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Statistical Modelling of Wind Speed and the Temperature of Narok County

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Abstract: *Kenya is one of the countries with energy shortage especially in the rural areas which results in high electricity demand in the country [3, 4, 12]. To reduce this shortage, more installation of wind power plants and solar panels is necessary to harness the wind energy and solar energy to reduce the shortage. This makes it significant to study wind speed and temperature behavior. The past studies related to wind study were examined using some statistical models like Weibull, lognormal, gamma, Rayleigh, and hybrid Weibull among other models. However, none of the studies have been able to model the temperature or develop a model to predict its distribution, especially in Narok county. This paper intended to model the wind speed and temperatures of Narok county using a joint exponential distribution which can help predict the probability of obtaining specific wind speed and temperature within the county. The study was able to model the joint probability distribution for wind speed and temperature together with the marginal distributions of wind speed and temperature. The study found out the average wind speed of Narok county was 2.4517 m/s with a standard deviation of 2.1941. The study found out the average temperature was 21.10* ^0C *with a standard deviation of 4.5684. The study also found that the wind speed and the temperature of Narok county were independently distributed.*

1. INTRODUCTION

The wind is the natural movement of air at a particular velocity while the temperature is the degree of hotness or coldness of a particular environment. The wind speed distribution is for the assessment of wind energy potential and the performance of the wind energy conversion system [2, 8]. The temperature on the other hand is associated with the degree of heat generated by the sun radiations in a particular area, these radiations are always harnessed using solar panels to generate solar energy.

Kenya is one of the countries with energy shortage especially in the rural areas which results in high electricity demand in the country [3, 4, 12]. As an alternative source of energy, wind technology, and solar energy is gaining a positive direction in the country with wind power projects and solar panels becoming more attractive. To aid in the productivity of this sector with the country, the study saw it wise to model the distribution of these two important factors to aid in the determination of the potentiality of both solar and wind energy production in Narok county [14, 19, 20].

Based on past studies it has been established that abundant wind is not evenly distributed all over Africa but East, Southern, and North African have excellent wind resources. Countries with good wind capacities include all those in North Africa, Nigeria, Chad, Ethiopia, Kenya, Djibouti, Somalia, Sudan, Tanzania, Zambia, Lesotho, Malawi, and South Africa [1, 2, 5].

In Kenya, the government is putting more effect and money on to help increase the capacity of wind energy in the country [10, 11]. It has quantified that in the next two or three years, the total wind installed capacity will amount to 500MW and 2GW wind capacity by 2030 [8,9]. As a result, there is a need to identify areas with the potentiality of wind energy production so that investors can be able to determine the regions where the wind plants can be installed to aid in more wind production.

Past studies have shown that the distribution of wind speeds can be modeled using various distributions such as;

1.1. Weibull Distribution

The Weibull distribution applied by [15, 21, 17].

$$f(\mu) = \frac{\beta}{\rho}\left(\frac{\mu}{\rho}\right)^{\beta-1} exp\left[-\left(\frac{\mu}{\rho}\right)^{\beta}\right] \; (\beta > 0, \mu > 0, \rho > 1) \quad (1)$$

Where:

f (u) is the probability of observing wind speed.

u is the wind speed.

b is the shape factor (parameter)which has no unit but range from 1.5 to 3.0 for most wind conditions

p is the value in the unit of wind speed called the Weibull scale parameter in m/s.

1.2. Lognormal Distribution

The two parameters lognormal distribution given as [6, 7, 16]:

$$f(p) = \frac{1}{k\sqrt{2p\pi}} \, exp\frac{(lnp-v)^2}{2k^2} \quad (2)$$

Where:

p is the log-normal random variable

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ln(p) is the normal random variable

v is the mean for a normal random variable

k is the standard deviation for the normal random variable

1.3. Gamma Distribution

The gamma distribution is also known to be a two-parameter family and therefore the distribution was also expressed in terms of the scale parameter and the shape parameter as the case with the Weibull distribution [6, 21].

$$\Gamma(\pi) = \int_0^\infty e^{-\theta}\,\theta^{\pi-1}d\theta \tag{3}$$

On the other hand, temperatures have also been known to vary from time to time within the region and the country, however, because of the nearness of the country to the equatorial line, the temperatures have been not to be too extreme but rather average most of the time. Despite the variations in temperatures, none of the past studies has determined a distribution that can be used to predict the probability of variation in the temperatures, especially in Narok county a factor that leaves a gap in the study of temperatures.

