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Wind Shear Coefficients and Energy Yields Estimations: Namibia Case Study of Arid Coastal and Inland Locations

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Abstract

Wind shear coefficient (WSC) analysis and energy yield estimation were performed at a coastal and an inland location in Namibia using 10-minute average wind speeds collected at the two locations over a period of one year (January to December 2013). To enable proper understanding of wind shear trends, WSCs, and roughness lengths, wind data were observed at two heights (i.e., 20.88 m and 48.14 m above ground level (AGL) at Terrace Bay (TB) and (23.49 m and 50.49 m AGL) at Okanapehuri (OP). The computations resulted in overall mean values of WSCs of 0.0463 and 0.24 at TB and OP, respectively, and roughness lengths (z_0) of 0.000000673 m and 0.526 m at TB and OP, respectively. The variations of WSCs and z_0 by months, hours and direction were thoroughly analysed and described. At the coast, sea/land interface significantly influenced WSCs and z_0, resulting in lower than expected mean values, whereas at OP, the transitional nature of the vegetation shaped the pattern observed. Based on the observed and extrapolated data, wind resource and energy yield were assessed, using wind turbines selected based on their utilisation factors. Finally, the extrapolated data was compared with the observed data. The effects of WSCs on energy yield were verified.

Keywords: Wind shear coefficient, wind resource assessment, hub height extrapolation, energy yield estimation, roughness length, sea/land breezes

INTRODUCTION

Accurate energy yield estimations of a wind energy project are based on knowledge of wind patterns on the site, and on the hub height of interest. Unfortunately, wind data observations are often done at a height lower than the desired hub height. To accommodate the growing height of modern wind turbines, thorough knowledge of wind shear trends and characterisations at a particular site is crucial [1-3]. Wind shear is the change in wind speed with height in the atmosphere. Good knowledge of wind shear aids suitable turbine design/selection, better energy yield computation and gives better understanding of the site-specific project risk [4]. Wind shear is site dependent. It is directly related to the wind speed, roughness length, atmospheric stability and height intervals [5, 6]. Temperature stratification is known also to significantly influence wind shear patterns resulting in shear variation by month, season, hour and year [2-7]. Different methods have been used to calculate wind shear coefficients to permit hub-height mean speed extrapolation [2]. All the methods contribute a non-negligible error to the extrapolated hub-height mean speed. Uncertainty due to hub-height extrapolation could reach 6% in a flat terrain [8]. Error in energy yield estimations is bound to be larger since errors in speed estimation are known to propagate into energy yield predictions, which varies to the cube of the speed [9]. Power law and log law are the most commonly used computational models to calculate WSCs [1-3]. In this study, both laws were used to calculate WSCs and z_0 at TB (wind speed measured at 20.88 m and 48.14 m) and at OP (wind speed measured at 23.49 m and 50.49 m) above ground level. Local air density, which has a direct impact on energy yield, was evaluated using the observed temperature. Energy yield estimations from the observed and predicted mean wind data were evaluated and compared.

BACKGROUND

Site Description and Data Summary

Wind data measured in a semi-arid inland and an arid coastal location were used for wind shear trends analysis and energy yield estimations. Terrace Bay (TB), a west coast rest camp situated in the Namib Desert, is part of the Skeleton Coast Park in the northern region of Kunene, Namibia (Figure 1). It is a desert with the landscape ranging from dunes to rocky canyons and extensive mountain ranges [10]. The TB wind measurement site is located at latitude S 19°59'34.41" and longitude E 13°02'22.31" at an altitude of 22 m above sea level. It is about 600m to the east of the Atlantic Ocean. Standing north-northeast (NNE) of the tower at TB is a gentle hill 35 m above sea level, situated about 195 m away from the foot of the tower. An 80 m latticed equilateral triangular communication tower was instrumented for the wind measurement. The anemometers at the two measurement heights are located facing the south-south-eastern (SSE) direction and the wind vane at 48.14 m faces the west-north-west (WNW) direction.

Okanapehuri (OP), the inland location, is about 67km north east (NE) of Karibib, in the Erongo region of Namibia (Figure 2). As part of the central plateau, it is situated in a semi-arid zone with vegetation densely covered with *Acacia mellifera* (black-thorn), a shrub or medium-sized tree that grows up to 9 metres in height [11]. The terrain is moderately flat. The OP experiment is located at latitude S 21°53' 16.80" and longitude E 16°29'44.16", at an altitude of 1 140 m above sea level.

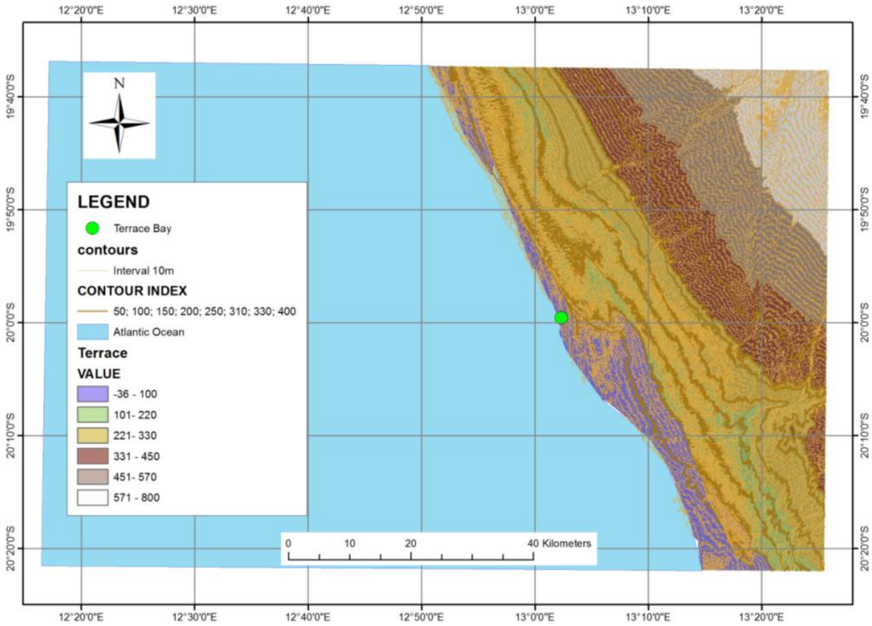

Figure 1: Map of Terrace Bay

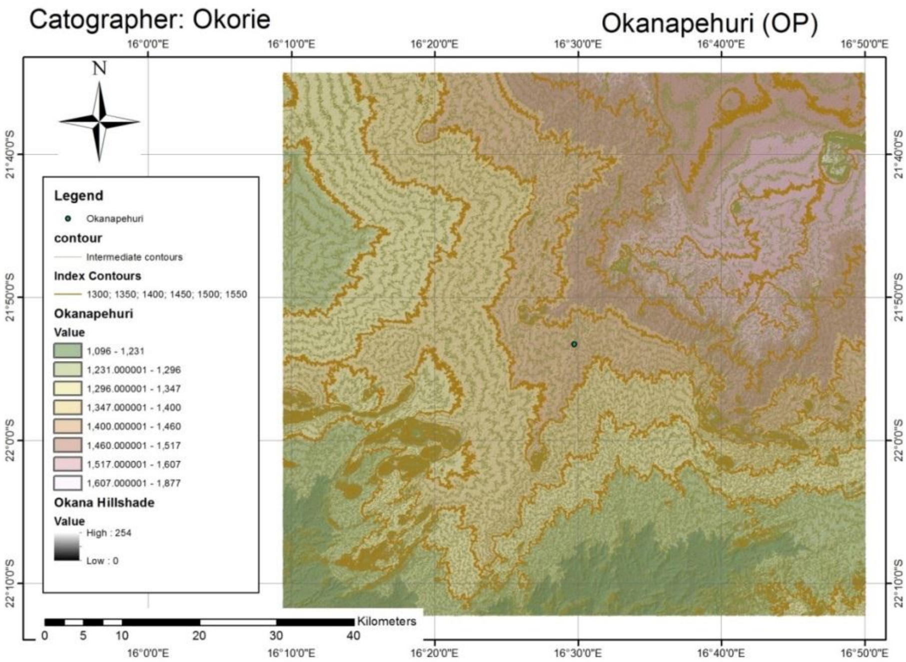

Figure 2: Map of Okanapehuri

Table 1 shows the summary of all meteorological parameters observed in TB and OP, including type, range and accuracy of sensors used.

