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Study of Diurnal and Seasonal Wind Characteristics for Wind Resource Assessment

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Abstract – *The wind characteristics of Hambantota (6.15° N and 81.07º E) have been assessed by collecting continuous wind data using an automated weather station for a period of 12 months to explore the possibility of implementing small scale wind turbine. The monthly average wind speeds vary in the range of 2.07 m/s to 4.46 m/s at 3 m height. Comparatively higher wind speeds exceeding 2 ms*$^{-1}$ *was observed during the middle of the day compared to the night and early morning hours. In order to characterize the wind speeds and to estimate the power density, Weibull distribution was used. The estimated annual power density exceeds 1,000 W/m*^{2} *at a height of 30 m. When the estimated wind power at different heights were compared, it was observed that at 30 m height the wind power increase by approximately a factor of 2 compared to the wind power at 3 m height. The study revealed that it is possible to harness wind energy in small scale during the day time, during the south west monsoon season.*

Keywords *– monsoons, Sri Lanka, Weibull distribution, wind power density, and wind speed.*

1. INTRODUCTION

Sri Lanka is a tropical country located in the Indian Ocean to the southwest of the Bay of Bengal, between latitudes 5° and 10° N and longitudes 79° and 82° E. The total population of the country is about 20 million. The population of the country is not evenly distributed within the available land area of 65,610 km^2. The Western province where the capital Colombo is located, is densely populated (about 30% of the total population) and has a very high demand on energy compared to the remaining eight provinces. Due to its geographical location, the country experiences two monsoons, the southwest monsoon and the northeast monsoon. The southwest monsoon is generally active during the period from May to September and the northeast monsoon is active during the period from December to February. In between the two monsoon seasons there are two inter-monsoon seasons. The central hills and southwestern part of the country belong to wet zone which receives ample rain throughout the year while most of the southeast, east, north and northwestern parts of the country belong to the dry zone which receives rain predominantly from northeast monsoon season. Since Sri Lanka is an agricultural country, in the dry zone, the water gathered from the seasonal rains is collected in tanks to use during the dry season. Other than the tanks in the dry zone there are number of reservoirs located in the major rivers and streams where the primary objective is power generation.

With the rapid development in the country, the demand for energy is increasing every year. The total energy requirement in the country during year 2010 was approximately 2000 MW [1]. Substantial portion of the country's energy requirement is generated through hydro power. In order to meet the growing demand, the government is promoting mini hydro power projects where the major investment is borne by the private sector. Apart from hydro power stations there are about seventeen thermal power stations and ten renewable energy plants operated by the Ceylon Electricity Board (CEB) and the private sector [1]. With the increase in the fuel prices, the demand for the renewable energy sources is increasing. Although there was less attention to renewable energy sources in the past, there is an increasing attention in recent years to develop power stations based on renewable energy sources such as wind. Several studies have already been carried out in the southeastern coast, western coast, northwestern coast, northern coast and central part of the island to assess the available wind resources [2].

Wind energy can be considered as a green technology as it has only minor impact on the environment [3]. On average, the ratio of wind power to incident of solar power is in the order of 2%, reflecting a balance between input and disruption by turbulence and drag on surfaces. Only a small fraction close to the earth's surface is accessible and a fraction of these locations have steady winds that are strong enough to be exploited [4].

Nevertheless, small scale wind turbines have been used to harness wind energy in domestic scale in order to meet the domestic energy requirement. It has been estimated that the technically usable wind energy potential as 30 trillion kWh. Due to unsteady nature of the wind, it is not possible to perform a real wind energy assessment by developing a mathematical model. Therefore, it is important to carry out long term observation of the wind characteristics at potential locations [5].

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Published results show that there are only a few local studies available in the public domain, related to wind characterization and analysis in Sri Lanka. One such study has been carried out under the Sri Lanka - Netherlands energy programme during the period of 1987 to 1989 in central highlands and in southern part of Sri Lanka [6]. The study revealed that major part of the wind energy can be harnessed during the period from June to September when the reservoirs used to store water for electricity generation is low. A recent study has been carried out to analyze the maximum wind power penetration levels in the western coast (Kalpitiya peninsula). The voltage stability, frequency stability and the transient stability of wind power has been discussed in this work [7].

Due to unsteady nature of the wind the power generated from wind energy systems are not stable. In order to address this issue a case study has been carried out to access the feasibility of integrating wind and hydro power resources. The study concludes that there is a strong possibility of system integration in Sri Lanka [8]. By using a computer generated model to predict the wind power production from wind farms, it has been concluded that cost of wind power generation is competitive compared to other available renewable sources [9].

The characteristics of wind speeds in ten districts have been analyzed in another study where Weibull scale parameter and shape parameter have been computed. Using the Weibull distribution for each district, seasonal variation of wind speed has been obtained. Based on the analysis it was concluded that Hambantota has a high wind potential compared to other locations investigated in the study [10].

The main objective of this work is to study general wind characteristics in Hambantota such as diurnal and monthly variations by collecting continuous data in short time intervals using an automated weather station. Although wind characteristics are already reported for Hambantota in a previous work [6], we believe that this study will strengthen the earlier findings. The study has also been extended to model the wind speed distributions with Weibull distribution to calculate the wind power potential at different heights to look into the possibility of implementing a small scale wind turbine.