The study at creating a model that could be used to assess both the distribution of wind speed and the temperature of Narok county. The study also intended to establish the marginal distribution of the two variables individuals and lastly, check the relationship between wind speed and temperature.

2. METHODS

2.1 Model Formulation

From past studies, it has been determined that temperature is directly proportional to wind speed and therefore temperature is believed to have a product effect on velocity hence the joint relationship of the two is given as [18].

$$P(V,T)\ \alpha\ VT \tag{4}$$

Introducing a constant of variation to introduce the equal sign, we get to have

$$P(V,T) = MVT \tag{5}$$

But the probability is non-negative therefore to ensure that the probability remains non-negative we introduce exponent on the right side of the equation., therefore we will have the following model,

$$P(V,T) = Ke^{M(VT)} \tag{6}$$

Therefore, the model will be

$$P = Ke^{M(VT)} \tag{7}$$

Where:

P is the joint probability of velocity and temperature.

V is the velocity.

K *and* M are constants.

T is the temperature.

Hence to estimate the constants we need to linearize the function by introducing the natural logarithm. Hence, we have,

$$\ln(P) = \ln(K) + M(VT) \tag{8}$$

Therefore, a linear function of VT and ln(P) will give the gradient M as the constant and the y-intercept C as ln(K). Hence, $K = e^C$. Therefore, fitting the model of VT against ln(P) will help obtain the two constants K and M. After linearization of the model to obtain the constant terms, the Levenburg Mazquard algorithm was used to obtain stable iterations of the constant K and M using the linear estimates as the starting values.

The marginal distribution of V was obtained from the joint distribution given as,

$$P(V) = \int_a^b Ke^{M(VT)}\,dT \tag{9}$$

$$P(V) = \left[\frac{K}{MV}e^{MV(b-a)}\right] \tag{10}$$

Therefore, the marginal distribution of Velocity was given as;

$$P(V) = \begin{cases} \frac{K}{MV}\left(e^{MVb} - e^{MVa}\right) & w \le V \le y \\ 0 & otherwise \end{cases} \tag{11}$$

Similarly, the marginal distribution of Temperature was derived as;

$$P(T) = \int_w^y \frac{K}{MV}e^{M(VT)}\,dV \tag{12}$$

$$P(T) = \left[\frac{K}{MT}e^{MT(y-w)}\right] \tag{13}$$

Therefore, the marginal distribution of Temperature was given as;

$$P(T) = \begin{cases} \frac{K}{MT}\left(e^{MTy} - e^{MTw}\right) & a \le T \le b \\ 0 & otherwise \end{cases} \tag{14}$$

The joint distribution function was given,

$$P(V,T) = \begin{cases} Ke^{M(VT)} & a \le T \le b\,, w \le V \le y \\ 0 & otherwise \end{cases} \tag{15}$$

The expected value for the joint distribution was given as;

$$E(VT) = \int_a^b \int_w^y VTKe^{M(VT)}\,dVdT \tag{16}$$

The variance-covariance the function was given as;

$$Var(VT) = Var(T) + Var(V) + Cov(VT) \tag{17}$$

3. RESULTS

3.1. Fitting the Distribution Function

The study used hourly wind data collected from 5 stations from the year 2016 to the year 2018 which comprised a total of 66858 observations. The study used the observations to fit a joint distribution model for the county that could be used to estimate the chances of obtaining certain wind speed and temperature within Narok county. The joint distribution function for the wind speed and temperature was given by the function:

$$p(V,T)=\begin{cases} K\exp\left(M\left(vt\right)\right) & a\le t\le b, w\le v\le y \\ 0 & otherwise \end{cases} \quad (18)$$

