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WIND CHARACTERISTICS ANALYSIS IN FOUR POTENTIAL TOWNSHIPS IN MYANMAR

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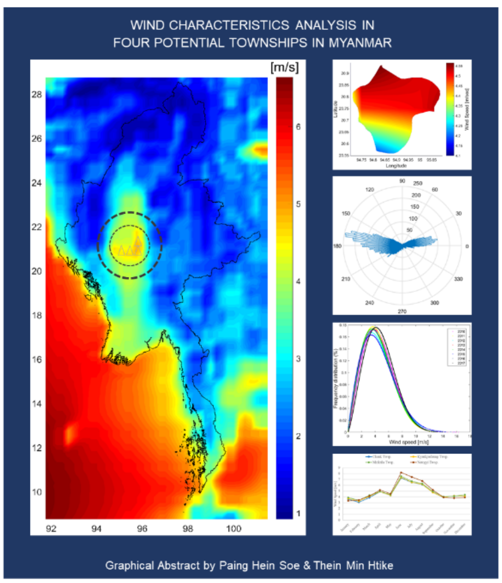
Graphical abstract



Abstract

Myanmar has set renewable energy aspirations in the energy mix of the country to meet growing energy demand and to increase clean access to electricity as indicated in Myanmar's Intended Nationally Determined Contribution. Among renewable energy resources, solar and wind energy are expected to contribute to 9% of total energy mix. Although there have been initiatives on the implementation of solar photovoltaic in Myanmar, implementation of wind energy has not been reported. Few studies on wind energy in Myanmar focused on resource assessment investigating the spatial variation of wind speed and power density. Little has been studied on the seasonal nature and persistence of wind in Myanmar from the perspective of energy generation. This study aims at generating wind speed and power density maps of Myanmar using most recent wind data from 2010 to 2017 to identify potential townships with favourable wind conditions. Prominent wind direction, seasonal variations and wind speed persistence were analyzed for four townships with favourable wind conditions. Weibull parameters suggest that frequency of wind is also favourable for wind energy generation. Hence, this study has identified Chauk, Kyaukpadaung, Meiktila and Natogyi townships as potential regions for wind energy development with estimated power producing time of 53.17% and 65.91% of a year at average wind speed of 4 m/s above. This study serves as a basis for further resource assessment for micrositing of wind turbines to identify feasible sites for wind energy generation in Myanmar.

Keywords: Auto-correlation, power density, seasonal wind variation, wind characteristics, wind persistence, wind resource assessment

1.0 INTRODUCTION

Energy demand in Myanmar is increasing due to economic development and it is expected to be 14.542 GW by 2030 [1]. According to Ministry of Electricity and Energy of Myanmar, electrification rate in Myanmar is 43% in 2018. To meet the growing demand and to achieve 100% electrification, the Government of Myanmar has set national energy policy "to explore and exploit all energy resources available in Myanmar" and "to compile systematic statistics on domestic demand and supply of various different kinds of energy resources of Myanmar".

Solar and wind energy are expected to contribute to 9% total generation in the 2030 national energy mix of Myanmar [1]. Although there are some installations and proposed projects on solar photovoltaic, currently there is no installation of wind energy except for a few micro-wind turbines. However, utility-scale wind farm projects with capacity of 263 MW at minimum hub height of 100 m have been agreed between wind energy developer and Ministry of Electricity and Energy to develop in six townships; Minhla, Minbu, Mindon, Ngape, Chauk, and Natmauk in Magway Region [2,3]. Apart from these, there has not been any active project on wind energy installation. Only a few studies reported wind energy potential of Myanmar focusing on spatial variation of wind speed and power density. However, little has been known about the seasonal variation of wind in Myanmar and its persistence which are important factors in estimating energy yield.

Janjai et al. quantified wind energy potential of Thailand by analyzing meteorological data over 15-year (1995 to 2009) using three-dimensional Karlsruhe Atmospheric Mesoscale Model (KAMM) with 1-hour time step and horizontal resolution of 3 x 3 km^2 [4]. Validation of model was conducted using wind measurement data from four stations situated in four domains of the country by estimating hourly wind speed at 100 m height. They revealed that most of the potential wind energy sites are situated in south of Thailand. Moreover, area of 550 km^2 which fulfilled the GIS given criteria resulting in wind turbine total energy capacity of 1100 MW were reported. Shu et al. carried out statistical analysis of wind energy assessment at different terrain sites in Hong Kong using Weibull distribution model [5]. Using wind data (2005 to 2010) from five meteorological stations, Weibull distribution of annual wind speed at each site was presented and operating probability was also calculated based on typical cut-in wind turbine speed and cut-out speed. Moreover, their study highlighted the seasonal variation, monthly variation and diurnal variation of wind speed. Their study concluded that the most promising areas for wind energy harnessing in Hong Kong are hilltops and offshore islands with maximum wind power density of 915.23 W/m^2 at hilltop site.

Yoreley et al. reviewed earlier studies on wind persistence highlighting its importance on determining best wind sites [6]. The authors offered analytical system based on autocorrelation method, conditional probability and speed duration curves to quantify wind persistence and evaluated number of uninterrupted working hours for the turbine. Having validated the performance of each method using wind data at five different sites in Mexico, the authors concluded that persistence valued estimated by the speed duration curve method is the most suitable to assess wind potential because it can show significant variation in persistence at different sites.

Masseran et al. investigated both stability and suitability of wind energy based on assessment of stationarity properties and variation of wind speed [7]. They evaluated degree of wind persistence on hourly wind speed data from 2007 to 2009 at ten stations in Peninsular Malaysia. Although these ten stations have quite low wind speed below 3 m/s, maximum wind speed range lie between 6 m/s and 12 m/s. Therefore, they performed wind speed persistence analysis in order to find the suitable site location for energy production. They reported that Chuping station has the least wind speed variance, Mersing is observed the most persistent site revealed by wind speed curve duration method. They revealed that Mersing has the most energy production potential compared to other sites although percentage of the time the wind speed can produce energy was only 18.2%. Based on the review, spatial and temporal variation of wind speed, its persistence, power density, Weibull distribution and energy production potential have been studied widely to identify suitable locations for wind energy development.

