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Analysis of wind regimes for energy estimation

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Abstract

Supplementing our energy base with clean and renewable sources of energy has become imperative due to the present day's energy crisis and growing environmental consciousness. Wind is one of the potential renewable energy sources, which can be harnessed in a commercial scale for various end-uses. A precise knowledge of wind regime characteristics is a pre-requisite for the efficient planning and implementation of any wind energy project. In the present study, a method for characterizing wind regimes, bringing out their energy potential, is discussed. A Rayleigh distribution was adopted for defining the distribution of wind velocity in terms of its probability density and cumulative distribution functions. Expressions to compute the energy density, energy available in the wind spectra in a time period and the energy received by turbine have been developed. A method to identify the most frequent wind speed and velocity that carries maximum amount of energy with it, is also discussed. The analysis of wind energy potential of a eight sites in Kerala, India, adopting this procedure is presented. The performance of three wind turbines differing in their working velocity band, at these sites are compared. The effect of cut-in and cut-out wind speeds on wind turbine performance are also analyzed.

1. Introduction

Owing to the present day's energy crisis, growing environmental concern and constantly escalating cost of fossil fuels, scientists, engineers and policy makers all

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Nomenclature

ρ	Air density, kg/m^3
k	Weibull shape factor
c	Weibull scale factor and, m/s
V	Wind velocity of interest, m/s
V_m	Average wind velocity, m/s
V_I	Cut-in wind velocity of the turbine
V_R	Rated wind velocity of the turbine, m/s
V_O	Cut-out wind velocity of the turbine, m/s
$V_{E\ MAX}$	Velocity containing maximum energy in a wind regime, m/s
$V_{F\ MAX}$	Most frequent wind velocity in a wind regime, m/s
$V(Z)$	Wind velocity at height Z, m/s
$V(Z_R)$	Wind velocity at the reference height, m/s
Z_0	Roughness height, m
E_D	Energy density, W/m^2
E_S	Total energy available in the wind spectra during the period, kWh/m^2
E_{WP}	Energy available for a wind pump during the time period, kWh/m^2
E_{AG}	Energy available for the aero generator during the period, kWh/m^2
T	Time period, h

over the world are making every effort to supplement our energy base with renewable sources. Wind is one of the potential renewable energy sources, which is being harnessed in a commercial scale today. With a global installation of 15 000 MW, wind has emerged out as the world's fastest growing energy source [1]. The decentralized and locally available nature of wind energy make it particularly attractive to the developing countries like India. Out of the presently identified 45 000 MW potential, 1167 MW capacity of wind power has already been installed in the country and many more ambitious projects will be commissioned in the near future [2].

A thorough understanding of the characteristics of the wind regime in which a wind turbine is expected to work is a pre-requisite for the successful planning and implementation of any wind power project. Knowledge of wind velocity distribution at different time scales and quantum of energy associated with these wind spectra are essential for the proper sizing and siting of a wind energy project. In the present analysis, a method to estimate the energy potential of a wind regime is proposed. Wind data collected from eight potential sites in Kerala, India, is analyzed using the proposed model. Performance of three different types of wind machines at these wind regimes are compared. The effect of cut-in and cut-out wind velocities on the performance of wind turbines at these sites are also analyzed in the present study.

2. Frequency distribution of wind speed

Attempts were made to define the wind regime characteristics using probability functions by fitting field data with standard mathematical functions describing frequency distributions. It is established that [3–6] Weibull distribution can be used to characterise wind regimes in terms of its probability density and cumulative distribution functions. Although efforts were made to fit the field data with other distributions like Pearson type VI distribution, Exponential distribution, Gamma distribution [7] and logistic distribution [8], Weibull distribution is well accepted and widely adopted for wind data analysis [9–12].

Weibull distribution can be characterized by its cumulative distribution function $F(V)$ and probability density function $f(V)$ where

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

and

$$f(V)=\frac{dF}{dV}=\frac{k}{c}\left(\frac{V}{c}\right)^{k-1}\exp-\left(\frac{V}{c}\right)^{k} \tag{2}$$

The use of Weibull distribution requires that the shape factor K and scale factor C, should be determined, for which adequate field data collected at shorter intervals of time is necessary. In many cases this may not be readily available.

A simplified case of Weibull distribution can be derived by assuming the shape factor k to be 2 which is known as the Rayleigh distribution. The distinct advantage of the Rayleigh distribution over Weibull distribution is that the probability density and cumulative distribution functions of a site can be calibrated simply from the average value of the wind velocity. The validity of the Rayleigh distribution for

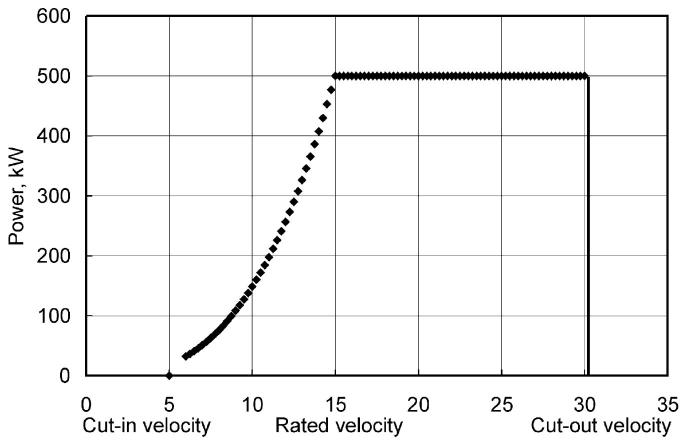

Fig. 1. Typical velocity power curve of a wind turbine.

