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Assessment of Wind Speed Characteristics and Available Wind Power Potential for Electricity Generation in Tanzania

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ABSTRACT

The energy demand and its associated crises are attracting significant attention due to population increase and economic growth especially in developing countries. Fossil fuel-based energy source stand as a prominent anthropogenic resource but they are accompanied with increased carbon emissions and heightened environmental concerns. Renewable energy sources such as wind energy can offers a lot of potential for sustainable growth in the energy sector of developing nations like Tanzania. Thus, this work investigated wind speed characteristics and available wind power potential in six selected regions in Tanzania with different topographical features for future electricity generation. The data of the wind speed of ten years available at a height of 10 m above ground level have been used to analyse monthly and annual variations of wind speed. Minimum and maximum average values of recorded wind speeds are presented in this paper. The Weibull shape k and scale c parameters have been estimated using the Weibull distribution function. Results indicate that the respective maximum average annual values of the shape and scale parameters for all sites are 2.54 and 8.21 m/s, which indicate that the wind speed is steady. The results show further that the Singida region has a maximum average annual wind speed of 7.29 m/s and a corresponding annual average wind power density of 237.30 W/m^2*. In conclusion, the results suggest that the Singida region can be considered a suitable site for wind energy generation on a large scale.*

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INTRODUCTION

Environmental pollution is a process which The growing global economy increases energy demand which has been supplied by fossil fuels in a large percentage. However, it is clear that the sustainability of fossil fuels is questionable because they are not replenished. Furthermore, much concerns have been raised regarding greenhouse gases and aerosols released by fossil fuel power plants (IPCC, 2015). Owing to these reasons, several countries have included renewable energy sources in their national energy plan. Renewable energy resource is often regarded as the best alternative because of its availability and environmentally benign (Fazelpour *et. al.*, 2015). Wind power is affordable, efficient, and commonly used due to its safety for the environment as well as its sustainability (Keyhani *et. al.*, 2010). As a promising form of clean and sustainable energy, the wind energy industry is growing rapidly throughout the world. The installed wind energy capacity all over the globe increased to 1 TW by the end of 2023, which indicates the need and the worth of this energy source in the future (GWEC, 2024). By the end of 2023, Tanzania's total grid installed capacity was 1,899.05 MW comprising hydro (32%), natural gas (63%), liquid fuel (4%), and others (1%). However, the demand for electricity in Tanzania is estimated to be growing at 10 – 15% per year, with currently only 24% of the total population having access to electricity (TanzaniaInvest, 2023). This energy demand will increase tremendously as the country transforms into an industrial economy. Therefore, it is important to explore alternative energy sources such as wind energy which is readily available in most parts of the country. However, one of the main drawbacks of wind energy is its variation in space and time. For optimal extraction of wind energy, detailed information on wind characteristics at the site of interest is essential before designing a wind farm project (Kumwenda, 2011). The utilization of wind power depends on a good knowledge of wind characteristics at the site(s) of relevance. The knowledge about the permanence of wind energy supply in a year is more important than that of the total amount of energy in a year (Samson and Kainkwa, 2019). Therefore, this study investigated the wind speed characteristics and the available wind power potential for electricity generation in six regions, namely, Singida, Mtwara, Tanga, Shinyanga, Mwanza, and Kilimanjaro.

MATERIALS AND METHODS

Data and Study site

The wind data used in this study were obtained from the Tanzania Meteorological Authority (TMA). The wind speed data were available at a height of 10 m above ground level from January 2010 to December 2019 and were measured using anemometers. These data were taken in each of the six regions of Singida, Mtwara, Tanga, Shinyanga, Mwanza, and Kilimanjaro as shown in Figure 1. As a pilot study, these six regions that have different topographical features were selected to represent the four major zones of Tanzania namely the southern zone (Mtwara), north zone (Kilimanjaro and Tanga), central zone (Singida), and lake zone (Shinyanga and Mwanza).