2. COLLECTION OF WIND DATA

The required wind data were collected using an automated weather station [11] installed at Hambantota botanical garden (coordinates 6.15° N and 81.07º E). The selected site has an altitude of about 30 m from the mean sea level and it is located in the southern part of Sri Lanka which belongs to the dry zone. The surrounding of the weather station is an open area without having obstacles for the flow of wind. The southwest, south and southeast directions are exposed to the coastal belt.

The automated weather station consists of a temperature sensor, a humidity sensor, a rain gauge, an anemometer and a wind wane. A three cup anemometer and a wind wane were used to measure the wind speed and the wind direction at a height of 9 feet (3 m). The anemometer consists of a rotary encoder wheel and an optical sensor which produce a pulse train proportional to the wind speed. All sensors were calibrated prior to use. The anemometer was calibrated using a wind tunnel in order to assure the accuracy of the measurements.

The wind data were recorded continuously for a period of one year starting from March 2011 to February 2012. The data were sampled in 10 second intervals, averaged for 10 minute and 1 hour intervals and recorded in an in-built data logger in the automated weather station.

In order to estimate wind speed at higher levels, data recorded at 10 minute time intervals at two different heights (10 m and 20 m) near the location where the weather station was installed were also used. The surroundings of the two locations have nearly identical terrain conditions.

3. WIND SPEED ANALYSIS

Table 1 show the monthly variation of wind speed in Hambantota, calculated using the data captured from the automatic weather station. Monthly mean, and the minimum and maximum wind speeds were obtained for each month by analyzing the wind speeds averaged over 10 minute intervals and the standard deviation was calculated considering the same data set separately for each month. The lowest mean wind speed was observed for the month of January (2.07 ms^{-1}) while the highest was observed for the month of July (4.46 ms^{-1}). The maximum wind speeds above 9.0 ms^{-1} were observed during the months from May to November which corresponds to the southwest monsoon season and the second inter-monsoon season. The mean temperature (not shown here) also showed a similar variation where the middle of the year tends to be relatively warm while the beginning of the year and the end of the year tend to be cooler.

The diurnal variation of mean wind speed, disaggregated into four seasons (southwest monsoon, northeast monsoon and two inter monsoons), is shown in Figure 1 and Figure 2. One of the key features common to all seasons is the existence of higher wind speeds (exceeding 2 ms^{-1}) during the middle of the day (from 6:00 h to 18:00 h) compared to the speeds around 1-2 ms^{-1} during the evening hours extending through the night to early morning hours.

In all seasons, the wind speeds tends to peak around 14:00 h. During the northeast monsoon season and first inter monsoon period the wind speeds are low compared to the wind speeds of southwest and second inter monsoon period. This is agreement with the measurements reported in earlier studies [6].

Hambantota is located in the dry zone and receives less rainfall compared to the wet zone. As a result, the area is very hot during the day time. The high wind speed during the day time is due to the low pressure region created over the land by the high temperature.

The analysis of the wind direction shows that the wind direction is correlated with the seasons (see Figure 3). This is not surprising since the monsoons are defined according to the wind patterns. During the northeast monsoon period more than 30% of wind is directed towards north/northeast direction while another 20% is directed towards northeast direction. Furthermore, nearly 15% of the wind is directed towards northeast/east and more than 10% of the wind is directed towards north. The persistence in wind direction is in slight disagreement with the earlier studies [6].

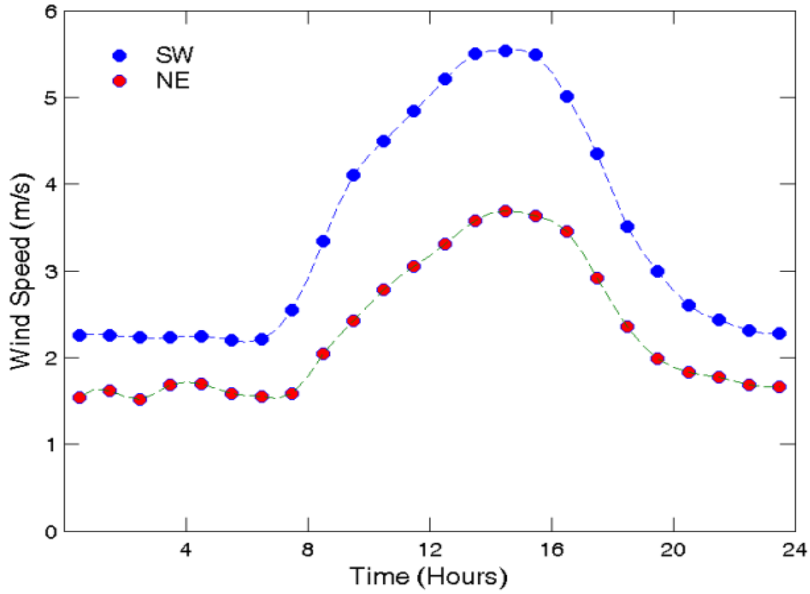

Fig. 1. Diurnal variation of wind speed (Southwest and Northeast monsoon periods).

