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Velocity and power density analysis of the wind at Letšeng-la-terae in Lesotho

Tebello Mathaba [a,b], Moeketsi Mpholo [a,b,*,1], Mosuoe Letuma [c]

[a] National University of Lesotho, Dept. of Physics and Electronics, Roma 180, Lesotho
[b] Materials Research and Engineering Center, Univ. of Pennsylvania, 3231 Walnut Street, Philadelphia, PA 19104-6202, USA
[c] Lesotho Meteorological Services, PO Box 14515, Maseru 100, Lesotho

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ABSTRACT

The wind profile of Letšeng-la-Terae in Lesotho is analyzed using a 2-year data of 10-min averages. Wind velocity distribution data is estimated as a Weibull distribution using the Graphical Method and Method of Moments. The optimal Weibull parameters for the bi-annual data are obtained using the Method of Moments and the values of the dimensionless shape parameter, $k = 1.76$, and the scale parameter, $c = 6.71$ m/s at 10 m above ground level. The calculated air density at the site is 0.875 kg/m^3 using the temperature and the pressure measurements. The data shows that the wind is prevalently from the West. The daily wind speed trends show that the interval between 5.00 am and 3.00 pm is the windiest for every month of the year. The months with the most and the least wind speeds are August and February, respectively. Letšeng-la-Terae is a class 4 wind energy site with a 95% confidence interval of both the bi-annual mean wind speed given by 5.97 ± 0.07 m/s and the bi-annual mean power density given by 208.56 ± 7.31 W/m^2, both calculated at 10 m above the ground level. The typical turbines on the site are expected to operate 82.8 ± 6.7% of the time. The results show that the site is ideal for large-scale electricity generation.

1. Introduction

1.1. Background

The site under consideration is Letšeng-La-Terae (in short it is normally referred to as Letšeng). It is located on the North-Eastern part of Lesotho, as shown on the map in Fig. 1. Lesotho is a country of about 1.9 million citizens. The climate of Lesotho is characterized by dry and cold winters with wet and warm summers. The winters and summers are accompanied by high and low pressure systems, respectively.

Less than 20% of households are connected to the electrical grid and the majority of the rural population uses biomass fuel as the main source of energy. “Lesotho’s main source of electricity is a 72 MW hydro-power station located in the North of the country at Muela”. During the cold winter months or whenever there is a high demand, electricity supply is supplemented by imports from South Africa and Mozambique. Failure to meet the winter’s demand, of more than 120 MW, resulted in load shedding in the winter of 2008 [1].

The goal of the Government of Lesotho (GoL) is to achieve a 35% electrification of households by 2015. Until recently, emphasis has been on solar energy as an alternative energy source and little attention has been given to the wind energy. There is currently a growing interest in wind energy [2]. There is a wide spread use and interest in the wind energy globally [3–6]. In spite of the high global interest, Africa is trailing the world with the least amount of installed wind energy capacity.

Although there might be a lot of regions on the African continent with a huge potential for producing electricity through wind, there is very little research going on and very few published literature [9]. The aim of this paper is to contribute to the global database of potential wind sites for massive electricity generation. This in turn will inform the international community of wind farm developers and equipment manufacturers with the aim of enticing them to invest in Lesotho hence generate some income and simultaneously help address the energy shortage situation of Lesotho. The results will also aid the international research community in terms of comparisons with other regions and in carrying out global wind models.

1.2. Assessment

The wind mast at Letšeng is situated at 29°01′09″S and 28°51′09″E at an altitude of approximately 3000 m above sea level.

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[*] Corresponding author. National University of Lesotho, Dept. of Physics and Electronics, Roma 180, Lesotho. Tel.: +266 52213529; fax: +266 22340000.

E-mail address: moeketsi@seas.upenn.edu (M. Mpholo).

[1] Tel.: +1 215 898 3144.

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Nomenclature

C	Weibull scale parameter
$f(V)$	Weibull density function
$F(V)$	Weibull distribution function
k	Weibull shape parameter
m	Shear coefficient
P	Air pressure
PD	Power density
R	Dry air gas constant
RMSE	Root mean square error
T	Air temperature
V	Wind speed
V_i	Wind speed at 10 m
$\tilde{V}_i$	Mid-point of a wind speed range
$\overline{V}$	Mean wind speed
Z_0	Roughness height
Z	Height above ground level
Z_R	Reference height
Greek Symbols	
ρ	Air density
σ	Standard deviation

The wind measurement site is located in the vicinity of the only operational large-scale mine in the country, the Letšeng Diamond Mine. This situation is ideal as the electricity generated could directly be used to power the mine. Moreover, since the mine is already connected to the national grid, there will be no extra costs incurred to erect the new transmission lines when the wind farm is built. Although there are no obstacles close to the measurement station, the whole area is situated on a hilly mountainous terrain.

2. Measurements

One year annual wind data is sufficient to predict long-term wind characteristics within a 10% error margin [8,10]. This paper analyzes the wind data spanning a period of 2 years, from the 1st January 2002 to 31st December 2003. This period is chosen because the equipment is currently not being serviced or calibrated so the initial data is considered to be more reliable.