Table 1: Operating ranges and accuracies of various sensors used for data acquisition

S.no	Parameter	Sensor type	Operating range	Accuracy
1	Wind speed	SW1C3	1.0 - 96 m/s	0.1 m/s
2	Wind vane	SW1 PV1	0 - 360°.	1°
3	Temperature	SW1 10K Probe	-40 - 52.5 °C	± 1.78°C
4	Solar radiation	Pyronemeter	5 -95%	± 5% RH
5	Pressure	SWP	15 - 115	± 1.5 kPa

Methods

Power Law

Hellman in 1916 proposed a simple yet effective model for vertical wind profile, which assumes that the ratio of wind speeds at two different heights can be found using eq. (1), termed power law [12].

$$v_2 = v_1 \left(\frac{h_2}{h_1}\right)^{\alpha} \quad \text{Equation1}$$

where v_1 and v_2 are wind speeds observed at heights h_1 and h_2, respectively. The Hellman index α is called the WSC. WSC, as earlier indicated, is directly dependent on wind speed, hub-height intervals and atmospheric stability [2], [5], [6]. From eq. (1), α does not encapsulate terrain roughness information and its validity has been restricted to lower atmospheric bodies [6], [13]–[15]. The value of α is calculated using eq. (2), as reported by [3-7].

$$\alpha = \frac{In(v_2/v_1)}{In(h_2/h_1)} \quad \text{Equation 2}$$

Logarithmic Law

The log law owes its origin to boundary layer fluid mechanics. Average velocity v at height z above ground level is calculated using eq. (3), as reported in [14].

$$v(z) = \frac{u_*}{k} In\left(\frac{z}{z_0}\right) \quad \text{Equation 3}$$

where $u_* = (\tau/\rho)^{\frac{1}{2}}$ is the friction velocity, k = 0.4 is the von Kármán constant and the roughness length is z_0. The z_0 measures the rate at which the wind speed changes with height above ground level, which is directly related to terrain roughness. A simpler physical model of eq. (3) for vertical height extrapolation is the log law (eq. 4).

$$v_2 = v_1 \frac{In(h_2/Z_0)}{In(h_1/Z_0)} \quad \text{Equation 4}$$

Eq. (4) is much easier to solve, as it eliminates u_* and k, that could be difficult to establish in the atmosphere [15]. Neutral stability is assumed, where convective heat transfer is negligible and the lapse rate (fall in temperature in the troposphere with height) is nearly adiabatic [6]. It is a simpler form of log linear law, which only depends on z_0 and is valid near the ground over a flat terrain. Solving eq. (2) and (4) by eliminating v_1 and v_2 gives a formula for calculating z_0 (eq. 5), as reported by Gualtieri and Secci [5].

$$z_0 = exp\left[\frac{h_2^{\alpha} In(h_1) - h_1^{\alpha} In(h_2)}{h_2^{\alpha} - h_1^{\alpha}}\right] \quad \text{Equation 5}$$

Air density

Air density is significantly influenced by the ambient air temperature and pressure and is calculated using eq. (6), as reported by [2; 5-6].

$$\rho = \frac{P}{R \times T} \quad \text{Equation 6}$$

where P is the air pressure [mbar or kPa], T the air temperature [K], and R is the specific gas constant for air [287.053 $J/kg\,.K$].

RESULT AND DISCUSSION

Data Description

Wind speeds below 3 m/s were excluded from analysis at both sites. The 10-minute average wind data were collected from both sites over a period of one year (January to December 2013). Mean month and annual WSCs of 2014 and 2015 at OP were analysed and compared to 2013 data.

Table 2: Summary of TB and OP 2013 wind data site statistics

					Terrace Bay						
Labels	Units	Height (m)	Mean	Min	Max	K	C	WPD (w/m^2)	St. Dev	TI	Sensor Direction
WS	m/s	20.9	5.91	0	21.7	2.11	6.64	173	0.58	0.13	SSE
WS	M/S	48.14	6.14	0	21.9	2.1	6.89	199	0.56	0.12	SSE
					Okanapehuri						
Ws	m/s	23.5	3.99	0.33	14.15	1.88	4.46	43	0.84	0.23	W
WS	m/s	50.49	4.79	0.36	16.32	1.88	5.37	82	0.83	0.22	W

Table 2 is the summary of TB and OP site wind data statistics. Average wind speed increased with height at both sites. TB registered average a wind speed of 5.91 m/s and 6.14 m/s at 20.88 m and 48.14 m heights, respectively, while OP recorded mean speeds of 3.99 m/s and 4.8 m/s at 23.5 m and 50.49 m, respectively. Wind power density (WPD) increased with height at both sites. The Weibull parameters k and c were estimated using maximum likelihood algorithm. The k values remained the same at both sites indicating a moderately higher spread away from the mean. The mean turbulence intensity (TI) decreased with height at TB and OP. On the average, TB recorded lower TI compared to OP. The mean air densities at the two sites were calculated using eq. (6) based on the temperature observed at both sites.

Table 3 is a summary of the monthly variations of mean air densities at both sites with overall mean values of $1.216\ \text{kg/m}^3$ and $1.045\ \text{kg/m}^3$ at TB and OP, respectively. At both locations, mean values of air density were higher in winter and lower in summer. In winter months (June, July and August), at the coastal location (TB), the mean values were 1.227 kg/m^3, 1.227 kg/m^3 and $1.229\ \text{kg/m}^3$. The transition months, May and September, recorded mean values of $1.216\ \text{kg/m}^3$ and $1.226\ \text{kg/m}^3$, respectively. The mean values in winter and transition seasons are very close to the default value ($1.225\ \text{kg/m}^3$), agreeing with findings reported in [1] at coastal locations in Southern Italy. At the inland location (OP), winter and transition months recorded higher values compared to summer seasons. The desert coastal location recorded higher mean values of air density than the inland location as expected.

Table 3: Monthly variation of mean air density (kg/m^3) at TB and OP in 2013

Month	TB	OP
Jan	1.204	1.032
Feb	1.204	1.032
Mar	1.205	1.035
Apr	1.214	1.046
May	1.216	1.051
Jun	1.227	1.060
Jul	1.227	1.062
Aug	1.229	1.060
Sep	1.226	1.049
Oct	1.223	1.037
Nov	1.215	1.035
Dec	1.205	1.040