Table 1
Details of the sites for which the wind data were analyzed

No.	District	Location of the site	Latitude (N)	Longitude (E)	Elevation from MSL (m)	Sensor height (m)
1	Trivandrum	Trivandrum	8.29	76.57	64	12.5
2	Aleppy	Aleppy	9.33	76.20	4	11
3	Eranakulam	Cochin	9.58	76.14	3	9.8
4	Idukki	Elappara	9.63	76.98	1010	5
5	Palghat	Palghat	10.46	76.39	97	2
6	Malapuram	Nellipuza	11.00	76.48	70	5
7	Calicut	Calicut	11.15	75.47	5	13.3
8	Kasargod	Cheruvathur	12.22	75.15	5	5

wind energy analysis has been thoroughly investigated, using long term wind data from several sites [13] and it is established that the Rayleigh distribution provides a reasonable fit with observed wind velocity and power histogram. Simplicity of this distribution in comparison with other distributions used for wind data analysis has also been identified. The American Wind Energy Association has also recommended the use of Rayleigh distribution for assessing wind energy potential. Hence, the Rayleigh distribution is adopted for defining the wind regime characteristics in this analysis.

With k=2, in Rayleigh distribution the cumulative distribution and probability density function could be simplified as

$$F(V)=1-\exp-\left[\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2\right] \tag{3}$$

and

$$f(V)=\frac{\pi}{2}\frac{V}{V_m^2}\exp-\left[\frac{\pi}{4}\left(\frac{V}{V_m}\right)^2\right] \tag{4}$$

3. Wind energy density and energy available in the wind spectra

The power available in a wind stream per unit area is given by

$$P=\frac{1}{2}\rho V^3 \tag{5}$$

Wind energy density of a site can be expressed as

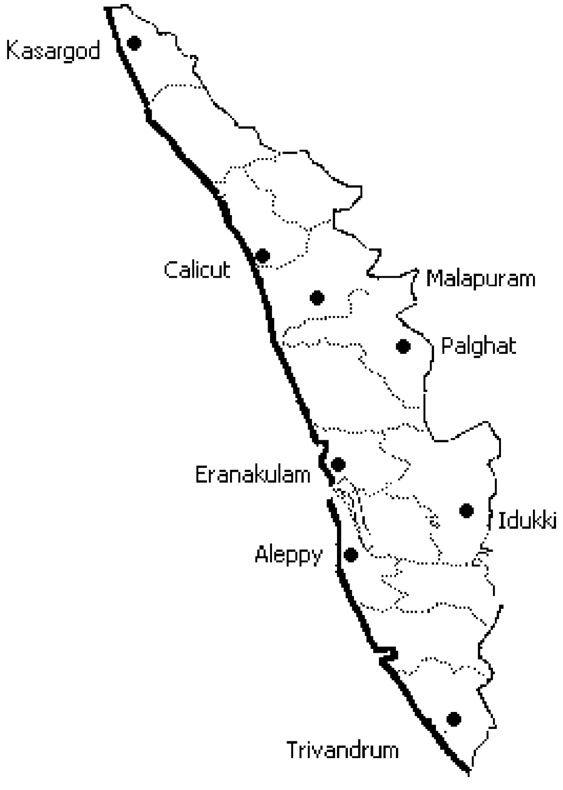

Fig. 2. Map of Kerala showing the study locations.

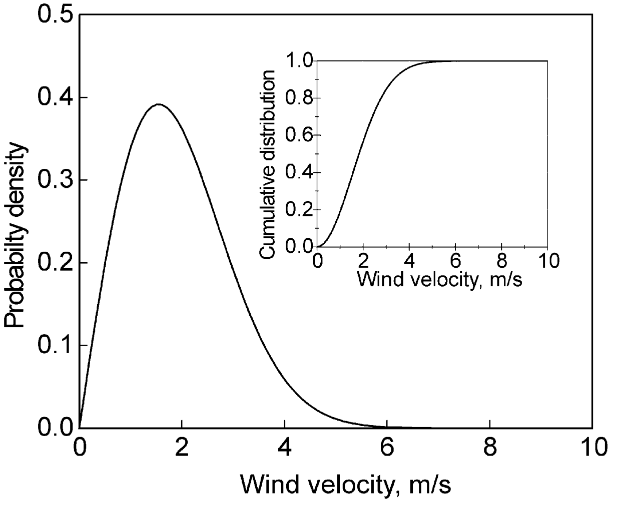

Fig. 3. Rayleigh distribution of wind velocity at Trivandrum.

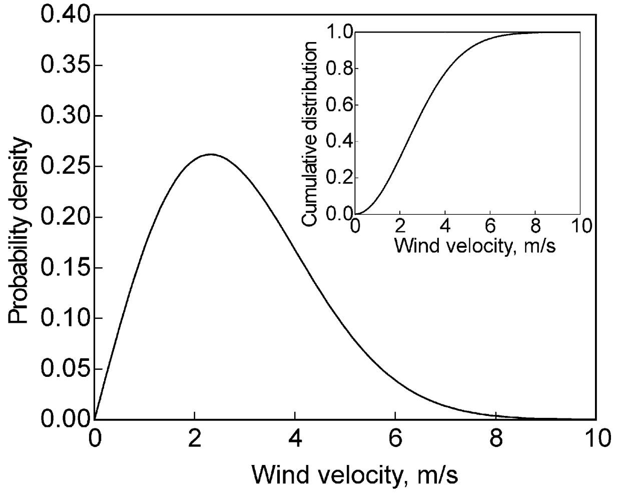

Fig. 4. Rayleigh distribution of wind velocity at Aleppy.