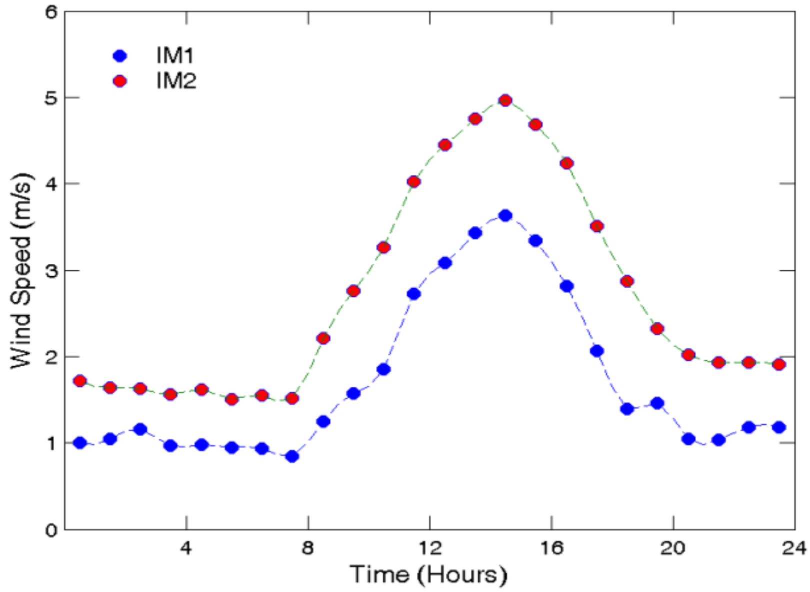

Fig. 2. Diurnal variation of wind speed (1st inter-monsoon and 2nd inter-monsoon periods).

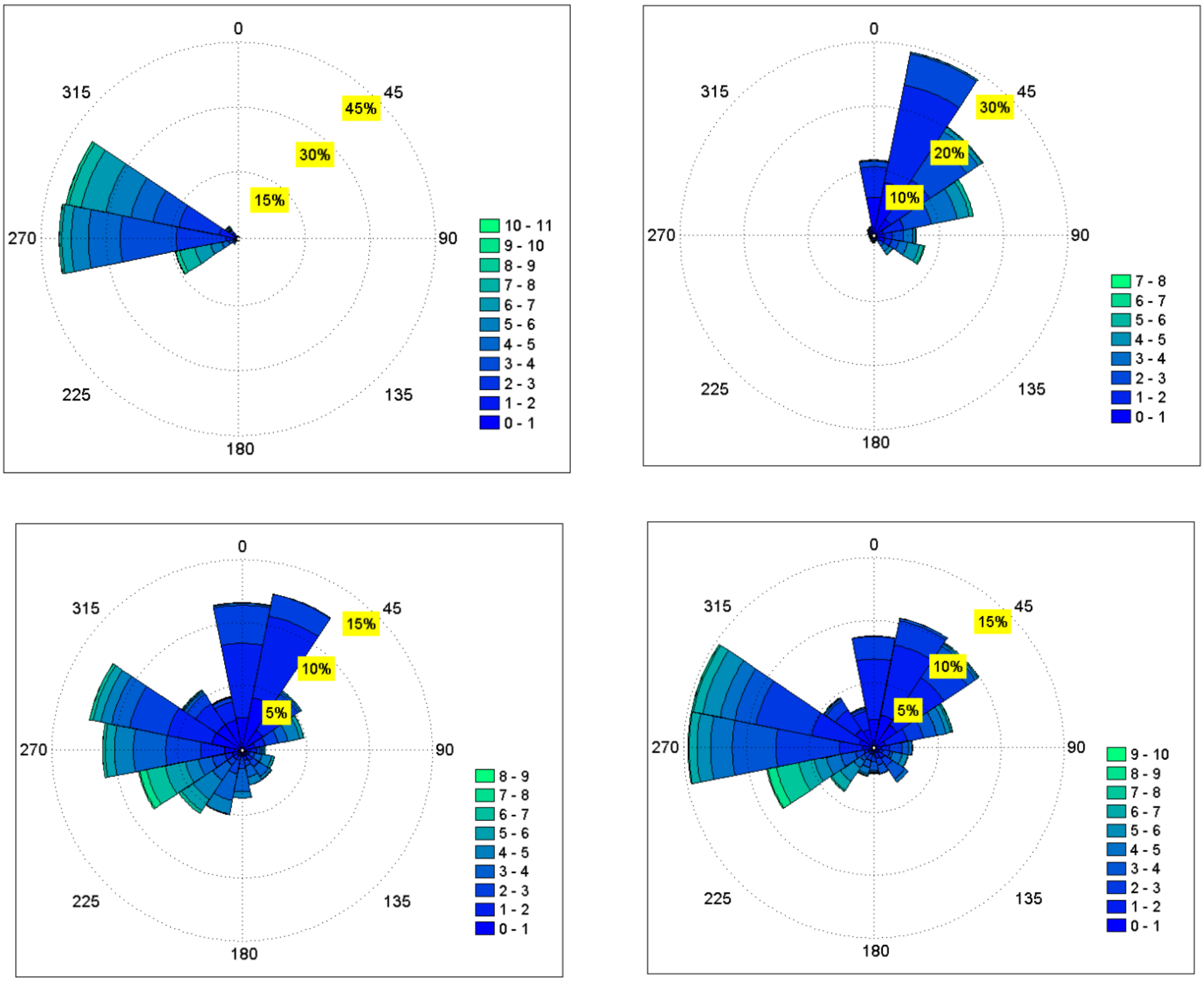

Fig. 3. Seasonal variation of the wind direction (a) Southwest monsoon (b) Northeast monsoon (c) 1st inter-monsoon (d) 2nd Inter-monsoon.

Table 1. Monthly variation of wind speed at Hambantota.