Figure 1: Geographical map of Tanzania showing the study regions.

WEIBULL DISTRIBUTION FUNCTION

Determinations of Weibull Parameters

The wind speed probability distribution functions are the main tools that are being used by many researchers (Komleh *et. al.*, 2015). These functions are widely used for different applications such as in determining distribution functions parameters for analyzing wind speed data and wind energy economics (Christofides and Pashardes, 1995).

In the Weibull distribution function, the probability density function, $f(V)$, gives the probability for a given wind speed V, while the cumulative density function, $F(V)$, gives the probability for the velocity equal to or less than V. The Weibull probability density function and Weibull cumulative distribution function are given by equations (1) and (2) (Chang, 2011; Guarient *et al.*, 2020; Kang *et. al.*, 2021):

$$f(V) = \frac{k}{c}\left(\frac{V}{c}\right)^{k-1} \exp\left(-\left(\frac{V}{c}\right)^{k}\right) \qquad (1)$$

and

$$F(V) = 1 - \exp\left(-\left(\frac{V}{c}\right)^{k}\right) \qquad (2)$$

where V is the wind speed (m/s), k is the dimensionless shape parameter and c is the scale parameter having the same unit with V.

There are several methods available in the literature for the determination of Weibull parameters *c* and *k*. Some of these methods include the graphical method, moment method, standard deviation method/empirical method, maximum likelihood method, energy pattern factor method, power density method, and the average wind speed method (Chang, 2011; Mohammadi and Mostafaeipour, 2013). Among these methods, the average wind speed method is commonly chosen due to its simplicity and small errors compared to other methods (Justus *et. al.*, 1978), and therefore, the average wind speed method was used to determine Weibull parameters *c* and *k* in this study.

The parameters c and k from the average wind speed method can be calculated by the mean wind speed, $\bar{V}$ of the observed wind speed data from the approximations given by equations (3) and (4) (Justus *et. al.*, 1978):

$$k = d_1\sqrt{\bar{V}} \qquad (1 \le k \le 10) \qquad (3)$$

and

$$c = \frac{\bar{V} \times k^{2.6674}}{0.184 + 0.816 \times k^{2.73855}} \qquad (4)$$

where d_1 is a site-specific proportionality constant with an average value of 0.94 when the mean wind speed is given in meter per second (Johnson, 2006).

The Weibull parameters k and c are important factors for wind farm site selection in the wind energy industry. The Weibull k value is an indication of the breath of the distribution of wind speeds and the Weibull c value indicates how ‘windy’ a location under consideration is. The lower k value corresponds to the broader distribution. In addition, lower average wind speed corresponds to lower Weibull k values (Foxon and Weisser, 2003).

Useful Site-Specific Wind Speeds

Basically, there are two types of wind speed that are of utmost interest in any wind energy assessment in a specific location. These are the maximum carrying energy or optimum wind speed (V_{opt}) and most probable wind speed, (V_{mp}). While V_{opt} is used to estimate the wind turbine design or rated wind speed, V_{mp} corresponds to the peak of the probability density function. The most probable wind speed denotes the most frequent wind speed for a given wind probability distribution and is expressed by equation (5) (Keyhani *et. al.*, 2010):

$$V_{mp} = c\left(1 - \frac{1}{k}\right)^{\frac{1}{k}} \qquad (5)$$

The maximum wind speed indicates the wind velocity at which most energy is available in a given wind regime. It is at this particular speed that engineers should ensure that the power coefficient is most efficient to allow for the highest energy conversion of a turbine. The V_{opt} can be calculated by equation (6) (Fazelpour *et al.*, 2017; Komleh *et al.*, 2015):

$$V_{opt} = c(1 + \frac{2}{k})^{\frac{1}{k}} \quad (6)$$

The wind turbine should be chosen with a rated wind speed that matches this maximum wind speed for maximizing energy output. Once V_{opt} is obtained for a site, the optimal rated wind speed of a wind turbine can be found (Johnson, 2006).