The measurement station has two anemometers, one at 10 m above ground level (a.g.l.) as recommended by the World Meteorological Organization and another at 25 m a.g.l. [3,8]. The direction of the wind is also measured at 25 m a.g.l. The temperature and pressure are monitored at 2 m a.g.l. The recorded data is for 10-min intervals. A MATLAB algorithm was developed to model the wind profile at the site.

3. Results

Interruptions of the data logger caused by taking the readings and by the sensor failure resulted in the loss of some data. For the two years, 96% of the data was recovered which meets the 90% requirement of WMO [11]. For most of the results, the mean values are used to depict the results. The uncertainty is shown as error bars which are either the 95% confidence interval (C.I.) or standard mean deviation depending on which is deemed more appropriate.

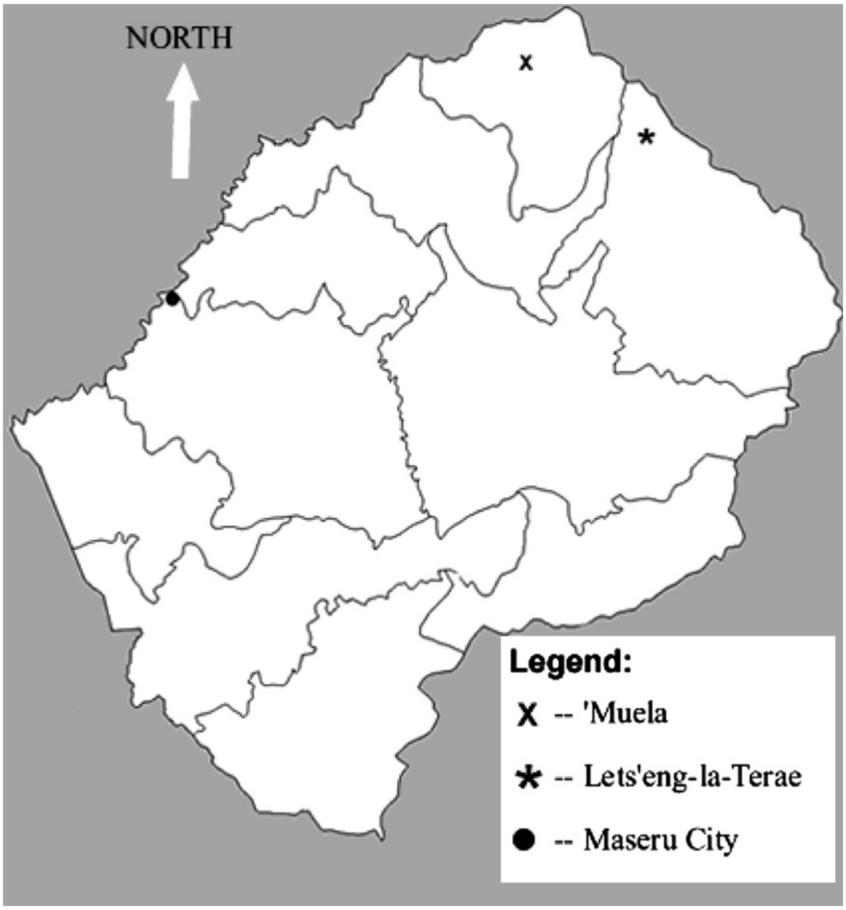

Fig. 1. Map of Lesotho.

The data analysis was done on the bi-annual data and our MATLAB model results were compared with the output from the Climate Analyst module of the Wind Atlas Analysis and Application Program (WAsP) [12].

3.1. *Wind shear profile*

The monthly mean wind speed data at both 10 m and 25 m a.g.l. was used to model the wind shear profile. The wind speed normally increases with increasing height. It is also affected by the surface roughness of the site. Two methods were employed to predict the variation of the wind speed with height using the collected data. The idea was to find the model that could best suit the data. The wind speed at a reference height Z_R, $V(Z_R)$, is related to the wind speed at any given height, Z, by Eq. (1) [13].

$$V(Z) = V(Z_R)q, \quad \text{where } q = (Z/Z_R)^m \tag{1}$$

The value of m is between 0 and 1 and will be calculated using wind speed data measured at 25 m and 10 m a.g.l. The value of m which gives the least value of the square of the root mean square error (RMSE) is taken to be optimal.

In the second method, the unknown wind speed at a height Z^R is shown in Eq. (2) [8].

$$V(Z_R) = V(Z)\frac{\ln\left(\frac{Z_R}{Z_o}\right)}{\ln\left(\frac{Z}{Z_o}\right)} \tag{2}$$

where $V(Z)$ is the known velocity at a height Z and Z_o is the roughness height. When data sets are available for two different heights, the roughness height can be determined which will then be used to determine velocities at any other height.

