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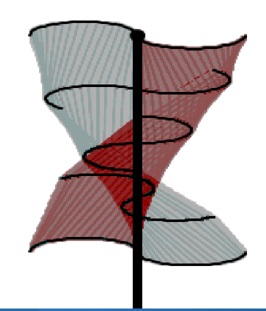
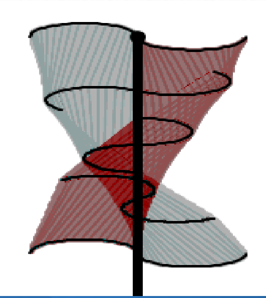
Comparative Analysis of Numerical Methods for Assessing Wind Potential in Fort Beaufort, South Africa, using Two-Parameter Weibull Distribution Model.



Ngwarai Shambira, Prof Golden Makaka, Dr Patrick Mukumba



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Title

Comparative Analysis of Numerical Methods for Assessing Wind Potential in Fort Beaufort, South Africa, using Two-Parameter Weibull Distribution Model.

Ngwarai Shambira, Prof: Golden Makaka & Dr Patrick Mukumba

Outline

Brief (Introduction & literature review)

Methodology

Results and discussions

Conclusion/Recommendations

Brief Introduction

- Electricity generation from wind energy may be a feasible solution to the national energy crisis, South Africa is experiencing.

- It might also assist in providing electricity to remote areas currently not connected to the national grid.

- The utilisation of wind energy which is clean, accessible and inexhaustible renewable energy, will reduce carbon dioxide emissions hence mitigating the effects of climate change (Shambira et. al 2020).

- In the 1990s, around 30,000 windmills were installed in South Africa mainly for water supply and agricultural purposes (Akinbami et al., 2021; Asamoah, 2003).
  - ✓ *limited use of wind energy for electricity generation due to cheaper coal availability* (Merem et al., 2022).

Brief Introduction

- Excellent wind energy potential in Eastern Cape, Western Cape, Northern Cape, and KwaZulu-Natal.
  - ✓ *Coastal regions: Annual mean wind speed of 6 m/s at 10m above ground level (Mostafaeipour et al., 2011)*
- **South Africa**
  - ✓ *Has attracted investment of R209.7 billion in 2020 of wind projects.*
  - ✓ *South Africa boasts thirty-three wind farms, with 22 , fully operational commercially (Macingwane, 2021)*
  - ✓ *wind energy industry has created 2723 jobs by commercialising 22 wind-independent power producers and reducing carbon dioxide, a greenhouse gas emission, by 6.4 million tonnes (McKenna et al., 2022).*

Brief literature review

- Hussain et al. (2023) studied wind power density in Pakistan's coastal areas using eight numerical methods. The energy trend and graphical methods performed poorly.

- Patidar et al. (2022) assessed wind characteristics and potential in offshore locations in Gujarat, India using the Weibull density function. The MLM method provided the most accurate evaluation of wind potential.

- Shafiqur Rehman et al. (2021) analyzed wind speed characteristics in South Africa. Port Elizabeth had the highest mean wind speed, while Bloemfontein had the lowest. Coastal areas showed favorable wind power characteristics, with Cape Town, East London, and Port Elizabeth identified as suitable sites for wind power deployment.

Aim of the study

- Wind potential estimates are not definite as the wind varies with time and location
  - *Hence* ***site-specific*** *wind resource assessment is crucial for accurately estimating wind potential and reducing investment risk in wind energy projects (Shambira et al., 2020).*

- To determine the wind characteristics and wind potential of an area, an accurate wind distribution model is essential.
  - *Therefore, this study examines eight numerical methods for estimating the Weibull parameters to obtain a suitable model.*

Methodology

Site description and wind speed data

- The study utilized five-and-a-half years of hourly wind speed data (January 2015-July 2020) obtained from Fort Beaufort weather stations through South African Weather services.

