Article

An assessment of wind power generation potential of Built Environment Wind Turbine (BEWT) systems in Fort Beaufort, South Africa

Terrence Manyeredzi [1,*], Golden Makaka [2]

University of Fort Hare Physics Department, Alice 5700, South Africa
[1,*] Correspondence: tmanyeredzi@gmail.com
[2] gmakaka@ufh.ac.za

Abstract: The physical and economic sustainability of using Built Environment Wind Turbine (BEWT) systems depends on the wind resource potential of the candidate site. Therefore, it is crucial to carry out a wind resource assessment prior to deployment of the BEWT. The assessment results can be used as a referral tool for predicting the performance and lifespan of the BEWT in the given built environment. To date, there is limited research output on BEWTs in South Africa with available literature showing a bias towards utility-scale or conventional ground based wind energy systems. This study aimed to assess wind power generation potential of BEWT systems in Fort Beaufort using the Weibull distribution function. The results show that Fort Beaufort wind patterns can be classified as fairly good and that BEWTs can best be deployed at $15m$ for a fairer power output as roof height wind speeds require BEWT of very low cut-in speed of at most $1.2ms^{-1}$.

Keywords: distributed system; power density; renewable energy; sustainability; utility scale; wind resource

1. Introduction

Eskom, the custodian of South Africa's national grid, is saddled with the government's optimism to triple the contribution by renewable energy from the current 4% national generating capacity to about 6000MW by 2020 [1]. This comes against Eskom's occasional failure to meet demand that compels the energy regulatory authority to impose strict load shedding schedules so as to ease pressure on the grid. The pressure in turn hampers Eskom's drive towards renewable energy use as it will be forced to focus more on meeting demand through traditional non-renewable technologies rather than promoting new renewable ones. One way of easing pressure on the national grid without the need of scheduling load shedding is promoting the use of distributed wind power systems. The major advantage of distributed wind power systems, as is the case with other distributed systems, is their proximity to end users. Distributed wind power systems can protect consumers from dearths due to technicalities associated with grid failure, transportation or capacity shortfalls since the system can be installed within the consumer's locality. Of particular interest in this study is the Built Environment Wind Turbine (BEWT) technology that [2] identified as a developing and less mature innovation than the utility-scale or conventional ground based distributed wind power systems.

BEWT refers to wind projects that are constructed on, in or near buildings. One of the main factors to consider when choosing a wind turbine for deployment as a BEWT is its performance, in terms of power output, within the given built environment. The built environment is known to be characterised by complex wind flow patterns [3] where wind direction variations are considerable. Thus, horizontal axis wind turbines (HAWT) with their yawing system may not be capable to track the fast and extensive variations in wind direction thus rendering HAWTs less effective for the built

Peer-reviewed version available at Sustainability 2018, 10, 1346; doi:10.3390/su10051346

environment [4]. On the other hand, vertical axis wind turbines (VAWTs) are more compact and their performance is independent of wind direction hence VAWTs are the preferred choice for deployment as BEWTs.

The power output of a wind turbine depends on wind speed that in turn is a spatiotemporal variable. Therefore it is important to carry out a wind resource assessment of the candidate site prior to deployment of the BEWT. This is crucial in assessing the physical and economic sustainability of deploying a particular wind turbine in the given environment. Carrying out site specific wind resource assessment gives the most reliable estimation of the wind resource potential but this may increase installation costs and even delay the deployment exercise. Knowledge of the wind resource potential of the host region for the candidate site(s) is therefore important as it can be used as a referral tool for predicting the performance and lifespan of the BEWT in the given built environment.

Wind speed is a random variable hence it can be represented statistically with Weibull distribution being recommended by most authors due to its flexibility, simplicity and capability to fit a wide range of wind data [5]–[7]. This paper is aimed at using the Weibull distribution function to assess the wind resource potential of Fort Beaufort, South Africa for the purpose of deploying BEWT systems. This may go a long way in promoting the adoption of BEWTs in South Africa and ease pressure on the national grid. South Africa is yet to adopt BEWT with available literature on wind power projects in the country (as is the case with other African countries) showing a bias towards wind resource potential assessment for establishing large-scale wind farms.