The best value of m was found to be 0.10 and its corresponding value of RMSE is 0.42 while Z_o was given by 0.0003 m with the corresponding value of RMSE of 0.42. Fig. 2 shows the projection of the shear profile using the bi-annual mean wind speed. One method seems to be more optimistic than the other. The projected annual mean wind speed at 50 m is 7.0 m/s using the first method of Eq. (1) while the same speed is only reached at a height of 60 m with the second method of Eq. (2). The velocity of the wind at this height is important because the hub height of many modern commercial turbines is around this height or higher [2,4].

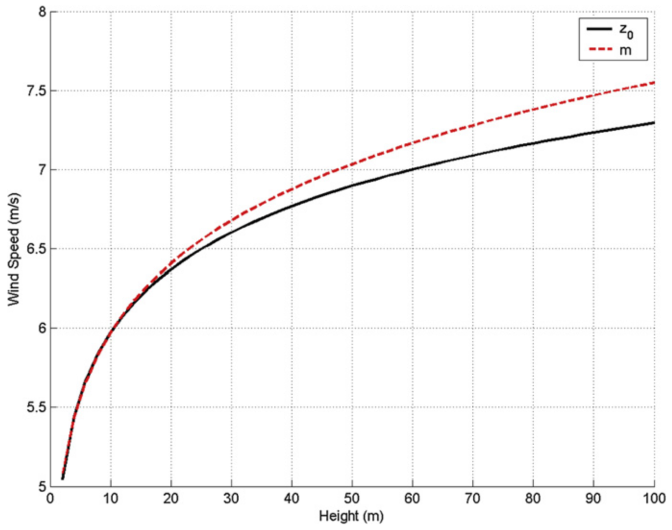

Fig. 2. Wind shear profile.

To check how well the two methods predict the wind speed profile with regard to height, they were used to predict the average hourly bi-annual mean of the actual data sets from 10 m to 25 m a.g.l. and vice-versa. Fig. 3 shows the actual hourly bi-annual mean of the wind speed both at 10 m and 25 m a.g.l, and the projected values using the two models. The models do not accurately project the data especially at both lower velocities and higher velocities. Using the coefficient of determination, the errors for m and Z_o are given by 3.83% and 3.68% when projecting upwards from 10 m to 25 m while when projecting downwards the errors are 2.70% and 2.64% compared with the actual data, respectively.

3.2. *Directional distribution*

The wind rose in Fig. 4 shows the directional distribution of the wind at the site. Most of the wind comes directly from the West. Overall, the wind is basically between the South-West and North-West quadrant. Comparison between the 2002 and 2003 data shows that the annual wind direction pattern is relatively consistent from year to year. Moreover, every month of the year receives most of its wind, above 25%, directly from the West.

The most crucial parameter is to determine the direction that gives the most energy as the wind energy is directly proportional to the amount of electricity that will be generated. As energy from the wind is proportional to the cube of velocity, the most prevalent wind direction may not necessarily provide the wind velocity that gives the most energy. Fig. 5 shows the relative directional distribution of the energy obtained at the site. The direction that gives the most wind as seen in Fig. 4 happens to be the same as the one that gives the most energy. This is a great advantage. Almost the same percentage of wind comes from WNW and WSW but WNW gives the most energy. There is hardly any energy contributed from the North-East-South direction. This means that the wind turbines should be built such that they can predominantly capture the wind from the West and WNW.

3.3. *Air density*

Density can be calculated using Eq. (3).

$$\rho = P/RT \tag{3}$$

where P is the pressure in Pascals (Pa), T is the temperature in Kelvins (K) and R is the dry air gas constant, 287 J/KgK, calculated

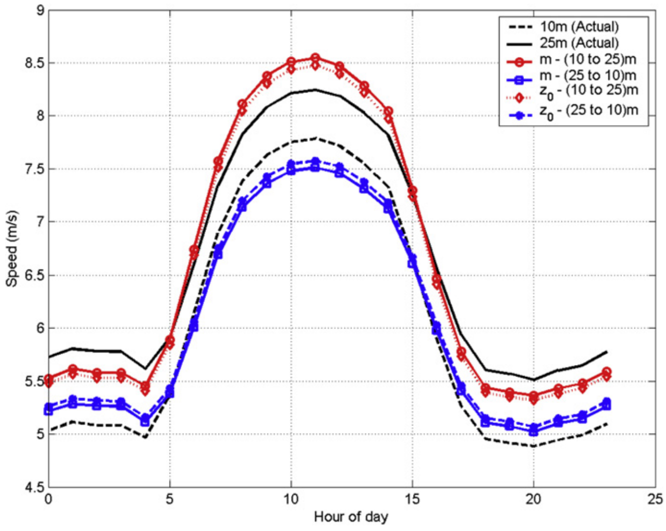

Fig. 3. Comparison of actual and predicted wind speed data using two models.