- The geographical coordinates of these weather stations are

Weather stations	Latitude	Longitude	Height (m)
Fort Beaufort	-32.7880	26.6290	455

Methodology : Fitting probability distributions to observed wind data

- ❖ Two-parameter Weibull distribution, was used to model the wind speed data at a height of 10 m AGL

  - ➢ *This distribution has been widely applied to many wind research studies to describe wind speed data because it is simple, adaptable and precise when compared to other distribution functions (Chaurasiya et al., 2018; Idriss et al., 2019; Bidaoui et al., 2019; Sadullayev et al., 2019; Adem Çakmakçı & Hüner, 2022; Ali et al., 2023).*

Weibull Cumulative distribution function (WcD) is given as $W(v) = 1 - e^{\left[-\left(\frac{v}{c}\right)^{k}\right]}$

Differentiating $W(v)$ with respect to v gives a Weibull probability distribution function (WpD) (bi-parameter):

$$w(v) = \frac{dW(v)}{dv} = \left(\frac{k}{c}\right)\left(\frac{v}{c}\right)^{k-1} \bullet e^{\left[-\left(\frac{v}{c}\right)^{k}\right]}$$

- ➢ k values show wind stability and Also, calm conditions must be excluded since c (≥1) (m/s) (Lopez-Rodriguez et al., 2020)

Methodology : Algorithms to calculate scale (c) and shape (k) for Weibull distribution

(1) **Mean, standard deviation method (Msdm)** $k = \left(\frac{\sigma_{std}}{v_{\text{ave}}}\right)^{-1.086}$ $c = \frac{v_{\text{ave}}}{\Gamma\left(1 + \frac{1}{k}\right)}$

(2) **Method of multi-objective moment (MofMoM)** (Usta et al., 2018; Safari et al., 2022).

$$\lambda_1\left(c\Gamma\left(1+\frac{1}{k}\right)-\bar{v}\right)^2+\lambda_2\left(c^2\Gamma\left(1+\frac{2}{k}\right)-\overline{v^2}\right)^2+\lambda_3\left(c^3\Gamma\left(1+\frac{3}{k}\right)-\overline{v^3}\right)^2$$

$\overline{v^r}$ is the r$^{\text{th}}$ sample moment, which is given by $\overline{v^r} = \frac{1}{n}\sum_{i=1}^{n} v_i{}^r$

Also λ_1 λ_2, λ_3 are, the weights are chosen so that $\lambda_1 + \lambda_2 + \lambda_3 = 1$

(3) **Probability-weighted moments based on power density method (PwmbpdM)** (Usta 2016).

$k = \frac{ln(2)}{ln\left(\overline{C}\right)}$ where $\overline{C}$ is given by $\overline{C} = \frac{v_{ave}}{\frac{2}{n(n-1)}\sum_{i=1}^{n} v_i(n-1)}$ v_{ave} is the average wind speed, and v_i is the ordered sample of the wind speed data

$c = \frac{\overline{v^3}}{\Gamma\left(1+\frac{3}{k}\right)}$ where $\overline{v^3}$ is the sample average of the cubic wind speed.

Methodology : Algorithms to calculate scale (c) and shape (k) for Weibull distribution

(4) **WAsP method (WM)** (Fazelpour et al., 2015; Solyali et al., 2016)

$$-InP = \left(\frac{\frac{1}{n}\sum_{i=1}^{n} v_i}{c}\right)^k$$

$$-In(P) = \left(\frac{\frac{1}{n}\sum_{i=1}^{n} v_i}{\sqrt[3]{\frac{\sum_{i=1}^{N} v_i^3}{n\Gamma\left(\frac{3}{k}+1\right)}}}\right)^k \quad c = \left(\frac{\sum_{i=1}^{n} v_i^3}{n\Gamma\left(\frac{3}{k}+1\right)}\right)^{0.5}$$

(5) **Openwind method (Owm)** (Rehman et al., 2020).

- *k is obtained by equation through an iterative procedure of the Brent Method, and then c is obtained*

$$c = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i}{\Gamma\left(\frac{1}{k}+1\right)} \qquad \sqrt[3]{\frac{\frac{1}{n}\sum_{i=1}^{n} v_i^3}{\Gamma\left(\frac{3}{k}+1\right)}} = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i}{\Gamma\left(\frac{1}{k}+1\right)}$$

(6) **Method of mabchour (momab)**

$$k = 1 + (0.483(v_{ave} - 2)^{0.51})$$

(7) **Energy pattern factor method (Epfm)**.

