WIND RESOURCES

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1 INTRODUCTION

This module is based on assembly of Section 1 of the Introduction to Wind Energy by E.H. Lysen [1] and some parts of Wind Pumping, a Handbook by J. van Meel and P. Smulders [2].

Introduction to Wind Energy was a CWD publication which is only available at the website of UCE (Utrecht Centre for Energy research) http://www.uce-uu.nl/?action=25&menuId=4 (CWD ceased to exist in 1990). It is still one of the best explanatory books in the field of Wind Energy.

The Wind Pumping Handbook was written for the World Bank by Van Meel and Smulders, both members of CWD as well at that time. Both the Introduction and the Worldbank Handbook were written for anyone interested in wind energy in the world. With permission of the authors, *ARRAKIS* uses part of this material for training courses. The modules of this course are for course participants only and not intended for use by other parties.

2 AVAILABLE WIND POWER

2.1 Energy extraction by a wind rotor

Air mass flowing with a velocity V through an area A represents a mass flow rate $\dot{m}$ of:

$$\dot{m} = \rho A V \ (kg/s) \quad \textbf{1}$$

and thus a flow of kinetic energy per second (or kinetic power) P_{kin} of:

$$P_{kin} = \frac{1}{2}(\rho A V)V^2 = \frac{1}{2}\rho A V^3 \ (W) \quad \textbf{2}$$

where

ρ = air density (kg/m^3)
A = area swept by the rotor blades (m^2)
V = undisturbed wind velocity (m/s)

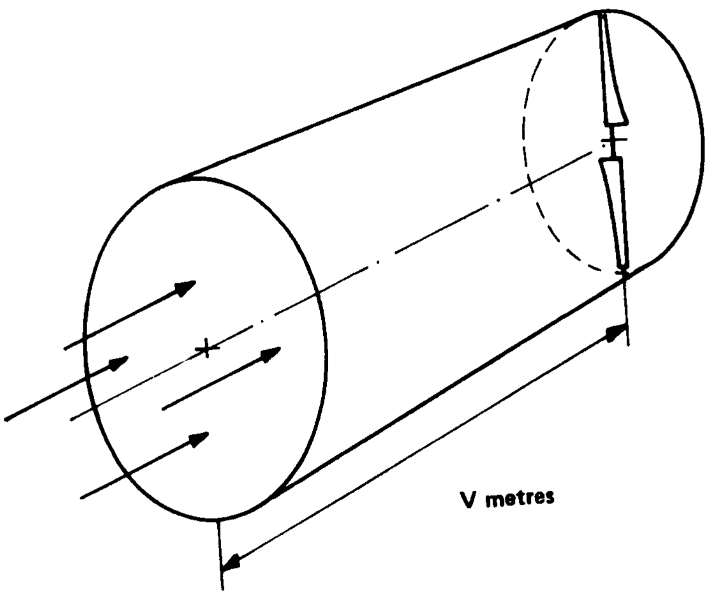


Figure 1 A volume $V*A$ of air is flowing every second through an area A. This represents a mass flow rate of ρAV (kg/s).

From this relation we conclude:

1. Wind power is proportional to the density of the air. This means that high in the mountains one gets less power at the same wind speed. Air density may vary from about 1.2 kg/m3 at sea level to only 0.7 kg/m3 at high altitude;
2. Wind power is proportional to the area swept by the rotor blades, or is proportional to the *square* of the diameter of the rotor;
3. Wind power is proportional to the *cube* of the wind velocity, so it pays to carefully select a good site for a windmill: 10% more wind gives 30% more power.

Not all the kinetic energy of the wind that passes through the rotor area, is extracted by the rotor: the wind is only 'slowed down'. It can be shown that a maximum amount of energy is extracted from the air flow if the wind speed at the rotor itself is reduced to $2/3 V_\infty$. Then the wind speed behind the rotor turns out to be $1/3 V_\infty$ and the theoretically maximum limit for the extracted power Pmax is equal to:

$$P_{\max} = \frac{1}{2}(2/3\ \rho A V_\infty) V_\infty^2 - \frac{1}{2}(2/3\ \rho A V_\infty)(1/3\ V_\infty)^2 \qquad \mathbf{3}$$