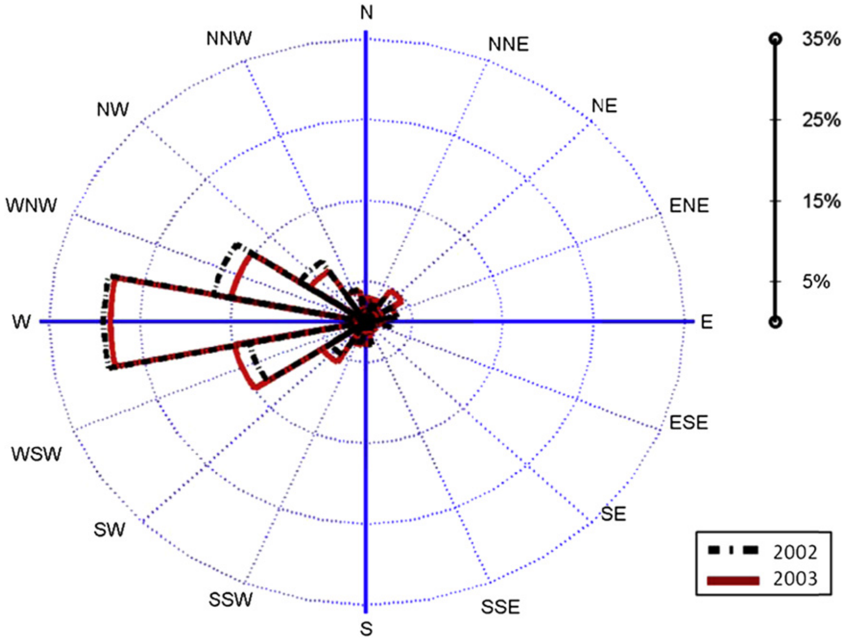

Fig. 4. Wind direction distribution rose.

using the mean molar mass of 28.9645 g/mol [8]. This shows that the air density calculations require the temperature and the pressure data. Table 1 shows the monthly mean temperatures and pressures for the two years. Mean temperatures are consistent with the climate of Lesotho because May, June and July (winter) are much cooler than November, December and January (summer). The bi-annual mean temperature and pressure are 279.5 K and 702.6 mBar, respectively. Letšeng is a fairly cool and low pressure area.

There is little variation in the temperature and the pressure values with the standard deviation of 2% and 0.5%, respectively. This means a little variance in air density. As a result, the annual average value of air density was used in power calculations. The mean density is found to be 0.875 kg/m^3 which confirms that the air tends to be thinner at high altitudes.

3.4. Wind speed patterns

The bi-annual monthly means in Fig. 6 indicate that the windiest month is August with 7.8 m/s in 2002 and 7.9 m/s in 2003. The least windy month is February with 5.2 m/s in 2002 and 3.9 m/s in 2003. The annual mean is given by 6.05 m/s in

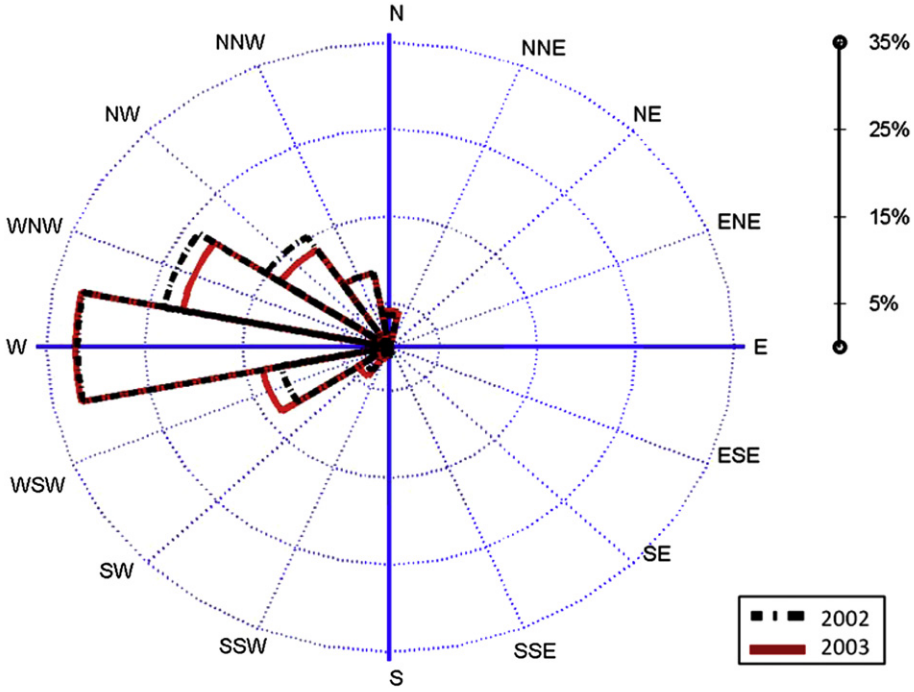

Fig. 5. Energy distribution rose.

Table 1
Monthly mean temperature and pressure.