2. Materials and Methods

2.1. Study area

Fort Beaufort is a town under Nkonkobe local municipality with a population density of $310km^{-2}$ and a household density of $89.11km^{-2}$ as per 2011 national population census [8]. Figure 1 summarizes the town's sources of energy for domestic use as provided by [9];

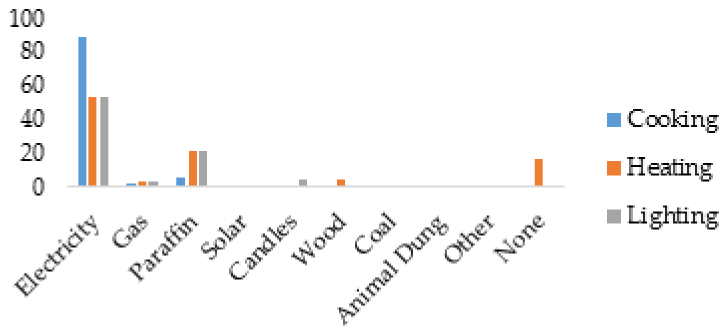

Figure 1: Graphical presentation of Fort Beaufort sources of energy for domestic use.

It can be observed from Figure 1 that Fort Beaufort population depends more on electricity for domestic purposes hence susceptible to power disruptions on the national grid.

2.2. Power output

The generic formula for estimating power output (P) of a wind turbine is;

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

Estimations of P using equation (1) are premised on the assumption that air density (ρ) is independent of wind speed [6] where A is area swept by the turbine blades and v is the speed of wind driving the turbine positioned at a height h above the ground. Equation (1) is useful when dealing with HAWTs and less reliable for VAWTs hence [10] formulated equation (2) for estimating power output of VAWTs;

$$P(v) = P_o \frac{v^3}{{v_o}^3}. \quad (2)$$

Peer-reviewed version available at *Sustainability* **2018**, *10*, 1346; doi:10.3390/su10051346

P_o is the nominal power corresponding to the nominal velocity v_o. Wind speed depends on topography and altitude [11], [12] hence wind speed measured at the weather station (v_s) of height H should be adjusted to v so as to cater for differences in height and topography between the weather station and the turbine. Reference [10] came up with equation (3) for estimating power output of a BEWT based on the corrected wind speed;

$$P(v) = \frac{P_o}{{v_o}^3}\left[v_s\left(\frac{h}{H}\right)\right]^3. \quad (3)$$

Equation (3) was successfully used to estimate power output of a turbine operating within the built environment at 15m height where building geometry was assumed not to influence wind speed. However, for a BEWT operating in/and on a building, building orientation with respect to the wind profile should be catered for when recalculating wind speed. Reference [13] used equation (4) to extrapolate a velocity profile from the meteorological station to the building while studying wind induced natural ventilation in residential areas;

$$v = \kappa v_s {h_b}^a. \quad (4)$$

Thus, equation (2) can be modified into (5);

$$P(v) = P_o \frac{[\kappa v_s {h_b}^a]^3}{{v_o}^3}, \quad (5)$$

where h_b is the building height and κ, a are constants for terrain conditions. Considering Fort Beaufort's peripheral zone that can be classified as sub-urban, the constants were assumed to be 0.35 and 0.25 for κ and a respectively.

The Psiclone Power Tree (Figure 2) was used as a reference BEWT;

Figure 2: Diagram of the Psiclone Power Tree [14].

Its operational specifications are presented in Table 1;

Table 1: Specifications of the BEWT

Nominal power output	500W
Nominal rotational Speed	400rpm
Cut-in speed	$0.5ms^{-1}$
Blade total area	$1.536m^2$

Equation (3) was therefore used to estimate the power output of a BEWT installed within a built environment at 15m height while equation (5) was used for a BEWT installed on a rooftop assumed to be $3m$. The Psiclone Power Tree is too bulky for use as a BEWT inside a building hence the assessment was limited to the two cases mentioned.