The data was first summarized into joint frequency density distribution as illustrated in table 1. The joint frequency density was used as the probability P. Using the linearized relationship $\ln(P)=\ln(K)+Mvt$

Based on the above equation, a linear function of $\ln(P)$ against vt would give use M as the gradient and $\ln(K)$ as the y-intercept. Thus, a summary statistic for the three variables was as illustrated in table 1;

Table 1.

Percentage Proportion	Wind Speed in meters per second	The temperature in degrees Celsius
9.5	0.48	14.61
22.1	0.94	16.17
16.0	1.43	17.56
11.6	1.86	19.27
8.7	2.30	20.24
6.7	2.73	20.94
5.3	3.17	21.26
4.5	3.54	21.88
3.5	3.91	22.37
3.0	4.27	22.84
2.5	4.65	23.15
1.9	4.96	23.67
1.5	5.30	23.99
1.1	5.68	24.15
0.7	5.94	24.76
0.5	6.27	25.14
0.3	6.57	25.46
0.2	6.92	25.56
0.1	7.24	25.76
0.1	7.47	26.32
0.1	9.09	26.57

A fitted linear function between the linear function of $\ln(P)$ against vt was as illustrated in equation (17),

$$\ln(P)=-1.264-0.02572vt \quad (19)$$

To affirm the relationship between $\ln(P)$ and vt, a Fisher's test was carried out at 95% level of confidence based on the following null and alternative hypothesis;

H_0: *All the model parameters are inadequate*

Against

H_1: *At least one model parameter is adequate*

The results of the test were as illustrated in table2;

Table 2.

Source of Variation	***Df***	***SS***	***MS***	***F***	***P-value***
Regression	1	56.68399	56.68399	296.6584	<0.001
Residual	19	3.630424	0.191075		
Total	**20**	**60.31442**			

The results as illustrated in table 2, showed that at least one of the model parameters (intercept or gradient) was significantly different from zero. An individual sample t-test was carried out on the model to determine the particular model parameter (intercept or gradient) that was significantly different from zero. The test was based on the following null and alternative hypothesis

$$\beta_i = 0$$

Against

$$\beta_i \neq 0$$

The test was carried out at 95% level of confidence and the results were as illustrated in table3;

Table 3

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-1.264	0.188	-6.719	<0.001	-1.6572	-0.870
Gradient	-0.02572	0.0015	-17.224	<0.001	-0.0288	-0.0226

The results in table 3, illustrates that both the intercept and the gradient of the linear function was significantly different from zero (p<0.001). The fitted linear model had an R-square of 0.9398, which illustrated that 93.98% of the variation in $\ln(P)$ could be accounted for by vt.

From the fitted model, the value of the constants K and M could be obtained as illustrated in table 4, together with their respective 95% confidence intervals;

Table4.

Constants	Value	*Lower 95%*	*Upper 95%*
K	0.2827	0.1907	0.4190
M	-0.02	-0.029	-0.023

To obtain stable values of the two constants (K and M), the study used the non-linear iteration method to stabilize the values of M and K using the linearized values as the initial values of the model. The results of the iterated values were as illustrates in table5;

Table 5.

Constants	Value	*Lower 95%*	*Upper 95%*
K	0.02429	0.01639	0.0360
M	-0.01793	-0.0245	-0.0129

3.2. Joint Probability Density Function

The results illustrated in table 4.5 showed that 95% level of confidence, that both model constants were significantly different from zero; therefore, we would rewrite the joint probability function as;

$$P(v,t)=\begin{cases}0.02429\exp(-0.01793vt) & 0\le v\le 10 \quad 14\le t\le 30\\ 0 & otherwise\end{cases} \tag{20}$$

After fitting the equation as illustrated in equation (18), the next level is to prove, if the function is a joint probability density function.