Month	Mean wind speed (ms^{-1})	Minimum wind speed (ms^{-1})	Maximum wind speed (ms^{-1})	Standard Deviation
January	2.07	0.20	3.30	0.67
February	2.41	0.30	6.50	1.31
March	2.18	0.30	8.30	1.48
April	2.60	0.30	8.50	1.68
May	4.22	0.30	9.30	1.85
June	4.40	0.30	9.80	1.76
July	4.46	0.30	9.70	1.72
August	3.95	0.30	9.00	1.89
September	3.94	0.30	10.20	1.89
October	3.10	0.30	9.40	2.05
November	2.23	0.30	9.70	1.36
December	2.17	0.30	7.80	1.22

Although during the southwest monsoon the wind direction was expected to be in the direction of southwest, data shows a different behavior. Analysis shows that 40% of wind is directed towards the west. A similar amount is directed towards the west/northwest while another 15% is directed towards the west/southwest. For the first intermonsoon season, the majority of the wind is aligned towards two directions north and west. A similar distribution of wind direction is observed for the second intermonsoon period as well. Since the two intermonsoons fall in between southwest and northeast monsoon periods, they show a transition of wind directions. Throughout the year, very little wind is seen in the south-east quardrant.

Wind speeds in a particular site over a period of time vary with time. In order to reduce statistical fluctuations in wind speed distributions, it is necessary to have long term wind data covering a period of at least one year. There are three statistical distributions generally used to represent wind speed distributions to reduce statistical fluctuations. They are Weibull, Lognormal and Gamma distributions. Once the wind speed distribution is known, the wind energy density for the particular location can be calculated [6].

The Weibull distribution provides a close approximation to the probability laws of many natural phenomena including wind speeds. It has been used to model parameters such as time to failure of mechanical or electrical systems [12]. In this study, the Weibull distribution was used to model the wind speed distribution measured over a period of one year.

The two parameter Weibull distribution function for wind speed is given by:

$$f(v) = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (1)$$

where *f(v)* is the probability of observing wind speed *v*, *k* is dimensionless Weibull shape parameter which indicates how narrow the wind distribution is and *c* is the scale parameter having dimensions of speed which indicate how windy the location under consideration is [12-14]. For most locations around the world the value of shape parameter *k* is approximately 2.

The cumulative distribution function of the Weibull distribution is [13],

$$F(v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (2)$$

To determine the shape parameter *k* and the scale parameter *c*, Equation 2 can be rearranged by taking the natural logarithm of both sides of the above equation twice to obtain the form of y = *m* x + *b* as:

$$\ln\{-\ln[1 - F(v)]\} = k\ln(v) - k\ln(c) \quad (3)$$

If the wind speed distribution can be represented by Weibull distribution, the plot of $\ln\{-\ln[1 - F(v)]\}$ versus $\ln(v)$ should be a straight line. The gradient of the straight line gives the shape parameter *k* whereas the scale parameter *c* can be computed from the intercept.

The mean wind speed v_m is related to the shape parameter *k* and the scale parameter *c* [13],

$$v_m = c\Gamma(1 + \tfrac{1}{k}) \quad (4)$$

where Γ is the gamma function.

In Figure 4 we show the results obtained by fitting the Weibull distribution function to the measured one hourly wind speed data.

It can be seen that the data can be fitted reasonably well with a straight line. The equation of the fitted straight line is $y = 2.107x - 2.904$ with $r^2 = 0.99$. The estimated shape parameter *k* and the scale parameter *c* were 2.107 and 3.968 ms^{-1} respectively. In Figure 5 we show the measured distribution of wind speeds together with the reconstructed wind speed distribution with the estimated shape parameter and scale parameter. It can be seen that the model slightly overestimates low wind speeds (below 2.5ms^{-1}) and underestimates the higher wind speeds (above 5.5 ms^{-1})

To study the seasonal variation of the wind speeds, using the same method, the shape parameters and the scale parameters were calculated for all four seasons separately. The results are shown in Table 2 together with the mean wind speed v_m.

The shape parameter ranges between 1.197 and 2.107 whereas the scale parameter ranges between 1.747 ms^{-1} and 3.968 ms^{-1}. As expected, the highest *c* value was observed for the southwest monsoon season followed by the second inter-monsoon season.

Table 2. Shape and scale parameter extracted from seasonal wind speed distributions.

Season	*k*	*c* (ms^{-1})	v_m (ms^{-1})
Southwest monsoon	2.107	3.968	3.51
Northeast monsoon	1.538	1.747	1.57
Inter monsoon 1	1.197	1.894	1.74
Inter monsoon 2	1.222	2.206	2.07