or

$$P_{\max} = \frac{16}{27}\frac{1}{2}\rho A V_\infty^3 \qquad \mathbf{4}$$

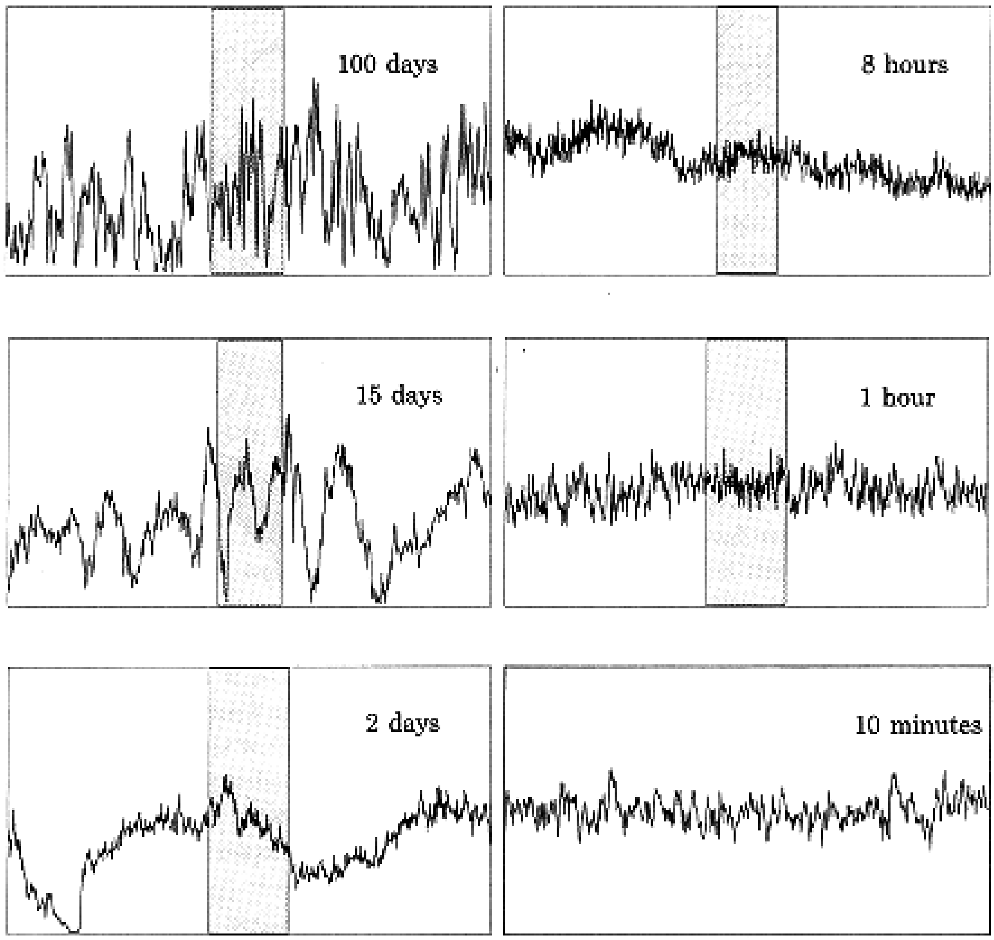
In other words, only a fraction of 16/27 (59.3%) of the kinetic energy of the wind can maximally be extracted by a wind turbine. This maximum value is known as the Betz-limit.

The fraction of extracted power is usually referred to as the rotor power coefficient C_p. In practice it seldom exceeds 40% if measured as the mechanical power of a wind rotor. The available output power of a wind energy system is further reduced by subsequent conversion into electrical or mechanical power, depending on the efficiency η of transmission and generator.

2.2 Wind speed fluctuations

In the previous section we considered a wind rotor in a constant air flow. However, wind is fluctuating! It is the character of the wind itself that makes wind energy technology to such a complex subject. Basically a wind energy conversion system does not deliver its output energy at a constant rate, but will give an variable energy output depending on the (momentaneous) wind speed. Nevertheless, we want it to meet at least our minimum energy demands and yet be economically feasible.

Long term and short term wind fluctuations according the European Wind Atlas [17]



In practice this implies that we should carefully define our energy demands:

- Minimum energy production (water/electricity) per week/month/year. This value, together with the average wind speed, will give the minimum rotor size (and a first estimate of cost price).
- Allowance of no energy production during a certain period (giving an impression about water storage tanks or batteries).
- Time of the year that the system is really producing energy.

In order to decide whether or not a wind energy system will satisfy our energy needs, we have to know more about the prevailing wind speeds at the future wind turbine site.

2.2.1 Wind data handling

As we all know from experience, the wind speed may vary from second to second. Even in regions where wind speed is considered relatively constant, it usually still shows strong short-term fluctuations. The wind seems volatile, unpredictable, and yet a reliable prediction is what we need for a rational decision. The key to get around the fluctuating character of the wind, is to consider the time scale on which these fluctuations occur.

Momentaneous, short term fluctuations indeed are quite unpredictable. However, on a daily basis one may already recognize a certain pattern. Also, wind speeds may be stronger in some month. Meteorological data show that the fluctuations in the yearly wind patterns are quite small, comparing one year to another. In other words: on a long-term basis, the wind speed at a given location is fairly well predictable (accuracy about 10%, [11]).

A time scale is also present in our energy demands. In case of a wind pump we would think about the amount of water pumped in one hour (or one day) needed for irrigation. We would not allow a long period without any water as crops would die. But we could accept a lower water production during the harvest period.

Since we define our demands over periods of hours, days, or months, momentaneous wind data are usually reduced to hour, day-, or month-averaged values. We only consider the momentaneous wind speed in the case of the maximum occurring gust speed, which is an important value for the design and safety of a wind turbine.