$$E_{pf} = \frac{(v^3)_{ave}}{(v\text{ave})^3} \qquad k = 1 + \frac{3.69}{E_{pf}{}^2}$$

$$c = \frac{v_{ave}}{\Gamma\left(1+\frac{1}{k}\right)}$$

(8) **Novel energy pattern factor method (Nepfm)**

values of the coefficients of g_n, h_n *for* $n = 0,1,2,3,4$ *are given*

and the values of the coefficients c_n *and* d_n *for* $n=0,1$ *are also given*

(Akdag & Güler, 2015)

$$k = \frac{g_4E_{pf}^4 + g_3E_{pf}^3 + g_2E_{pf}^2 + g_1E_{pf}^1 + g_0}{h_4E_{pf}^4 + h_3E_{pf}^3 + h_2E_{pf}^2 + h_1E_{pf}^1 + g_0}$$

$$c = \frac{v_{ave}(k^2 + d_1k + d_0)}{k^2 + c_1k + c_0}$$

Methodology: Goodness of fit test.

(1) **Mean absolute Bias error (MaBE)** (Teyabeen et al., 2018; Mohammadi et al., 2016).

$$MAE = \frac{1}{n}\left(\sum_{i=1}^{n}\left|\mathrm{WPD}_{\mathrm{i,wbl}} - \mathrm{WPD}_{\mathrm{i,obs}}\right|\right)$$

(2) **Root mean square error (RMsE)** Tizgui et al., 2017; Teyabeen et al., 2018; Chaurasiya et al., 2018

$$RMS = \left(\frac{1}{n}\sum_{i=1}^{n}\left(WPD_{i,wbl} - WPD_{i,obs}\right)^{2}\right)^{\frac{1}{2}}$$

(3) **Wind power density error (WPDE)** Mohammadi et al., 2016

$$\mathrm{WPDE} = \left|\frac{WPD_{i,wbl} - WPD_{i,obs}}{WPd_{i,obs}}\right|$$

Methodology: Goodness of fit test of distributions.

(4) **Kolmogorov–smirnov test (KS)** $K = \max\left[L(\mathrm{v}) - M(\mathrm{v})\right]$

L(v) *is cumulative distribution function of model*
M(v) cdf *evaluated by using* observed *actual data*

(5) **Anderson darling test** $AD = -n - \frac{1}{n}\sum_{i=1}^{n}(2i-1)\left[\mathrm{In}\,\mathrm{G}(Y_i) + \mathrm{In}(1\text{-}\ \mathrm{G}(Y_{n-i+1}))\right]$

G(Yi) *is cdf for specific distribution ith sample, calculated when the data is sorted in ascending order*

(6) **Chi-squared test** $\chi^2 = \frac{\sum_{i=1}^{N}(O_i - E_i)^2}{E_i}$

- low values indicates a good fitting between our distributions with the observed actual wind data

Classification of wind resources

- For this current study to determine the wind resource availability using wind power densities, the (Fazelpour et al., 2017; Fazelpour et al., 2015; Assowe Dabar et al., 2019) classification is used as presented in Table below.