2.3. Wind speed data

Wind speed data spanning a ten year period from 2006 to 2016 used in this study was obtained from the South African Weather Services Department. Since v is a stochastic variable, the most probable wind speed (v_{pr}) corresponding to the most probable power output was determined from Weibull parameters k and c [15] using the formular;

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 April 2018 doi:10.20944/preprints201804.0138.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 1346; doi:10.3390/su10051346

$$v_{pr} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}}, \quad (6)$$

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad 1 \le k \le 10, \quad (7)$$

where $\bar{v}$ is the average wind speed and σ is the corresponding standard deviation of the measured wind speeds.

$$c = \frac{\bar{v}k^{2.6674}}{0.184+0.816k^{2.73855}}. \quad (8)$$

The constant k is the shape parameter while c is the scale parameter for the Weibull distribution based on the mean wind speed-standard deviation approach [5], [16]. Knowledge of v_{pr} is fundamental to estimating the potential of the preferred choice of a BEWT in the given environment. A large v_{pr} (and hence large power output) can support a turbine with a large cut-in speed and conversely. The probability density function, $f(v,k,c)$ is then given by;

$$f(v,k,c) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \text{for } v > 0 \text{ and } k, c > 0. \quad (9)$$

The maximum wind speed corresponding to maximum power output is obtained from k and c using the formular;

$$v_{max} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}}. \quad (10)$$

2.4. Power density

Wind power density (P_d) is generally considered a better indicator of wind resource potential than wind speed [6]. It is a measure of the power available per unit square area (A) swept by the wind turbine. The wind power density can be estimated using the Weibull distribution as;

$$P_d = \frac{P(v)}{A} = \frac{1}{A}\int_0^{\infty} P(v) f(v,k,c) dv. \quad (11)$$

Thus, wind resource potential can be rated using a magnitude-based assessment categorisation in Table 1 [6], [15] as;

Table 2: Categorization of wind resources.

	$P_d(Wm^{-2})$
Fair	< 100
Fairly good	$100 \le P_d < 300$
Good	$300 \le P_d < 700$
Very good	$700 \le P_d$

3. Results and Discussion

3.1. Wind and power density distribution

Wind speed ranges from 0 to $14.8ms^{-1}$ for the ten year period that was considered. Table 3 summarizes seasonal average values of wind speed and corresponding power output for the BEWT at $3m$ and $15m$ height.

Table 3: Seasonal average wind speed and corresponding power output for the BEWT at $3m$ and $15m$ height.

Season	BEWT on/within the house				BEWT at $15m$ height			
	v (ms^{-1})		$P_d(Wm^{-2})$		v (ms^{-1})		$P_d(Wm^{-2})$	
	v_{max}	v_{pr}	P_{dmax}	P_{dpr}	v_{max}	v_{pr}	P_{dmax}	P_{dpr}
Summer	2.1	1.2	5.6	1.0	6.8	3.9	192.3	35.2
Autumn	1.5	1.1	2.1	0.8	4.9	3.6	71.8	28.4
Winter	1.7	1.4	2.9	1.7	5.5	4.5	99.5	57.6
Spring	2.0	1.2	4.9	1.2	6.5	4.0	169.3	40.3
Overall	1.8	1.3	3.6	1.2	5.9	4.1	123.1	41.5

It can be observed from Table 1 that a BEWT deployed at $3m$ gives a less power density than one deployed at $15m$ as is expected since wind speed increases with altitude. The unimodal seasonal probability densities for wind speed are presented graphically.