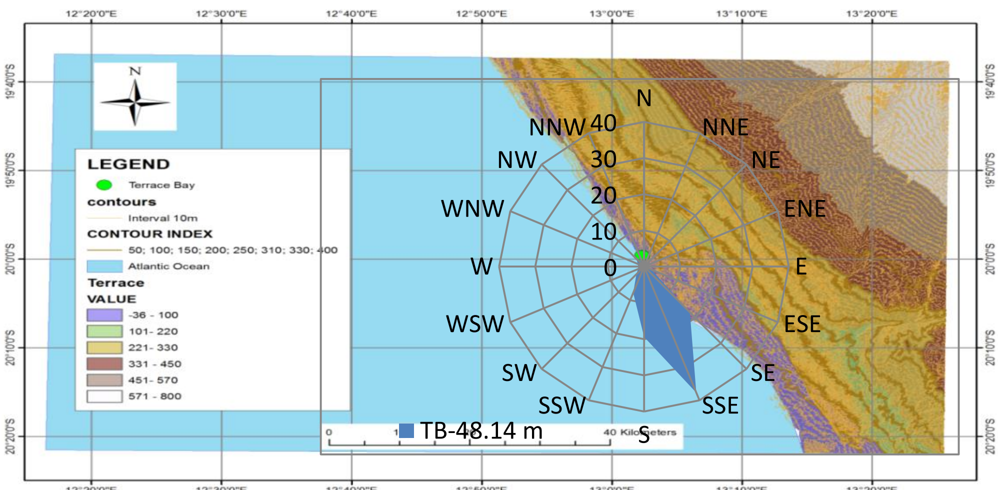

Figure 3a: Wind rose at Terrace Bay from measured data collected at 48.14 m AGL

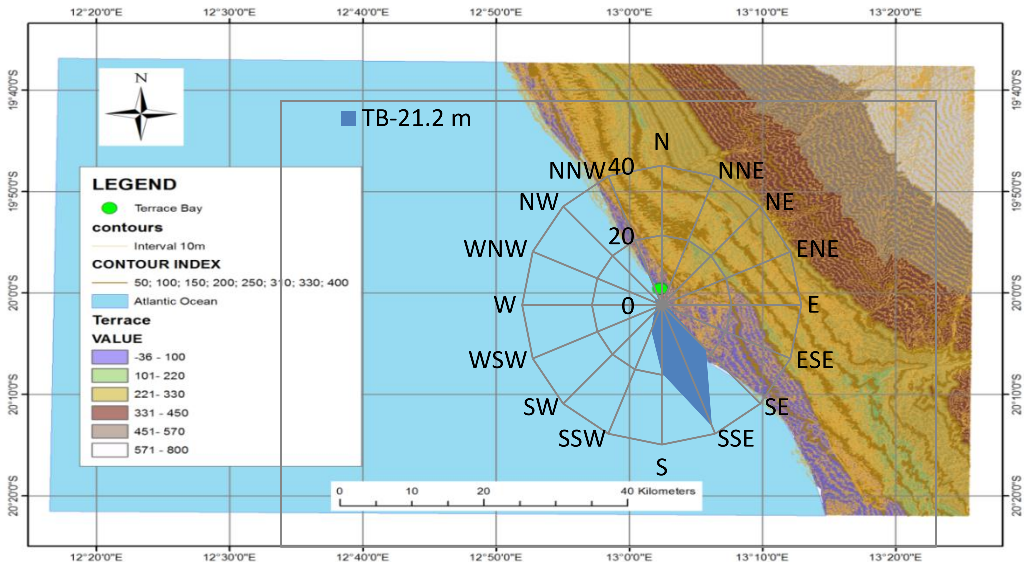

Figure 3b: Wind rose at Terrace Bay from measured data collected at 28.88 m AGL

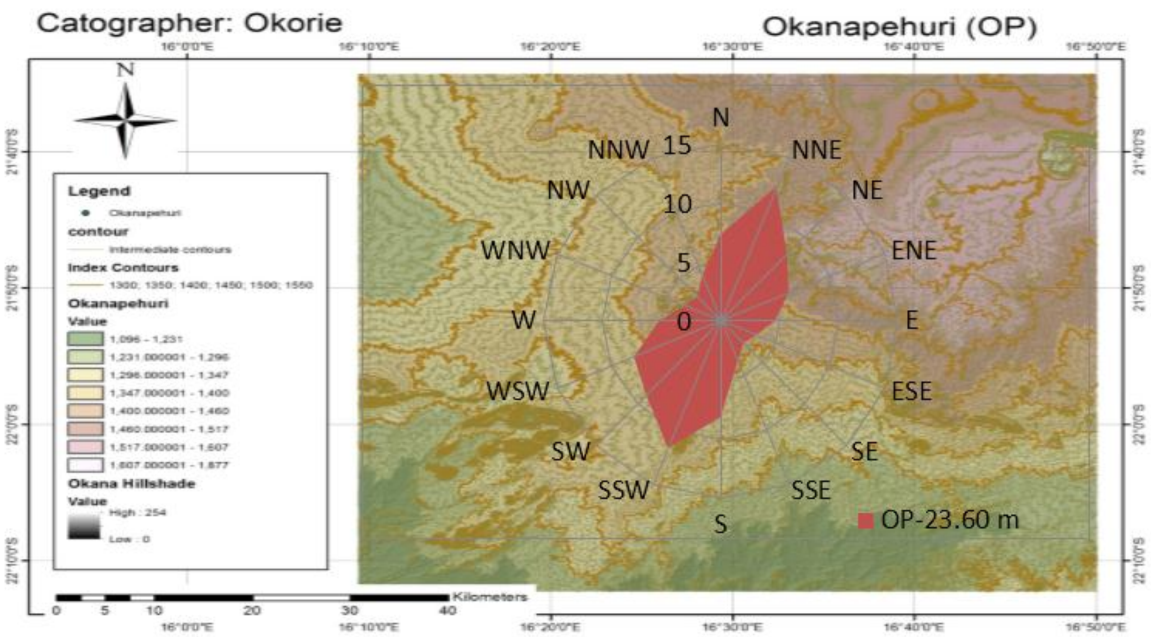

Figure 3c: Wind rose at Okanapehuri from measured data collected at 23.49 m AGL

Figure 3a, Figure 3b, Figure 3c and Figure 3d show wind roses measured at the inland and coastal locations in 2013, with TB at 48.14 m (Figure 3a), TB at 20.88 m (Figure 3b) OP at 23.49 m (Figure 3c) and OP at 50.49 m (Figure 3d).

Figure 3a and Figure 3b are wind roses at 20.88 m and 48.14 m, respectively, at the coastal location. Wind direction at the two heights appeared to be constrained in a particular direction with SE–SSW being the most predominant wind direction. Topography had little or negligible influence on the wind veer, as evidenced in a similar pattern of the wind rose structure recorded at 20.88 m and 48.14 m, respectively, where mean wind speed in the sectors SE, SSE, S and SSW was 5.21 m/s, 6.90 m/s, 7.12 m/s and 5.2 m/s, respectively. At OP, the inland location, topography had no significant influence on veer. Wind roses obtained at heights 23.49 m and 50.49 m have the same structural pattern, both indicating predominant wind directions N-E and S-W, as shown in Figure 3c and Figure 3d.