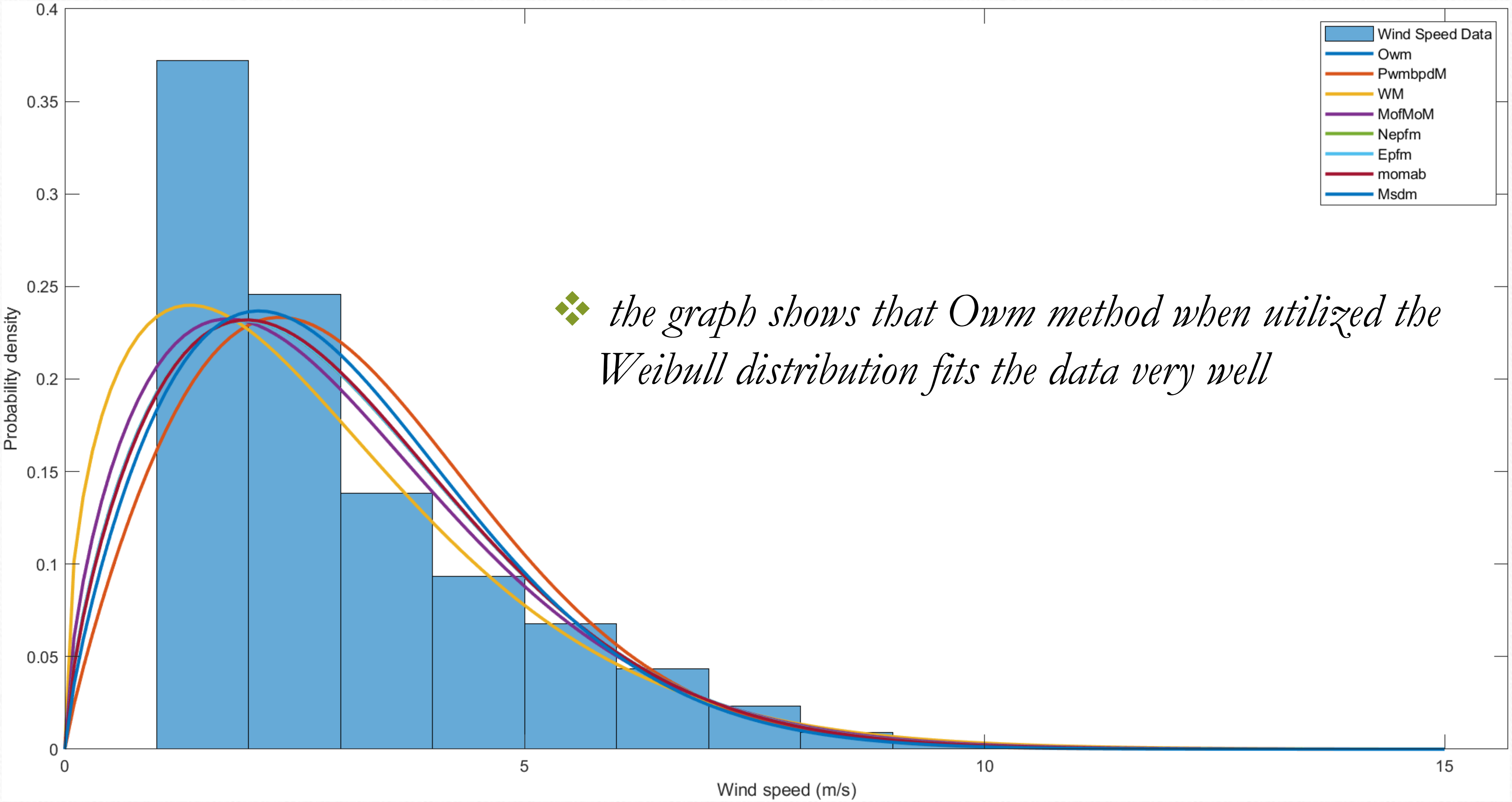
Class	Fair	Fairly Good	Good	Very good
P (W/m^2)	$P < 100$	$100 \leq P < 300$	$300 \leq P < 700$	$P \geq 700$

Results and discussions : Assessment of wind speed properties

- The overall average wind speed is 2.999 m/s with a standard deviation of 1.77 m/s.
- A positive skewness of 1.37 obtained showed that wind speed data is skewed to the right.
  - *also it implies that values of the measured wind speed are above the average wind speed (2.999m/s) which reflects a better wind performance at the site.*
- A positive kurtosis of 1.75 below 3 was obtained and therefore depicted wind speed data that has few extreme values