Month	Mean temperature (K)	Mean pressure (mBar)
January	283.6	702.9
February	283.5	703.6
March	282.5	703.6
April	280.7	703.6
May	276.3	701.8
June	273.5	702.2
July	274.8	703.6
August	274.9	700.7
September	278.2	702.2
October	281.3	702.7
November	281.4	702.2
December	282.8	702.4
Combined	279.5 ± 3.7	702.6 ± 0.9

2002 and 5.89 m/s in 2003. The 95% confidence interval (C.I.) of the bi-annual mean is given by 5.97 ± 0.07 m/s. The error bars for the monthly means depict the 95% C.I. The windiest periods of the year are the warm months from August to December. Winter (May, June and July) is accompanied by an increase in electricity demand yet it has moderate wind means which are less than the annual average. The average values of calm winds, lull, and gusts are also depicted. These values are not expected to affect the energy production as their duration is very small but they are important for the structural stability of the turbine as it has to be able to withstand them [14]. The results show that there is never a period when there is no wind and the highest average gust is a moderate 10 m/s in August.

Fig. 7 shows that the hourly mean speed in August can go higher than 9 m/s for more than 5 h. A cooler season Autumn/Fall (February, March and April), has some of the lowest mean speeds. The daily averages can go as low as 3 m/s. However, Fig. 7 shows that the wind speed at the site rarely goes below 3 m/s. In fact apart from the months of February, March and July the hourly mean speeds never drop far below 4 m/s.

The diurnal mean speeds in Fig. 7 reveal that the windiest period of the day is between 5.00 am and 3.00 pm with a peak around 10 am for every month of the year. This consistency is desirable because it will ease the prediction of wind turbines power output. The availability of the strong wind, hence the power at 5.00 am is desirable because it would help meet the morning peak energy demand. The diurnal trend is also good because it guarantees power during most part of the working hours of a day (8.00 am–5.00 pm) without a need for a storage mechanism.

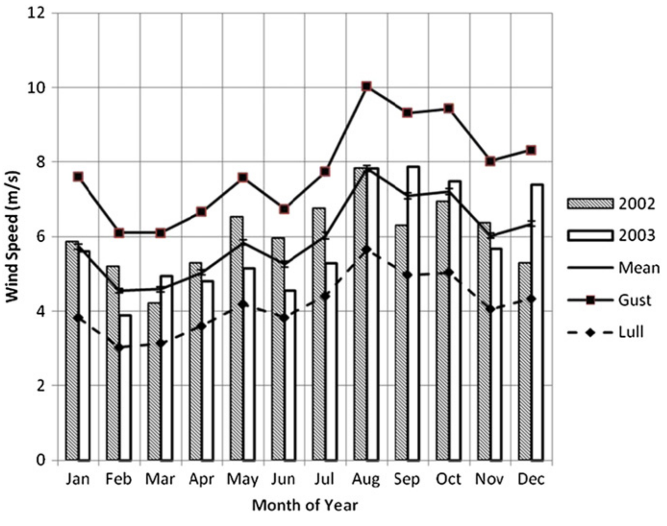

Fig. 6. Monthly mean wind speed at 10 m above ground level.

3.5. *Weibull distribution*

The Weibull parameters of both the Graphical Method and the Method of Moments obtained are shown in Table 2 [15]. Fig. 8 shows that the Method of Moments gives a better model of the wind distribution's histogram. This is confirmed by the corresponding values obtained from the WAsP software as shown in Table 2.

Fig. 8 indicates that there are very small chances (about 0.12%) of having very fast winds, i.e. speeds greater than 20 m/s. This shows that this site is ideal for electricity generation using wind as most wind turbines have a safety feature that stops them from rotating when they experience very fast winds. Therefore, at this site the wind turbines will very rarely be stopped hence continuous production is guaranteed.

3.6. *Power density*

In assessing the wind energy potential, the wind speed, the power density and their directional distribution are of primary importance. The power density, *PD*, of a site is given by Eq. (4).

$$PD = 0.5\rho\overline{V}^3 \tag{4}$$

where $\overline{V}^3$ is the mean wind speeds cubed and ρ is the density of the surrounding air. Power density is a measure of the available wind strength on the site per unit area.

Fig. 9 shows the wind power densities for each month. The mean value of the air density obtained using Eq. (3) was used for the calculations. The 95% C.I. of the bi-annual mean power density is 208.56 ± 7.31 W/m^2. The error bars show the average monthly C.I. The C.I. is moderately below 4% hence a very low variation is expected. A minimum monthly mean of 88 W/m^2 occurs in February while the maximum mean of 356 W/m^2 occurs in August. These months correspond to the least windy and windiest months respectively, as shown in Figs. 6 and 7.

Estimating the wind power density from the Weibull distribution parameters using the Method of Moments results in the confidence interval of around 3% as shown in Table 2. Hence, the Method of Moments used for obtaining Weibull distribution function is a good model for the wind distribution pattern. The Graphical Method under-estimates the power density.

According to the international system of classification of wind energy sites used by the US Department Of Energy, Letšeng is a class 4 site [7]. Class 4 includes sites with the wind power density in the range 200–250 W/m^2 and annual mean wind speed in the range 5.6–6.0 m/s at 10 m a.g.l. According to Li et al. [7] this site is suitable for large-scale electricity generation.