3.1.1. Summer

The wind speed distribution for summer is presented on Figure 3;

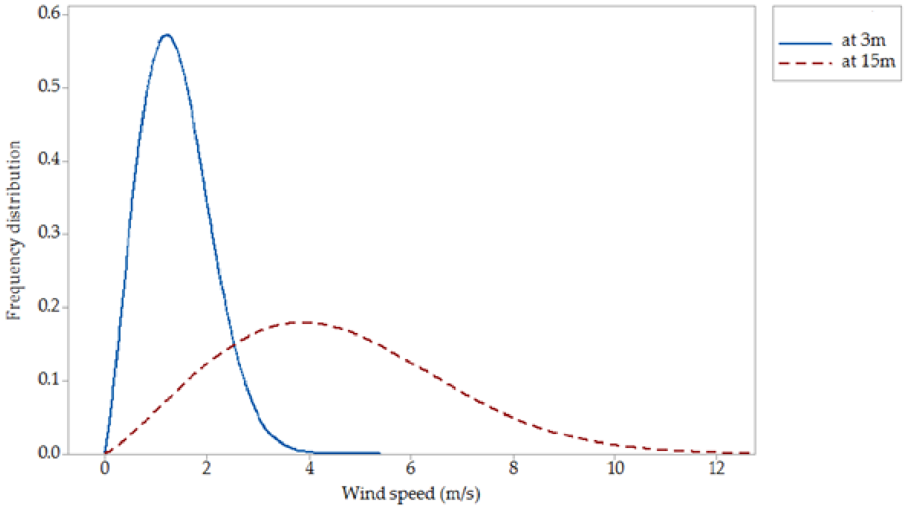

Figure 3: Summer Weibull probability density function plot for Fort Beaufort.

Figure 3 shows that the distribution of wind speed in summer is slightly skewed towards lower wind speeds hence the probability of having above average wind speeds is relatively low. Considering Figure 4 in conjunction with Table 4, it can be realized that both v_{pr} and v_{max} for summer are both less than the cut-in speed of the Power Tree at a $3m$ height. This shows that the Psiclone Power Tree cannot be supported at this height. On the other hand, both v_{pr} and v_{max} at $15m$ for summer are greater than the cut-in speed hence the Power Tree can be supported as a BEWT at this height. Thus, with reference to the summer wind distribution, a BEWT can be deployed at $3m$ if its cut-in speed is at most 1.2ms^{-1} and such technologies are generally expensive considering the returns in terms of power output and production costs. Using the categorization on Table 2, the most probable power density at $3m$ is $35.2Wm^{-2}$ while at $15m$ it is $192.3Wm^{-2}$ as shown on Table 5. The power densities can therefore be categorized as fair and fairly good respectively. Table 6 also shows that the maximum power densities achievable in summer are $5.6Wm^{-2}$ and $192.3Wm^{-2}$ at $3m$ and $15m$ respectively.

3.1.2. Autumn

Wind speed distribution for autumn is shown on Figure 4. The distribution of wind speeds is almost symmetrical with a slight positive skew hence the probability of having above average wind speeds in autumn is comparatively low.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 April 2018 doi:10.20944/preprints201804.0138.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 1346; doi:10.3390/su10051346

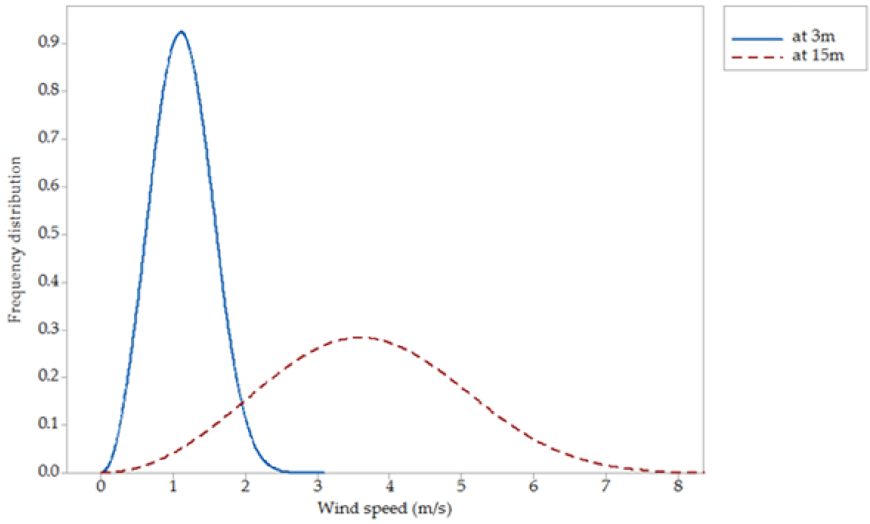

Figure 4: Autumn Weibull probability density function plot for autumn.