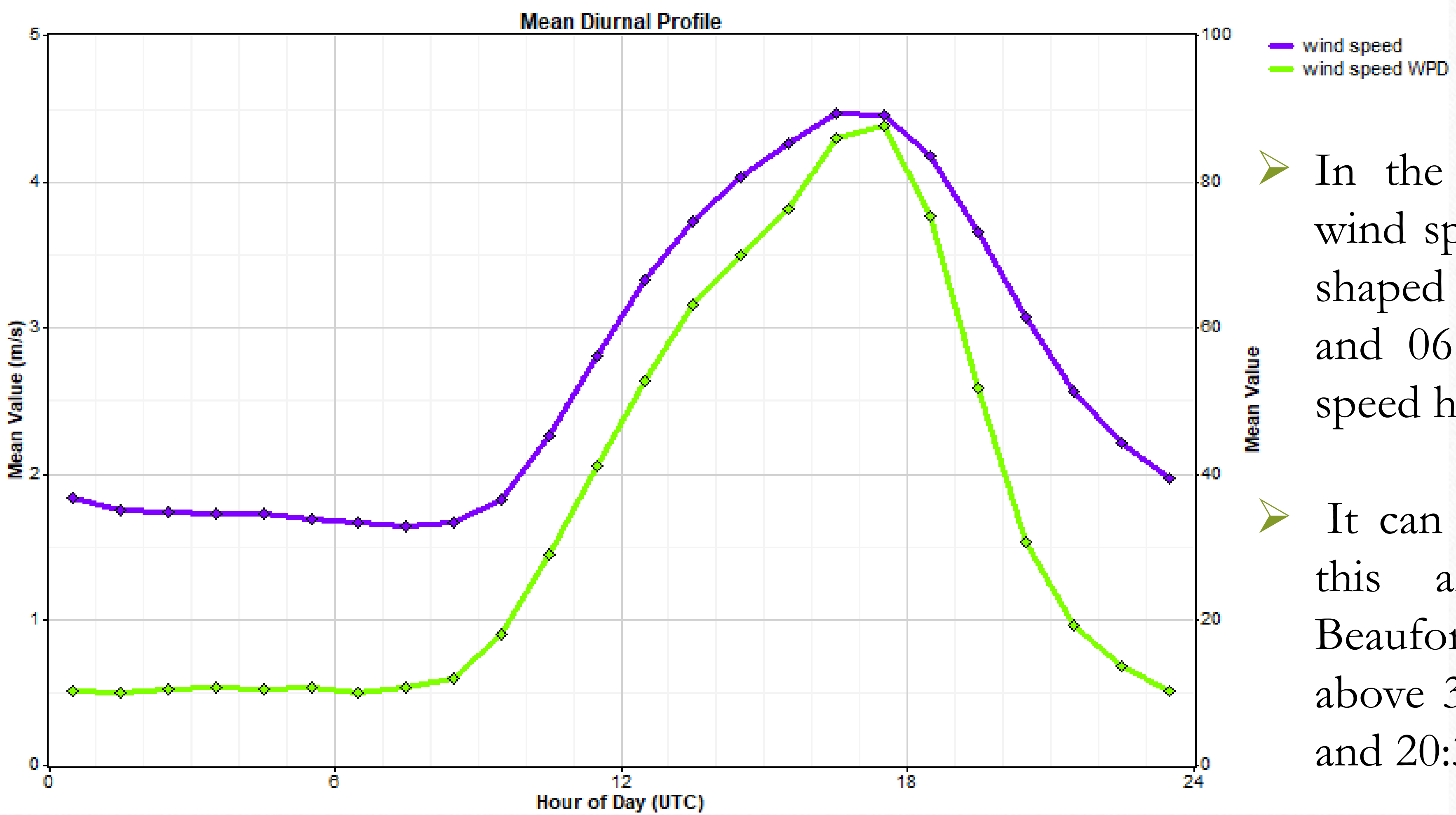
Statistic	Value
Sample Size	43723
Range	13.90
Mean	2.999
Variance	3.14
Std. Deviation	1.77
Coef. of Variation	0.59
Std. Error	0.01
Skewness	1.37
Excess Kurtosis	1.75

Results and discussions : Fitting probability distributions to observed wind data



- *the graph shows that Owm method when utilized the Weibull distribution fits the data very well*