3.7. *Turbine operation availability*

The mean speed does not give a full picture as the mean value could fall within the operational range of the turbine but find that most of the time the wind speed values are either higher than the cut-off speed or lower than the cut-in speed. The cut-in and cut-off speeds are turbine depended. However, for a typical turbine the cut-in speed is 3 m/s and the cut-off speed is 25 m/s. In order to keep the discussion general, these figures will be used to determine the turbine operation availability at Letšeng. The energy generated and hence the capacity factor are also turbine depended hence they are not determined in this work.

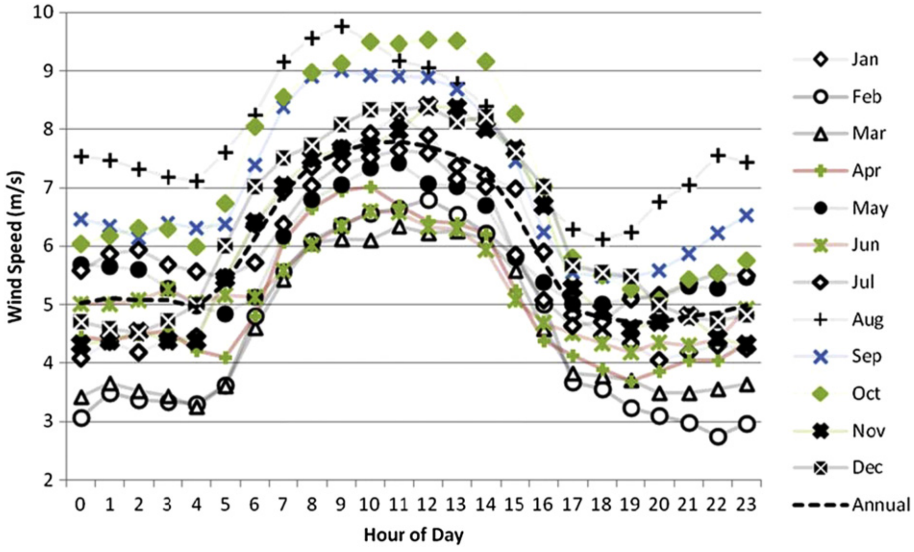

Fig. 7. Monthly diurnal mean wind speed at 10 m above ground level.

Due to the rough terrain in Lesotho, transporting turbines with very long blades will be a serious challenge if not impossible; hence the calculations are done assuming a turbine of a 50 m hub height as those should not pose serious trouble to transport. Hence the wind speed values are all extrapolated to 50 m height a.g.l. using the shear Eqs. (1) and (2). Fig. 10 shows the hourly availability figures which follow the same pattern as wind speed in Fig. 7, as expected. The turbine is mostly available around mid-day. The minimum availability is around 75%, which is pretty good. The error bars depict the standard deviation (STD) values which prove that the individual values do not deviate much from the mean. Fig. 11 shows the monthly availability of the turbine. Even in February and March when the wind speeds are the lowest, the turbine will still be operational over 70% of the time. The bi-annual average availability is given by 82.8 ± 6.7%.

4. Discussion

The models used to predict the wind speed with regard to height give an error of about 4% from the actual data. Moreover, the value of the roughness height obtained, $Z_o = 0.0003$ m, is not correct as this would classify the site as being as smooth as the ocean surface. Although there is hardly any vegetation in the area the main challenge is that it is situated on a hilly terrain. There is a high likelihood that there is a higher wind speed just before the wind reaches the mast due to hill effects hence this definitely will affect the models as they are primarily based on flat surfaces. The best way would be to build masts such that readings could be taken

Table 2
Comparison of results obtained from different models.

Item	Actual data	Graphical method prediction		Method of moments prediction		WAsP prediction
		Value	Error (%)	Value	Error (%)	Value
Power density (Wm^{-2})	209.7	172.7	17.7	204.6	2.5	210
Mean speed (m/s)	5.97	5.45	8.7	5.97	0	5.94
Shape parameter [k]	–	1.62	–	1.76	–	1.70
Scale parameter [c] (m/s)	–	6.09	–	6.71	–	6.7

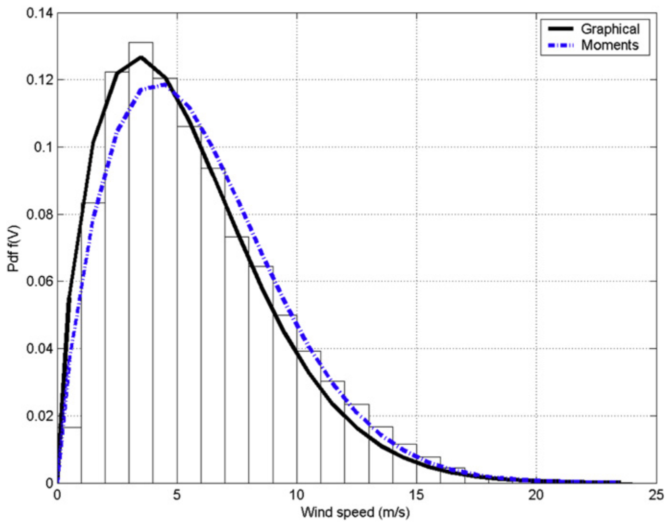

Fig. 8. Weibull wind distribution profile.