Theorem

By definition, if the function is a probability density function then, the partial integral with respect to velocity and temperature (v and t) on the given limits will yield to a value of 1;

Proof

$$\int_{14}^{30}\int_{0}^{10}0.02429\exp(-0.01793vt).dvdt$$

$$=\int_{14}^{30}-1.354713\left[\frac{\exp(-0.1793t)-1}{t}\right].dt$$

$$=-1.354713\int_{14}^{30}\frac{\exp(-0.1793t)-1}{t}.dt$$

$$=-1.354713\times -0.7382952514=1.0002\approx 1$$

Hence the joint function is a probability density function.

3.3. Marginal Probability Density Function of Wind Velocity (v)

Based on equation (18), we can obtain the marginal probability function of velocity by partially integrating the joint probability density function with respect to temperature (t) as follows;

$$\int_{14}^{30}0.02429\exp(-0.01793vt).dt$$

$$\left[\frac{0.02429\exp(-0.01793vt)}{-0.01793v}\right]_{14}^{30}$$

$$\left[\frac{-1.354713\exp(-0.01793vt)}{v}\right]_{14}^{30}$$

$$\frac{-1.354713}{v}\left[\exp(-0.5379v)-\exp(-0.2510v)\right]$$

$$-1.354713\left[\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}\right]$$

Therefore

$$P(v)=\begin{cases}-1.354713\left[\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}\right] & 0\le v\le 10\\ 0 & otherwise\end{cases}$$

(21)

Is the Marginal probability density function of velocity. As initially done earlier, we need to prove that the marginal distribution is a probability density function.

Theorem

If a joint distribution is a probability density function, the marginal distribution is also a probability density function. If a marginal distribution is a probability density function, then the integral along the limits will yield a result of 1.

Proof

$$\int_0^{10} -1.354713\left[\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}\right].dv$$
$$= -1.354713\int_0^{10}\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}.dv$$
$$= -1.354713 \times -0.7382953 = 1.0001 \approx 1$$

Hence, the marginal distribution is a probability density function

3.4. Marginal Probability Density Function of Temperature

Based on equation (18), we can obtain the marginal probability function of temperature by partially integrating the joint probability density function with respect to wind velocity (v) as follows;

$$\int_0^{10} 0.02429\exp(-0.01793vt).dt$$
$$= \left[\frac{0.02429\exp(-0.01793vt)}{-0.01793t}\right]_0^{10}$$
$$= \left[\frac{-1.354713\exp(-0.01793vt)}{t}\right]_0^{10}$$
$$= \frac{-1.354713}{t}\left[\exp(-0.1793t)-1\right]$$
$$= -1.354713\left[\frac{\exp(-0.1793t)-1}{t}\right]$$

Therefore,

$$P(t) = \begin{cases} -1.354713\left[\frac{\exp(-0.1793t)-1}{t}\right] & 14 \le t \le 30 \\ 0 & otherwise \end{cases}$$

(22)

Is the Marginal probability density function of temperature. As initially done earlier, we need to prove that the marginal distribution is a probability density function.

Theorem

If a joint distribution is a probability density function, the marginal distribution is also a probability density function. If a marginal distribution is a probability density function, then the integral along the limits will yield a result of 1.

Proof

$$\int_{14}^{30} -1.354713\left[\frac{\exp(-0.1793t)-1}{t}\right].dt$$
$$= -1.354713\int_{14}^{30}\frac{\exp(-0.1793t)-1}{t}.dv$$
$$= -1.354713 \times -0.7382953 = 1.0001 \approx 1$$

Hence, the marginal distribution is a probability density function

3.5. Characteristics of the Two Variables

3.5.1. Wind Velocity Characteristics

The wind velocity of the county could be derived from the marginal probability function of wind speed.