For the studies on wind energy potential in Myanmar, Thi Thi Soe et al. carried out pre-feasibility study of wind energy resource in Myanmar particularly with wind power density map [8]. Hourly wind speed data at 50 m height were taken from MERRA with grid resolution 2/3° longitude and 1/2° latitude. Based on MERRA wind dataset, wind power density map was generated using ArcMap 10, ArcGIS software. They reported that wind power density is lower than 80 W/m^2 in the whole country except in coastal regions. They classified three groups of states and regions ranging wind power density level. First group of lowest level lower than 50 W/m^2 includes States of Kachin, Kayah, Kayin, Chin, Shan and Bago Region. Moderate group of Sagaing, Mandalay, Magway Regions and Mon State vary from 20 W/m^2 to 80 W/m^2. They revealed that the highest wind power density are Rakhine State, Ayeyarwaddy Region, Yangon Region and Tanintharyi Region ranging from 80 W/m^2 to 126 W/m^2. Although wind power density in Myanmar has been estimated, the previous study did not include wind direction and wind persistence analysis as well as seasonal variations. However, it paved the way to wind resource assessment analysis for Myanmar. To evaluate wind energy potential in Myanmar, there is still a need to conduct detailed analyses of temporal variation of wind speed and power density, wind persistence, site measurements, Weibull distribution and energy production potential.

The main aim of this study is to identify locations with favorable wind potentials in Myanmar and analyze wind characteristics at those locations. Wind speed and power density maps of Myanmar were first generated based on most recent wind dataset. Based on the power density, the study identified four townships with favorable wind potentials and evaluated temporal variations, wind persistence and Weibull parameter distribution of wind speed at four potential townships. Insight knowledge on wind characteristics at four potential townships would help decide where site measurement should be conducted for siting of wind turbines.

2.0 METHODOLOGY

2.1 Data Source

Wind resource dataset were downloaded by using Windographer Data Downloader 3.0.0 provided by AWS Truepower, LLC. Data source is European Centre for Medium-Range Weather Forecasts and dataset is ERA5 hourly wind speed, wind direction, temperature and pressure. Data resolution is 0.25 degree of grid point for both latitude and longitude and all data requested are at 100 m height and from 2010 to 2017, totally 8 years. Analyses of wind speed, power density, persistence, wind rose and Weibull distribution were done using MATLAB programming.

2.2 Method of Bin For Wind Speed And Power Density

Method of bins was used to calculate wind power density which is a key factor for wind resource analysis and feasibility of wind potential. Time series data of hourly wind speed were separated into N_B bins for each specified wind speed interval. In this study, wind speed interval was increased by one meter per second: from zero to cover maximum wind speed at each location. For wind speed data lied within interval of each bin, respective number of occurrences are calculated. Then, using midpoint $u_{j,m}$ of each bin, wind power density $\bar{P}_A$ is calculated by;

$$\bar{P}_A = \frac{1}{2} \cdot \frac{1}{N} \cdot \sum_{j=1}^{N_B} (\rho_j \cdot u_{j,m}^3 \cdot f_j) \quad (1)$$

where, N is length of time series data, N_B is number of bins, f_j is number of occurrences for each bin j, ρ_j is air density for each bin j.

For air density, most studies use air density at standard temperature and pressure. This study calculated air density using ideal gas law for each temporal wind data with respective pressure p and temperature T;

$$\rho = \frac{p}{R\,T} \tag{2}$$

where, specific gas constant for dry air (287.058 J/(kg·K)) is used for R. Mean wind speed $\overline{U}$ was also calculated in the similar way of wind power density by using

$$\overline{U} = \frac{1}{N}.\sum_{j=1}^{N_B}(u_{j,m}.f_j) \tag{3}$$

where, temporal series data vary with time span of interest: seasonal, yearly or average 8-year wind resource assessment respectively.

2.3 Auto-Correlation Based Wind Persistence

Autocorrelation function (ACF) shows the correlation between successive points in a series, so it is related to stochastic process memory in time-domain. Therefore, this method ACF was applied for wind persistence analysis which gives useful information to wind resource assessment. The autocorrelation coefficient $\boldsymbol{r_k}$ is evaluated by;

$$r_k = \frac{\sum_{i=1}^{n-k}[(u_i - \tilde{u})(u_{i+k} - \tilde{u})]}{\sum_{i=1}^{n}(u_i - \tilde{u})^2} \tag{4}$$

where, u_i is the time series data, $\tilde{u}$ is the average velocity, n is the number of data series and k is the time lag. Magnitude of correlation, r_0 is 1 starting from without time lag k zero. Then, correlation of shifted time series data starting from r_1 till first zero occurrence duration gives the persistence value. The area bounded by the period of duration and coefficient r_1 is assumed to be triangle area and this area is taken as the persistence of these time series data. This approach to persistence analysis was also used in some other studies on wind resource assessment [6], [9]. In this study, finding area under the curve between this duration was done by using numerical integration method with trapezoidal rule to obtain more accurate persistence value.

2.4 Weibull Distribution

Many studies [10]–[14] suggested that Weibull distribution can be used to assess wind energy potential and convey wind speed frequency distribution at a particular location. This study also calculates probability distribution function using Weibull distribution as follows:

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1}.exp\left[-\left(\frac{u}{c}\right)^{k}\right] \tag{5}$$

where u is wind speed and k and c are dimensionless shape parameter and scale parameter respectively.

There are many methods to determine these parameters such as graphical method, method of moment estimation, L-moment estimation method, power density method, maximum likelihood estimation and empirical method. Among them, empirical method is used in this study to calculate Weibull parameters. Empirical method of Justus was introduced by Justus in 1977 as following equations [15];

$$k = \left(\frac{\tilde{u}}{\sigma}\right)^{-1.086} \tag{6}$$

$$c = \frac{\tilde{u}}{\Gamma(1+\frac{1}{k})} \tag{7}$$

where, σ is the standard deviation of wind speed u.