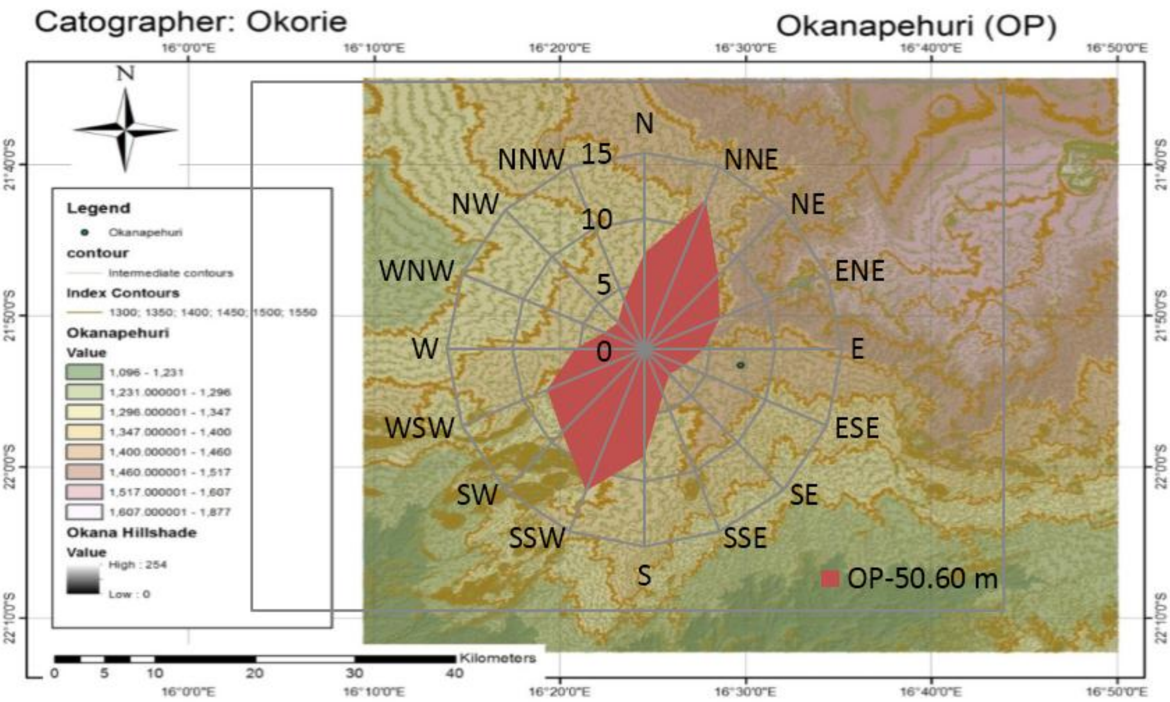

Figure 3d: Wind rose at Okanapehuri from measured data collected at 50.49 m AGL

Wind Shear Trend and Analysis

The WSCs at TB and OP have been computed using power law eq. (2). The computation is based on 10-minute average wind speed observed at 20.88 m and 48.14 m ($\alpha_{20.14-48.14}$) in the coastal location (TB) and at 23.49 m and 50.49 m ($\alpha_{23.49-50.49}$) at the inland location (OP). The wind WSCs obtained from the observed wind speeds at TB ($\alpha_{20.88-48.14}$) and OP ($\alpha_{23.49-50.49}$) are designated as α_1 and α_2, respectively. The mean WSC at TB was lower than expected with an overall value of 0.0463 and the mean value of the roughness length z_0 was 0.000000673 m. At OP, the shear trend for three years 2013, 2014 and 2015 was independently evaluated and compared. The overall WSCs in 2013, 2014 and 2015 were 0.24, 0.253 and 0.269, respectively, whereas the overall roughness lengths were 0.526 m, 0.657 m and 0.824 m, respectively. This indicates a 5.14 % and a 10.78 % increase in WSCs in 2014 and 2015, respectively, when compared with 2013 data. The z_0 increased by 20.24 % and 36.17 % in 2014 and 2015, respectively, when compared with 2013 values. The overall mean value of WSCs for the three years (2013-2015) at OP is 0.254.

Studies have shown that WSC variation has a direct relationship with the thermal condition of a location and can be explained on the basis of thermal stratification of the atmospheric body at that location [6, 16-20]. Previous studies (such as [1, 3, 17, 18]) reported that higher monthly mean values for WSC are recorded during winter months and lower values during summer months. This trend can be explained by the fact that in summer months the temperature on the ground surface and surroundings is higher. This can cause expansion and increased merging/mixing of air near the surface. Due to higher mixing of air above the ground surface, lower values of WSC are obtained. In the winter season, the reverse is the case, as air on the ground is cooler than air above the ground resulting in less merging and mixing of air, hence, higher values of WSC during the winter season.

Figure 4 shows the monthly WSC variation at both sites. Although the WSC values in the coastal location (TB) are generally low, this trend was partially observed, with July (the peak winter month) recording the highest WSC value (0.065). The same value of 0.043 was recorded for the other winter months (June and August). The mean values of WSCs in transition months (May and September) were 0.041 and 0.042, respectively.

At OP, discrepancies were more noticeable. Although June (a winter month) recorded the second highest value of 0.28 compared to April's 0.282, the pattern of WSCs was significantly influenced by the vegetation as suggested by [21]. The OP site, as earlier stated, is densely covered with *Acacia mellifera,* a shrub or medium sized-tree that grows up to 9 m in height.

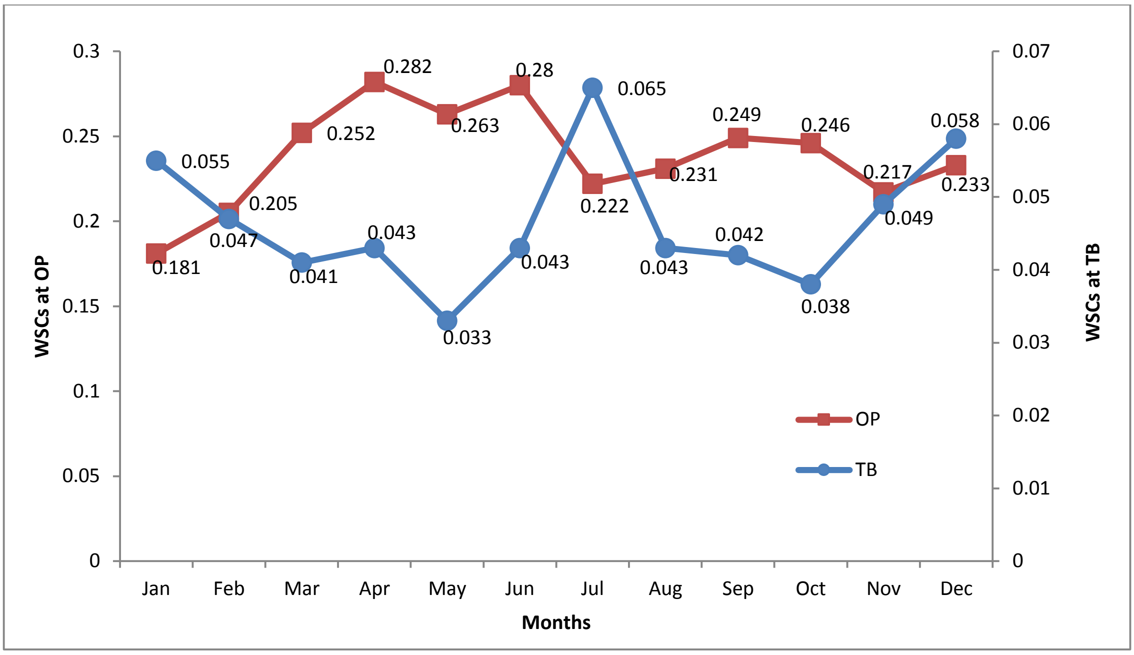

Figure 4: Monthly variations of WSCs (α_1 and α_2) at TB and OP in 2013

The leafing and shedding of leaves influences the WSC due to the effect of the tree canopy [2]. The shrubs only come into full leaf from November onwards and shed leaves during the winter months (June and July) [11]. As the trees begin to leaf, the WSCs increase as well; hence the steady increase in WSCs observed from January to the winter months when leaf shedding began. WSCs decrease as the trees shed leaves; hence the pattern observed from July to November.

Figure 5 shows the diurnal variation of WSCs at both sites. The pattern of the observed WSCs at both sites correlates with the diurnal heating/cooling cycle of air above the ground, and thus of atmospheric stability. This trend agrees with other findings in literature (such as, [1, 3, 5, 15-17]). In the early hours of the day (night stable hours) between 00h00 and 06h00, the hourly mean WSC values for both locations were high and almost constant, and started to decrease as the sun rose, as the temperature of the earth and the air above it rose, reaching minimum values at about 08h30. The condition was maintained throughout daylight hours up to 16h30, after which the values started to increase as the sun set, reaching maximum values at 21h30 and remaining relatively constant during the night stable hours.