The following table shows the hour-averaged wind speeds recorded during one month (720 hours) at Praia, Cabe Verdian Islands in June 1975.

hour / day	1h	2h	3h	4h	5h	6h	7h	8h	9h	10h	11h	12h	13h	14h	15h	16h	17h	18h	19h	20h	21h	22h	23h	24h	Mean diurnal speed
1	9.4	10.0	8.8	9.4	9.7	10.0	10.9	11.4	11.9	13.9	13.9	14.2	13.9	13.3	13.6	13.6	13.1	11.1	11.1	10.6	10.6	10.9	10.9	9.7	11.6
2	9.4	8.3	8.6	9.2	9.2	8.9	10.3	10.6	11.1	12.2	11.1	11.4	11.1	9.7	9.4	9.1	8.6	8.6	9.1	8.6	8.6	8.3	8.1	7.5	9.5
3	6.7	7.5	8.3	6.9	6.1	7.9	9.7	10.9	10.8	10.8	10.0	10.3	10.3	10.3	10.3	10.3	9.2	9.2	9.6	8.6	8.3	6.4	5.8	5.0	8.7
4	4.4	4.4	4.4	4.2	4.4	5.6	6.9	9.2	9.8	11.1	10.8	11.1	9.6	9.8	9.7	9.2	9.2	9.2	7.2	7.5	6.1	5.3	4.4	4.2	7.5
5	3.9	3.9	4.4	3.9	4.2	4.7	5.3	6.7	8.3	10.3	9.7	10.0	10.8	11.6	12.5	12.2	10.8	8.3	6.1	6.4	7.2	6.7	6.9	8.6	7.7
6	8.1	6.9	7.2	7.9	8.9	8.1	8.6	9.4	10.8	11.7	11.9	12.5	12.2	12.5	11.1	10.8	10.0	9.7	10.0	10.3	10.0	9.2	9.5	9.7	9.9
7	7.2	6.1	6.1	4.2	3.1	3.3	5.3	8.1	10.0	10.0	11.9	9.7	7.5	6.7	4.2	3.3	3.0	1.4	1.7	2.5	2.2	4.7	5.3	4.2	5.5
8	3.3	5.0	4.4	2.5	4.2	3.3	4.4	6.4	6.9	8.6	8.9	8.9	9.2	9.7	8.6	10.3	10.0	8.6	7.8	8.9	5.8	5.8	5.0	6.7	6.9
9	3.6	4.4	6.4	6.1	6.4	7.5	7.9	8.9	10.0	9.4	8.3	8.6	10.0	10.6	9.2	10.0	7.5	6.9	5.8	6.4	5.0	4.4	4.7	4.4	7.2
10	4.4	5.0	5.0	4.4	5.0	4.4	4.7	5.6	6.9	8.6	8.9	8.6	8.6	7.2	7.8	7.8	7.2	6.4	5.8	6.1	4.7	5.0	5.3	5.0	6.2
11	5.3	5.3	4.2	4.7	5.9	3.9	5.6	5.9	6.9	7.2	7.5	6.1	4.7	6.1	7.8	8.3	8.3	6.9	6.1	5.3	5.3	5.0	5.3	5.0	6.0
12	5.3	4.7	4.7	4.7	4.2	4.2	5.9	6.9	8.3	9.2	8.6	9.2	8.9	8.1	8.1	9.4	8.9	7.5	7.2	6.7	5.8	6.9	6.9	6.1	7.0
13	4.7	5.3	5.0	5.6	5.3	5.3	7.5	7.2	9.4	9.7	10.0	9.7	9.4	9.7	9.7	9.4	9.4	8.9	7.5	6.4	6.9	5.8	6.4	6.4	7.6
14	5.3	6.7	8.3	8.1	7.9	7.5	8.3	9.7	9.4	11.1	9.7	9.7	8.9	8.6	7.8	8.1	8.1	7.8	7.5	7.2	6.1	5.0	5.0	4.4	7.8
15	4.7	6.1	7.5	8.3	7.6	6.8	7.2	7.5	8.3	10.3	10.0	8.6	9.4	9.4	10.0	10.0	9.6	8.3	6.7	6.4	6.7	6.1	6.4	6.7	7.9
16	6.9	6.9	6.4	5.9	6.4	7.5	7.5	8.6	9.2	9.7	9.7	8.9	9.4	9.1	9.7	9.7	9.2	8.6	8.1	6.4	4.7	4.7	4.4	4.7	7.7
17	4.4	5.3	5.3	5.0	5.3	5.6	6.3	6.9	8.6	10.0	10.3	10.3	10.3	10.3	10.6	9.7	6.4	5.8	5.6	5.8	6.1	4.2	2.5	3.1	6.9
18	4.4	5.0	6.1	5.9	6.1	6.9	6.1	6.4	5.8	8.9	9.2	9.7	9.2	8.1	5.6	5.9	6.1	8.9	7.8	5.6	5.9	6.7	6.4	6.4	6.8
19	5.6	5.6	5.3	4.4	7.5	8.1	7.8	6.7	8.3	9.4	8.1	6.4	6.7	5.6	4.7	3.4	3.1	6.7	6.1	6.7	5.9	5.6	5.9	5.6	6.2
20	6.1	5.3	3.1	3.3	4.2	5.0	5.9	6.1	6.7	6.4	8.1	8.1	8.1	8.9	8.9	5.6	6.4	7.8	8.1	9.2	8.6	8.4	7.8	7.2	6.8
21	6.9	6.4	7.9	8.3	8.9	7.5	6.4	7.5	7.2	8.9	8.3	7.2	5.9	5.9	5.8	9.7	9.2	8.9	11.1	11.1	10.9	11.4	11.1	11.1	8.5
22	10.0	9.7	10.0	10.3	10.0	10.8	10.8	11.4	11.7	11.1	12.2	11.1	10.3	8.9	9.2	9.7	9.4	9.4	9.1	9.7	9.1	9.1	8.3	7.5	10.0
23	6.4	6.1	6.7	6.9	7.2	5.9	6.7	6.9	6.9	8.9	6.4	5.0	5.3	6.1	6.7	5.3	4.4	6.2	7.5	8.1	8.3	6.9	5.3	5.0	6.6
24	5.8	5.3	6.1	6.1	5.8	6.2	7.8	7.8	6.9	6.4	5.8	5.9	5.9	3.3	2.8	4.2	3.9	2.5	5.9	6.9	6.4	5.3	2.2	1.9	5.3
25	1.4	1.4	2.2	3.1	3.4	4.2	3.9	6.1	6.7	5.8	4.7	5.6	3.6	4.2	4.4	3.1	1.9	2.2	3.1	5.0	5.0	6.7	6.9	7.2	4.3
26	5.6	4.4	5.0	5.3	4.4	2.8	2.8	5.8	6.7	7.2	9.2	9.2	8.1	6.7	6.7	4.2	6.4	8.1	6.9	5.7	6.1	5.9	5.3	4.4	6.1
27	4.2	3.9	3.1	3.1	2.2	3.3	4.7	3.1	4.4	6.9	6.1	5.6	5.6	4.7	4.2	4.4	3.8	4.4	5.6	5.6	5.3	5.9	4.7	5.0	4.6
28	5.0	5.3	3.6	4.2	4.2	2.8	5.0	4.7	4.2	6.1	8.3	11.1	11.1	13.6	13.1	12.5	12.5	11.9	11.4	11.4	10.6	10.6	11.1	11.1	8.6
29	10.6	11.1	11.4	11.1	10.8	10.3	11.4	12.2	12.2	11.7	11.9	11.6	11.1	10.0	11.1	11.1	10.0	9.4	9.4	10.0	8.6	6.9	6.1	5.6	10.3
30	5.6	5.3	5.8	5.6	5.9	6.2	6.7	6.9	6.9	6.9	8.1	8.6	6.9	5.3	3.9	6.9	6.9	6.9	5.6	5.9	6.4	5.6	5.9	4.7	6.3
mean monthly at x hour	5.82	5.89	6.05	5.95	6.15	6.15	6.94	7.72	8.37	9.28	9.25	9.11	8.73	8.47	8.24	8.24	7.75	7.55	7.35	7.37	6.91	6.65	6.33	6.14	7.35 mean monthly