3.0 RESULTS AND DISCUSSION

3.1 Average Wind Speed And Power Density

Figure 1 shows mean wind speed and mean wind power density maps averaged over 8-years wind data from 2010 to 2017 generated by using Equations (1) to (3). The highest mean wind speeds are found in coastal areas and central plain of the country. The same finding was also reported by Thi Thi Soe et al. [6]. It is also noted here that mean wind speed of about 6 m/s is found in some offshore areas particularly off the southwest and west coastal lines.

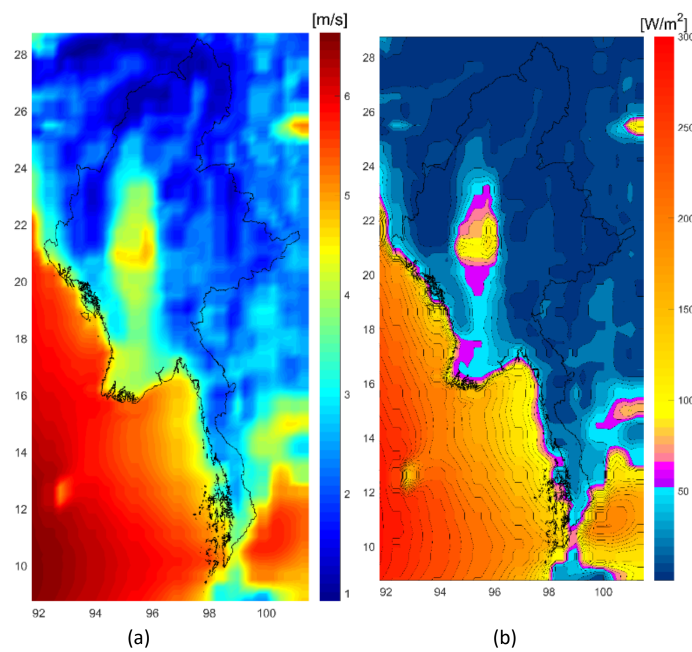


Figure 1 Wind map averaged over 8 years from 2010 to 2017
(a) Wind speed map (b) Wind power density map

From the results of these maps, onshore areas with best wind conditions in Myanmar are generally categorized as two groups: the first group with wind speed between 4 m/s ~ 6 m/s which is in coastal areas, and the second group (4 m/s ~ 5 m/s) in central areas of the country. The corresponding regions to those areas are tabulated in Table 1.

As seen in Table 1, maximum wind power density in coastal areas is 170 W/m^2 and that in central areas is 130 W/m^2. Therefore, it may be implied that wind class is Myanmar is not favourable for wind energy generation. However, if seasonal variations are checked and/or site measurements can be done in these two areas, some potential sites might be found.

Table 1 Areas with best wind speed and power density in Myanmar

Areas with Best Wind Speed and Power Density	Mean Wind Speed	Mean Wind Power Density
Coastal areas of Rakhine State, Mon State, Tanintharyi Region, Ayeyarwaddy Region and Yangon Region	4 m/s ~ 6 m/s	80 W/m^2 to 170 W/m^2
Central areas of Mandalay Region and Magway Region	4 m/s ~ 5 m/s	80 W/m^2 to 130 W/m^2

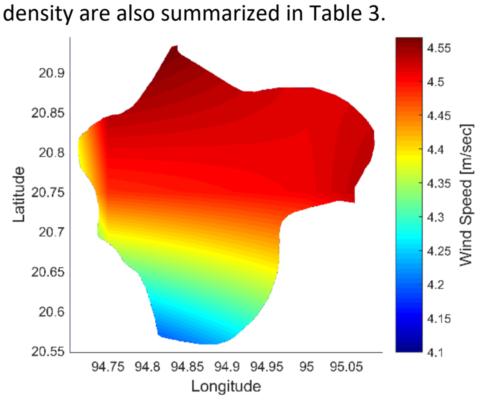
3.2 Averaged Wind Speed

To this purpose, four townships in central areas with highest wind power potential were selected for further evaluation of wind characteristics. Table 2 shows latitude and longitude of four selected townships in central area of Myanmar. Locations in all townships are accessible by road transport which is one of the important considerations for site measurements and wind turbine site selection.

Table 2 Location of four selected townships in central area of Myanmar

Township	Chauk	Kyaukpadaung	Meiktila	Natogyi
Region	Magway	Mandalay	Mandalay	Mandalay
(Lat, Lon) [deg]	N 20.75, E 95.00	N 20.75, E 95.25	N 20.75, E 95.75	N 21.25, E 95.75

Eight-year averaged wind speed and power density maps were generated for the four townships. Figure 2 shows 8-year averaged wind speed maps and all the townships have mean wind speed above 4 m/s and Meiktila township has the highest minimum wind speed, 4.3 m/s and highest maximum wind speed, 4.8 m/s among all townships. Average wind speed and power density are also summarized in Table 3.



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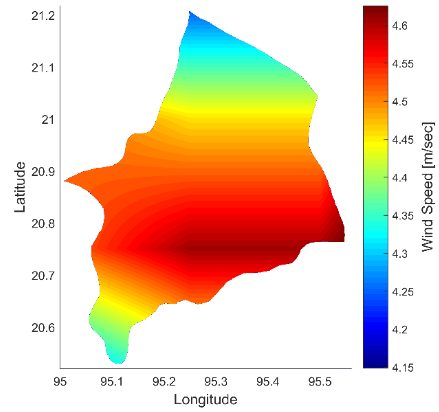

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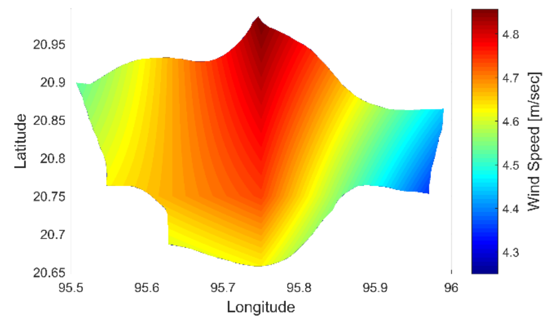

(c)

Figure 2 Mean wind speed map of selected townships (8-year averaged)

(a) Chauk Twsp. (b) Kyaukpadaung Twsp. (c) Meiktila Twsp. (d) Natogyi Twsp.