Cumulative Distribution Function

Based on the marginal probability density function of speed we could derive the cumulative distribution function for wind speed as follows;

$$F(v) = \int_0^{v} -1.354713\left[\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}\right].dv \quad (23)$$

Average Velocity

Based, on the probability density function of velocity, we can obtain the average wind velocity for Narok county as follows;

By definition

$$E(v) = \int vP(v).dv$$

Therefore;

$$E(v) = \int_0^{10} v -1.354713\left[\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}\right].dv \quad (24)$$
$$= -1.354713\int_0^{10}\exp(-0.5379v)-\exp(-0.2510v).dv$$
$$= -1.354713 \times -1.8098$$
$$= 2.4517$$

Average Variation in Wind Velocity

We could estimate the average variation of the wind velocity about the mean based on the standard deviation of the marginal distribution of wind velocity. This can be estimated as follows;

By definition

$$std(v) = \sqrt{\operatorname{var}(v)}$$
$$but$$
$$\operatorname{var}(v) = E(v^2) - (E(v))^2 \quad (25)$$
$$therefore,$$
$$std(v) = \sqrt{E(v^2) - (E(v))^2}$$

Hence, from the marginal distribution of velocity we can obtain the variance as follows;

$$E(v^2) = \int_0^{10} -1.354713v^2\left[\frac{\exp(-0.5379v)-\exp(-0.2510v)}{v}\right].dv$$
$$= -1.354713\int_0^{10} v\left[\exp(-0.5379v)-\exp(-0.2510v)\right].dv$$
$$= -1.354713 \times -7.9905$$
$$= 10.8249$$
$$E(v) = 2.4517$$
$$\operatorname{var}(v) = 10.8249 - (2.4517^2) = 10.8249 - 6.0108 = 4.8141$$

(26)

Hence, we can get the standard deviation of velocity as;

$$std(v) = \sqrt{4.8141} = 2.1941$$

From the above results, the coefficient of variation for the wind speed could be determined as follows;

$$C.V = \frac{std(v)}{E(v)} = \frac{2.1941}{2.4517} = 0.8949 \quad (27)$$

3.5.2. Temperature Characteristics

Various characteristics of temperature for the county could be derived from the marginal probability function of temperature.

Cumulative Distribution Function

Based on the marginal probability density function of temperature we could derive the cumulative distribution function for wind speed as follows;

$$F(t) = \int_{14}^{t} -1.354713\left[\frac{\exp(-0.1793t)-1}{t}\right].dt \quad (28)$$

Average Temperature

Based, on the probability density function of temperature, we can obtain the average temperature for Narok county as follows;

By definition

$$E(t) = \int tP(t).dt$$

Therefore;

$$E(t) = \int_{14}^{30} t -1.354713\left[\frac{\exp(-0.1793t)-1}{t}\right].dt \quad (29)$$
$$= -1.354713\int_{14}^{30} \exp(-0.1793t)-1.dv$$
$$= -1.354713 \times -15.57256244$$
$$= 21.10$$

Average Variation in Temperature

We could estimate the average variation of the temperature about the mean based on the standard deviation of the marginal distribution of temperature. This can be estimated as follows;

By definition

$$std(t) = \sqrt{\text{var}(t)}$$
$$but$$
$$\text{var}(t) = E(t^2) - (E(t))^2 \quad (30)$$
$$therefore,$$
$$std(t) = \sqrt{E(t^2) - (E(t))^2}$$

Hence, from the marginal distribution of temperature we can obtain the variance as follows;

$$E(t^2) = \int_{14}^{30} -1.354713t^2\left[\frac{\exp(-0.1793t)-1}{t}\right].dt \quad (31)$$
$$= -1.354713\int_{14}^{30} t[\exp(-0.1793t)-1].dt$$
$$= -1.354713 \times -344.0435448$$
$$= 466.0803$$
$$E(t) = 21.10$$
$$\text{var}(t) = 466.0803 - (21.10^2) = 466.0803 - 445.21 = 20.8703$$