Available and Extractable Wind Power density

Wind power can be categorised as either available or extractable. Available wind power is the power that is available in a cross-section area perpendicular to the wind stream. The available wind power density $\boldsymbol{P_a}$ of the wind at speed $\boldsymbol{V}$ (m/s) per unit area perpendicular to the wind direction is given by equation (7) (Anani *et al.*, 1988):

$$P_a = \frac{1}{2}\rho V^3 \quad (7)$$

where P_a, is the available wind power density, ρ is the air density which is taken as 1.225 kg/m^3 and V is the wind speed data.

On the other hand, the extractable wind power density P_e is the power, which can be extracted from the wind stream depending on the available wind power and the operating characteristics of the wind turbine. The extractable power density is given by the equation (8) (Johnson, 2006):

$$P_e = \frac{1}{2}C_p\rho V^3 \quad (8)$$

where C_p is the power coefficient with the maximum value of 0.593, which is known as the Betz limit or the Betz coefficient (Bansal *et al.*, 1990). The wind power that intercepts the wind turbine is not what the wind machine can produce as it cannot capture all of it. However, the actual value will depend upon the type, and design of the machine and on the operating conditions.

Apart from defining wind power density, one can use the concept of available wind energy. The available wind energy per period, E under consideration can be calculated by equation (9) (Gipe, 1999):

$$E = Pt \quad (9)$$

where t is the total time in hours during that period, and P is the estimated power density. All data analyses were carried out using ROOT version 5.34 software.

RESULTS AND DISCUSSIONS

Wind Speed Analysis

The monthly average wind speed of the six selected regions (Tanga, Mtwara, Singida, Kilimanjaro, Mwanza, and Shinyanga) for ten years, from 2010 to 2019 are depicted in Figure 2. It can be noticed that the lowest monthly mean wind speed was 0.51 m/s observed in May 2010, August 2011, and June 2018 (Kilimanjaro) while the highest monthly average wind speed of 9.77 m/s was found in September 2017 (Singida). Figure 2 (c) shows that the wind speed variations are very high, especially at the early months of the year (January-March) that ranges from 1.54 m/s to 7.72 m/s. Furthermore, the average values of the monthly wind speed for four regions namely Kilimanjaro, Tanga, Mwanza, and Shinyanga regions are below 5 m/s which is not suitable for electricity generation (Twidel and Weir, 2005). Also, the results in Figure 2 show that the average monthly wind speed does not show a consistent pattern in all six regions.