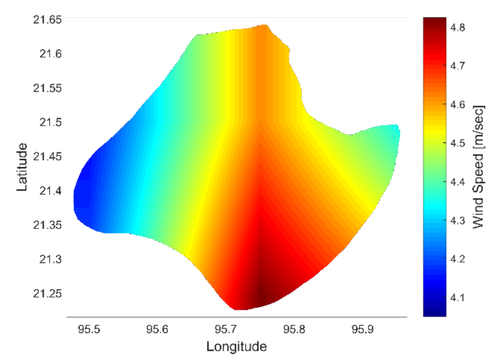

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Fig 2 *(continued)*

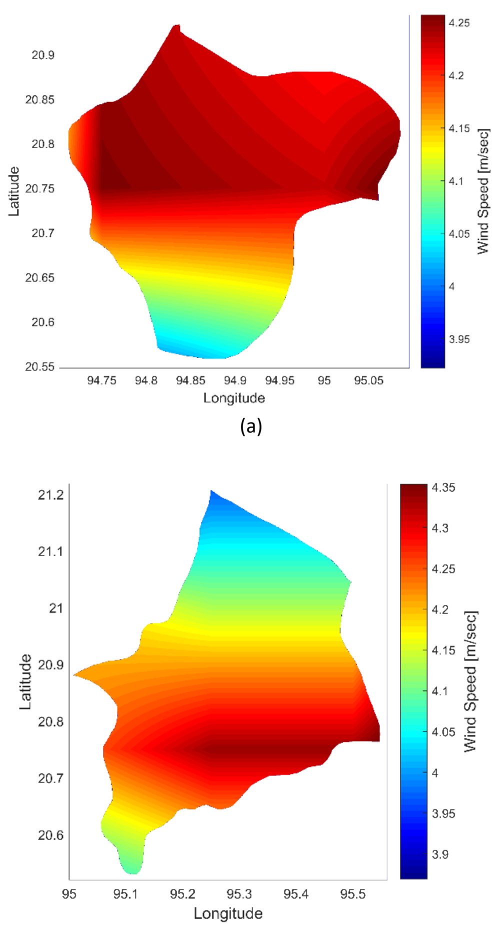
3.3 Seasonal variation of wind speed

After 8-year averaged analysis on township-level maps, seasonal wind speed variations are also studied for these townships. Myanmar is located in the tropical monsoon climate region and described by three main seasons: summer or hot weather season, rainy or southwest monsoon season and winter or northeast monsoon season. Summer is from March to mid-May, rainy season from mid-May to October, and winter from November to February in Myanmar. Township-level seasonal wind speed maps of the selected townships in summer for 2017 are shown in Figure 3. maximum wind speed of around 4.55 m/s than other two townships. Minimum wind speed is found nearly 4 m/s in summer and the highest minimum wind speed is also in Meiktila township.

Table 3 Wind speed, power density and persistence for selected townships in Myanmar

		2010-2017		2017					
		8-Year Average		Summer		Rainy Season		Winter	
Township, Region	Data	Min	Max	Min	Max	Min	Max	Min	Max
Chauk, Magway Region	Wind Speed	4.20	4.56	4.02	4.26	5.16	5.78	3.48	3.81
	Wind Power Density	79	109	66	83	122	181	39	50
	Persistence			6	13	157	166	20	24
Kyaukpadaung, Mandalay Region	Wind Speed	4.25	4.63	3.97	4.35	5.30	5.79	3.11	3.85
	Wind Power Density	81	105	62	76	126	180	28	52
	Persistence			9	13	154	162	18	24
Meiktila, Mandalay Region	Wind Speed	4.35	4.86	4.18	4.55	5.37	6.09	3.40	3.97
	Wind Power Density	86	122	64	86	135	199	37	57
	Persistence			10	13	157	168	19	22
Natogyi, Mandalay Region	Wind Speed	4.15	4.83	3.82	4.57	5.28	6.17	2.96	3.66
	Wind Power Density	87	127	61	92	150	218	27	44
	Persistence			10	12	155	192	16	24

For rainy season in 2017, township-level wind speed maps are shown in Figure 4 and found as the windiest season among the three seasons. Rainy season is also important since it is the longest season of five and half months occupying nearly the half of the year. Minimum wind speed above 5 m/s is observed in all townships. Maximum wind speed of nearly 5.8 m/s is found in



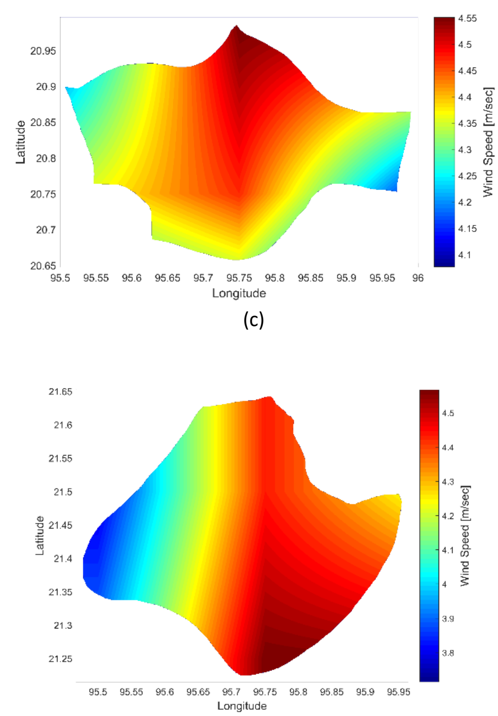


Figure 3 Seasonal wind speed map of selected townships in summer for 2017 (a) Chauk Twsp. (b) Kyaukpadaung Twsp. (c) Meiktila Twsp. (d) Natogyi Twsp.

Chauk and Kyaukpadaung townships and up to around 6.1 m/s in Meiktila and Natogyi are observed.