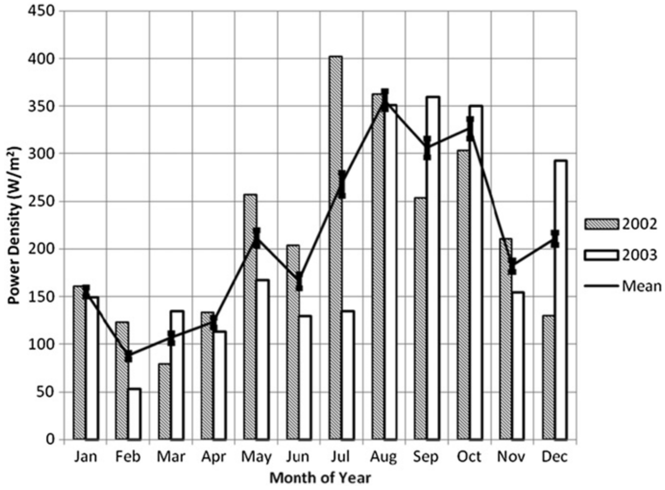

Fig. 9. Monthly wind power density.

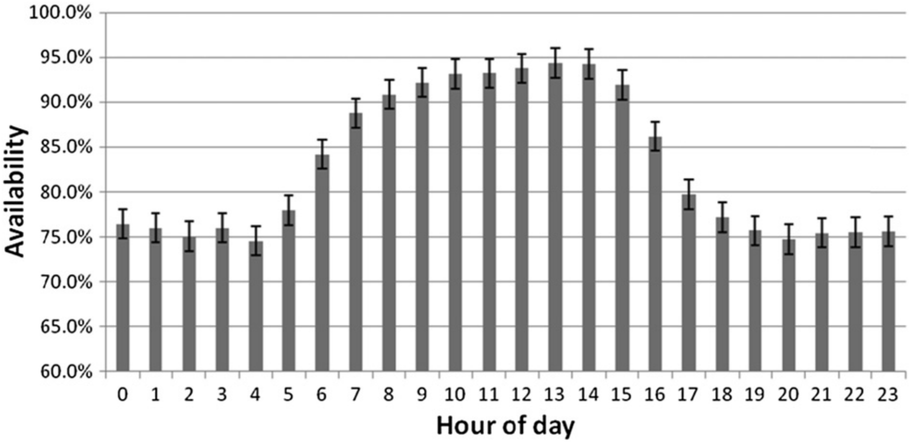

Fig. 10. Hourly turbine operation availability.

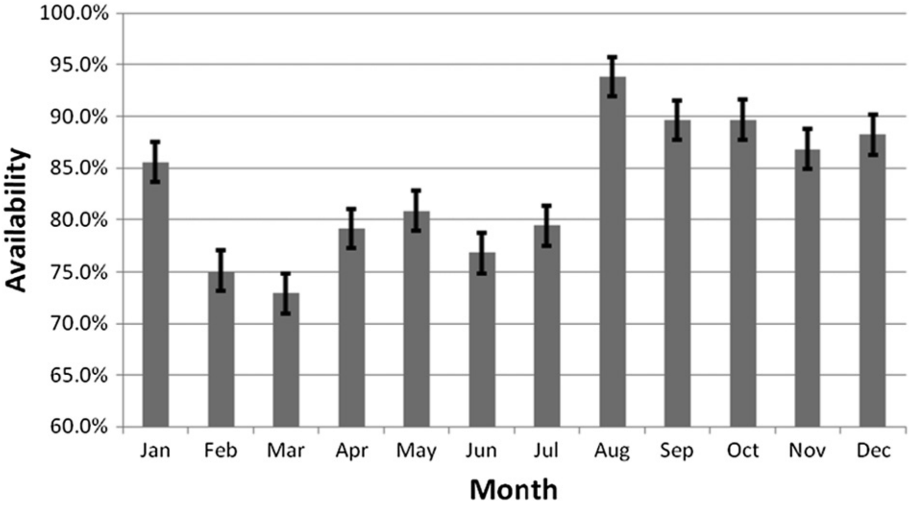

Fig. 11. Monthly turbine operation availability.

at all the relevant heights but this is not always possible. The alternative is to take short term measurements using equipment such as SODAR (SOund Detection And Ranging) and LIDAR (LIght Detection And Ranging) which are ground-based remote sensing devices [16]. Results from these equipment can then be used to correct the shear profile models.

For the two years that were considered the variations are generally far less than the 10% error hence the data can be relied to give good long-term predictions. For example, the annual wind speed mean in 2002 is 6.05 m/s while in 2003 it is given by 5.89 m/s. That's a reduction of 2.64%. Although the variation between the same months in the two years may differ by a slightly higher percentage, the wind speed trend is primarily the same as depicted by Fig. 6.