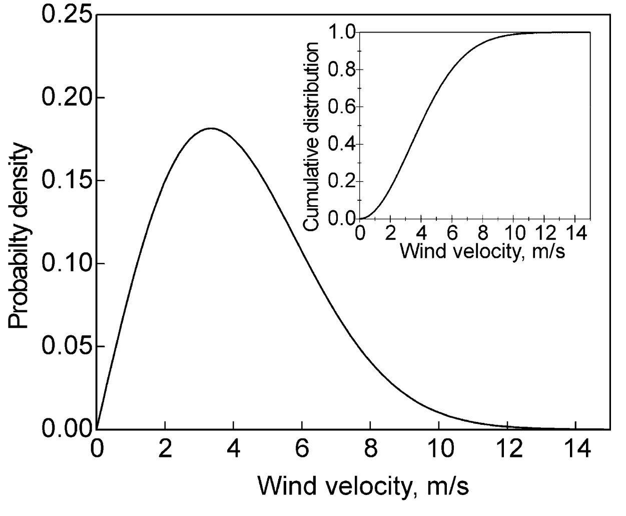

Fig. 5. Rayleigh distribution of wind velocity at Idukki.

$$E_{\mathrm{I}}=\int_{0}^{\infty} P\, f(V)dV \tag{6}$$

From Eqs. (4)–(6) and taking

$$K=\frac{\pi}{4V_{\mathrm{m}}^{2}} \tag{7}$$

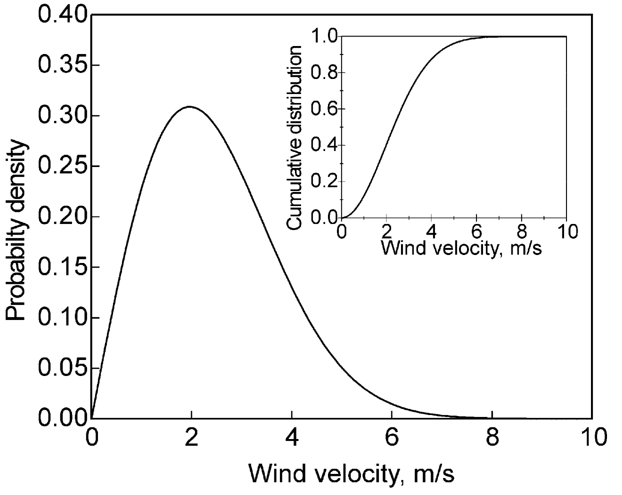

Fig. 6. Rayleigh distribution of wind velocity at Eranakulam.

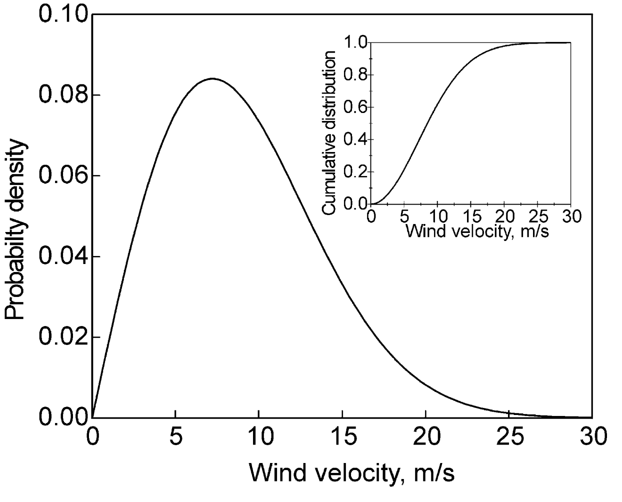

Fig. 7. Rayleigh distribution of wind velocity at Palghat.

the wind energy density would yield to be

$$E_{\mathrm{I}}=K\rho\int_{0}^{\infty} V^4\exp(-KV^2)dV \tag{8}$$

Eq. (8) can be solved by reducing it to a gamma integral and can be evaluated as

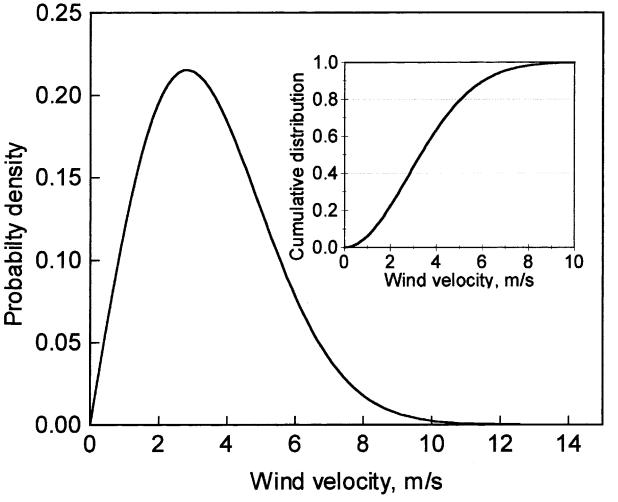

Fig. 8. Rayleigh distribution of wind velocity at Malapuram.