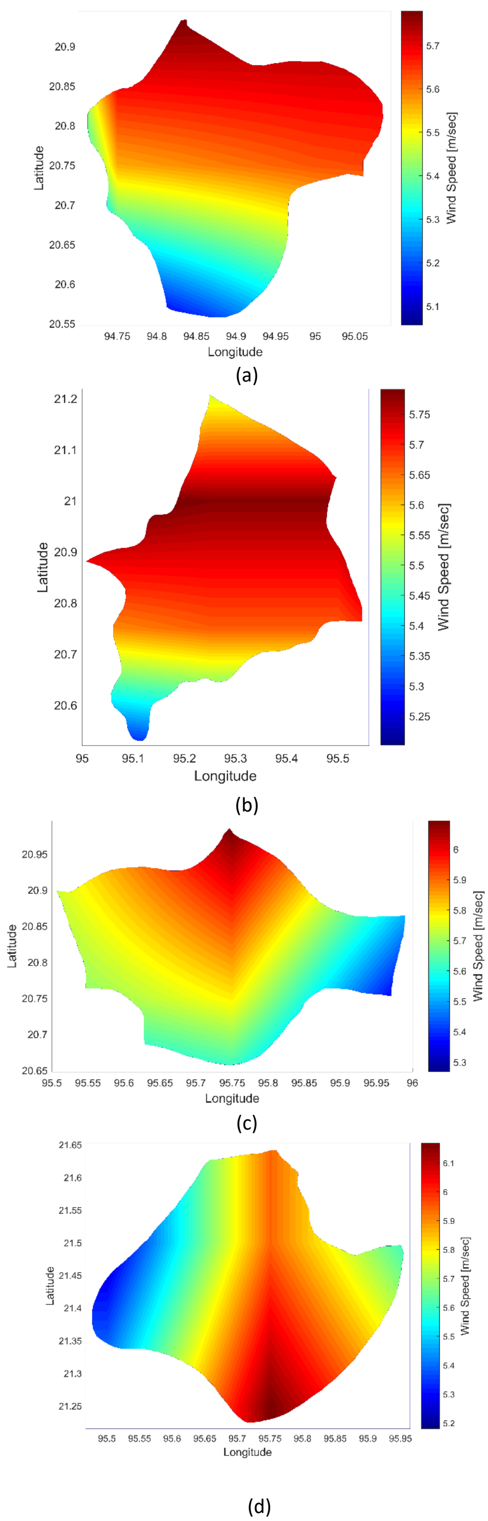


Figure 4 Seasonal wind speed map of selected townships in rainy season for 2017 (a) Chauk Twsp. (b) Kyaukpadaung Twsp. (c) Meiktila Twsp. (d) Natogyi Twsp.

Figure 5 shows township-level seasonal wind speed maps for winter in 2017. In winter, Natogyi has the lowest maximum wind speed of nearly 3.7 m/s and highest maximum wind speed of nearly 4 m/s is observed in Meiktila township.

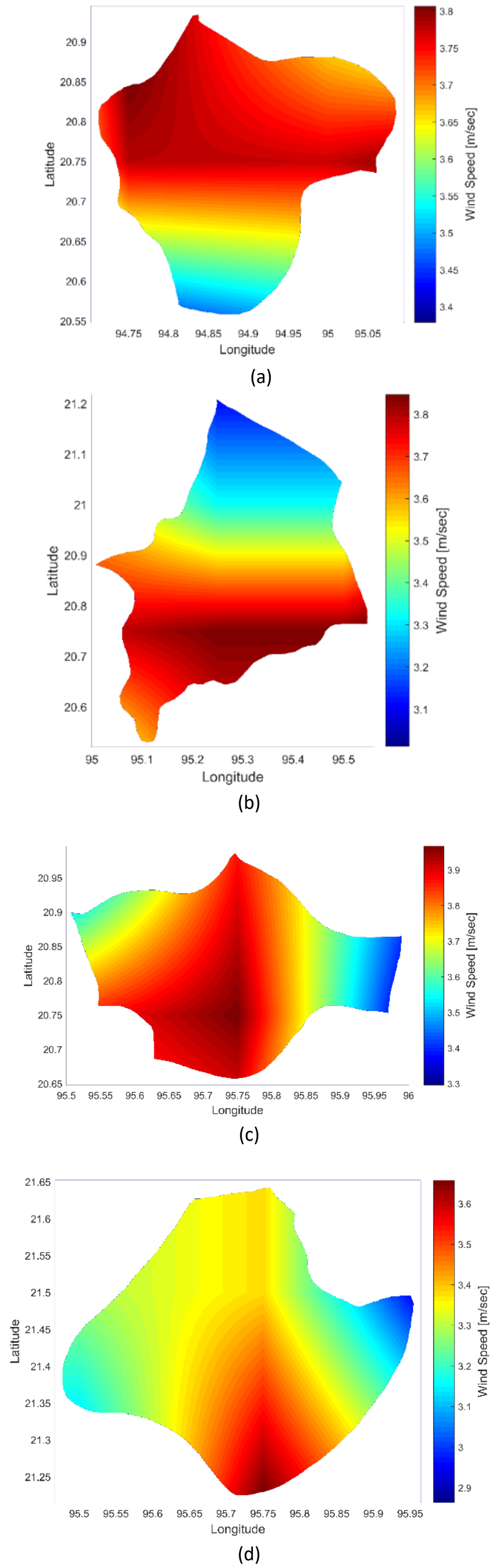


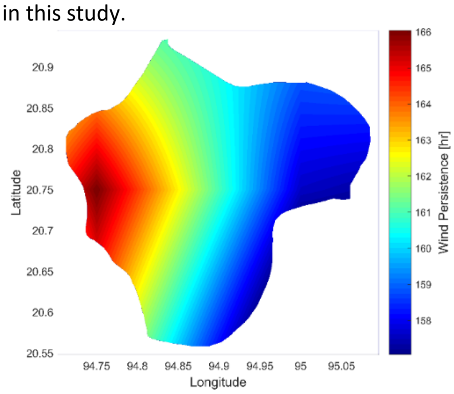
Figure 5 Seasonal wind speed map of selected townships in winter for 2017 (a) Chauk Twsp. (b) Kyaukpadaung Twsp. (c) Meiktila Twsp. (d) Natogyi Twsp.