Hence, we can get the standard deviation of temperature as;

$$std(t) = \sqrt{20.8703} = 4.5684$$

From the above results, the coefficient of variation for the temperature could be determined as follows;

$$C.V(t) = \frac{std(t)}{E(t)} = \frac{4.5684}{21.10} = 0.2165 \quad (32)$$

3.6. Relationship between Wind Speed and Temperature of Narok County

The relationship between wind speed and temperature could be determined by checking the existence of a linear relationship between the two variables. The existence of a linear relationship between two variables is studied through correlation analysis. By definition, the correlation between wind velocity and the temperature is given by;

$$correlation(v,t) = cor(v,t) = \frac{\text{cov}(v,t)}{std(t) \times std(v)} \quad (33)$$

Where

$\text{cov}(v,t)$ is the covariance between wind speed and temperature which by definition is given by;

$$\text{cov}(v,t) = E(vt) - E(v)E(t) \quad (34)$$

Where

$$E(vt) = \int\int vtP(vt).dvdt \quad (35)$$

From the joint distribution function, we can, therefore, obtain the joint expectation as follows;

$$E(v,t) = \int_{14}^{30}\int_{0}^{10} vt0.02429\exp(-0.01793vt).dvdt$$
$$= 0.02429\int_{14}^{30}\left[t\int_{0}^{10} v\exp(-0.01793vt).dv\right].dt$$
$$= \frac{0.02429}{0.01793^2}\int_{14}^{30} \frac{1-0.1793t\exp(-0.1793t)-\exp(-0.1793t)}{t}.dt$$
$$= 75.55565\int_{14}^{30} \frac{1-0.1793t\exp(-0.1793t)-\exp(-0.1793t)}{t}.dt$$
$$= 75.55565 \times 0.66166 = 49.9918$$

Therefore, the covariance between velocity and temperature will be given as;

$$\text{cov}(v,t) = E(v,t) - E(v)E(t) = 49.9918 - (21.10 \times 2.4517) = 49.9918 - 51.73087 = -1.7391$$

From the above results we can obtain the coefficient of correlation as follows;

$$cor(v,t) = \frac{\text{cov}(v,t)}{std(v) \times std(t)} = \frac{-1.7391}{4.5684 \times 2.1941} = -0.1735$$

To test for the adequacy of the correlation coefficient, the t-test for correlation was used which was calculated using the test statistic;

$$t = \frac{cor(v,t)}{\sqrt{\frac{1-cor(v,t)^2}{n-2}}}$$

$$t = \frac{-0.1735}{\sqrt{\frac{1-0.0301}{21-2}}} = \frac{-0.7563}{0.9848} = -0.768$$

The p-value for the correlation coefficient was 0.452, this shows that there was not sufficient evidence to show that the wind speed was correlated to the temperature. Hence the two distributions are independent.

4. CONCLUSION

The study was able to model the joint distribution for the wind speed and temperature of Narok county as;

$$P(v,t) = \begin{cases} 0.02429\exp(-0.01793vt) & 0 \le v \le 10 \quad 14 \le t \le 30 \\ 0 & otherwise \end{cases}$$

The marginal distributions for wind speed for Narok county were given as;

$$P(v) = \begin{cases} -1.354713\left[\frac{\exp(-0.5379v) - \exp(-0.2510v)}{v}\right] & 0 \le v \le 10 \\ 0 & otherwise \end{cases}$$

On the other hand, the marginal distribution of temperature was given as;

$$P(t) = \begin{cases} -1.354713\left[\frac{\exp(-0.1793t) - 1}{t}\right] & 14 \le t \le 30 \\ 0 & otherwise \end{cases}$$

The study established that the wind speed and the temperature of Narok county were independently distributed. The fitted joint distribution and the marginal distributions were both determined to be probability density functions.

RECOMMENDATION

The study recommends that the fitted distribution be used by investors to assess the potentiality of Narok county in producing wind and solar energy, as the distributions can be used to get the chances of obtaining specified wind speed and the temperatures on Narok county.

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