The modal wind speeds are $1.1ms^{-1}$ and $3.6ms^{-1}$ at $3m$ and $15m$ height respectively. The corresponding modal power densities are $0.8Wm^{-2}$ and $28.4Wm^{-2}$ at the respective heights hence they are both categorized as fair. The maximum power density values are $2.1Wm^{-2}$ at $3m$ and $71.8Wm^{-2}$ at $15m$. Therefore, wind conditions in autumn are not favourable for operating a BEWT since both P_{dpr} and P_{dmax} are categorized as fair for the respective heights.

3.1.3. Winter

The probability of having average or higher wind speeds in winter is relatively low since the probability distribution for winter is again slightly skewed towards low wind speeds as shown on Figure 5.

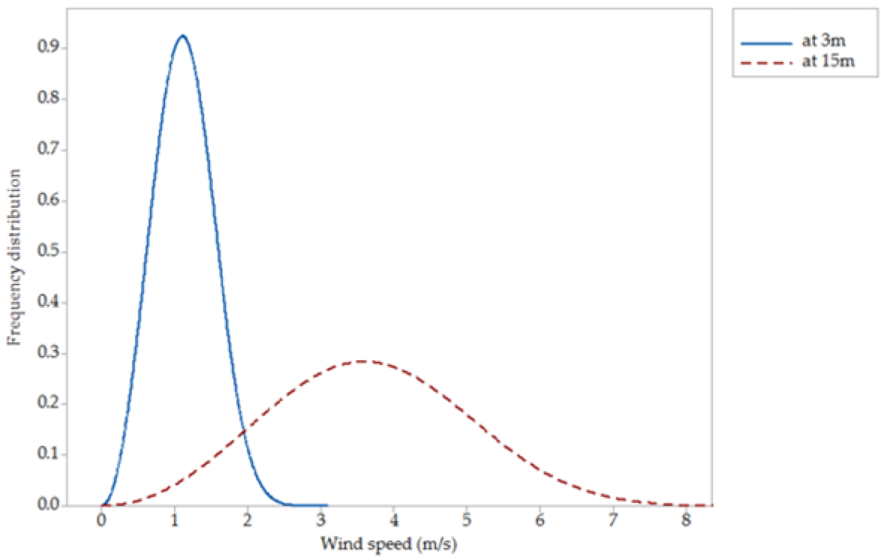

Figure 5: Weibull probability density function plot for winter

The modal power densities are both categorized are $1.7Wm^{-2}$ and $57.6Wm^{-2}$ at the respective heights hence categorized as fair. Thus, wind conditions are comparatively favorable for operating a BEWT to those for autumn. The corresponding maximum power densities achievable in winter are $2.9Wm^{-2}$ at $3m$ and $99.5Wm^{-2}$ at $15m$, both which fall under the fair category.

3.1.4. Spring

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 11 April 2018 doi:10.20944/preprints201804.0138.v1

Peer-reviewed version available at *Sustainability* **2018**, *10*, 1346; doi:10.3390/su10051346

The distribution for wind speeds in spring is shown on Figure 6;