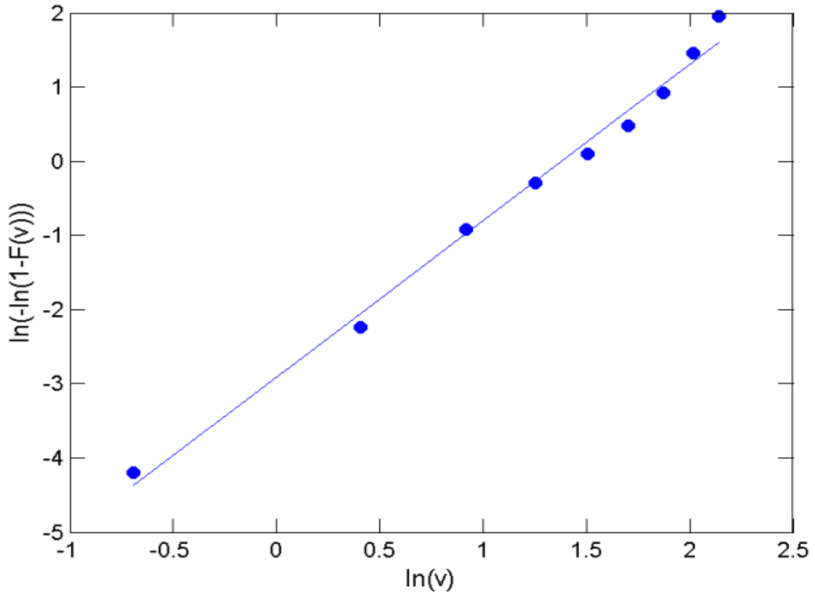

Fig. 4. One hourly wind speed data fitted with Weibull distribution function (Southwest monsoon season).

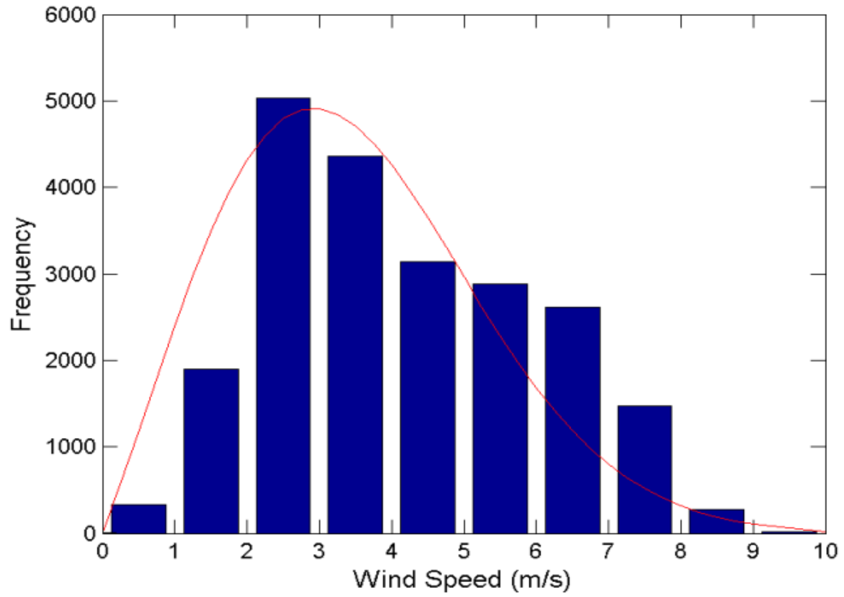

Fig. 5. Comparison of Weibull distribution with the actual wind speed distribution for southwest monsoon season.

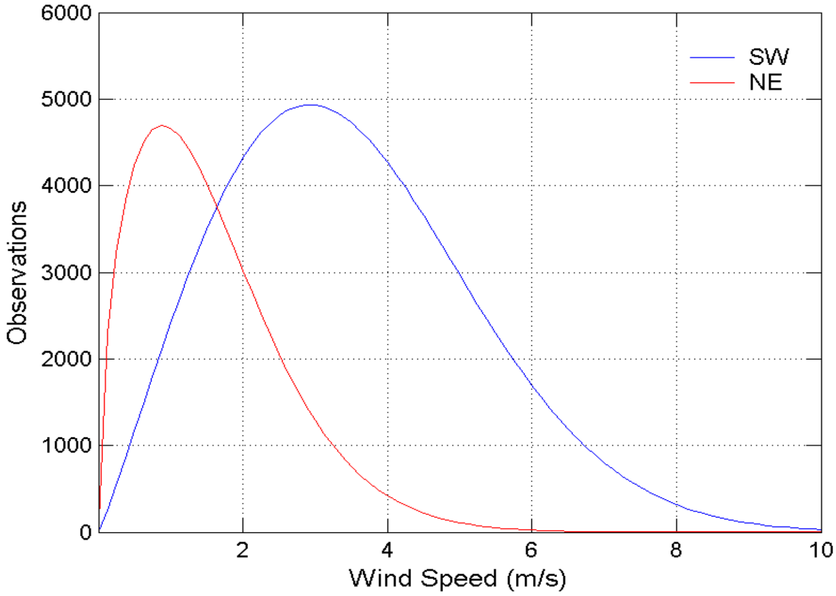

Fig. 6. Reconstructed wind speed distributions for southwest monsoon and northeast monsoon seasons.

Figure 6 shows the distribution of seasonal wind speeds reconstructed through the Weibull distribution for southwest monsoon and northeast monsoon seasons. The reconstructed wind speed distributions for southwest and northeast monsoon seasons show that compared to southwest monsoon season, the probability of occurring low wind speeds in northeast monsoon season is high. During the southwest monsoon season, highest occurrence of wind speed was observed around 3 ms^{-1} whereas during the northeast monsoon season highest occurrence was around 0.75 ms^{-1}. The reconstructed wind speed distributions clearly show that the southwest monsoon season has a higher tendency of observing larger wind speeds compared to the northeast season.

The reconstructed wind speed distributions for two inter-monsoon seasons shown in Figure 7 indicate that the wind speed distributions for two inter-monsoon seasons are nearly identical. The highest occurrence of wind speeds were in the range of 0.5 ms^{-1} to 1 ms^{-1} for first inter-monsoon and second inter-monsoon season respectively.