Chauk and Kyaukpadaung townships are observed to have around 3.8 m/s as the highest wind speed for winter. Therefore, in terms of wind speed for seasonal variation, winter has the lowest and rainy season has the highest wind speed. Seasonal variations are also summarized in Table 3.

3.4 Seasonal Variation Of Wind Persistence

Wind persistence is also one of the significant parameters to characterize wind resource assessment. Using auto-correlation based method, township-level seasonal wind persistence maps were generated for the selected townships by using Equation (4). For rainy season, wind persistence maps are shown in Figure 6. Maximum wind persistence between 160 hours and 170 hours are observed in Chauk, Kyaukpadaung and Meiktila townships. Natogyi township has maximum wind persistence up to around 190 hours and all townships have minimum of wind persistence hours above 150 hours. Seasonal wind persistence maps for summer and winter are not reported here but summarized in Table 3.

Table 3 summarizes data on wind characteristics: wind speed, power density and persistence for the selected four townships in central part of the country. As seen in Table 3, although averaged wind speed varies between 4.15 m/s and 4.86 m/s, maximum wind speeds in the rainy season are 5.78, 5.79, 6.09, 6.17 m/s for Chauk, Kyaukpadaung, Meiktila and Natogyi townships respectively with power density of 180, 181, 199, 218 W/m^2. These results indicate that Meiktila and Natogyi are best candidate townships for further resource assessment and the assessment should be done in the remaining townships as well because site measurements with spatial correlations and extrapolation will reveal more accurate results than current findings in this study.



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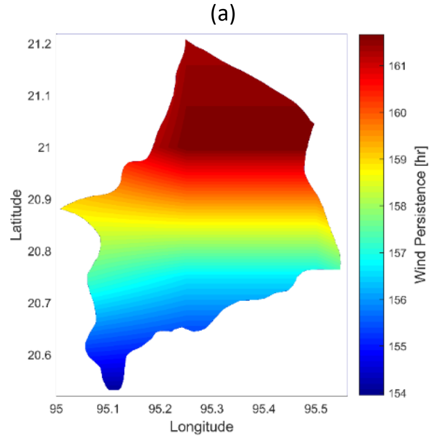

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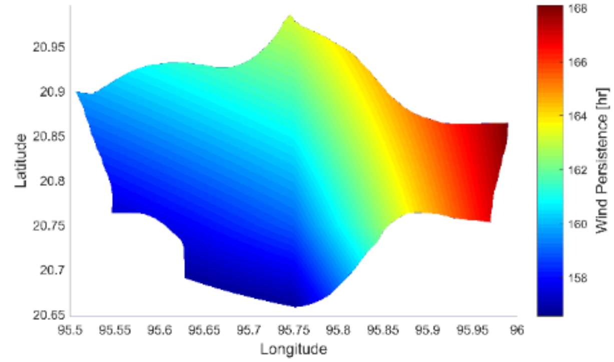

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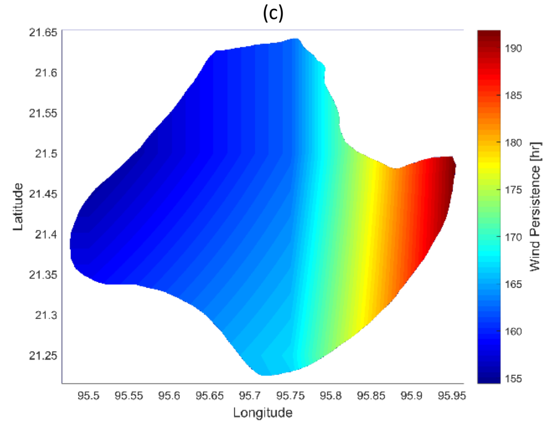


(d)

Figure 6 Seasonal wind persistence map of selected townships in rainy season for 2017 (a) Chauk Twsp. (b) Kyaukpadaung Twsp. (c) Meiktila Twsp. (d) Natogyi Twsp.

3.5 Annual Variation And Wind Rose

Figure 7 shows variations of monthly mean wind speed at the four potential townships for 2017. As seen in the figure, the wind speed varies between 3 and 8.2 m/s. Meiktila and Kyaukpadaung townships have wind speed of 4 m/s and above from March to December while this range is from April to October for other townships. This result is significant because cut-in speed of most utility scale wind turbines is 4 m/s indicating that Meiktila and Kyaukpadaung townships have 10 months of wind turbine operations and Chauk and Natogyi have 7 months of operating time.

Therefore, it can be concluded that all four townships should be further assessed for potential development of wind energy project. Moreover, among all four townships, Natogyi townships has the highest wind speed from April to December with a noticeable maximum difference of around 1 m/s compared to the maximum values in other townships.

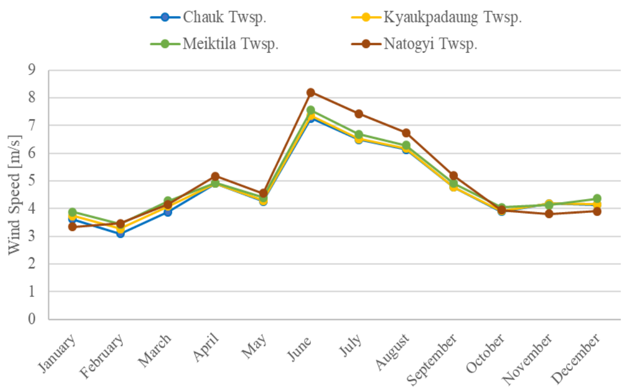
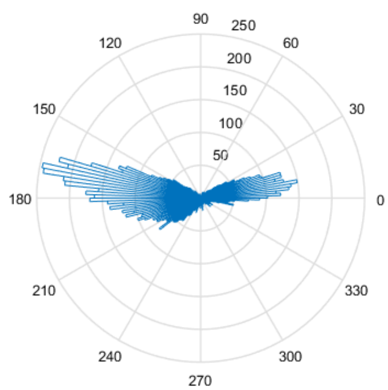


Figure 7 Monthly mean wind speed at selected locations for 2017

Wind rose is essential in siting wind turbines because wind turbines should face the prominent wind direction during the windiest period and the site should be clear off any barrier or terrain in the upstream of the turbine. Therefore, wind rose diagrams are useful in wind turbine siting and wind farm layout design. Figure 8 shows wind rose diagrams for the four townships. Prominent wind directions at all townships is west-north-west.



