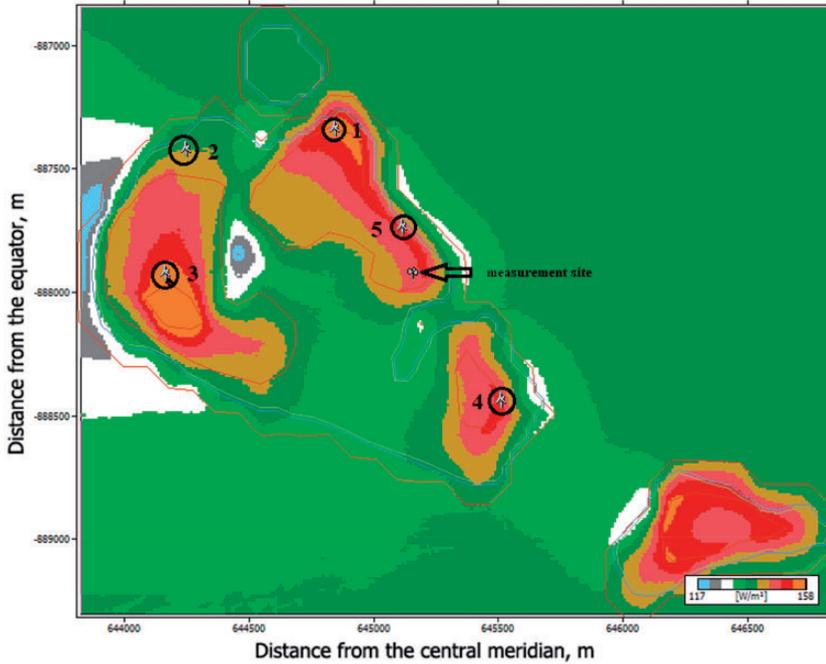


Figure 28. High resolution wind power density map of Nukufetau site. The circles indicate the location of preferred installation sites for the turbines.

Nukufetau it is between 117 and 158 W/m². From the resource grids, it can be depicted that Funafuti has a better potential of harvesting wind energy than Nukufetau.

Annual energy production

The AEP for the two measurement sites were calculated using the WAsP software. Vergnet 275kW wind turbines were used for the AEP estimation. These turbines have been installed previously in the region and are performing well; also there are personnel trained on this turbine. For estimation of AEP, the hub height of the turbine was taken as 34 m, a rotor diameter of 32 m, a cut-in speed of 3.56 m/s, rated wind speed of 12.2 m/s with an air density of 1.16 kg/m³, and a cut-out wind speed of 25 m/s. The air density was calculated based on the average local atmospheric pressure and ambient temperature. There were five suitable sites selected after the wind resource assessment for the AEP calculation. Figure 29 shows the power curve for the Vergnet 275 kW wind turbine.

Vergnet 275 kW wind turbines have been selected for their many advantages:

- Easy to maintain,
- Easier to lower during cyclones,
- Have been installed in other PICs like Fiji and Vanuatu which are performing well.

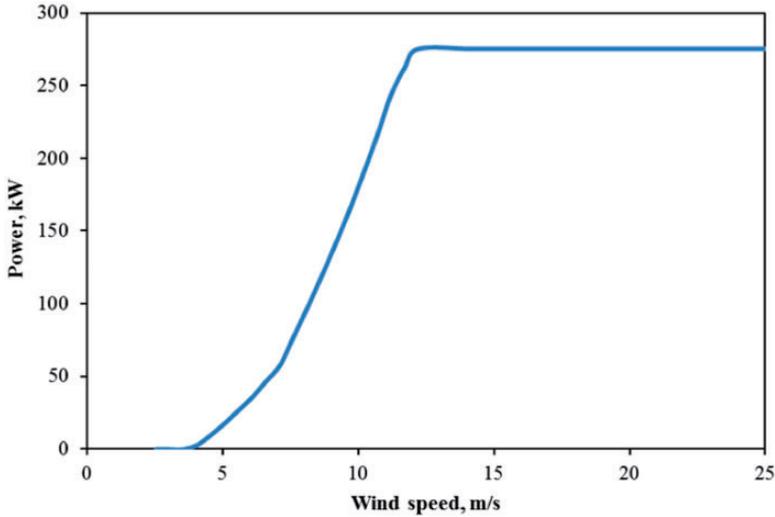


Figure 29. Power curve for the Vergnet 275 kW wind turbine.