The surface friction causes the wind to change its magnitude close to the surface of the earth. The measured wind speed at a common height can be extrapolated to estimate the potential wind speeds at a higher elevation by:

$$V = V_0 \times \left(\frac{h}{h_0}\right)^{\alpha} \tag{5}$$

where V is the wind speed at required height h, V_0 is the wind speed measured at height h_0 and α is the power law exponent which depends on the location, shape of the terrain on the ground and the stability of the air [15].

In order to calculate the value of α, the wind speed recorded simultaneously at 10 minute intervals at heights of 10 m and 20 m were used. Figure 8 shows the measured wind speeds at 10 m height against the wind speeds at 20 m height for the month of July. Except for very low wind speeds (below 0.5 ms^{-1}), the wind speeds at two heights vary linearly. Thus, by fitting a straight line fit to monthly data, the value of α for each month can be estimated from the gradient of the graphs.

The value of α was found to vary from 0.04 to 0.21 during the year which average to 0.13 for the terrain considered. Using the estimated values of α and the continuous measurements carried out at 3 m height, the wind speeds at 10 m, 20 m and 30 m heights were calculated for each month. Those results are tabulated in Table 3.

Figure 9 shows the values of wind speeds estimated at 3, 10, 20 and 30 m heights separately for the four seasons. As expected, the wind speed increases when the height above the ground increases. The 1st inter-monsoon shows lower wind speeds compared to 2nd inter-monsoon when the height above the ground increases beyond 10 m. South west monsoon shows higher wind speeds at all heights compared to other seasons. Northeast monsoon season show lower wind speeds at different heights compared to other seasons.

4. WIND ENERGY ANALYSIS

In this work, the wind power density was determined by considering the Weibull distribution parameters (c and k). However the wind power generated by a wind turbine depends on the wind speed, the Weibull parameters as well as the characteristics of the wind turbine [3]. A real wind turbine cannot convert the kinetic energy of the wind to mechanical energy with 100% efficiency due to mechanical losses in the wind turbine itself.

The wind power incident on an area A can be given by:

$$P(v) = \frac{1}{2} A \rho v^3 \tag{6}$$

where ρ is the density of air (kg m^{-3}), v is the velocity of the wind (m s^{-1}) and A is the area (m^2) perpendicular to the direction of the wind. In this case, the area can be taken as the area swept by the wind turbine blades when it is rotating. Since the wind speed varies with time, it is necessary to consider the average wind power which is given by [16]:

$$P_w = \frac{1}{2} A \rho \int_0^{\infty} v^3 f(v)\, dv \tag{7}$$

If $f(v)$ is the Weibull density function representing the wind speed distribution, the average wind power can be given by [16]:

$$P_w = \frac{1}{2} A \rho v^3 \frac{\Gamma(1+3/k)}{[\Gamma(1+1/k)]^3} \tag{8}$$

The wind power density is usually given in W m^{-2}, density of air ρ in kg m^{-3} and mean wind speed v in m s^{-1}, k is the dimensionless shape parameter and Γ is the gamma function.

Table 3. Monthly mean wind speed at 10 m, 20 m and 30 m heights and monthly α value.

Month	α	Wind speed at 10m height (m/s)	Wind speed at 20m height (m/s)	Wind speed at 30m height (m/s)
January	0.124	2.39	2.61	2.74
February	0.119	2.77	3.01	3.16
March	0.095	2.45	2.62	2.72
April	0.143	3.10	3.42	3.63
May	0.143	5.02	5.54	5.88
June	0.143	5.22	5.57	6.11
July	0.145	5.31	5.87	6.23
August	0.079	4.35	4.59	4.74
September	0.036	4.13	4.24	4.30
October	0.096	3.49	3.73	3.87
November	0.176	2.76	3.12	3.35
December	0.210	2.80	3.24	3.53

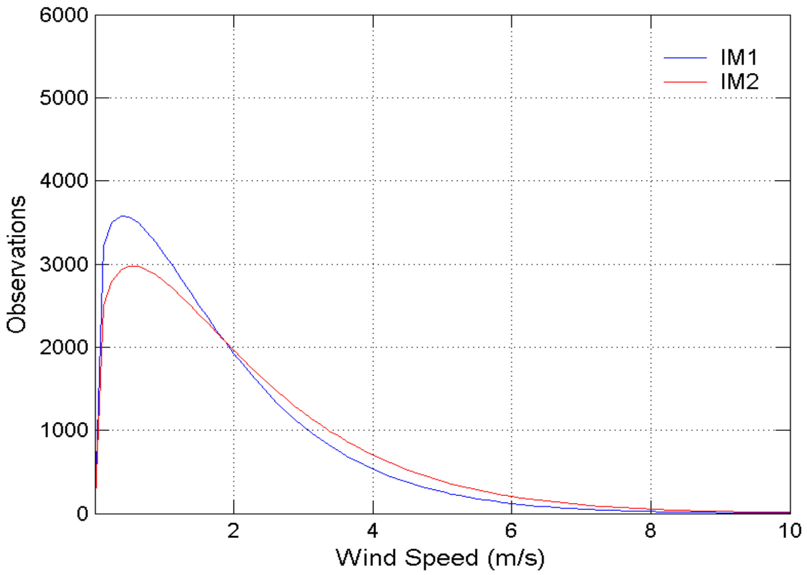

Fig. 7. Reconstructed wind speed distributions for 1st and 2nd inter-monsoon seasons.