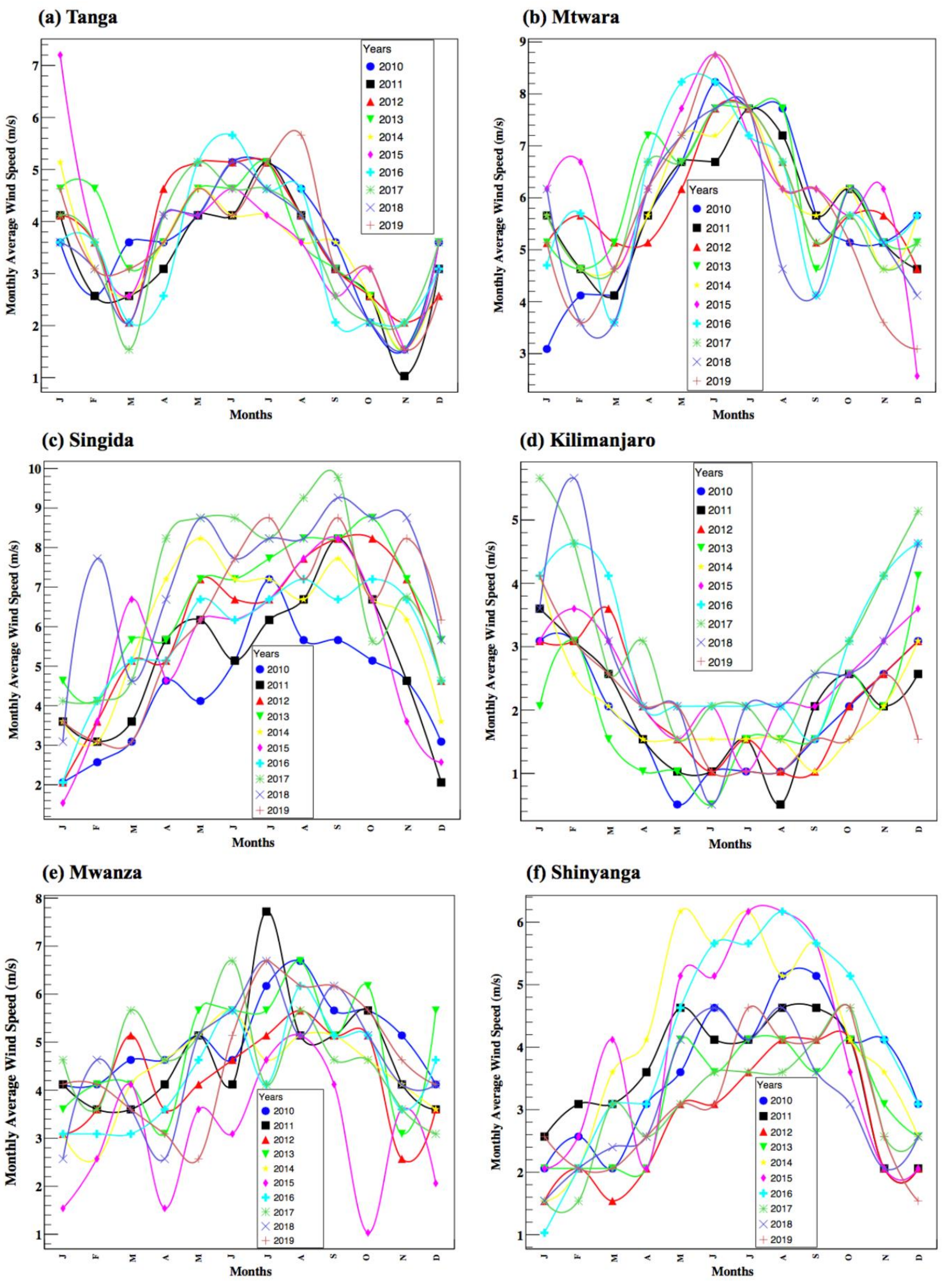

Figure 2: Monthly average wind speed from January 2010 to December 2019 of all six regions.

The computed annual average wind speeds from 2010 to 2019 for six selected study sites are represented in Figure 3. From this Figure, it can be noted that the highest average annual wind speed was 7.29 m/s for Singida in 2018 while the lowest wind speed (approximately 2.01 m/s) was observed in Kilimanjaro in 2010. The annual average values of wind speed for two regions namely Singida and Mtwara are above 5 m/s which is appropriate for electricity generation on a large scale while those sites with average values below that are not good for electricity generation (Twidel and Weir, 2005). These results suggest that the wind speed characteristics at these two sites in Singida and Mtwara regions are promising for electricity generation on a large scale.