Figure 6 shows WSC variation with direction at the coastal location. The sea/land breezes that are generated by air pressure difference-induced wind flow due to thermal capacity difference of the land and sea water along TB coastal line had a significant influence on the pattern of WSCs. The lower-than-expected values of WSCs (ranging from -0.071 to 0.157) that are observed were due to sea/land interface. Between (SW-S), WSCs are predominantly negative with computed values of -0.049, -0.071 and -0.056 for direction sectors SW, WSW and W, respectively.

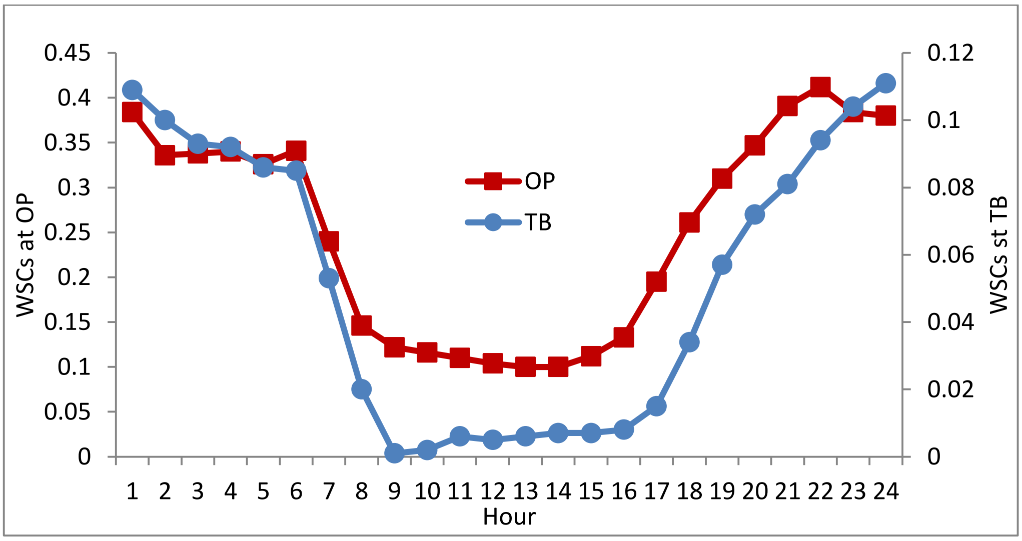

Figure 5: Diurnal variations of WSCs ($\alpha_1$and α_2) at TB and OP in 2013

These sectors directly face the water body of the Atlantic Ocean and are bound to be strongly influenced by sea/land breezes. This trend is in agreement with several findings in literature (such as [1, 22, 23]. Gualtieri [1] in a study carried out at Brindisi and Termini Imerese (both in the southern coastal location of Italy) observed that lower WSCs occurred under sea winds while higher readings were recorded under inland winds with mean WSC values (α_{10-50}) reaching as low as 0.059 at some direction sectors facing the sea. At TB, WNW-SE inland WSCs ranged from 0.015 to 0.15, being higher than WSCs recorded by direction sectors under strong influence of the sea breeze. Again, the influence of the gentle hill in N-NNE is evident, resulting in the highest values of WSC (range 0.09 to 0.15) recorded in the coastal location. Lower values of WSCs at TB were due to land/sea breeze interaction. Further investigation may require verification of the energy potential of sea/land breezes. A similar study was carried out by [22] in Llobregat Delta in Barcelona City, Spain.

At OP, mean WSC values ranging from 0.09 to 0.42 were recorded. Between ENE-to-W WSCs ranging from 0.09 to 0.256 were recorded and between WNW-to-NE mean WSC values ranging from 0.214 to 0.422 (being the highest values) were obtained.

WSC values are influenced by the heterogeneous nature of the vegetation of the site during summer and winter. The computed values agree with several literature findings (such as [1, 3, 17-19, 24]) on open plain and agricultural land.

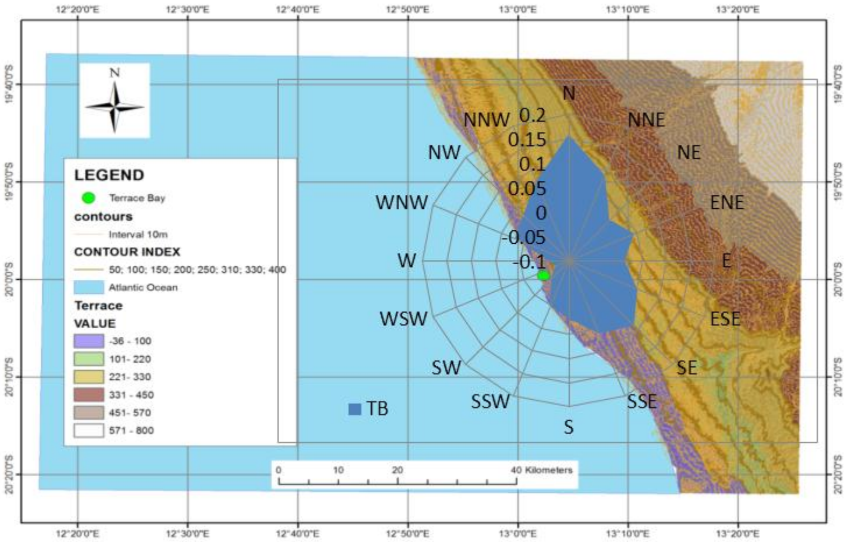

Figure 6: Variation of WSCs ($\alpha_{20.88-48.14}$) by direction at TB in 2013

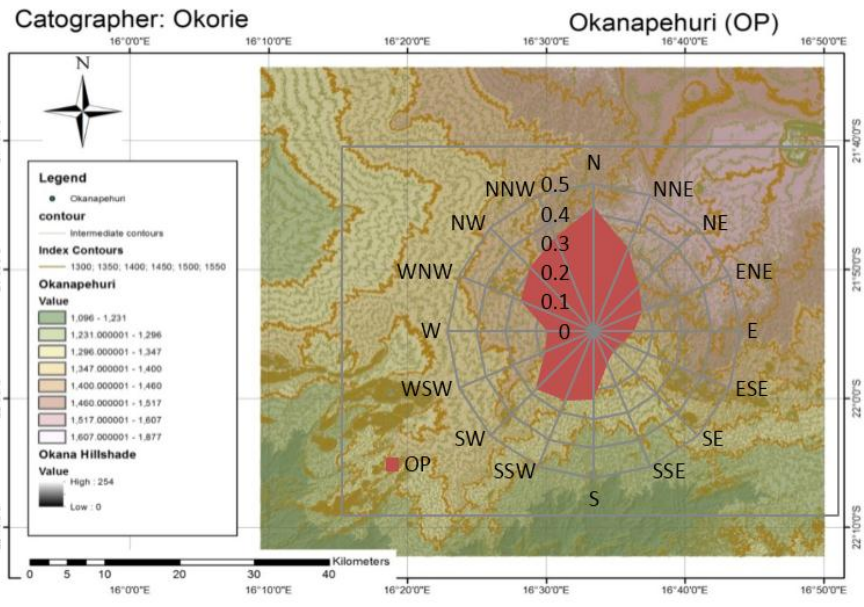

Figure 7: Variation of WSCs ($\alpha_{23.49-50.49}$) by direction at OP in 2013

Roughness Length Z_0(m)

The roughness length z_0 was computed using eq. (5). The overall mean roughness lengths (z_{01} and z_{02}) at TB and OP are 0.000000673 m and0.526 m, respectively. The computed value at the inland location (OP) agrees with literature (such as [19, 24]) that published tables specifying z_0 values for different terrains. According to the studies, the z_0 values for green urban areas and transitional woodlands/shrublands are in the range 0.5 m to 0.6 m. The value of z_0 computed at OP, a semi-arid zone, densely covered with *Acacia mellifera*, falls within this range. At TB, the specified z_0 range for very smooth surface, calm open sea, beaches, dunes, sand plains, intertidal flats and other zones close to the water body is 0.00001 m to 0.0003 m but the computed values at this location were far below the range. The lower-than-expected values were attributed to the effect of land/sea breezes at the coast. Figure 8 and Figure 9 are the monthly and diurnal variations of z_0 at both sites.