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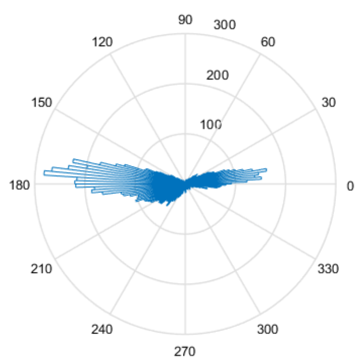

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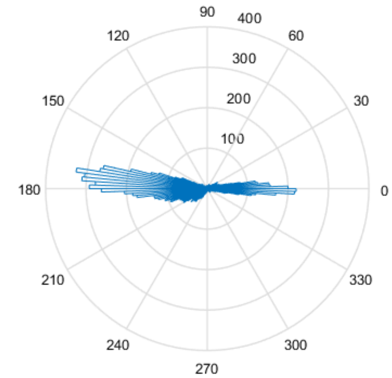

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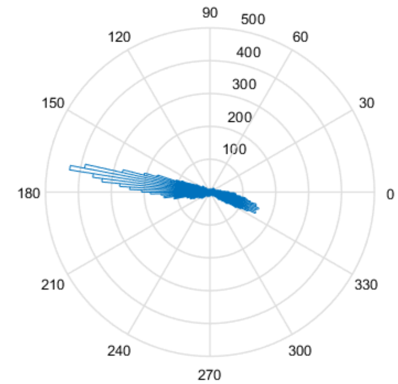

(d)

Figure 8 Wind rose diagram at specific location in selected township for 2017 (a) At (N 20.75, E 95) in Chauk Twsp. (b) At (N 20.75, E 95.25) in Kyaukpadaung Twsp. (c) At (N 20.75, E 95.75) in Meiktila Twsp. (d) At (N 21.25, E 95.75) in Natogyi Twsp.

3.6 Weibull Distribution

Weibull distribution can be used to describe the wind variation for a typical site. Figure 9 shows Weibull distribution of yearly wind speed from 2010 to 2017 at each specific location situated in the selected four townships generated by using Equations (5) to (7). Analysis of Weibull parameters k and c shows that 2015 is the worst case year and 2017 is the best case year. Weibull parameters for the worst case and best case years for each specific site are arranged in tabular form (Table 4).

As seen in the Table 4, 2015 and 2017 are found to be the worst case and best case years for Weibull parameters. Weibull parameter k ranges from 1.82 to 2.35, and 5.09 and 5.64 for Weibull parameter c. In the best case year 2017, Meiktila has highest k value and Natogyi township has lowest k value. For both 2015 and 2017, Meiktila and Kyaukpadaung have higher k values than other townships. It can be seen from the Table 4 that at all four sites, operating wind (above 4 m/s) lasts for longer than 4370 hours (more than half a year) even for the worst case year 2015. For the best case year 2017, minimum operating period is found at Natogyi with 5309 hours and maximum period at Meiktila with 5774 hours.

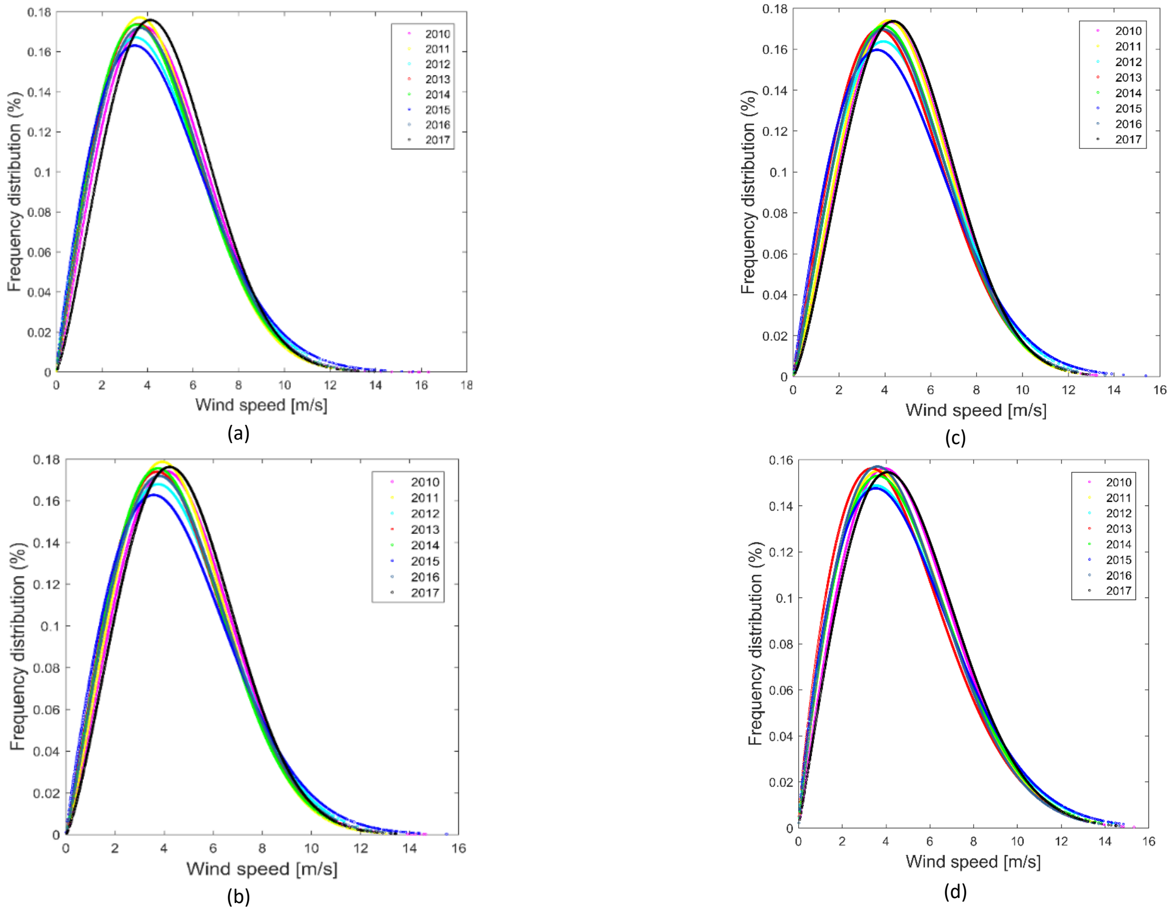

Figure 9 Weibull distribution at specific location in selected township
(a) At (N 20.75, E 95) in Chauk Twsp. (b) At (N 20.75, E 95.25) in Kyaukpadaung Twsp. (c) At (N 20.75, E 95.75) in Meiktila Twsp. (d) At (N 21.25, E 95.75) in Natogyi Twsp