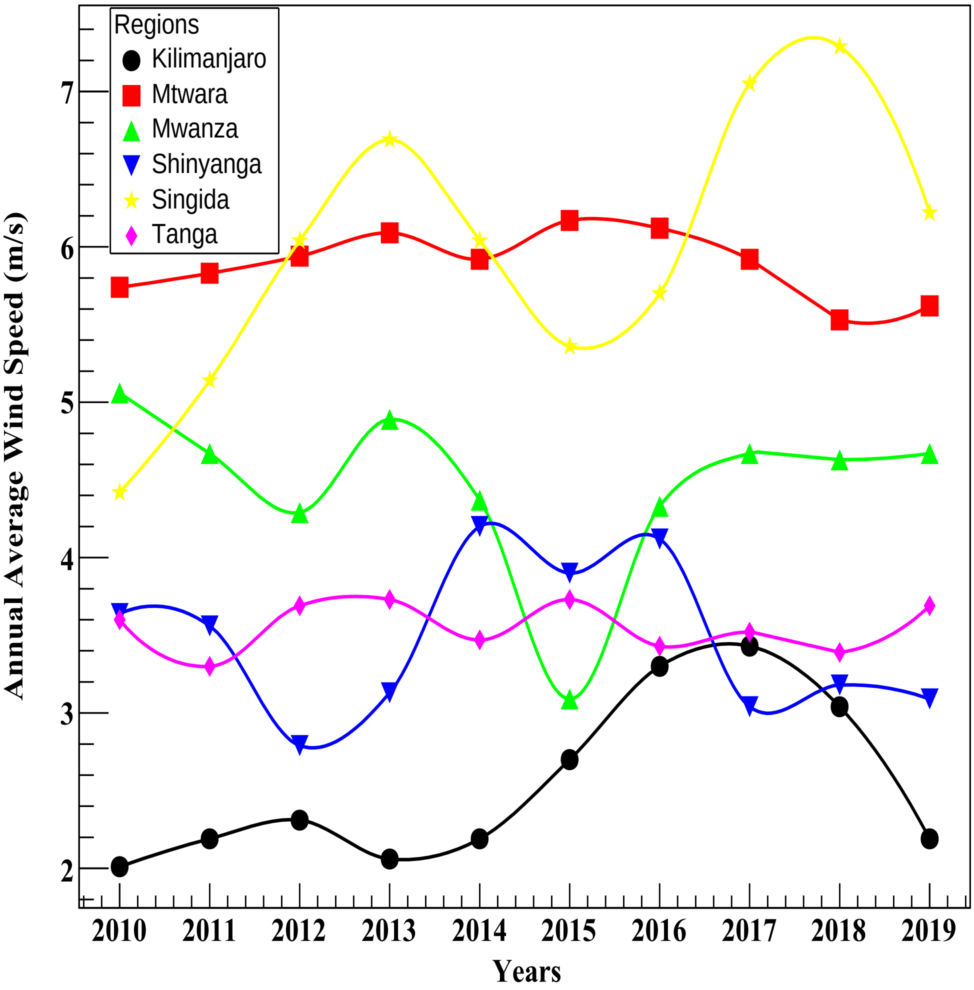

Figure 3: Annual average wind speed from 2010 to 2019 for all six regions.

Therefore, Singida and Mtwara regions give a promising wind speed potential for large-scale electricity generation. However, it is important to consider other parameters for the two regions. Tables 1 and 2 represent the annual average values of the two Weibull parameters (scale parameter *c* and shape parameter *k*) as well as two characteristics of wind speeds that are most probable V_{mp} and optimum V_{opt} wind speed calculated from ten years wind speed data of Mtwara and Singida regions, respectively. Table 1 shows that the minimum annual average values of *k* and *c* are 2.21 and 6.24 m/s respectively, for Mtwara while Table 2 shows the minimum annual average values of *k* and *c* are 1.98 and 4.98 m/s, respectively for Singida for the considered period. The results from Tables 1 and 2 portray that the maximum values of the Weibull distribution scale parameter *c*, are 6.97 m/s observed in 2015 and 8.21 m/s observed in 2018 in Mtwara and Singida, respectively. Also, the results show further that the maximum values of *k* are 2.34 noted in 2015 (Mtwara) and 2.54 observed in 2018 (Singida).