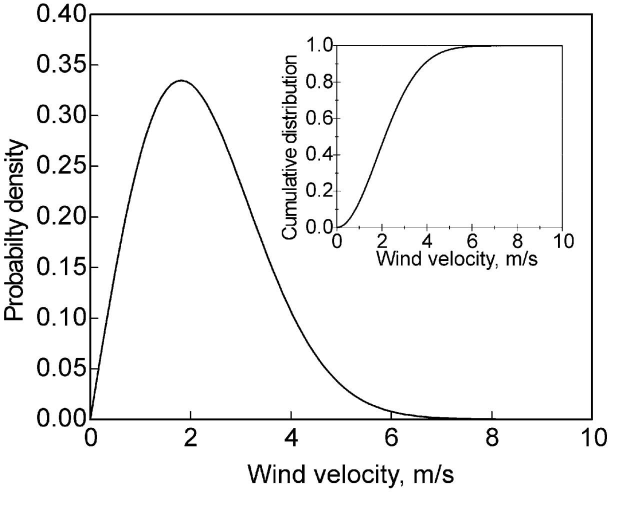

Fig. 9. Rayleigh distribution of wind velocity at Calicut.

$$E_{\mathrm{I}}=\frac{3}{8}\frac{\rho\sqrt{\pi}}{K^{1.5}} \tag{9}$$

Once the energy density is estimated, energy that is available in the wind spectra for a duration (that is in a day, month or in a year) can be expressed as

$$E_{\mathrm{S}}=T\,E_{\mathrm{I}}=\frac{3}{8}\,\frac{T\rho\sqrt{\pi}}{K^{1.5}} \tag{10}$$

Table 2
Wind energy potential of Trivandrum

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\ MAX}$ (m/s)	$V_{F\ MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	E_{WP-1} (kW-hr/m2/month)	E_{WP-2} (kW-hr/m2/month)
January	1.39	3.08	2.22	2.22	1.11	0	0.44	1.47
February	1.54	4.1	2.95	2.44	1.22	0.01	0.89	2.21
March	1.7	5.63	4.05	2.71	1.36	0.07	1.74	3.34
April	1.8	6.68	4.81	2.87	1.44	0.16	2.4	4.13
May	2.28	13.58	9.78	3.64	1.82	1.79	7.27	9.23
June	2.41	16.04	11.55	3.85	1.92	2.76	9.08	11.04
July	2.58	19.68	14.17	4.12	2.06	4.48	11.78	13.7
August	2.76	24.09	17.35	4.4	2.2	6.89	15.07	16.9
September	2.48	17.48	12.58	3.96	1.98	3.4	10.15	12.09
October	1.8	6.68	4.81	2.87	1.44	0.16	2.4	4.13
November	1.29	2.46	1.77	2.06	1.03	0	0.23	1.03
December	1.24	2.18	1.57	1.98	0.99	0	0.16	0.84
Annual	1.94	8.37	6.02	3.1	1.55	0.38	3.52	5.38

where T is the time period. For example if E_S is expressed monthly, T should be taken as 720 h.

4. Most frequent wind velocity and velocity carrying the maximum energy

Using Eqs. (4) and (7), the probability density function can be expressed as

$$f(V)=2\,KV\exp-(KV^2) \tag{11}$$

Hence the velocity for which the probability density is maximum or in other words, the most frequent wind speed is given by

$$V_{\mathrm{F\ max}}=\frac{1}{\sqrt{2K}} \tag{12}$$

Since power available from a wind stream is proportional to the cube of its velocity, it is not the most frequent wind speed but a wind speed usually higher than that would carry maximum amount of energy with it. A wind turbine is designed to work at its maximum efficiency point at a wind velocity usually termed as the design wind speed (V_D). Hence it is advantageous that the design wind speed of a machine and the wind speed corresponding to the maximum amount of energy is made as close as possible. Once the velocity responsible for maximum energy is identified for a particular site, the designer could design his system to be most efficient at this velocity or a planner could select a machine having design wind speed very close

Table 3
Wind energy potential of Aleppy

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\,MAX}$ (m/s)	$V_{F\,MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	E_{WP-1} (kW-hr/m2/month)	E_{WP-2} (kW-hr/m2/month)
January	2.64	21.08	15.18	4.21	2.11	5.21	12.83	14.72
February	2.8	25.15	18.11	4.47	2.23	7.51	15.86	17.67
March	3.15	35.82	25.79	5.03	2.51	14.33	23.73	25.25
April	3.15	35.82	25.79	5.03	2.51	14.33	23.73	25.25
May	3.33	42.31	30.47	5.31	2.66	18.8	28.48	29.7
June	3.17	36.5	26.28	5.06	2.53	14.79	24.24	25.73
July	3.07	33.16	23.87	4.9	2.45	12.55	21.78	23.38
August	2.93	28.82	20.75	4.68	2.34	9.75	18.58	20.31
September	2.96	29.72	21.4	4.72	2.36	10.32	19.24	20.95
October	2.56	19.23	13.84	4.09	2.04	4.25	11.45	13.37
November	2.24	12.88	9.27	3.57	1.79	1.54	6.75	8.71
December	2.77	24.35	17.54	4.42	2.21	7.04	15.26	17.09
Annual	2.9	27.95	20.12	4.63	2.31	9.21	17.93	19.68