The Weibull parameters obtained are $k = 1.76$ for the dimensionless shape parameter and $c = 6.71$ m/s for the scale parameter. Basically this means the wind speed on average is around 6.71 m/s which is really a good figure for commercial operation of the site. The value of k is normally between 1 and 3 with a high value indicating that the wind distribution peaks around a certain value. In this case the value of 1.76, which is roughly 2, shows a typical good wind distribution which can even safely be approximated by Raleigh distribution that is normally used by most turbine manufacturers when they plot their power curves.

The projected annual mean wind speed at 50 m a.g.l. is around 7.0 m/s. This speed falls within the range 7.0–7.5 m/s of Class 4 sites [7]. This correspondence verifies the results of the shear profile model shown in Fig. 2.

5. Conclusion

The analysis shows that Letšeng is a Class 4 site with 95% C.I. of both the bi-annual mean wind speed given by 5.97 ± 0.07 m/s and the bi-annual mean power density of 208.56 ± 7.31 W/m^2 both calculated at 10 m a.g.l. The minimum speed is hardly ever below 3 m/s and the maximum speed also is hardly ever above 25 m/s which are usually the cut-in and cut-out speeds for most turbines, respectively, this results in the bi-annual turbine operation availability of 82.8 ± 6.7%. This means the plant will be operational most of the time and there is no danger of structural damage due to high wind velocities as the maximum average gust is at a moderate 10 m/s. Although the power density is slightly low due to the low density of 0.875 kg/m^3 primarily because of the high altitude of about 3000 m, the site has a potential of producing electricity for large-scale distribution as opposed to two other sites Masitise and Sani which were recently analyzed [2]. Masitise is a class 2 site while Sani falls under class 3. Both sites may not be ideal for grid-connected electricity production but they have sufficient wind for off-grid electricity production.

The site is mostly windy between 5 am and 3 pm with the peak around 10 am. This is ideal as the electricity produced could help tackle the morning peak demand without a need for a storage medium. Both the predominant wind direction and the wind speed that gives the most energy are from the West which is ideal as the wind farm could then be designed to maximize capturing the wind from primarily one direction.

This study is an initial assessment of the viability of the site for electricity generation using the wind. Although the site already shows sufficient potential for grid-connected generation, further investigations have to be carried-out. These would include research into the recommended types of wind turbines to be installed, detailed projections of energy yield, suitable electricity tariffs and financial analysis of constructing a wind farm including acquisition of the necessary land.

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References

[1] Inglesi R. Aggregate electricity demand in South Africa: conditional forecasts to 2030. Applied Energy 2010;87:197–204.
[2] Mpholo M, Mathaba T, Letuma M. Wind profile assessment at Masitise and Sani in Lesotho for potential off-grid electricity generation. Energy Conversion and Management 2012;53:118–27.
[3] Makkawi A, Tham Y, Asif M, Muneer T. Analysis and inter-comparison of energy yield of wind turbines in Pakistan using detailed hourly and per minute recorded data sets. Energy Conversion and Management 2009;50: 2340–50.
[4] Fyrippis I, Axaopoulos PJ, Panayiotou G. Wind energy potential assessment in Naxos Island, Greece. Applied Energy 2010;87:577–86.
[5] Bekele G, Palm B. Wind energy potential assessment at four typical locations in Ethiopia. Applied Energy 2009;86:388–96.
[6] Soler-Bientz R, Watson S, Infield D. Preliminary study of long-term wind characteristics of the Mexican Yucatán Peninsula. Energy Conversion and Management 2009;50:1773–80.
[7] Li M, Li X. Investigation of wind characteristics and assessment of wind energy potential for Waterloo region, Canada. Energy Conversion and Management 2005;46:3014–33.
[8] Sathyajith M. Wind energy: fundamentals, resource analysis and economics. Berlin: Springer–Verlag; 2006.
[9] Wissea JA, Stigter K. Wind engineering in Africa. Journal of Wind Engineering and Industrial Aerodynamics 2007;95:908–27.
[10] Aras H. Wind energy status and its assessment in Turkey. Renewable Energy 2003;28:2213–20.
[11] Celik AL. A statistical analysis of wind power density based on the Weibull and Rayleigh models at the Southern region of Turkey. Renewable Energy 2004; 29:593–604.
[12] Wind Atlas Analysis and Application Program (WAsP), [website] http://risoe.dtu.dk/WAsP.aspx [last accessed 19th Nov 2011].
[13] Ramachandra TV, Subramanian DK, Joshi NV. Wind energy potential assessment in Uttara Kannada district of Karnataka, India. Renewable Energy 1997; 10:585–611.
[14] Tomson T, Hansen M. Influence of wind speed gusts on power generation. Proceedings of the Estonian Academy of Sciences - Engineering 2002;8(4): 276–85.
[15] Akdağ SA, Dinler A. A new method to estimate Weibull parameters for wind energy applications. Energy Conversion and Management 2009;50:1761–6.
[16] Lackner MA, Rogers AL, Manwell JF, McGowan JG. A new method for improved hub height mean speed estimates using short-term hub height data. Renewable Energy 2010;35:2340–7.