Wind Energy Potential for Small-scale WEC Systems in Port Elizabeth

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Abstract. South Africa is the highest emitter of greenhouse gases in the continent, and 18\textsuperscript{th} in the world. Electricity generation in South Africa is heavily dependent on fossil fuels for its energy needs. Hence, it is a necessity to shift to renewable energy sources for electricity production in order to mitigate carbon emissions. This paper discusses the potential for electricity generation through small-scale wind energy conversion (WEC) systems in Port Elizabeth that is considered to be South Africa’s windiest city. A wind energy study was conducted through analyses of the local weather data. The study shows that Port Elizabeth has an annual wind power density of 138 W/m\textsuperscript{2}. The area studied has great wind power potential, especially for small-scale wind energy production. The Weibull method has been applied to predict wind power potential in Port Elizabeth, South Africa. Furthermore, the Weibull method was applied to model the probability function of the wind speed due to its user friendliness and flexibility.

1. Introduction

Renewable energy sources such as hydro, solar, wind, ocean thermal, geothermal and biomass energy have attracted significant focus worldwide due to their non-polluting and inexhaustible characteristics. Wind energy has proven to be the most suitable, inexpensive and effective source for power generation and is used extensively in various countries across Asia and European Countries that have the largest wind energy installed capacities also account for the largest wind turbine manufacturing market share [1]. These countries include Germany, China, India, Spain, Denmark, and the United States of America. The use of modern renewable energy sources such as solar and wind in Africa lags behind other regions. In 2011, the continent’s estimated installed wind power capacity was 1.1GW. This constitutes less than 1% of the continent’s total installed electricity generation capacity. The North Africa sub-region holds the majority of the continent’s existing wind energy installed capacity. In sub-Saharan Africa, the biggest installed wind power capacity is in East Africa; wind power capacity of up to 186MW has been installed in seven countries within this sub-region [1]. Other sub-regions have made little or no progress at all such as Central Africa. The South African Wind Energy Association (SAWEA) states that 62% of South Africa’s current energy consumption can be generated by wind power harvesting [2]. It is cheaper and environmentally friendly to generate electricity from wind compared to fossil fuels. Furthermore, the Renewable Energy Independent Power Producer Program (REIPPPP) reported that the price of wind power generation has decreased by 42% and averages 74 cents per kWh in South Africa.
2. Background

The awareness of energy conservation is rapidly increasing as a result of global warming and increased electricity costs. The electricity prices in South Africa have risen in nominal and real terms throughout the past years. The regulator has agreed to this inflation increase for the next five years, causing concern among Eskom’s customers [2]. Therefore, it is necessary to consider ways in which electricity can be accessible and affordable for the majority of households in South Africa. South Africa has an average wind speed of 5 m/s in some escarpment and coastal regions. However, this paper focuses on Port Elizabeth the windiest city in South Africa [1]. Table 1 shows the average wind speed of the study location.

Table 1. Average speed and measuring height in Port Elizabeth

| Station        | Average mean speed (m/s) | Height above ground level (m) | Height above sea level (m) |
|----------------|--------------------------|------------------------------|---------------------------|
| Port Elizabeth | 5.5                      | 10                           | 60                        |

The above information was obtained from the weather data recorded by the South African Weather Service (SAWS). Mean wind speeds equivalent of or above 4 m/s are highly suitable for small-scale wind power applications [4]. However, no small-scale WEC systems have been built for Port Elizabeth households and industrial areas in South Africa. The potential for wind power along the coastline has been somewhat neglected, hence it is necessary to produce more research work related to wind power.

3. Methodology

3.1. Site and Data Collection

Wind characteristics evaluations were conducted around South African windiest town, namely, Port Elizabeth. The compiled geographic data shows wind characteristics of a period of one year (January to December 2017). SAWS supplied the wind characteristics data, in addition, the data were measured at meteorological weather stations in Port Elizabeth. The measurements were taken at a standard height of 10 m above the ground.

3.2. Weibull Distribution Function

There are various distribution functions that can be applied in order to determine the probability density function of wind speed. However, in this study the Weibull distribution function (WDF) was used to establish the frequency curve of the wind speed probability function. The two-parameter Weibull probability density function is given as [4]:

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

(1)

Where \( v \) is the observing speed, \( k \) is the Weibull shape parameter, \( c \) is the Weibull scale parameter and \( f(v) \) is the probability of the observing speed. The Weibull parameters illustrate the wind potential of the site under evaluation. The shape parameter \( k \) indicates how 'peaked' the wind distribution is, whereas the scale parameter \( c \) indicates the 'windiness' of the site under consideration. The corresponding cumulative probability function of the Weibull distribution is given as [5]:

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

(2)

3.3. Parameter Estimation

Various researchers such as Dale & Ackerman [6] and Mulugeta & Drake [7] have used the maximum likelihood method to estimate the Weibull parameters. The shape parameter \( k \) can be estimated as follows [8]:

[Insert equations and references as needed]
\[ k = \left( \frac{\sigma}{\bar{v}} \right)^{-1.086} \quad (1 \leq k \leq 10) \quad (3) \]

Where \( \sigma \) is the wind speed variation, and \( \bar{v} \) is the mean wind speed. The wind speed variance and mean wind speed can be determined based on the Weibull parameters as given below:

\[ \bar{v} = \frac{1}{n} \sum_{i=1}^{n} v_i \quad (4) \]

And

\[ \sigma^2 = \frac{1}{n-1} \sum_{i=1}^{n} (v_i - \bar{v})^2 \quad (5) \]

Where \( n \) & \( v_i \) are the number of observed non-zero wind speeds and wind speed, respectively. The scale parameter \( c \) is estimated by the following [8]:

\[ c = \left( \bar{v} \right) \left( \Gamma \left( 1 + \frac{1}{k} \right) \right)^{-1} \quad (6) \]