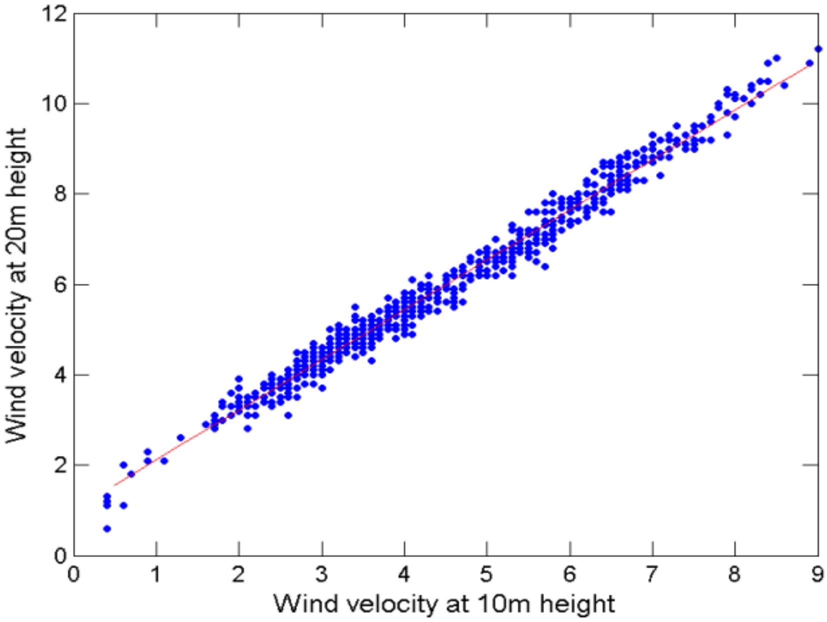

Fig. 8. Wind speed at 10m height against wind speed at 20m height for the month of July.

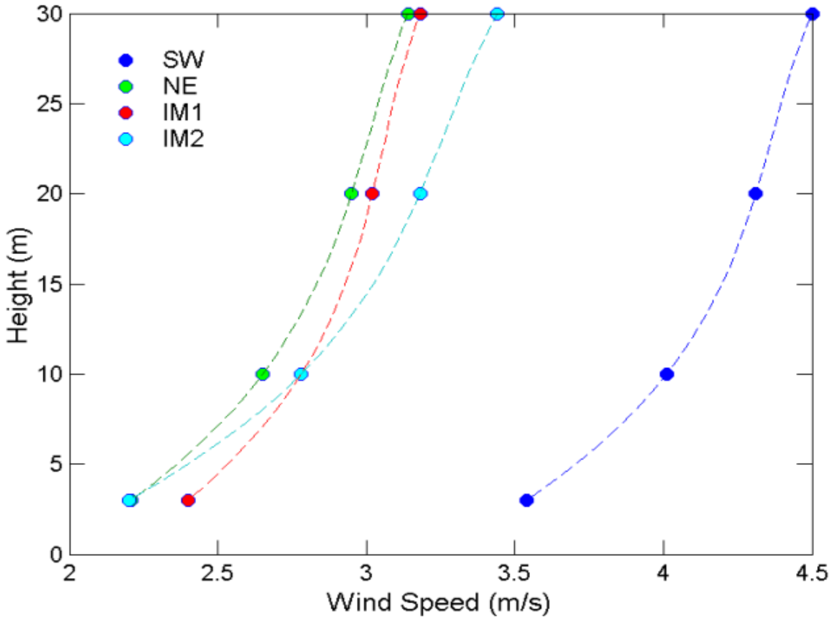

Fig. 9. Variation of seasonal mean wind speed with height.

Using the measured wind data at 3 m height, wind speeds at 10, 20, 30 and 40 m heights were calculated using equation 5. Then the power densities for same heights were calculated using Equation 8. The values of α and the shape parameters *k* corresponding to each month were used in the calculation. The calculated values are shown in Table 4. The shape parameter for different months varies from 1.3 to about 3.1. Low values of shape parameters indicate months having weak monsoonal winds whereas months with high values of shape parameters indicate the months having strong monsoonal winds. This observation agreed with the previously reported results [6].

At 3 m height the calculated annual power density is 672.7 Wm^{-2} (data not shown) which is not economically viable to harness from a wind turbine. Our interest is mainly on small scale wind turbines which can be mounted above 10 m height. The data show that the annual power density can be doubled at a height of

30 m (1171.3 Wm^{-2}) compared to the power density at 3 m height.

Figure 10 shows the variation of power density by month at 10 m height and 30 m height. It can be seen that there is a high variability in the power output which is expected from the variation of wind patterns. There is significant increase in the power density exceeding 150 Wm^{-2} at 30 m height in May, June and July months where the southwest monsoon is active. As reported in an earlier study [6], if the reservoir capacity peak in May and then decrease gradually until October/November where the lowest values are reached, wind power can provide a contribution to sustain the reservoirs; at least partly.

Figure 11 show the diurnal variation of the power density during southwest monsoon season and northeast monsoon period. The data show that the power density is high during the day time compared to night time as expected from diurnal variation of wind speeds. The power density is low during northeast monsoons season compared to southwest monsoon season.