The monthly variation of z_0 (Figure 9) is directly related to the heating and cooling of the air above the ground level [1, 3]. It has the same pattern as the monthly variation of WSCs (Figure 4). At TB, the maximum value of z_{01} (0.00000685 m) occurred in July, the peak winter month in Namibia. At OP (the inland location), discrepancies, as reported in monthly variation of the WSCs, are evident. The computed value of z_{02} in April is 0.978 m. In May and June, they are 0.759 m and 0.955 m, respectively. Although June recorded the second highest value after April, the pattern of z_0 is also influenced by the vegetation pattern of the site, as suggested by [2]. Being a site densely covered with transitional medium-sized trees or shrubs, the z_0 values are affected by leafing and shedding of leaves in each season of the year, as mentioned earlier. *Acacia mellifera* comes into full leaf in November and sheds leaf during the winter months [11]. This explains the steady increase in z_0 from January to June and lower but fairly steady values from July to November.

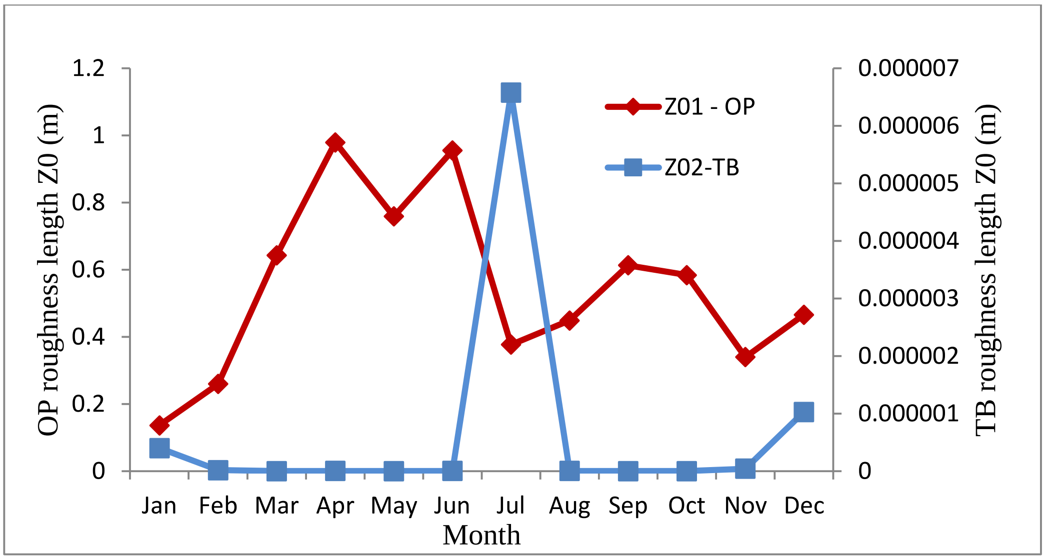

Figure 8: Monthly variation of z_0 at TB and OP in 2013

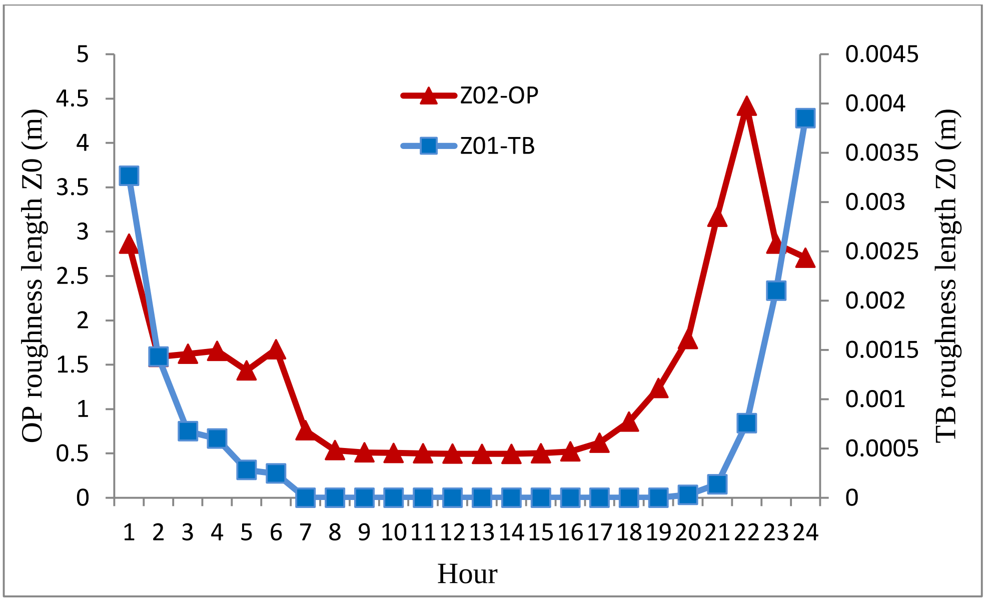

Figure 9: Diurnal variation of z_0 at TB and OP in 2013

Figure 10 is the diurnal variation of z_{01} and z_{02}. The variations have the same pattern as the WSCs (Figure 4). The z_0 pattern at both sites correlates to the diurnal heating/cooling cycle of air above the ground, and thus of atmospheric stability, agreeing with a number of findings in literature (such as 1, 3, 5, 15-17]). During the night stable hours between 00h00 and 06h00, the hourly mean WSC values for both locations are high, and start to decrease as the sun rises (the temperature of the earth and the air above it rises) reaching minimum values at about 07h00 at TB and 08h00 at OP.

Throughout the daylight hours, the minimum condition is maintained up to 16h30 at OP and 20h00 at TB, thereafter, the values start to increase as the sun sets, reaching a maximum value at 21h30 at OP and 23h30 at TB. The maximum value of z_{02} (4.417 m) occurred between 21h00 and 22h00 at OP whereas at TB, the maximum value (0.00385 m) occurred between 23h00 and 24h00.

WSCS EFFECT ON HUB-HEIGHT EXTRAPOLATION AND ENERGY YIELD ESTIMATION

Mean wind speeds beyond the observed heights at the coast (TB) and inland (OP) locations were obtained by extrapolation using the power law (eq. 1). Mean WSCs ($\alpha_1 = 0.046$) and ($\alpha_2 = 0.24$) at TB and OP, respectively, were used as the exponent in eq. 1 to extrapolate time series data in order to obtain the wind resource at the measured heights (48.14 m at TB and 50.49 m at OP). A third exponent, the rule of thumb $1/7^{th}$ ($\alpha_3 = 0.143$) power law was used to evaluate wind resources at the same heights on both sites and then compared to values obtained using α_1 and α_2. Based on the utilisation factor, suitable wind turbines were selected for energy yield estimation. The technical data of such turbines are summarised in Table 4. Tables 5 and 6 are the summaries of the wind resource and energy yield estimates at TB using an Alstom ECO 122/2700 class III wind turbine and an Enair 160 wind turbine with rated speed of 12 m/s. Tables 7 and 8 are summaries of the wind resource and energy yield estimates at OP using an Alstom ECO 122/2700 class III wind turbine and an Enair 160 wind turbine.