Figure 2: The mean hourly wind speed in Juni 1975 at Praia (Meteorological Service Centre, Rep. Cape Verdian Islands). Velocities are in meters per second.

2.2.1.1 Time distribution

Knowledge about time-dependent fluctuation pattern of the wind speed is necessary to know if wind power is available in a certain period (a part of the day, a number of consecutive days, a month, etc.).

Plotting the monthly average of each hour of the day shows the diurnal fluctuations of the wind speed in that particular month, as depicted in Figure 3; in the same figure also the monthly average is shown.

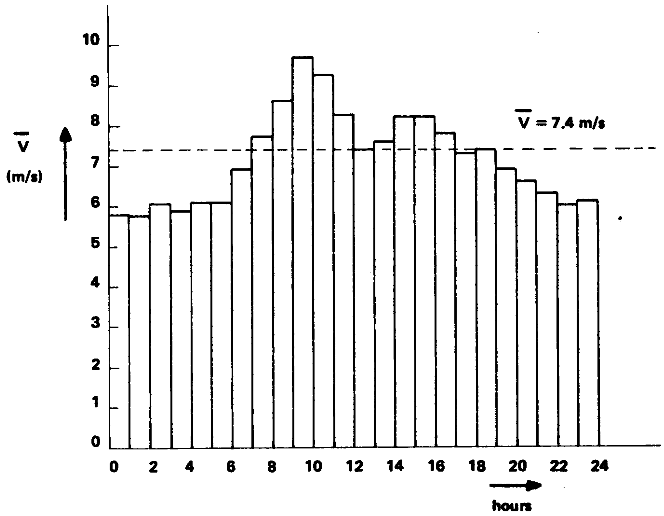


Figure 3 Diurnal pattern of the wind speed at Praia airport in the month of June 1975.