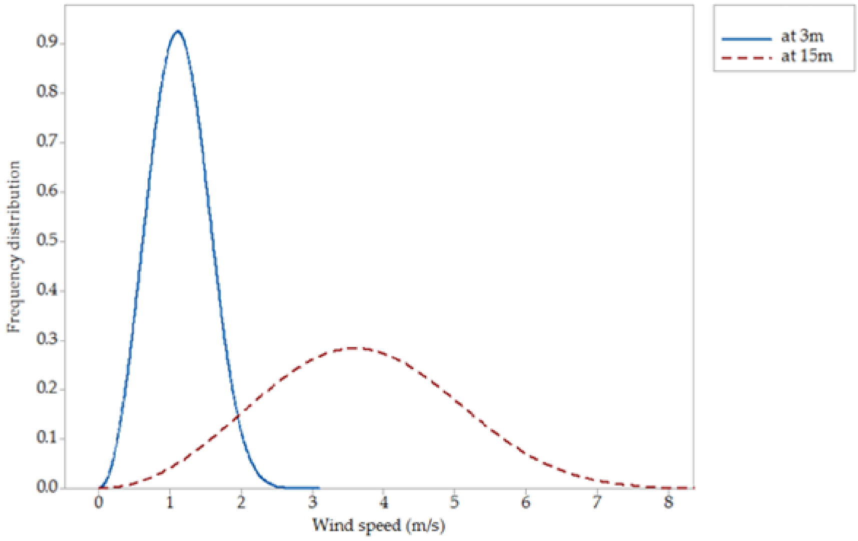

Figure 6: Weibull probability density function plot for spring.

It can be observed that the distribution is skewed towards low wind speeds. The most probable power densities are; $1.2Wm^{-2}$ and $40.3Wm^{-2}$ at the respective heights. Thus, wind conditions for Fort Beaufort can be categorised as fair for operating a BEWT with maximum power densities achievable being $4.9Wm^{-2}$ at $3m$ and $169.3Wm^{-2}$ at $15m$.

3.1.5. Overall

Generally, the wind speed distribution for Fort Beaufort is slightly skewed towards low wind speeds (Figure 7) hence the probability of having below average wind speeds is slightly high.

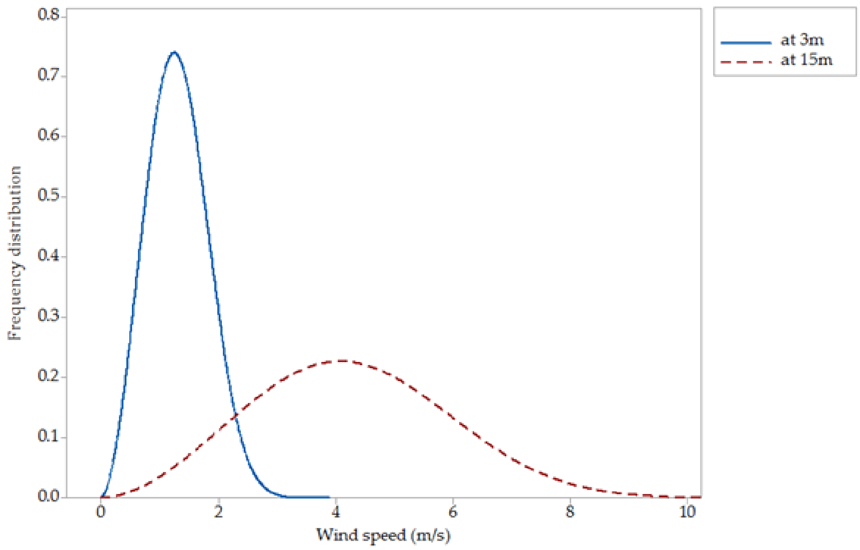

Figure 7: Fort Beaufort Weibull probability density function plot.

The average modal power densities for Fort Beaufort are $1.2Wm^{-2}$ and $41.5Wm^{-2}$ at $3m$ and $15m$ respectively. Thus, wind conditions for Fort Beaufort can be categorized as fair for operating a BEWT with maximum power densities achievable being $3.6Wm^{-2}$ at $3m$ and $123.1Wm^{-2}$ at $15m$.