Results and discussions : Daily averages of wind speed and wind power density



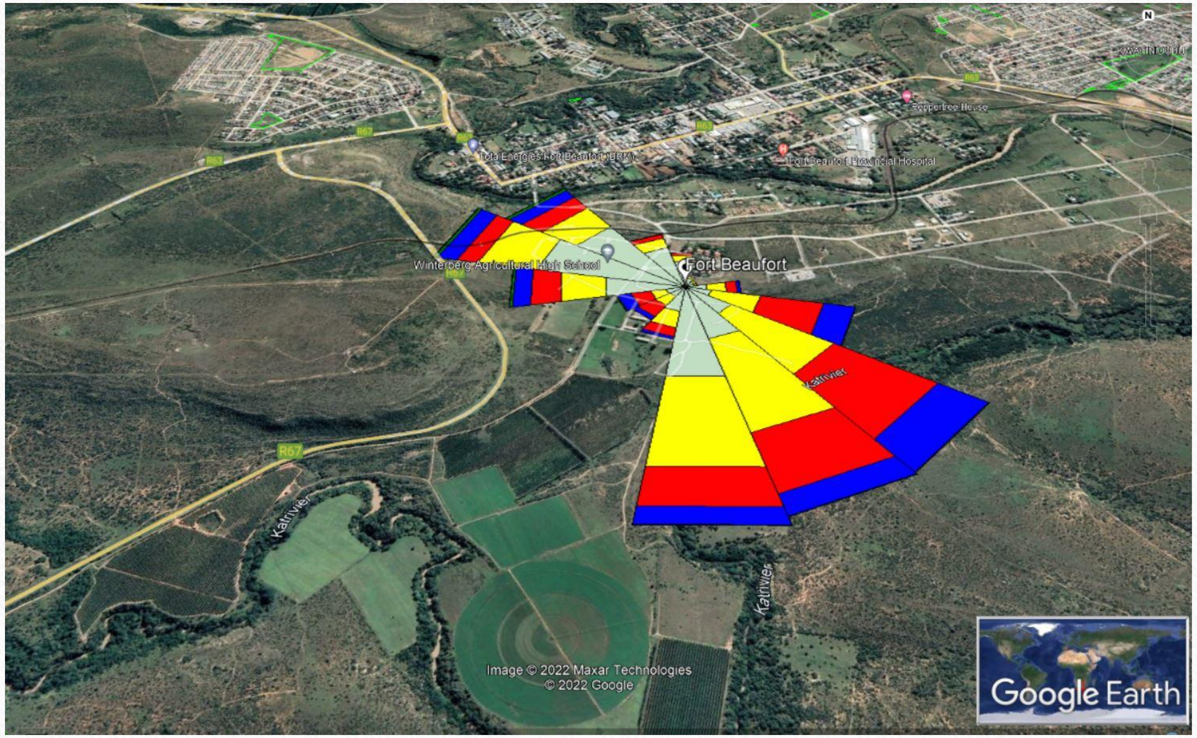
- In the afternoon, average wind speed profile is dome shaped and between 21:00 and 06:00 the mean wind speed has lowest values

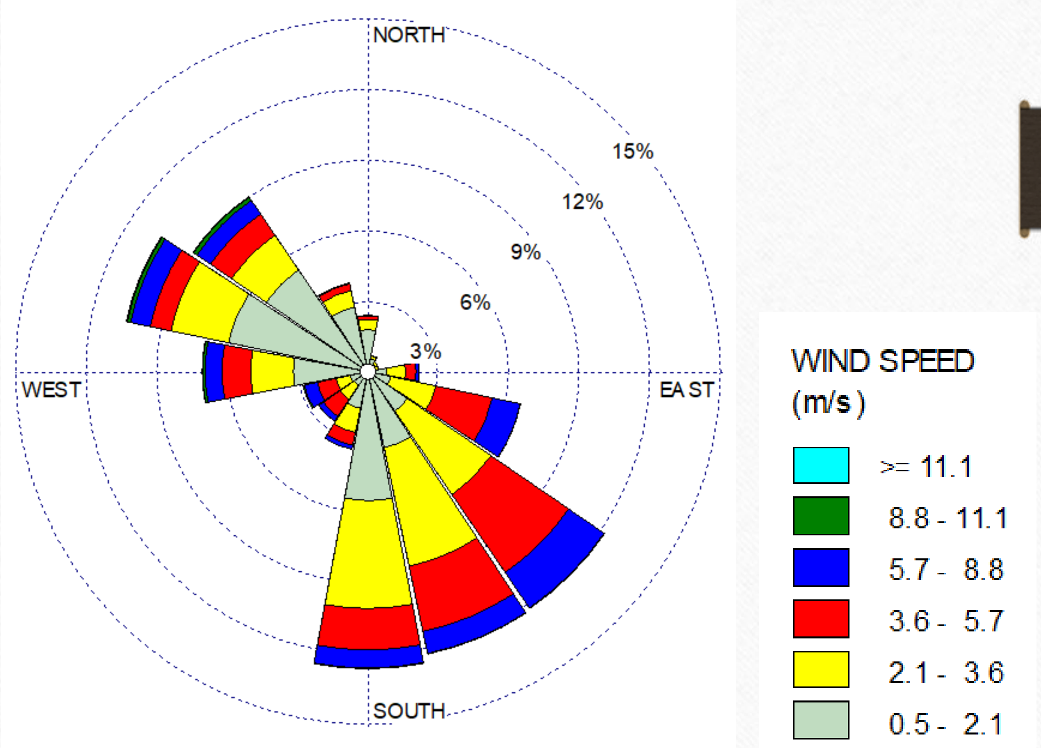
- It can be concluded from this analysis that Fort Beaufort has wind speeds above 3m/s between 12:00 and 20:30.