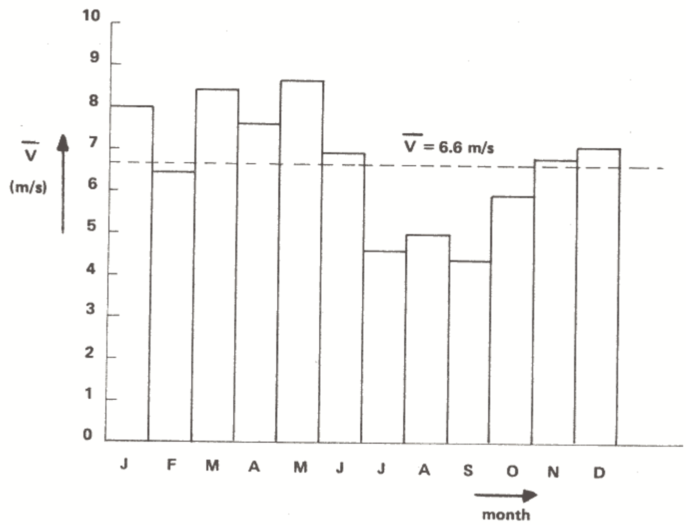


Figure 4: The monthly average wind speeds at Praia airport in the year 1978 and compared with the annual average wind speed.

Another kind of information that can be obtained from the table is the presence of longer periods with low wind speeds (lulls). If we define a lull as a period in which the wind speed is lower than a certain reference speed, we can determine how many times this occurred by looking at the hour-averaged wind speeds in the table. This type information is valuable for the calculation of the size of storage tanks, in case of water supply by using wind pumps or wind electric pumping systems.

2.2.1.2 Frequency distribution

In order to calculate the total energy output over a given period, one should first determine how many hours during this period a given wind speed occurred, i.e. determine the frequency distribution of the wind speed.

To arrive at this frequency distribution we must first divide the wind speed domain into a number of intervals or "bins", mostly of equal width of 1m/s or 0.5m/s. Then, starting at the first interval of 0-1m/s, the number of hours is counted that the wind speed was in this interval. When the number of hours in each interval is plotted against the wind speed, the frequency distribution emerges as a histogram (*Figure 5*, with data taken from *Figure 2*).

interval (m/s)	hours/ month
0-1	0
1-2	6
2-3	13
3-4	32
4-5	70
5-6	120
6-7	126
7-8	56
8-9	89
9-10	81
10-11	64
11-12	42
12-13	11
13-14	9
14-15	1
Total	720

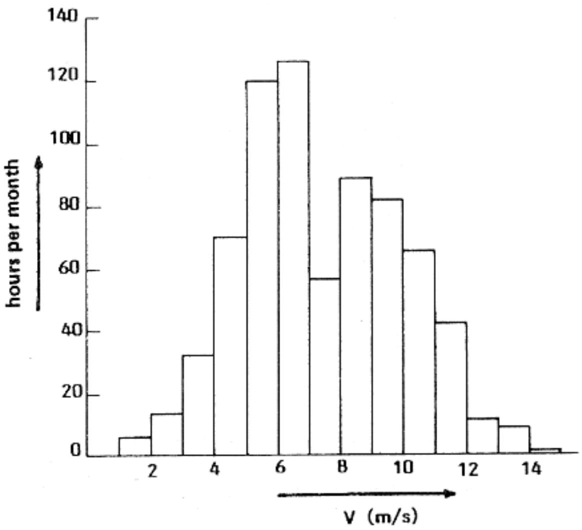


Figure 5 Frequency distribution of wind speeds at Praia (table and graph).

The top of this histogram, being the most frequent wind speed, is generally *not* the average wind speed. In trade wind areas with quite steady winds speeds this might be the case, but in other climates the average wind speed is generally higher than the most frequent wind speed (see also Figure 6).

Given the frequency distribution, the average wind speed is calculated as follows:

$$\overline{V} = \frac{t_1 V_1 + t_2 V_2 + \bullet\bullet\bullet + t_i V_i + \bullet\bullet\bullet + t_n V_n}{t_1 + t_2 + \bullet\bullet\bullet\, t_n} \qquad \mathbf{5}$$

with

t_i = number of hours in wind speed interval i
V_i = *middle* of wind speed interval i
$\overline{V}$ = average wind speed

This calculated average wind speed of course must be the same as the one calculated directly from the original data (by summing all hourly data and dividing them by the number of hours).

Then the energy output of a wind turbine is calculated by multiplying the number of hours in each interval with the power that the turbine produces at that wind speed, and add the results for each wind speed interval.

It is often important to know the number of hours that a windmill will run or the time fraction that a windmill produces more than a given power. In this case it is necessary to add the number of hours in all intervals above the wind speed that corresponds to that power level. The result is the *duration distribution* which is easily found by adding the number of hours of each interval to the sum of all hours of the *higher* intervals. So it is best to start with the highest interval, with zero hours of wind speed higher than the upper boundary of the interval and subsequently add the number of hours of the next lower interval, etc. This is done in Figure 6 with the information from Figure 5.