4. Conclusion

The most probable seasonal power density for Fort Beaufort is in the range of $0.8Wm^{-2}$ to $1.7Wm^{-2}$ at $3m$ height. At $15m$ height, the most probable seasonal power density ranges from $28.4Wm^{-2}$ to $57.6Wm^{-2}$. Thus, seasonal wind conditions for Fort Beaufort can be categorized as fair to fairly good for operating a BEWT with maximum power densities achievable being $3.6Wm^{-2}$ at $3m$ and $123.1Wm^{-2}$ at $15m$. However, the BEWTs can best be deployed at $15m$ for a fairer power output as roof height wind speeds require BEWT of very low cut-in speed of $1.2ms^{-1}$ that are not readily available on the market. Therefore, it is recommended to install BEWTs at $15m$ otherwise low cut-in speed BEWTs should be used on rooftops

Acknowledgments: I am grateful to the South African Weather Services for freely providing me with data that was used in this study.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Burger, J. Unpacking renewable energy in Africa. *How we made it in Africa*, **2017**. Available online: https://www.howwemadeitinafrica.com/unpacking-renewable-energy-africa/59248/.(Accessed on 10 March 2018).
2. Fields, J.; Oteri, F.; Preus, R.; Baring-gould, I. Deployment of Wind Turbines in the Built Environment: Risks , Lessons , and Recommended Practices. *National Renewable Energy Laboratory*. **2016**, NREL/TP-5000-65622.
3. Abdi, D.S.; Bitsuamlak, G.T. Wind flow simulations in idealized and real built environments with models of various level of complexity. *Wind Struct. An Int. J.* **2012**, *vol. 22*, *no. 4*, pp. 503–524, 10.12989/was.2016.22.4.503.
4. van Bussel, G. J. W.; Mertens, S. M. Small wind turbines for the built environment. *Fourth Eur. African Conf. Wind Eng.***2005**, pp. 1–9, 10.1109/PES.2005.1489306.
5. Ayodele, T.; Jimoh, A.; Munda, J; Agee, J. Statistical analysis of wind speed and wind power potential of Port Elizabeth using Weibull parameters. *J. Energy South. Africa*. **2012**, *vol. 23*, *no. 2*, pp. 30–38.
6. Fazelpour, F; Soltani, N; Rosen, M. A. Wind resource assessment and wind power potential for the city of Ardabil, Iran. *Int. J. Energy Environ. Eng*. **2015**, *vol. 6*, *no. 4*, pp. 431–438.
7. Parajuli, A. A Statistical Analysis of Wind Speed and Power Density Based on Weibull and Rayleigh Models of Jumla, Nepal. *Nepal. Energy Power Eng*. **2004**, *vol. 8*, *no. 8*, pp. 271–282.
8. Frith, A. Census 2011 — Main Place Fort Beaufort. Available online: https://census2011.adrianfrith.com/place/276071. (Accessed on 22 February 2018).
9. Statistics South Africa. Main Place | Statistics South Africa. 2011. Available online: http://www.statssa.gov.za/?page_id=4286&id=2206. (Accessed on 22 February 2018).
10. Eryomin, D.I; Yagfarova, N. I.; Turarbekov, M. K. Mathematical model to calculate the performance. *IJASEAT* **2016**, *vol. 4*, *no. 1*, pp. 23–25.
11. Erdik, T.; Law, P.; Şen, Z.; Altunkaynak, A.; Erdik, T. Wind velocity vertical extrapolation by extended power law. *Adv. Meteorol.* **2012**, pp. 1–6.
12. Maharani, Y. N.; Lee, S.; Lee, Y. Topographical Effect on Wind Speed over Various Terrains: A Case Study for Korean Peninsula. Seventh Asia-Pacific Conf. Wind Eng. Taipei, Taiwan, 2009.
13. Larsen, T. S.; Heiselberg, P. Single-sided natural ventilation driven by wind pressure and temperature difference. Aalborg University, 2008.
14. Psiclone. Psiclone | 500w Generator. Available online: http://www.psiclone.co.za/500w/. (Accessed on 21 February 2018).
15. Akpinar, E. K.; Akpinar, S. A statistical analysis of wind speed data used in installation of wind energy conversion systems. *Energy Conversion and Management* **2005**, *vol. 46*, pp. 515–532.
16. Adaramola, M. S.; Agelin-Chaab, M.; Paul, S. S. Assessment of wind power generation along the coast of Ghana. *Energy Convers. Manag*. **2014**, *vol. 77*, *no. 2014*, pp. 61–69