Table 4
Wind energy potential of Idukki

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\,MAX}$ (m/s)	$V_{F\,MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	E_{WP-1} (kW-hr/m2/month)	E_{WP-2} (kW-hr/m2/month)
January	6.2	273.1	196.63	9.89	4.95	183.65	141.92	90.93
February	5.4	180.44	129.92	8.62	4.31	119.92	109.04	81.64
March	3.42	45.84	33	5.46	2.73	21.29	31.03	32.05
April	2.74	23.57	16.97	4.37	2.19	6.59	14.68	16.53
May	3.89	67.45	48.57	6.21	3.1	37.01	46.24	45.15
June	4.73	121.26	87.31	7.55	3.77	76.89	79.75	68.01
July	4.49	103.73	74.68	7.16	3.58	63.91	69.57	61.94
August	4.61	112.27	80.83	7.36	3.68	70.24	74.62	65.04
September	2.46	17.06	12.28	3.93	1.96	3.21	9.84	11.78
October	3.3	41.18	29.65	5.27	2.63	18.01	27.66	28.94
November	4.13	80.72	58.12	6.59	3.3	46.83	55.12	52.03
December	4.89	133.99	96.47	7.8	3.9	86.26	86.7	71.74
Annual	4.19	84.29	60.69	6.69	3.34	49.48	57.44	53.73

to this velocity. (This is applicable only if the selection of design wind speed is not constrained by other factors. For example, in the case of water pumping wind mills with positive displacement piston pumps, selection of design wind speed is greatly influenced by the pump characteristics).

Energy corresponding to a particular wind speed can be expressed as

Table 5
Wind energy potential of Eranakulam

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\ MAX}$ (m/s)	$V_{F\ MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	E_{WP-1} (kW-hr/m2/month)	E_{WP-2} (kW-hr/m2/month)
January	2.33	14.49	10.44	3.72	1.86	2.13	7.94	9.9
February	2.52	18.34	13.2	4.02	2.01	3.81	10.79	12.72
March	2.75	23.83	17.16	4.39	2.19	6.74	14.87	16.71
April	2.58	19.68	14.17	4.12	2.06	4.48	11.78	13.7
May	2.97	30.02	21.61	4.74	2.37	10.51	19.46	21.16
June	2.44	16.65	11.99	3.89	1.95	3.03	9.53	11.48
July	2.61	20.37	14.67	4.16	2.08	4.84	12.3	14.2
August	2.66	21.57	15.53	4.24	2.12	5.47	13.19	15.07
September	2.49	17.69	12.74	3.97	1.99	3.5	10.31	12.25
October	2.19	12.04	8.67	3.49	1.75	1.27	6.14	8.09
November	1.99	9.03	6.5	3.18	1.59	0.5	3.98	5.87
December	2.05	9.87	7.11	3.27	1.64	0.68	4.58	6.49
Annual	2.46	17.06	12.28	3.93	1.96	3.21	9.84	11.78

$$E_V = P\, f(V) \tag{13}$$

Hence from Eqs. (4), (5) and (7), one gets

$$E_V = K\, \rho\, V^4 \exp(-KV^2) \tag{14}$$

From Eq. (14) E_V would be maximum at wind velocity $V_{E\ Max}$ such as

$$V_{E\ max} = \sqrt{\frac{2}{K}} \tag{15}$$

5. Energy available for a wind turbine

A wind turbine is designed to function at a velocity band between its cut-in wind speed (V_I) and cut-out wind speed (V_O). Usually the unit will start functioning at the cut-in speed showing increase in power produced with increase in wind speed up to the rated wind speed (V_R) of the turbine. At velocities between the rated wind speed and cut-off wind speed, the unit is designed to produce constant power corresponding to the rated velocity of the machine (Fig. 1). At wind velocities higher than the cut-out speed, the machine is completely shut down to avoid damage to the system resulting from highly intensive thrust forces.

Table 6
Wind energy potential of Palghat

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\ MAX}$ (m/s)	$V_{F\ MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	E_{WP-1} (kW-hr/m2/month)	E_{WP-2} (kW-hr/m2/month)
January	9.14	874.96	629.97	14.59	7.29	475.68	201.02	84.71
February	8.3	655.21	471.75	13.24	6.62	390.01	194.5	89.96
March	7.38	460.59	331.63	11.78	5.89	295.71	178.32	93.49
April	7.29	443.95	319.64	11.63	5.82	286.67	176.16	93.64
May	10.06	1166.66	839.99	16.05	8.03	564.71	201.28	78.1
June	11.07	1554.5	1119.24	17.67	8.83	652.89	195.93	70.71
July	11.44	1715.64	1235.26	18.26	9.13	682.09	192.97	68.09
August	11.07	1554.5	1119.24	17.67	8.83	652.89	195.93	70.71
September	10.33	1263.13	909.46	16.48	8.24	589.4	200.32	76.11
October	7.11	411.87	296.54	11.35	5.67	268.76	171.54	93.79
November	6.74	350.86	252.62	10.76	5.38	232.9	160.71	93.43
December	8.58	723.79	521.13	13.69	6.85	418.83	197.47	88.36
Annual	9.04	874.96	629.97	14.59	7.29	475.68	201.02	84.71