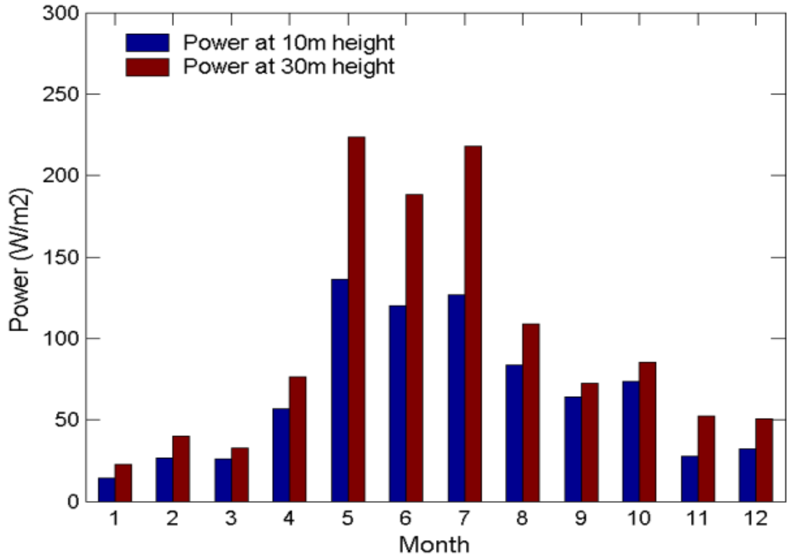

Fig. 10. Monthly variation of wind power density for 10 m and 30 m heights.

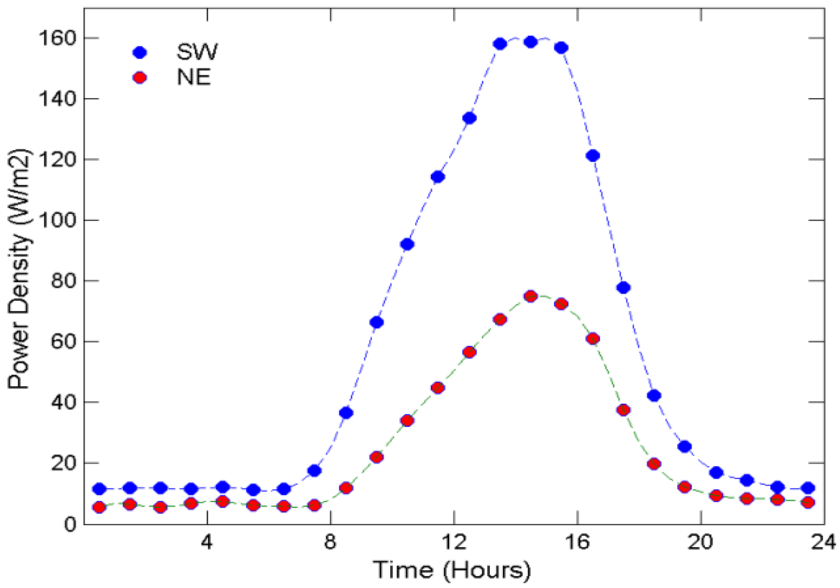

Fig. 11. Monthly variation of wind power density for 10 m and 30 m heights.

Table 4. Monthly shape parameter and power density at 10 m, 20 m, 30 m and 40 m heights.

Month	k	Mean Power Density (W m^{-2})			
		10m Height	20m Height	30m Height	40m Height
January	2.268	14.24	16.60	22.55	24.90
February	1.870	26.59	33.64	40.07	45.89
March	1.441	25.86	32.90	32.62	38.38
April	1.371	56.95	61.84	76.44	91.80
May	2.172	136.41	183.27	223.87	252.19
June	3.089	120.26	156.96	188.16	222.77
July	3.072	126.67	181.49	218.28	262.64
August	2.335	83.41	97.63	108.67	112.83
September	2.704	64.31	69.17	72.35	74.04
October	1.457	73.36	87.81	85.46	102.54
November	1.788	27.76	42.08	52.35	65.46
December	1.635	32.23	48.01	50.49	69.30

5. CONCLUSIONS

In this work, the wind characteristics of Hambantota have been assessed by collecting continuous wind data using an automated weather station for a period of 12 months at a height of 3 m.

One of the key features common to all seasons is that wind speeds exceed 2 ms^{-1} during the middle of the day and lower wind speeds of around 1-2 ms^{-1} exist during the evening hours extending through the night to early morning hours of the day. In all seasons, the wind speeds tend to peak around 14:00 h. During the northeast monsoon season and first inter-monsoon period the wind speeds are comparatively low compared to the wind speeds of southwest and second inter-monsoon period.

The wind speed distributions for southwest and northeast monsoon seasons show that compared to southwest monsoon season, the probability of occurring low wind speeds in northeast monsoon season is high. During the southwest monsoon season, highest occurrence of wind speed was observed around 4 ms^{-1} where as during the northeast monsoon season highest occurrence was around 1.5 ms^{-1}. The wind speed distributions clearly show that the southwest monsoon season has a higher tendency of observing larger wind speeds compared to northeast season.

When the estimated wind power at different heights were compared, it was observed that at 30 m height, the annual wind power output increases by approximately a factor of 2 compared to the annual wind power output at 3 m height. At 30 m height, wind power exceeding 50 Wm^{-2} can be harnessed during day time for a period of seven months to sustain the reservoirs. The power density is low during northeast monsoons season compared to southwest monsoon season.

ACKNOWLEDGEMENT

The wind data for this study was obtained from the automated weather station installed at Hambanthota botanical garden. We wish to acknowledge the support given by the officials at Hambanthota botanical garden, Sri Lanka.

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