Where \( \Gamma (x) \) is the gamma function, calculated as:

\[ \Gamma (x) = \sum_{s=0}^{\infty} s^{x-1} (e^{-s}) \, ds \quad (7) \]

Integrating by parts the value of gamma function can be easily found as,

\[ \Gamma \left( \frac{x}{2} \right) = \left( \frac{x}{2} - 1 \right) \quad (8) \]

If \( x \) is even, otherwise, taking into account that,

\[ \Gamma (0.5) = \sqrt{\pi} \quad (9) \]

And,

\[ \Gamma (x + 1) = x \quad (10) \]

The recursion formula should be used:

\[ \Gamma (x) = (x - 1) \Gamma (x - 1) \quad (11) \]

And, used here by their kind courtesy.

### 3.4 Wind Power Density

The establishment of the wind power density per unit area is important when evaluating locations with wind energy potential. The wind power that flows at a speed \( v \) through a fin sweep area \( A \) increases as the cube of its velocity and is given by:

\[ P(v) = \frac{1}{2} \rho AV^3 \quad (12) \]

Wind power density (WPD) is normally expressed in Watts per square meter (W/m\(^2\)), this takes the frequency distribution of the wind speed into account. Furthermore, WPD depends on air density and the cube of the wind speed. Hence, it is generally considered a better indicator of the wind energy potential than wind speed.

\[ P_w = \frac{1}{2} \rho c^3 \Gamma \left( 1 + \frac{3}{k} \right) \quad (13) \]

Where \( \rho \) is the air density that can be determined as follows:

\[ \rho = \frac{P}{RT} \quad (14) \]

Where \( P \) & \( T \) are the average pressure and temperature, \( R \) is the dry gas constant.

### 4. Wind Energy Analysis

#### 4.1 Wind Characteristics

In this paper the recorded data for 2017 is used for analysis. The South African coastline’s wind characteristics are evaluated across 12 months, i.e., on a yearly basis. Table 2 illustrates the mean monthly speeds from January to December in 2017.

| Location     | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|--------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Port Elizabeth | 6.2 | 5.7 | 5.4 | 4.5 | 4.5 | 5.4 | 4.8 | 5.4 | 5.6 | 6.0 | 5.7 | 5.6 |
Table 2 illustrates the highest wind speed magnitudes in Port Elizabeth to be 6.2 m/s. The wind speed range was at its lowest from April to July. The lowest wind speed magnitudes were observed to be 4.5 m/s to 4.8 m/s. Therefore, these recordings clearly indicate that the summer season is the windiest time of the year in the South African coastal region.

4.2. Weibull Probability Density Function
The Weibull probability density function (WPDF) is predominantly determined by the distribution function of the wind speed. The WPDF was applied in this study because it only consists of a few key parameters that can illuminate the characteristics of a wide range of wind speed data, such as hourly time-series wind speed data that may always be enormous. Hence, the WPDF is the most practical and simplest method to use in this application. Furthermore, it is easy to obtain the wind power potential and the economic viability, once the wind speed distribution is known. The shape parameter \( k \) indicates how ‘peaked’ the wind distribution is, whereas the scale parameter \( c \) indicates the ‘windiness’ of the site under consideration.

4.2.1. Weibull Probability Density Function in Port Elizabeth.

4.2.2. Port Elizabeth is classified as one of the windiest areas on the South African coastline [9]. The data were measured at a meteorological weather station in Port Elizabeth. The measurements were taken at a standard height of 10 m above the ground. Table 3 shows information related to the station location.

| Station     | Period (Months) | Latitude | Longitude | Height above sea level (m) |
|-------------|-----------------|----------|-----------|---------------------------|
| Port Elizabeth | Jan-Dec        | 33.99    | 25.62     | 60                        |

4.3. Wind Power Density
The wind power density in Port Elizabeth was determined by utilizing the wind parameters from the Weibull probability distribution. This statistical method is now considered to be a standard approach and is widely accepted for the evaluation of local wind probabilities. Equation (10) was applied to show wind power potential in the considered location, since it is generally considered a better indicator of the wind energy potential than wind speed.

4.3.1. Weibull Power Density in Port Elizabeth. Table 4 shows that the annual wind power density in Port Elizabeth (PE) varied from 77 W/m\(^2\) to 200 W/m\(^2\) throughout the year. The overall wind power density of the site is 138 W/m\(^2\). Hence, the power potential is 1209 kWh/m\(^2\) per year.

| Month | \( V_m \) (m/s) | \( C \) (m/s) | \( k \) | \( V_{maxE} \) (m/s) | WPD (W/m\(^2\)) |
|-------|-----------------|---------------|--------|----------------------|-----------------|
| January | 6.2             | 6.900        | 3.081  | 8.117                | 200             |
| February | 5.7             | 6.380        | 2.910  | 8.259                | 159             |
| March | 5.4             | 6.044        | 2.782  | 7.343                | 134             |
| April | 4.5             | 5.052        | 2.715  | 6.191                | 78              |
| May | 4.5             | 5.019        | 2.033  | 7.114                | 77              |
| June | 5.4             | 6.093        | 2.351  | 7.917                | 138             |
5. Conclusion
Port Elizabeth has an annual wind speed with maximum energy and wind power density of 7.565 m/s and 138 W/m², respectively. However, some months during spring and summer reach a peak of 200 W/m². The overall wind power density of the site is 138 W/m². Therefore, Port Elizabeth has a wind power potential of 1209 kWh/m² per year. Based on these findings Port Elizabeth has a great potential for wind power generation. Therefore, small-scale WEC systems would be suitable for areas around Port Elizabeth.

6. References
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