Table 7
Wind energy potential of Malapuram

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\ MAX}$ (m/s)	$V_{F\ MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	E_{WP-1} (kW-hr/m2/month)	E_{WP-2} (kW-hr/m2/month)
January	5.68	209.99	151.19	9.06	4.53	140.8	121.05	85.74
February	4.57	109.37	78.75	7.29	3.65	68.09	72.92	64.02
March	2.5	17.9	12.89	3.99	1.99	3.6	10.47	12.4
April	2.38	15.45	11.12	3.8	1.9	2.51	8.64	10.6
May	2.62	20.61	14.84	4.18	2.09	4.96	12.48	14.37
June	3.18	36.85	26.53	5.07	2.54	15.03	24.49	25.97
July	3.06	32.83	23.64	4.88	2.44	12.34	21.54	23.16
August	4.57	109.37	78.75	7.29	3.65	68.09	72.92	64.02
September	2.82	25.7	18.5	4.5	2.25	7.84	16.26	18.06
October	2.38	15.45	11.12	3.8	1.9	2.51	8.64	10.6
November	2.62	20.61	14.84	4.18	2.09	4.96	12.48	14.37
December	6	247.52	178.21	9.57	4.79	166.58	134.16	89.28
Annual	3.53	50.4	36.29	5.63	2.82	24.56	34.31	35.01

Hence the wind spectra useful for power production, taking the machine characteristics in to consideration, would be decided by this cut-in, rated and cut-off wind velocities of the turbine. The energy available in the wind spectra, useful for power production would, therefore be reduced to

Table 8
Wind energy potential of Calicut

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\ MAX}$ (m/s)	$V_{F\ MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	$E_{WP\text{-}1}$ (kW-hr/m2/month)	$E_{WP\text{-}2}$ (kW-hr/m2/month)
January	2.2	12.2	8.79	3.51	1.76	1.32	6.26	8.22
February	2.55	19	13.68	4.07	2.03	4.14	11.28	13.2
March	2.77	24.35	17.54	4.42	2.21	7.04	15.26	17.09
April	2.74	23.57	16.97	4.37	2.19	6.59	14.68	16.53
May	2.99	30.63	22.05	4.77	2.39	10.9	19.91	21.6
June	2.18	11.87	8.55	3.48	1.74	1.22	6.02	7.97
July	2.15	11.39	8.2	3.43	1.72	1.07	5.67	7.62
August	1.95	8.5	6.12	3.11	1.56	0.41	3.61	5.47
September	2.13	11.07	7.97	3.4	1.7	0.99	5.44	7.38
October	1.95	8.5	6.12	3.11	1.56	0.41	3.61	5.47
November	1.83	7.02	5.06	2.92	1.46	0.2	2.62	4.38
December	1.85	7.26	5.22	2.95	1.48	0.22	2.77	4.55
Annual	2.27	13.4	9.65	3.62	1.81	1.72	7.14	9.1

$$E_T = T \int_{V_I}^{V_R} P(V)\, f(V)\, dV + T\, P_R \int_{V_R}^{V_O} f(V)\, dV \tag{16}$$

Eq. (16) can be rearranged and simplified as

$$E_T = T\, K\, \rho \int_{V_I}^{V_R} V^4 \exp(-KV^2) dV + T\, P_R \int_{V_R}^{V_O} f(V)\, dV \tag{17}$$

Applying the relationship,

$$\int f(V) dV = F(V) \tag{18}$$

in Eq. (18) and inserting the value of $F(V)$ from Eq. (3), one gets

$$E_T = T\, K\, \rho \int_{V_I}^{V_R} V^4 \exp(-KV^2) dV + \frac{1}{2}\rho\, V_R^3 T[\exp(-K\, V_R^2) - \exp(-K\, V_O^2)] \tag{19}$$

The integral in Eq. (19) cannot be solved by analytical methods. However the expression can be integrated by numerical techniques using Simpson's rule.

Table 9
Wind energy potential of Kasargod

Month	V_m (m/s)	E_D (W/m^2)	E_S (kW-hr/m^2/month)	$V_{E\ MAX}$ (m/s)	$V_{F\ MAX}$ (m/s)	E_{AG} (kW-hr/m2/month)	$E_{WP\text{-}1}$ (kW-hr/m2/month)	$E_{WP\text{-}2}$ (kW-hr/m2/month)
January	3.06	32.83	23.64	4.88	2.44	12.34	21.54	22.54
February	3.54	50.83	36.6	5.65	2.82	24.87	34.62	34.77
March	3.78	61.89	44.56	6.03	3.02	32.92	42.41	41.54
April	3.62	54.36	39.14	5.78	2.89	27.42	37.12	36.99
May	3.58	52.58	37.86	5.71	2.86	26.12	35.86	35.88
June	3.89	67.45	48.57	6.21	3.1	37.01	46.24	44.71
July	4.09	78.4	56.45	6.53	3.26	45.11	53.59	50.47
August	4.17	83.09	59.83	6.65	3.33	48.59	56.66	52.76
September	3.1	34.14	24.58	4.95	2.47	13.2	22.5	23.47
October	2.78	24.62	17.73	4.44	2.22	7.2	15.46	16.61
November	3.02	31.56	22.72	4.82	2.41	11.51	20.6	21.64
December	3.38	52.58	37.86	5.71	2.86	26.12	35.86	35.88
Annual	3.5	49.13	35.37	5.59	2.79	23.64	33.4	33.67