Larger wind turbines could also be used at these locations, but are not preferred due to the following reasons:

- The initial cost of the turbines is quite high.
- Since these are small island nations, it would not be prudent to use larger wind turbines, the maintenance costs will become too high due to logistic issues. Also, large turbines have generally high maintenance and repair costs (Chen et al., 2020).
- The larger the wind turbine, the more noise and vibrations it generates which will not be acceptable for small islands.

The average power generated by a turbine is estimated by taking the average wind speed for the time interval from time t_i to $t_i + \Delta t$ for the period of N observations is expressed as

$$\bar{P}_w = \frac{1}{N} \sum_{t=1}^N P_w(U_t) \quad (31)$$

where $P_w(U_t)$ is the power output defined by the turbine power curve. The energy yield from the turbine can be expressed as

$$E = \sum_{t=1}^N P_w(U_t)(\Delta t) \quad (32)$$

The sites selected for installing the turbines for the purpose of AEP estimation are close to the shoreline and are not in a mountainous region. The hub heights of the turbines are chosen to be 34 m AGL. Since the measurements of wind speed and direction were performed at 34 m AGL and the analysis is also done at 34 m AGL, the error in the estimation

Table 9. AEP from five Vergnet 275 kW turbines in Funafuti.

Turbine site	Location (m)	Power density	Net AEP (MWh)	Capacity factor (%)
1	(739,925.6, -934,519.1)	249	610.696	25.35
2	(740,805, -936,647)	264	641.148	26.61
3	(741,615, -940,000)	231	570.095	23.66
4	(740,795, -944,028)	223	551.731	22.90
5	(739,055, -944,798)	222	547.665	22.73

AEP: annual energy production.

Table 10. AEP from five Vergnet 275 kW turbines in Nukufetau.

Turbine site	Location (m)	Power density	Net AEP (MWh)	Capacity factor (%)
1	(644,851, -887,363)	153	388.669	16.13
2	(644,253.4, -887,446.2)	140	353.986	14.69
3	(644,170.1, -887,947.0)	157	399.115	16.57
4	(645,517, -888,463)	149	378.646	15.72
5	(645,120, -887,760)	149	378.07	15.69

AEP: annual energy production.

of the AEP will be negligible. The annual AEP of the site assuming five wind turbines are installed is 2921.34 MWh for Funafuti and 1848.49 MWh for Nukufetau. The average capacity factors for the all five sites together are 24% and 16% for Funafuti and Nukufetau, respectively. The capacity factor is the generated AEP over the expected AEP for the wind farm. The wake loss for all the turbines is 0% since the turbines are located away from each other and the wake of any turbine does not affect any other turbine's power output (Jain, 2016). From the analysis as shown in Tables 9 and 10, it was estimated that the AEP ranged between 547 and 641 MWh for Funafuti while for Nukufetau, it was between 535 and 400 MWh. It was also observed that the WPD for the Funafuti site was between 203 and 277 W/m² which is very good for harvesting wind energy. However, Nukufetau has a lower WPD of between 117 and 158 W/m².

Economic analysis

An economic analysis for installing five wind turbines at both the sites was carried out. For the analysis, the following assumptions were made:

- All amounts are in US\$.
- The lifetime (T) of the turbine is assumed to be 20 years.
- The interest rate (r) and inflation rate (i) are considered to be 12% and 3%, respectively.
- Operational maintenance/repair costs (C_{omr}) are considered to be 25% of the annual cost of the turbine (machine price/lifetime).
- Scrap value (S) is taken as 10% of the cost of the turbine and civil work.
- Investment (I) includes the cost of the turbine plus its transportation cost to Fiji and the cost of the civil work and the costs associated with grid integration.