Table 4: Technical specifications of the wind turbines used for energy yield analysis

2.7 MW Alstom ECO 122/2700 class III wind turbine					
Wind turbine	***Rotor diameter(m)***	***Rated power(kW)***	***Cut-in Speed (m/s)***	***Rate Speed (m/s)***	***Cut-out speed (m/s)***
Alstom ECO	122	2700	3	12	25
		Enair 160			
Enair 160	6.1	7.5	1	12	19.25

Table 5: Wind resource and energy yield calculated at 48.14 m at the coastal location (TB) using 2.7 MW Alstom ECO 122/2700 class III wind turbines

Parameters	**Values of parameters obtained**		
	Measured at 48.14 m	***Extrapolated from 20.88 m to 48.14 m using α=0.046***	***Extrapolated from 20.88 m to 48.14 m using α=0.143***
Data used	52415	52415	52415
Recovery rate (%)	100	100	100
Mean speed (m/s)	6.14	6.14	6.66
Weibull k	2.10	2.11	2.11
Weibull c	6.89	6.90	7.48
WPD (w/m^2)	249	249	317
Energy Parameter			
AEY (GWh/y)	7.353	7.307	8.431
NCF (%)	31.09	30.89	35.65
AF (%)	91.94	92.35	93.11
EFLH (h/y)	2723	2705	3123

Table 6: Wind resource and energy yield estimate calculated at 48.14 m at the coastal location (TB) using an Enair 160 rotor diameter 6.10 m and rated power 7.50 kW wind turbine

Parameters	**Values of parameters obtained**		
	Measured at 48.1 m	***Extrapolated from 20.88 m to 48.14 m using α = 0.046***	***Extrapolated from 20.88 m to 48.14 m using α = 0.143***
Energy Parameter			
AEY (MWh/y)	22.723	22.625	25.657
NCF (%)	34.58	34.44	39.05
AF (%)	97.2	97.4	97.6
EFLH (h/y)	3029	3017	3421

Table 7: Wind resource and energy yield calculated at 50.49 m at the coastal location (OP) using a 2.7 MW Alstom ECO 122/2700 class III wind turbine

Parameters	**Values of parameters obtained**		
	Measured at 50.5 m	***Extrapolated from 23.49 m to 50.49 m using α = 0.24***	***Extrapolated from 23.49 m to 50.49 m using α = 0.143***
Data used	52415	52415	52415
Recovery rate (%)	100	100	100
Mean speed (m/s)	4.80	4.80	4.45
Weibull k	1.88	1.88	1.88
Weibull c	4.46	5.36	4.98
WPD (w/m^2)	129	130	104
Energy Parameter			
AEY (GWh/y)	4.035	3.991	3.285
NCF (%)	17.06	16.87	13.89
AF (%)	85.46	85.35	83.82
EFLH (h/y)	1494	1478	1217

Table 8: Wind resource and energy yield estimate calculated at 50.5 m at the inland location (OP) using an Enair 160 rotor diameter 6.10 m and rated power 7.50 kW wind turbine

Parameters	**Values of parameters obtained**		
	Measured at 50.5 m	***Extrapolated from 23.49 m to 50.49 m using α = 0.24***	***Extrapolated from 23.49 m to 50.49 m using α = 0.143***
Energy Parameter			
AEY (MWh/y)	13.37	13.30	11.48
NCF (%)	20.34	20.30	17.48
AF (%)	95	94.7	94.4
EFLH (h/y)	1782	1774	1531

The aim was to quantify how shear extrapolation using α_1, α_2 and α_3 affects wind resource when compared to the observed data at hub heights of interest. Similar literature studies (such as 1, 3, 16]) have reported that errors in energy yield estimations is more pronounced due to error propagation from mean speed extrapolation. At TB, the measured wind speed at 48.14 m is 6.14 m/s. Wind speed extrapolated from 20.88 m to 48.14 m using $\alpha_3(0.143)$ is 6.66 m/s, indicating an overestimation of 7.81 %. The Weibull parameter k is not affected by height extrapolation. Measured and extrapolated values using α_3 (0.143) show a moderate spread away from the mean whereas there was an overestimation of 7.89 % of the Weibull parameter c when compared to the measured data. This is expected as parameter c has a direct relationship with mean wind speed. The measured wind power density is $249\ \mathrm{w/m^3}$ and extrapolated value using $\alpha_3(0.143)$ is $317\ \mathrm{w/m^3}$, indicating an overestimation of 21.5 %.

Using a 2.7 MW Alstom ECO 122/2700 turbine (Table 5), the Annual Energy Yield (AEY – GWh/y) at the coastal location for the measured data at 48.14 m is 7.353 GWh/y. The value obtained after extrapolating from 20.88 m to 48.14 m through 1/7th, α_3 (0.143) power law is 8.431 GWh/y. This indicates a 14.66 % overestimation of AEY. α_3 (0.143) also overestimates the Net Capacity Factor (NCF), availability factor (AF) and the Equivalent Full Load hour (EFLH) by 14.67 %, 1.27 % and 14.67 %, respectively. Again, using the overall site WSC $\alpha_2(0.046)$, the values of the wind resource parameters were the same but underestimations of 0.43 %, 0.41 % and 0.40 % for AEY, NCF and EFLH, respectively, were encountered. In comparison, the AF was overestimated by 0.21 %. The less than 1 % difference in AEY, NCF, AF and EFLH between the observed and extrapolated data using the overall site WSC (0.0463) is expected considering the lower values of the WSC and the fact that wind data were measured at two heights. The difference is due to variability of wind speed distribution after extrapolation.

An Enair 160 wind turbine, rated power 7.5 kW, was utilised for energy yield estimation at the coastal location as summarised in Table 6. AEY (MWh/y), NCF (%), AF (%) and FLH (h/y) were overestimated by 12.91 %, 12.93 %, 0.41 % and 12.94 %, respectively, when compared to the values of time series data obtained after extrapolation through α_3 (0.143) and the measured values. Also, AEY (MWh/y), NCF (%) and EFLH (h/y) were underestimated by 0.43 %, 0.41 % and 0.40 %, respectively, when the data were extrapolated to 48.14 m using the overall site WSC, α_2 (0.0463). AF of the extrapolated data overestimates the measured values by 0.21 %. The minor percentage difference in this case is due to slight variation in wind speed distribution after hub-height extrapolation, as stated earlier. Wind energy parameters calculated at TB show that it is a fairly suitable site for wind energy extraction.

At OP, the overall site WSC (0.24) is 40.42 % higher than power law coefficient $\alpha_3(0.143)$. Wind resource and energy yield estimations of the measured and extrapolated data were evaluated and compared (Table 6). The observed wind speed at 50.5 m is 4.8 m/s. When $\alpha_3(0.143)$ is used for speed extrapolation, the mean speed at 50.5 m is 4.45 m/s. This represents an underestimation of 7.29 %. The Weibull parameter k is not affected by height extrapolation. Measured and extrapolated values using α_3 (0.143) have the same value 1.88. The value clearly indicates a moderate spread away from the mean, whereas Weibull parameter c was overestimated by 1.58 %, as reported earlier. The wind power density estimated from the measured data is $129\ \mathrm{w/m^3}$ and the value obtained when extrapolated through $\alpha_3(0.143)$ is $104\ \mathrm{w/m^3}$. This indicates 19.35 % underestimation when the extrapolated value is compared to the measured value.

Again, using an 2.7 MW Alstom ECO 122/2700 (Table 7), the Annual Energy Yield (AEY – GWh/y) at the inland location for the measured data at 50.49 m is 4.035 GWh/y. The value obtained after extrapolating from 23.49 m to 50.49 m through 1/7th, α_3 (0.143) power law is 3.285 GWh/y. There is an 18.57 % underestimation of AEY when the value obtained using extrapolated wind data is compared to the observed data. α_3 (0.143) also underestimates NCF, availability factor (AF) and the Equivalent Full Load hour (EFLH) by 22.82 %, 1.92 % and 18.54 %, respectively. Again, when the overall site WSC $\alpha_2(0.24)$ was used, the values of the wind resource parameters were the same but underestimations due to variability of wind speed distribution of 1.09 %, 1.11 % and 1.07 % of AEY, NCF and EFLH, respectively, were encountered, whereas AF indicated an overestimation of 0.13 % when the extrapolated data was compared to the observed data.