6. Analysis of wind data

The wind energy potential of some districts in Kerala state, lying in the southern part of India has been assessed using the method discussed above. Geographically the state is located at 10° 46′ N latitude and 76° 39′ longitude. Eight districts of the state viz. Trivandrum, Aleppy, Eranakulam, Idukki, Palghat, Calicut, Malapuram and Kasargod were included in the study. Details of locations representing these

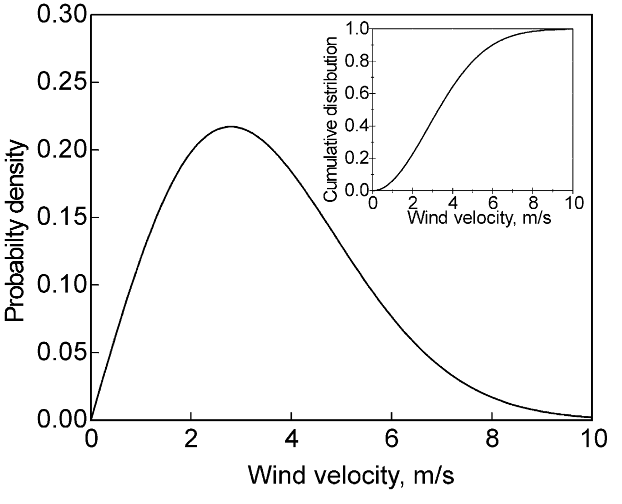

Fig. 10. Rayleigh distribution of wind velocity at Kasargod.

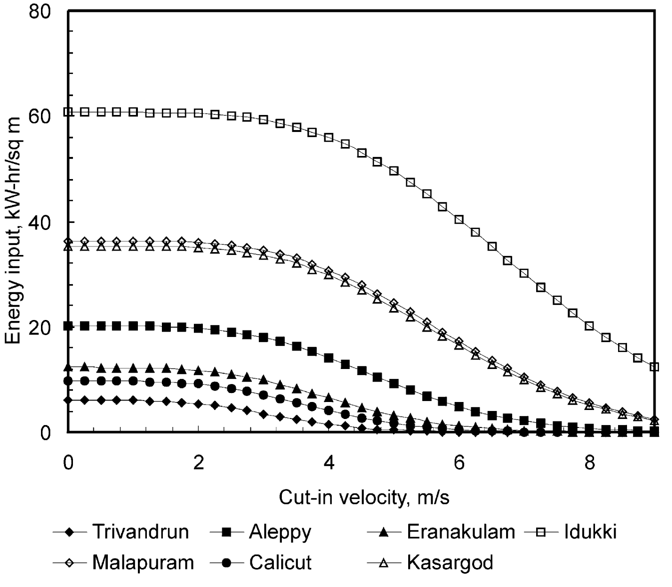

Fig. 11. Effect of cut-in velocity on monthly energy input to the wind turbine.

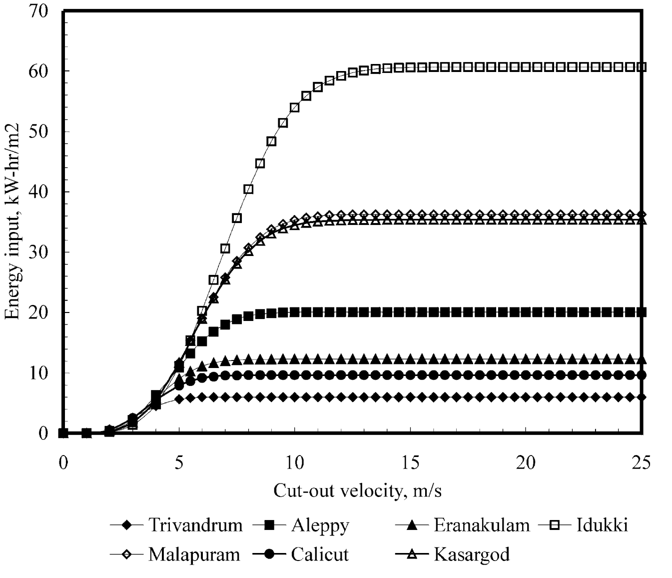

Fig. 12. Effect of cut-out velocity on the monthly energy input to the turbine.

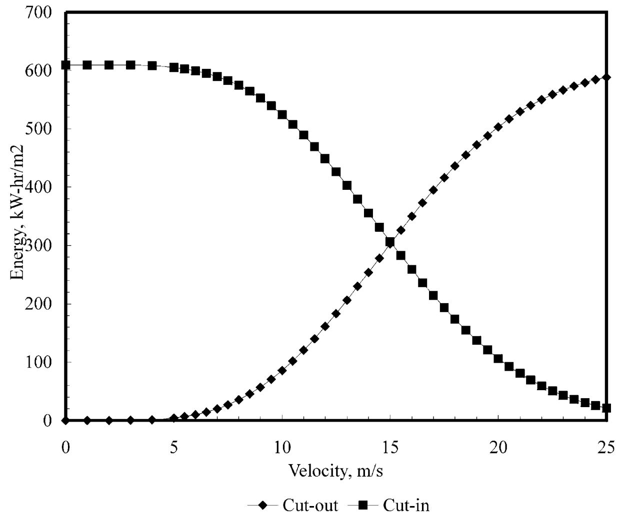

Fig. 13. Effect of cut-in and cut-out velocities on energy input to the turbine at Palghat.

districts are shown in Table 1 and Fig. 2. These sites were selected on the basis that the rural areas of these districts constitute the major agricultural belt of the state. As water pumping for irrigation is identified as one of the viable application of wind energy, selection of these sites for the study was logical.