In addition, from Table 1 the highest and the lowest V_{mp} for 10 m are respectively 5.49 m/s and 4.76 m/s whereas for V_{opt} the lowest values are 8.35 m/s and the highest is 9.08 m/s. In Table 2 the maximum and the minimum values of V_{mp} are respectively 6.74 m/s and 3.48 m/s while for V_{opt} the lowest value is 7.09 m/s and the highest is 10.33 m/s.

Table 1: Annual average wind speed, Weibull parameters and specific wind characteristics from 2010 to 2019 for Mtwara region.

Years	V (m/s)	k	c (m/s)	V_{mp} (m/s)	V_{opt} (m/s)
2010	5.74	2.25	6.49	5.00	8.60
2011	5.83	2.27	6.58	5.10	8.69
2012	5.94	2.29	6.71	5.22	8.81
2013	6.09	2.32	6.87	5.39	8.98
2014	5.92	2.29	6.68	5.19	8.79
2015	6.17	2.34	6.97	5.49	9.08
2016	6.12	2.33	6.91	5.43	9.02
2017	5.92	2.29	6.68	5.19	8.79
2018	5.53	2.21	6.24	4.76	8.35
2019	5.62	2.23	6.34	4.85	8.45

Table 2: Annual average wind speed, Weibull parameters and specific wind characteristics from 2010 to 2019 for Singida region.

Years	V (m/s)	k	c (m/s)	V_{mp} (m/s)	V_{opt} (m/s)
2010	4.42	1.98	4.98	3.48	7.09
2011	5.14	2.13	5.81	4.32	7.92
2012	6.04	2.31	6.82	5.34	8.94
2013	6.69	2.43	7.54	6.07	9.66
2014	6.04	2.31	6.82	5.34	8.94
2015	5.36	2.18	6.05	4.56	8.17
2016	5.70	2.24	6.44	4.95	8.55
2017	7.05	2.50	7.95	6.47	10.06
2018	7.29	2.54	8.21	6.74	10.33
2019	6.22	2.34	7.02	5.53	9.13

Wind Power and Energy Density

Figure 4 displays the annual mean power density based on actual data for all six regions for the ten-year period. This shows that the lowest average power density was 5.12 W/m^2 observed in Kilimanjaro in 2010 while the highest average power density was 237.30 W/m^2 observed in Singida 2018. According to the wind power density classification shown in Table 3, sites can be classified based on their wind power density (Ammari *et. al.*, 2015; Komleh *et. al.*, 2015). Areas designated as class 1 are generally not suitable for large-scale wind energy applications while class 2 areas are marginal. Areas that can be classified as class 3 or greater are suitable for most large-scale wind energy applications (Mohammadi and Mostafaeipour, 2013; Elliot *et. al.*, 1986). Based on the calculated values of annual wind power density (>200 W/m^2), shown in Figure 4, indicate that the Singida region is in class 4 and suitable for the installation of large-scale wind energy farms. From the calculated values shown in Figure 4, the higher wind speeds throughout the year resulted in a higher wind power density for both years, which was more than 200 W/m^2.

Table 3: Classes of wind power density at 10 m and 50 m.

Wind power class	10 m		50 m	
	Wind power density (W/ m^2)	Wind speed (m/s)	Wind power density (W/ m^2)	Wind speed (m/s)
1	0 - 100	0 - 4.4	0 - 200	0 - 5.6
2	0 – 150	4.4 - 5.1	200 - 300	5.6 - 6.4
3	150 – 200	5.1 - 5.6	300 - 400	6.4 - 7.0

4	200 – 250	5.6 - 6.0	400 – 500	7.0 - 7.5
5	250 – 300	6.0 - 6.4	500 – 600	7.5 - 8.0
6	300 – 400	6.4 - 7.0	600 – 800	8.0 - 8.8
7	400 – 1000	7.0 - 9.4	800 – 2000	8.8 - 11.9
8	>1000	>9.4	>2000	>11.9