An Enair 160 wind turbine, rated power 7.5 kW, was also used for energy yield computation at Okanapehuri (Table 8). AEY (MWh/y), NCF (%), AF (%) and EFLH (h/y) were underestimated by 14.14 %, 14.07 %, 0.63 % and 14.08 %, respectively, when compared to the values obtained when wind data were extrapolated through α_3 (0.143) and the observed values. Also, AEY (MWh/y), NCF (%), AF (%) and EFLH(h/y) were underestimated by 0.52 %, 0.17 %, 0.32 % and 0.45 %, respectively, when mean speed was extrapolated to 48.14 m using the overall site WSC, α_2 (0.0463). Wind energy key indicators computed so far point towards a site that is poorly suitable for wind energy extraction.

CONCLUSION

The wind data analysed and compared are 10-minute average wind speeds collected over a period of one year, January to December 2013, at a coastal (Terrace Bay) and an inland (Okanapehuri) location in Namibia. Wind data collected in 2014 and 2015 from OP were also analysed and the annual and monthly mean values of WSCs compared to 2013 values. At both sites, wind data were observed at two different heights, 20.88 m and 48.14 m at TB and 23.49 m and 50.49 m at OP.

The WSCs and z_0 patterns at both sites were fully described and the findings are as follows:

- The overall mean values of WSCs at TB and OP were found to be 0.0463 and 0.24, respectively. The overall mean values of the roughness length (z_0) were 0.000000673 m at TB and 0.526 m at OP.
- The overall mean value of WSCs for the year 2014 and 2015 at OP were computed to be 0.253 and 0.269,

respectively. The monthly mean values of WSCs at OP in 2013, 2014 and 2015 were investigated with no significant trend evident though the mean value for 2015 was higher and this could be attributed to more rainfall received in 2015 at OP.

- The pattern of diurnal WSCs correlates with the diurnal heating/cooling of the air above ground level, resulting in higher values being recorded during the night stable hours and minimum values throughout the daylight hours. Again, the z_0 hourly variation has a pattern similar to that of the WSCs whereby higher values were recorded during the night stable hours and lower values predominated during the daylight stable hours. At OP, a maximum value of z_{02}(4.417 m) was computed between 21h00 and 22h00 whereas, at TB, maximum value of z_{01}(0.00385 m) occurred between 23h00 and 24h00. The observed variation is also due to the diurnal heating/cooling of the troposphere.
- The monthly variations of WSCs and z_0 at each site share a similar pattern. At TB, the overall mean values of both parameters were significantly influenced by the sea/land breezes. In agreement with the literature, higher values of WSCs and z_{01} occurred in July, the peak winter month. The observed pattern is due to higher mixing of the air above ground level during the summer months, resulting in lower WSCs than in winter months when the mixing of air is lower. At OP, the vegetation is densely covered with medium-sized trees/shrubs. The leaves and shedding of leaves significantly influenced the pattern of WSCs and z_{02}. As shrubs begin to leaf, the values of WSCs and z_{02} increase as well; hence the steady increase observed from January to June before shedding of leaves begins. As the trees shed leaves, the values of WSCs and z_{02} decrease. This explains the observed pattern from July to November.
- The WSCs variation with direction at the coastal location (TB) is directly influenced by sea/land interface, resulting in lower than expected mean values. The sectors facing the water body of the Atlantic Ocean are under the strong influence of sea/land breezes with mean values in the negative range. Significant influence of topography on WSCs variation is also evident. This has resulted in higher WSCs on N-NNE, the sectors that are facing the gentle hill that is located 195 m from the foot of the tower. Further investigation is required to understand how much influence sea/land breezes have on the measured wind data at TB and other coastal bodies in Namibia. At OP, the computed values mean WSCs agreed with several literature findings for similar topography. Though WSC variation appeared not to be influenced dramatically by the topography at OP, the transitional nature of the vegetation seasonally may have contributed to the pattern of WSCs across the sectors.

Wind resource assessment and energy yield estimation at each location has been performed using wind data measured at 48.14 m at TB and 50.49 m at OP or at the topmost anemometer on each site. Based on the utilisation factor, two turbines were selected for the energy yield estimation. The influence of WSC variations on resource and energy yield assessment at each site were investigated by using wind data extrapolated from 20.88 m to 48.14 m and from 23.49 m to 50.49 m at TB and OP, respectively, through 1/7th power law and by using the overall mean values of WSCs computed from the measured data at both sites.

The following conclusions based on each location specific characteristic have been drawn:

- The measured wind speed at TB was 6.14 m/s. Using the time series 10-minute average wind speed data extrapolated from 20.88 m to 48.14 m through α_3 (0.143), the mean wind speed was 6.66 m/s; indicating a 7.81 % overestimation of wind speed. With mean power density of $249\ \mathrm{w/m^3}$, TB is fairly suitable for wind energy extraction. 2.7 MW Alstom ECO 122/2700 wind turbine gives AEY of 7.353 GWh/y for the measured data at 48.14 m and 8.431 GWh/y for wind data extrapolated through α_3 (0.143), resulting in AEY overestimation by 14.66 %. The NCF, AF and EFLH were also overestimated by 14.67 %, 1.27 % and 14.67 %, respectively. Wind data was extrapolated using the computed overall site mean WSC (0.24). When compared to the measured data, a less than 1 % difference to all the parameters compared earlier was evident. The slight difference can be traced to variability of wind speed distribution after extrapolation. Similarly, using an Enair 160 wind turbine, rated power 7.5 kW, overestimations of 12.91 %, 12.93 % 0.41 % and 12.94 % for AEY, NCF, AF, and EFLH, respectively, were observed when data extrapolated using α_3 (0.143) was compared to the measured data. Interestingly, the 2.7 MW wind turbine performs better in terms of AEY output than the 7.4 kW wind turbine. However, the 7.5 kW wind turbine performs better that the 2.7 MW turbine in terms of the other parameters compared.
- At OP, the observed wind data at 50.49 m was 4.8 m/s. The mean value of wind speed extrapolated using α_3 (0.143) was 4.45 m/s. The wind speed was underestimated by 7.29 %. With power density of $129\ \mathrm{w/m^3}$, therefore, OP is poorly suited for wind energy extraction. A 2.7 MW Alstom ECO 122/2700 wind turbine gives AEY of 4.035 GWh/y for the measured data at 50.49 m and 3.285 GWh/y for wind data extrapolated through α_3 (0.143), resulting in AEY underestimation by 18.57 %. The NCF, AF and EFLH were also underestimated by 22.82 %, 1.92 % and 18.54 %, respectively. Similarly, using an Enair 160 wind turbine, rated power 7.5 kW, underestimations of 14.14 %, 14.07 % 0.63 % and 14.08 % for AEY, NCF, AF, and EFLH, respectively, were observed when data was extrapolated using α_3 (0.143) and then compared to the measured data. A

similar trend occurs again; the 2.7 MW wind turbine performed better in terms of AEY output than the 7.4 kW wind turbine. However, the 7.5 kW wind turbine performed better than the 2.7 MW turbine in terms of the other parameters that were compared.

Finally, the effect of wind shear and WSCs on hub height wind data extrapolation and energy yield estimation was examined. The results of the study show that using the $1/7^{th}$ power rule for wind data extrapolation is not the most appropriate option. For the coastal location, the effect of sea/land breezes and coastal upwelling has to be thoroughly analysed to help in planning and harnessing of wind energy in Terrace Bay. For both locations, knowledge on the influence of terrain is critically vital.

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