Results and discussions : Wind direction

- Wind Rose present data on wind speed and direction occurrences (Tahir et al.,2021).
  - *This information is crucial for site selection, as it helps identify the optimal locations for installing wind turbines to maximise wind power utilisation (Hussain et al., 2023)*

- The dominating wind mostly comes from the South -East direction (SE) of Fort Beaufort area.





Results and discussions : The goodness of fit test

Algorithm	Kolmogorov Smirnov	Rank	Anderson Darling	Rank	Chi-Squared	Rank	RSME	Rank	WPDerror	Rank	Mabe	Rank	Ave Rank
Owm	0.13002	1	1014.6	1	8745.3	1	0.07361	1	9.948E-14	1	0.4392	1	**1**
PwmbpdM	0.13416	2	1049.6	2	9919.9	3	0.07755	2	6.519E-06	2	0.4944	3	**2**
WM	0.14451	6	1058	4	9102.2	2	0.07941	3	2.774E-05	3	0.4692	2	**3**
Nepfm	0.14422	4	1056.7	3	9931	4	0.07942	4	1.117E-02	5	0.4957	4	**4**
MofMOM	0.14281	3	1164.3	6	9933.3	5	0.08220	7	8.603E-04	4	0.4979	5	**5**
Epfm	0.14446	5	1058.3	5	9983.4	6	0.07947	5	5.294E-02	6	0.4981	6	**6**
momab	0.16372	7	1293	7	12836	8	0.07973	6	3.017E-01	7	0.5224	7	**7**
Msdm	0.2078	8	1825.4	8	10746	7	0.08354	8	2.443E+00	8	0.5695	8	**8**

Results and discussions: calculation of wind power density and classification

		Weibull parameters		Wind Power Density		
	Algorithm	Shape (k)	Scale (c)	WPdwbl	WPdobs	% Error margin
1	Owm	1.679048803	3.358002058	38.452176	38.452176	9.94760E-14
2	PwmbpdM	1.867853000	3.522606000	38.452182	38.452176	6.51889E-06
3	WM	1.444533000	3.079657000	38.452148	38.452176	2.77382E-05
4	MofMoM	1.599217000	3.273809000	38.451315	38.452176	0.00086026
5	Nepfm	1.679380000	3.358006000	38.441002	38.452176	0.01117348
6	Epfm	1.680868000	3.358266000	38.399233	38.452176	0.05294280
7	momab	1.689512843	3.359496866	38.150480	38.452176	0.30169588
8	Msdm	1.771723996	3.369759722	36.009513	38.452176	2.44266266

$$WPd_{obs} = \frac{1}{2}\rho v^3$$

$$WPd_{wbl} = \frac{1}{2}\rho c^3 \Gamma\left(\frac{3}{k}+1\right)$$

- *Owm is the best with a value of 38.452176 W/m² compared to actual WPD for observed wind speed data (38.452176W/m²) with* 9.95E-14 % *error margin.*

- *The mean standard deviation method (Msdm) performed poorly with an error margin of* 2.44%

Conclusion/ Recommendations

- The analysis showed that the best algorithm to calculate the Weibull scale and shape parameters for the two-parameter Weibull distribution is Open wind .
  - *It is recommended that the two-parameter Weibull distribution can be used fit the observed wind data of the Fort Beaufort area if the k and c parameters are estimated using Open wind algorithm.*
- Overall power density estimated for the Fort Beaufort area 38.452176 W/m^2 at a height of 10 m and falls in the fair category according to Fazelpour classification.
  - *It is therefore recommended that small scale wind power generation projects should be utilised in this area for purposes of (lightning, charging of batteries or pumping of water).*
  - *Augmentation systems like concentrators, diffusers, and invelox are recommended to lower cut-in wind speeds for wind turbines, enabling operation in areas with wind speeds below 5 m/s (Shambira et al ,2021).*
- It is recommended to also utilize evolutionary metaheuristic algorithms.

Thank your for your attention