For obtaining the present value of cost (PVC), the following equation is used

$$PVC = I + C_{omr} \left[\frac{1+i}{r-i} \right] \left[1 - \left(\frac{1+i}{1+r} \right)^T \right] - S \left(\frac{1+i}{1+r} \right)^T \quad (33)$$

The Vergnet 275 kW turbine with the transportation cost of bringing the turbine to Tuvalu is US\$650,000 with all the civil works. The operation and maintenance cost is US\$8125. US\$58000 is the scrap value which is 10% of initial cost. The interest rate is 0.12 while the inflation rate is 0.03. Using equation (32), the PVC is estimated to be US\$714,716.42.

As described earlier, five turbines were placed and analysis was carried out using the WASP software for each of the two sites. For Funafuti, the average AEP is 584.27 MWh while in Nukufetau, it is 379.7 MWh. The maintenance period (downtimes) for both the sites has been neglected. In Tuvalu, the cost of a single unit of electricity is USD\$0.28 for domestic and \$0.39 for industrial consumers. The cost of producing energy using Vergnet wind turbines in Funafuti is US\$0.06/kWh while in Nukufetau, it is US\$0.09/kWh. The production cost is simply the PVC quotient of the lifetime of the turbine multiplied by the average AEP of the site.

The profit made in 20 years after recovering the cost of installing a turbine is between US \$2,557,179 and US\$4,557,283 in Funafuti if it is sold to consumer at the given rates by Tuvalu Electricity Limited. On the other hand, the profit made in Nukufetau over a period of 20 years is between US\$1,411,588 and US\$2,246,922. The recovery cost of the PVC will be between 3.13 and 4.21 years for Funafuti and between 4.83 and 6.72 years for Nukufetau.

Conclusions

Detailed wind resource assessments for two sites in Tuvalu are performed. The average annual wind speeds were 6.19 and 5.36 m/s at 34 m AGL at the Funafuti and Nukufetau sites, respectively. Analysis of separate daytime and night time wind speeds indicated strong effects of sea-breeze and land-breeze. The mean TIs at the Funafuti and Nukufetau sites were estimated to be 9.07% and 11.76%, respectively, at 34 m AGL, which are below the allowable levels for wind turbines. The Weibull parameters were estimated for both the sites using 10 different methods. WASP was the best method for finding the Weibull parameters at the Funafuti measurement site with a WPD of 228.18 W/m² while EMJ was the best method for Nukufetau with a WPD of 145.10 W/m². For each site, five potential locations were chosen for turbine installation, performance analysis as well as economic analysis. The average AEP calculated for Funafuti was 584.27 MWh while in Nukufetau, it was 379.7 MWh. The payback period for installing the Vergnet 275 kW wind turbine in Funafuti is between 3.13 and 4.21 years. However, Nukufetau has a longer time period for the return of investment which is between 4.83 and 6.72 years. Thus, Tuvalu has a reasonably good potential for harvesting wind energy and becoming independent of imported fossil fuels for power generation.

Data Accessibility Statement

Sample data are provided with the manuscript. Full data will be made available upon request and after approval from the respective Governments.

Declaration of conflicting interests

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Supplemental material

Supplemental material for this article is available online.

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Appendix

Notation

A	scale factor, m/s
AGL	above ground level
COE	coefficient of efficiency
EPF	energy pattern factor method
h	height
k	shape factor
LS	least squares method
MAE	mean absolute error
MAPE	mean absolute percentage error (%)
ML	maximum likelihood method
MML	modified maximum likelihood method
MO	moments method
MQ	median and quartiles method
MM	method of multi-objective moments
n	number of observations
R^2	coefficient of determination
RMSE	root mean square error (m/s)
TI	turbulence intensity (%)
\bar{U}	mean wind speed (m/s)
U_m	median wind speed (m/s)
WAsP	wind atlas analysis and application program
WPD	wind power density (W/m^2)
WSC	wind shear coefficient
Γ	gamma function
σ	standard deviation of wind speed (m/s)