Source: (Hughes, 2000; Yasser *et. al*., 2023)

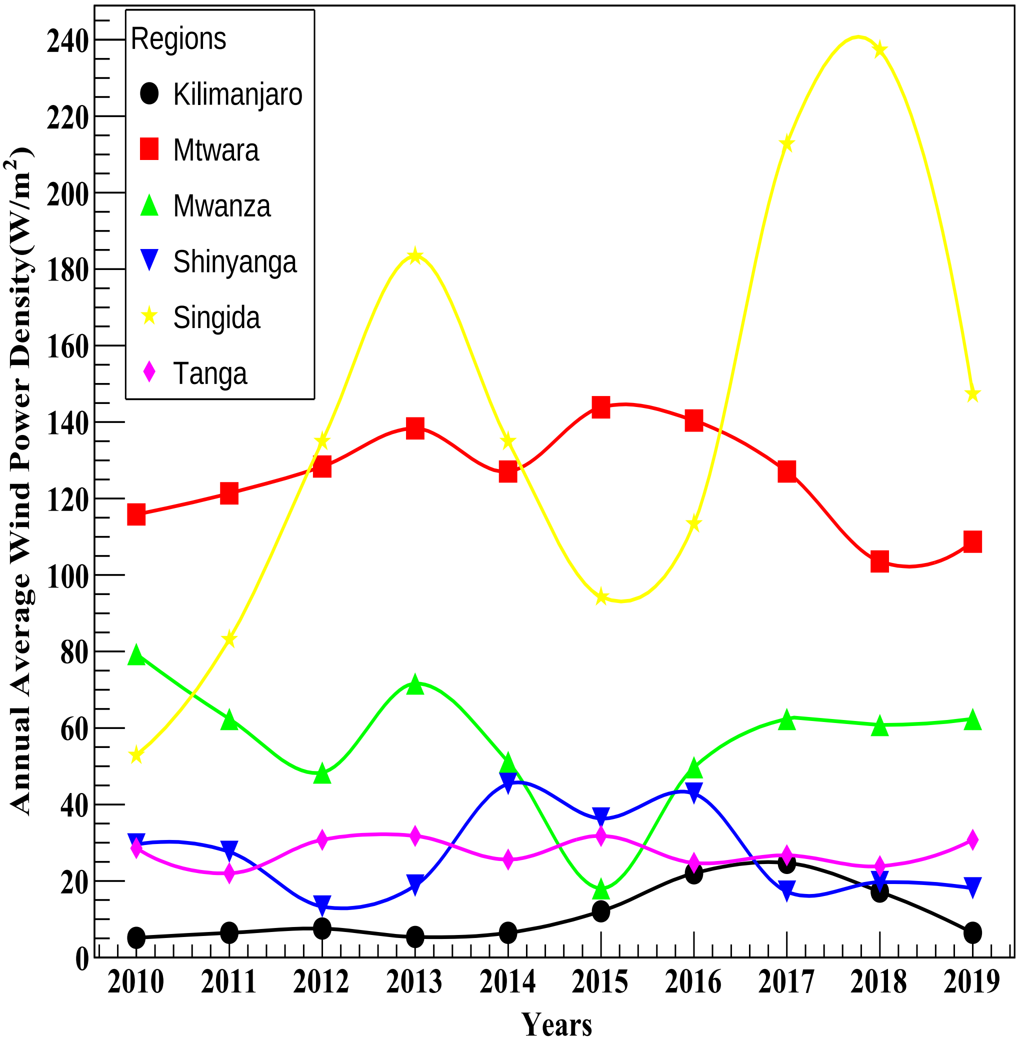

Figure 4: Annual average wind power density from 2010 to 2019 for all six regions.