Interval	frequency	duration **V>V'**	cumulative **V<V'**	
(m/s)	hours	hours	hours	%
0-1	0	720	0	0
1-2	6	714	6	0.8
2-3	13	701	19	2.6
3-4	32	669	51	7.1
4-5	70	599	121	16.8
5-6	120	479	241	33.5
6-7	126	353	367	51.0
7-8	56	297	423	58.8
8-9	89	208	512	71.1
9-10	81	127	593	82.4
10-11	64	63	657	91.2
11-12	42	21	699	97.1
12-13	11	10	710	98.6
13-14	9	1	719	99.9
14-15	1	0	720	100.0
Total	720			

Figure 6 The frequency distribution of Praia (June 1975) transformed into a duration and a cumulative distribution. The upper boundary of the interval is indicated by V'.

The duration values are commonly plotted with the wind speed on the vertical axis, as shown in Figure 8. Here the length of each horizontal column indicates the duration of the time that the wind speed was *higher* than the upper boundary of the wind speed interval. If the histogram is approximated by a smooth curve through the values at the middle of each interval then a duration curve results.

By studying the shape of this duration curve an idea is obtained about the kind of wind regime. The flatter the duration curve, i.e. the longer one specific wind speed persists, the more constant the wind regime is. The steeper the duration curve, the more irregular the wind regime is.

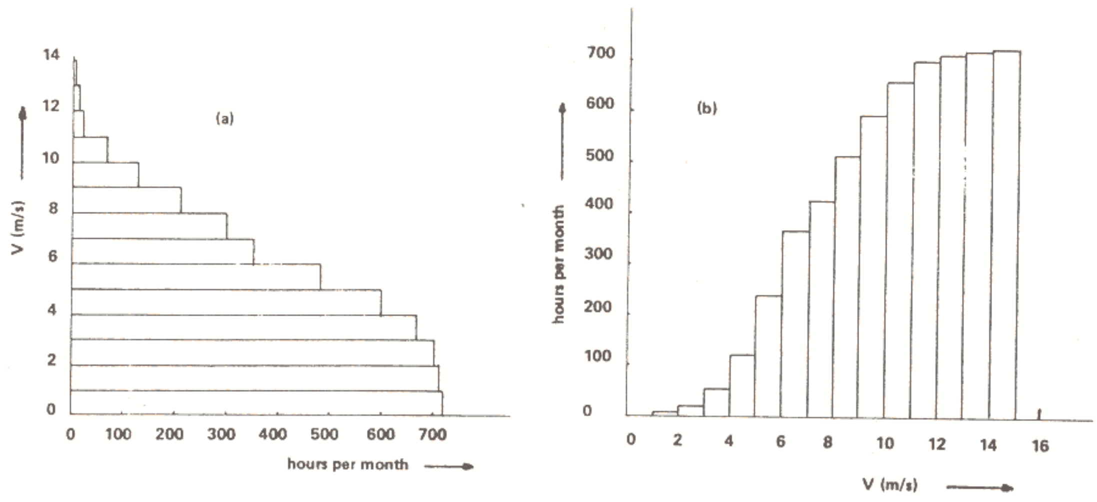


Figure 7 Histograms of the duration distribution (a) and the cumulative distribution (b) for the Praia data (June 1975).

In other cases it is preferred to plot the time during which the wind speed was *smaller* than a given wind speed, and when this is plotted versus the wind speed a cumulative distribution results.

2.2.2 Wind regimes

After having drawn a number of velocity duration histograms or velocity frequency histograms and approximating them by smooth curves one will notice a similarity in the shape of these curves. This is even clearer if the wind speed values are made dimensionless by dividing them by the average wind speed of that particular distribution. It is quite logical in such a situation to look for mathematical functions that accurately describe the wind frequency and duration.
These functions can be used later on, as a tool to predict the output of a wind turbine, and as mathematical description of the wind speed pattern -the wind regime- in a more extended zone.

In this respect much attention has been paid to the Weibull function, since it matches well with experimental data [10-13]. This section deals with the Weibull function and the method to estimate its parameters from a given distribution.

2.2.3 *Wind regime representation*

A wind regime can analytically be described by two functions with the following general form:

1. The *cumulative distribution function* $F(V)$ indicating the time fraction or probability that the wind speed V is smaller than or equal to a given wind speed V'.

$$F(V) = P(V \leq V') \text{ (dimensionless)} \quad \mathbf{6}$$

2. The probability density function or the *velocity frequency curve*.

$$f(V) = \frac{dF(V)}{dV} \text{ (s/m)} \quad \mathbf{7}$$

The Weibull distributions are characterised by a two-parameter representation of $F(V)$ and $f(V)$.

$$F(V) = 1 - \exp[-(\frac{V}{c})^k] \quad \mathbf{8}$$

and

$$f(V) = \frac{dF}{dV} = \frac{k}{c}(\frac{V}{c})^{k-1} \exp[-(\frac{V}{c})^k] \quad \mathbf{9}$$

with:

k = shape factor

and

c = scale factor

The average wind speed $\overline{V}$ can be found from:

$$\overline{V} = \int_0^\infty V\, f(V)\, dV \text{ (m/s)} \quad \mathbf{10}$$

After some work, the equations 9 and 10 can be written dimensionless as:

$$F(x) = 1 - \exp[-Gx^k] \qquad 11$$

$$f(x) = kG\,x^{k-1}\exp[-G\,x^k] \qquad 12$$

in which x is the reduced wind speed (dimensionless)

$$x = \frac{V}{\overline{V}} \qquad 13$$

and G is an approximation defined by the following formula:

$$G = 0.568 + \frac{0.434}{k} \qquad 14$$

In Figures 9 and 10 some Weibull functions are shown for several values of k . The relation between equation 10 and equation 13 is:

$$f(V) = \frac{f(x)}{\overline{V}} \qquad 15$$

Common values for k are k=2 and k=3. By substituting these values into the equations 11 and 12 we obtain:

$k = 2 \rightarrow G = \dfrac{\pi}{4} \approx 0.7854$

$$F(x) = 1 - \exp[0.7865\,x^2]$$

$$f(x) = 1.571\,x\exp[-0.7854\,x^2] \qquad 17$$

$k = 3 \rightarrow G \approx 0.7121$

$$F(x) = 1 - \exp[0.7121\,x^2] \qquad 18$$

$$f(x) = 2.136\,x\exp[-0.7121\,x^2] \qquad 19$$

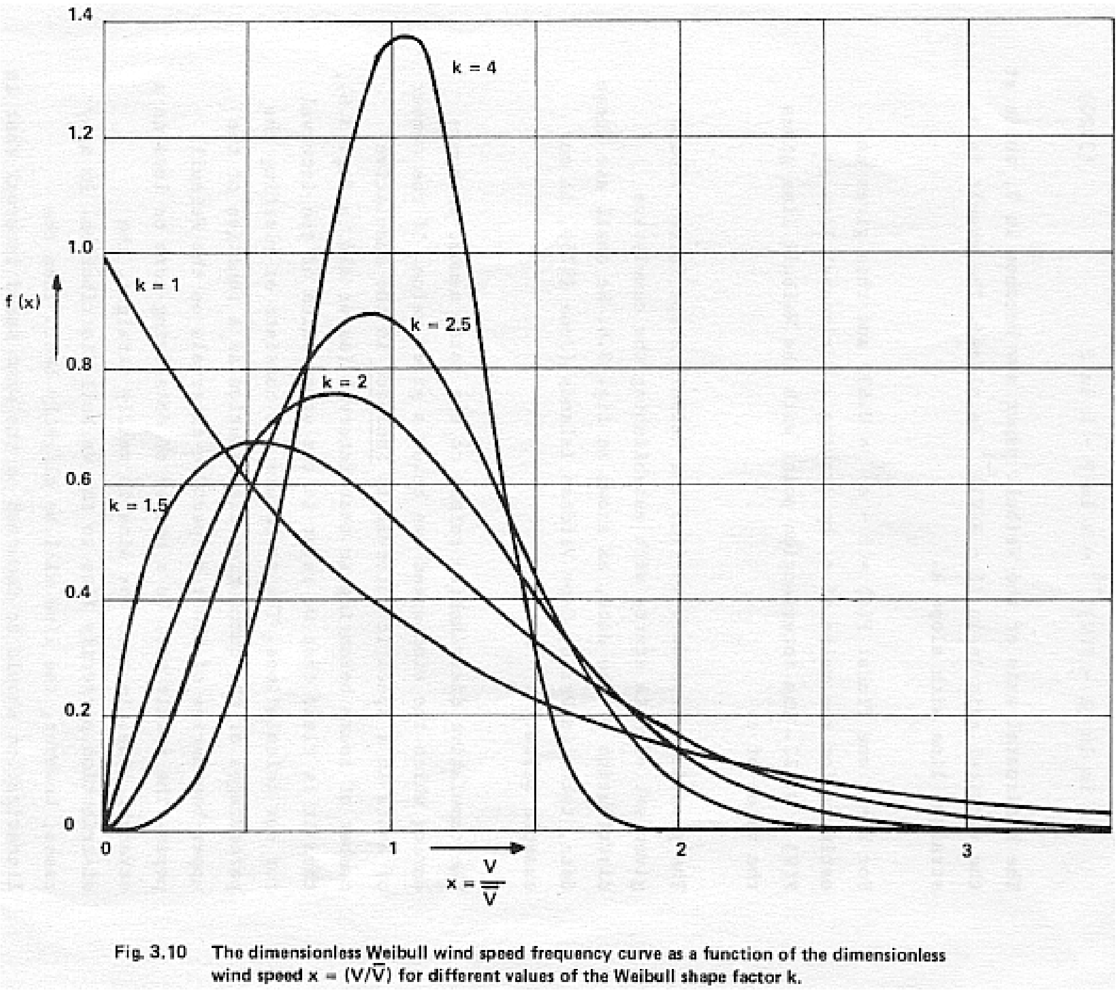


Figure 8 *The shape of the Weibull wind velocity distribution for various values of the shape factor k (frequency f(x)) against reduced wind speed x =* $V/V_{average}$*, with V = wind speed and* $V_{average}$ *= average wind speed.*