Twelve years wind data were available from Trivandrum, Aleppy, Cochin, Palghat and Calicut whereas for Kasargod, two year's data could be collected. For the other two districts, Idukki and Malapuram, data were available only for one year. However, as one year data is sufficient to predict the long term trend in wind velocity with an accuracy of 10% and a confidence level of 90% [14,15], the data collected could be used to bring out useful conclusions on the wind regime characteristics of these regions.

It is evident from Table 1 that the sensors at different study locations were set at different heights from the mean ground level. The horizontal component of wind velocity would vary considerably under the effect of frictional and impact forces on the ground. Hence the wind speeds from the locations had to be adjusted to a uniform height prior to the analysis. The standard height recommended by the World Meteorological Organization (WMO) is 10 m above the ground level. Moreover the tower height of some commercial wind pumps in India are 10 m. Hence the wind velocities from the locations were transformed to that of 10m mast height using the relationship

$$\frac{V(Z)}{V(Z_{\mathrm{R}})}=\frac{\ln\left(\frac{Z}{Z_0}\right)}{\ln\left(\frac{Z_{\mathrm{R}}}{Z_0}\right)} \tag{20}$$

In order to analyze the wind energy potential in detail and to compare the performance of wind machines at these sites adopting the methodology proposed, a computer programme was developed in "C" language. The programme required information on site characteristics in terms of the average wind velocity and the wind machine characteristics in terms of its cut-in, rated and cut-out wind speeds as the in put.

Three types of wind machines were considered in the programme.

1. An aero-generator with 5 m/s cut-in, 15 m/s rated and 30 m/s cut-out wind speeds [16];
2. A modern wind pump with power regulation device and having the cut-in, rated and cut-out wind speeds 3 m/s, 10 m/s and 15 m/s respectively [17];
3. A simple mechanical wind pump without any power regulation devices suitable for weaker wind spectra. These machines cut in at around 2.5 m/s and simply cut out at 10 m/s [18].

7. Results and discussion

The annual probability density and cumulative distribution of wind speeds at the sites are displayed in Figs. 3–10. The density function indicates the fraction of time for which the velocity "*V*" probably prevail at the site. The most frequent wind speed expected at these sites are represented by the peak of the probability density curve. The cumulative distribution function indicates the fraction of time that the wind velocity is below a particular speed "*V*". The time for which a wind machine could be functional at these sites can be estimated from the difference of values of cumulative distribution function corresponding to the cut-in and cut-out velocities of the machine. It can also be observed that the chances of extremely high wind (grater than 25 m/s), occurring at these sites are limited.

The monthly average wind velocity, energy density, energy available in the wind spectra, velocity of maximum energy carrier, most frequent wind velocity and the energy received by the three wind machines were computed using the programme. The results of the analysis are shown in Tables 2–9, which are self-explanatory.

Among the eight sites, wind spectra appears to be strongest at Palghat and weakest at Trivandrum. In general the wind energy potential is high during the months from April to August. Although the wind spectra are not strong enough for wind-electric generation except for, wind powered water pumping appears to be a viable option in almost all the study locations. Higher wind speeds in the months of June, July and August are of less interest for wind powered irrigation projects as these periods coincides with the monsoon season in the state. Irrigation starts in November and is continued till the end of May. During these months the wind is strong enough to energize the commercial wind pumps popular in India (cut in velocity 2.0 m/s) indicating the feasibility of wind powered irrigation in these regions.

Comparing the performance of the two types of wind pumps at these sites, wind pumps of type-II, functional at a higher velocity band is suitable for Palghat. On the other hand, simple mechanical wind pumps working at lower wind velocities (Type-III) are found to receive energy more efficiently from all other sites.

The effect of cut-in and cut-out wind speeds on the energy received by the wind turbines at these sites is shown in Figs. 11–13. Since the wind spectra at all the sites except Palghat are found comparable in strength, they are grouped together and the result for Palghat is presented separately. From Fig. 11 it is seen that the energy input to the turbine is not much affected up to a cut-in wind speed of 2 m/s. From 2 m/s to 3 m/s, the energy input starts declining noticeably and above 3 m/s the effect is more prominent. Similarly, observing the effect of cut-out velocity on energy input to the turbines at these sites, it is seen that no appreciable gain can be expected by keeping the cut-out velocity of the turbine above 10 m/s. Hence wind machines with a working velocity band of 2 m/s to 10 m/s is suitable for these locations. However, in contrast, the cut-in velocity may be fixed up to 6 m/s without any noticeable energy loss, for machines to be installed at Palghat. Similarly observing the effect of cut-out velocity, it is evident that the machine would not be able to utilize a appreciable portion of the energy available in the wind spectra if it is shut down at a velocity lesser than 25 m/s.

8. Conclusions

A method for analyzing the wind energy potential of a site is presented and discussed. Assuming the Rayleigh distribution, wind energy potential of a site can be characterized in terms of energy density, energy available for a period, most frequent wind speed and wind speed of maximum energy carrier, adopting the proposed method. The procedure is further extended to compute the energy received by a wind machine from the spectra, by incorporating the machine characteristics in terms of its cut-in, rated and cut-out wind speeds. Wind data from eight districts in Kerala, India are analyzed using the proposed method. The characteristics of wind machines in terms of cut-in and cut-out wind speeds, best suited for these sites are identified.

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