The annual average wind power and energy density for the Mtwara and Singida regions are tabulated in Tables 4 and 5, respectively. From Table 4 the minimum available average wind power and energy density are 103.58 W/m^2 and 907.98 kWh/m^2, correspondingly whereas the maximum available mean wind power and energy density are 143.87 W/m^2 and 1261.16 kWh/m^2 respectively. Furthermore, Table 4 shows that the maximum and minimum extractable wind power densities were 85.31 W/m^2 in 2015 and 61.42 W/m^2 in 2018, respectively. Table 5 depicts that the highest value of available wind power density was 237.30 W/m^2 in 2018 while the lowest one was 52.89 W/m^2 found in 2010. The results (Table 5) show further that the available energy density values range between 463.63 kWh/m^2 and 2080.17 kWh/m^2. The maximum extractable wind power density in this study was found to be 140.72 W/m^2 in 2018, noticed in the Singida region while the minimum extractable power was 31.36 W/m^2 in 2018 as depicted in Table 5.

Table 4: Annual average power density and energy density from 2010 to 2019 for Mtwara region.

Years	Power Density (W/ m^2)		Energy Density (kWh/ m^2)	
	Available	Extractable	Available	Extractable
2010	115.84	68.69	1015.45	602.16
2011	121.37	71.97	1063.93	630.91
2012	128.37	76.12	1125.29	667.3
2013	138.34	82.04	1212.69	719.13
2014	127.08	75.36	1113.98	660.59
2015	143.87	85.31	1261.16	747.87
2016	140.40	83.26	1230.75	729.83
2017	127.08	75.36	1113.98	660.59
2018	103.58	61.42	907.98	538.43
2019	108.72	64.47	953.04	565.15

Table 5: Annual average power density and energy density from 2010 to 2019 for Singida region.

Years	Power Density (W/ m^2)		Energy Density (kWh/ m^2)	
	Available	Extractable	Available	Extractable
2010	52.89	31.36	463.63	274.93
2011	83.18	49.33	729.16	432.39
2012	134.96	80.03	1183.06	701.55
2013	183.39	108.75	1607.59	953.31
2014	134.96	80.03	1183.06	701.55
2015	94.32	55.93	826.81	490.3
2016	113.43	67.26	994.33	589.64
2017	212.80	126.19	1865.41	1106.19
2018	237.30	140.72	2080.17	1233.54
2019	147.39	87.4	1292.02	766.17

CONCLUSIONS

Assessment of wind speed characteristics and available wind power potential for the six regions of Singida, Mtwara, Tanga, Shinyanga, Mwanza, and Kilimanjaro were carried out in this work. Ten years wind speed data were used to analyze and compute different indicators for the assessment of the wind power potential of the study sites. Based on the results the maximum average annual wind speed was 7.29 m/s observed in Singida in 2018 while the minimum annual wind speed of 2.01 m/s was observed in Kilimanjaro in 2010. The lowest monthly mean wind speed was 0.51 m/s observed in May 2010, August 2011, and June 2018 (Kilimanjaro) while the highest monthly average wind speed of 9.77 m/s was found in September 2017 (Singida). Weibull shape parameter k for all six regions ranges from 1.33 to 2.54 with the highest annual average value of 2.54 observed in the Singida region. The higher values of k show that the wind speed was steady at the site. The scale parameter c ranged from 2.19 m/s to 8.21 m/s with the maximum annual average value of 8.21 m/s. The most probable wind (V_{mp}) and maximum energy carrying wind (V_{opt}) values were in the range from 0.77 m/s to 6.74 m/s and from 4.36 m/s to 10.33 m/s respectively. The Singida region shows the maximum annual average available wind power density and energy density of 237.30 W/m^2 and 2080.17 kWh/m^2, respectively. The results revealed that the Singida region is in class 4 and can be considered as a promising zone for wind power generation projects such as small standalone systems or large wind farms. Further research is recommended to study the economic analysis of the available data for the

Singida region as potential site for large-scale electricity production.

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Conflict of Interest

We declare no conflict of interest in this research work.

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