These results further confirm the suitability of the four townships for siting wind turbines. Wind speed of higher than 6 m/s also lasts for about 1/3 of a year even for the worst case year 2015 at all sites.

3.7 Discussions

Although Myanmar generally has low wind speed, some potential locations for wind energy could be identified. Such revelation is important to meet country's target of contribution of solar and wind energy as 9% of national energy mix. Both this study and previous study by Thi Thi Soe et al. found out that coastal areas and central regions have best wind conditions in Myanmar [6]. At four selected townships in the central part of Myanmar, although mean wind speed is low, based on analysis of seasonal variation characteristics of wind in the rainy season, wind speed of nearly 6 m/s at 100 m height was found for Chauk and Kyaukpadaung townships while 6 m/s and above was found for Meiktila and Natogyi townships.

These results are quite positive because for the considerations of wind power project, wind speed of at least 6 m/s is necessary. Results on yearly variations also show favourable wind conditions with wind speed of 4 m/s with maximum period of 7 months a year for Chauk and Natogyi, and 10 months for Meiktila and Kyaukpadaung. These periods at all townships cover the months of March, April and May and hence indicating that wind power might be of important considerations to complement hydropower which is normally low due to low water level during those months. Moreover, peak wind speeds in June and July (Figure 7) can also complement low solar energy in the rainy season.

Using time-domain auto-correlation method for persistence analysis; this study shows that rainy season has the highest persistence values in all four townships. Persistence value is found to be a minimum of 162 hours in Kyaukpadaung and a maximum of 192 hours in Natogyi. Based on results of Weibull parameter distribution, for all four townships, 2015 is the worst year with lowest k value of 1.82 in Natogyi. Therefore, further analysis or resource assessment should be done based on the year 2015 since energy production estimation should be done for worst case year so that economic consequences by worst case year could be compensated

Table 4 Weibull parameters at specific locations of selected township in Myanmar for 2015 (worst case year) and 2017 (best case year)

Township	Chauk		Kyaukpadaung		Meiktila		Natogyi	
(Lat, Lon) [deg]	N 20.75, E 95		N 20.75, E 95.25		N 20.75, E 95.75		N 21.25, E 95.75	
Year	2015	2017	2015	2017	2015	2017	2015	2017
Weibull Parameter k	1.90	2.27	1.95	2.31	1.95	2.35	1.82	2.05
Weibull Parameter c	5.09	5.33	5.18	5.40	5.29	5.54	5.48	5.64
Hours ($u \geq 4$ m/s)	4658	5349	4766	5503	4988	5774	4853	5309
Hours ($u \geq 6$ m/s)	2642	2443	2688	2474	2839	2727	2888	2775

Power producing time estimated by Weibull parameters show that operating hours at 4 m/s and above for Chauk, Kyaukpadaung, Meiktila and Natogyi townships vary between 4658 and 5774 hours (53.17% and 65.91% of a year) and those for wind speed of 6 m/s and above vary 2443 and 2839 hours (27.89% and 32.41% of a year). All these results indicate that the four potential townships are suitable candidates for wind turbine sites. Further wind resource assessment by site measurements should be done and estimation of energy generation based on specific time duration method using manufacturer's power curve should also be conducted.

4.0 CONCLUSION

This study aimed to contribute to resource assessment of wind energy in Myanmar. First, mean wind speed and power density averaged over 8 recent years (2010 to 2017) were presented. Second, for four selected potential townships in the central part of Myanmar, spatial variations of yearly and seasonal wind speed, and prominent wind directions were analysed for the years 2010 and 2017. Based on all these analyses, the following conclusions can be drawn:

- Coastal areas and central parts of Myanmar have potential locations for wind energy development.
- Chauk, Kyaukpadaung, Meiktila and Natogyi townships have favourable wind potential for utility scale wind turbine sites with 7 to 10 months operating time at wind speed 4 m/s above
- Wind speed and wind speed persistence are the highest in the rainy season and the prominent wind is west-north-west for all the townships.
- Meiktila and Natogyi townships have higher wind speed while Meiktila and Kyaukpadaung have longest period of wind conditions 4 m/s and above.
- Operating hours at all four sites are favourable for wind turbine sites with more than half a year operating period of wind turbines.

This study has provided insight into the characteristics of wind from the perspective of wind speed, power density, prominent direction, seasonal variations, and persistence. The detailed maps on characteristics of wind in four selected townships and results on operating hours of the wind by Weibull distribution analysis would serve a basis for further conducting micrositing of wind turbines. In future works, estimation of energy yield should be done by using specific duration time method based on power curve of selected wind turbines and wind dataset with finer spatial resolution and/or site measurement data in recommended potential sites in this study.

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NOMENCLATURE

c	dimensionless scale parameter
f_j	number of occurrences for each bin j
k	dimensionless shape parameter
N	length of time series data
N_B	number of bins
p	pressure of air (N/m^2)
$\bar{P}_A$	wind power density (W/m^2)
R	specific gas constant for dry air
r_k	auto-correlation coefficient
T	temperature of air (K)
u	wind speed (m/s)
$u_{j,m}$	wind speed of mid-point of bin j
$\bar{U}$	mean wind speed (m/s)
ρ_j	air density of bin j (kg/m^3)
σ	standard deviation of wind speed

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