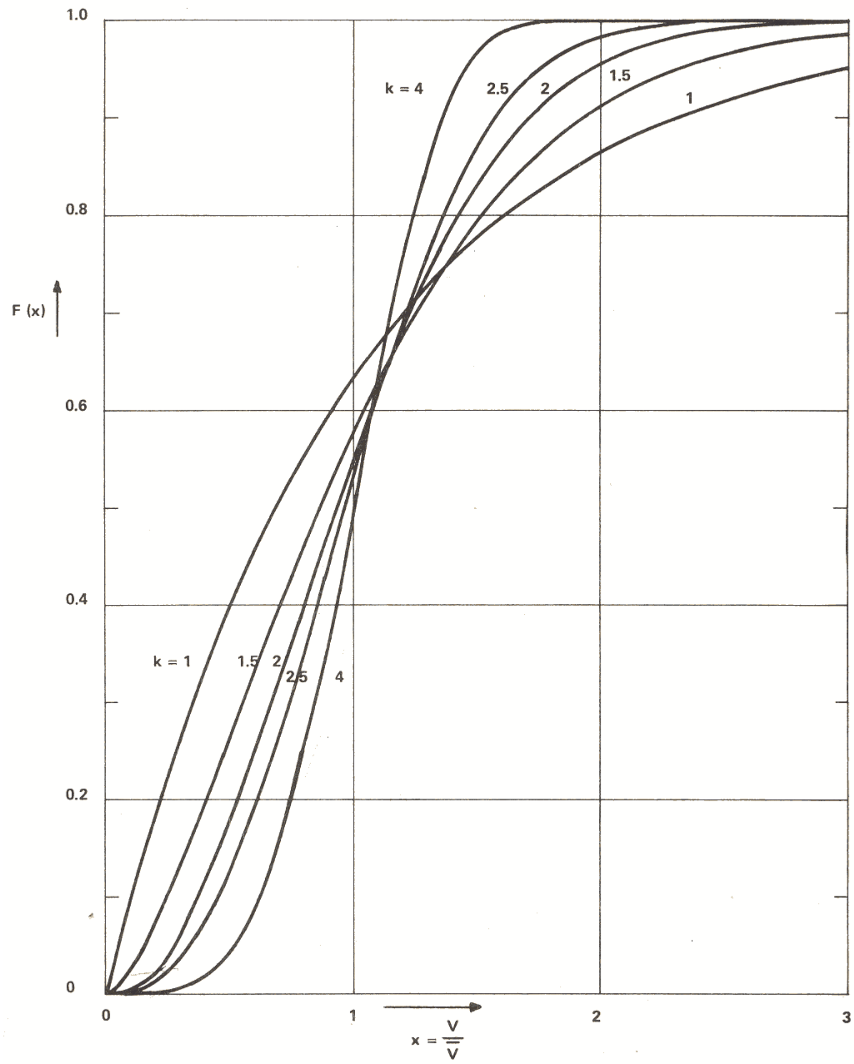


Figure 9 *The Weibull cumulative distribution function F(x) as a function of the dimensionless wind speed $x=(V/V_{average})$ for different values of the Weibull shape parameter k.*

The Weibull distribution is shown in Figure 9 for various values of the shape factor k . A small value of k corresponds to a variable wind, a large value to a more constant wind; roughly the following k -values are found for different climates:

k = 1.5	Strongly variable wind: polar regions, thermal winds (land/sea, mountain/valley), winds having a strong day/night variation.
k = 2.0	moderately variable wind: moderate climates.
k = 3.0	constant winds: trade winds, tropical regions.

In practice, the procedure to find the Weibull shape factor from a given set of data starts with establishing the cumulative distribution of the wind speed (the total number of hours during which the wind speed was below a given value). If the number of hours in a specific interval is *included* in the cumulative number of hours belonging to that interval then it is clear that we refer to the upper value of the interval for our calculations.

The procedure now consists of plotting the percentages of the cumulative distribution as a function of the upper boundaries of their respective intervals on Weibull paper. The result will be a number of dots lying more or less on a straight line. If the line is totally straight, the distribution perfectly fits a Weibull distribution. In many cases, however, the line will be slightly bent. Then the linearization should be focused on the wind speed interval that is most interesting for our wind energy application, i.e. between $0.7\overline{V}$ and $2\overline{V}$.

In order to find k, draw a second line through the ``+ ", marked `` k estimation point", and *perpendicular* to the Weibull line. The intersection of this second line with the linear k-axis on top of the paper gives the desired k-value. The c-value, if required, is simply the intersection of the Weibull line with the dotted line, marked `` c estimation". Ideally this procedure should be applied to the data for a number of years, not to data from one month only. If the monthly k-values are required then the use of wind data from a number of identical months of subsequent years will give more reliable results.

If a considerable percentage of calm is found in the frequency distribution, the Weibull analysis should be applied only to the percentage of time during which the wind is blowing [16].

For the reader's convenience a sheet of Weibull graph paper is included.

3 WIND RESOURCE ASSESSMENT

3.1 General

A first approach to wind assessment for a country or a region should be the use of existing information. In an ideal situation, hour mean values as in the Praia case are available over a prolonged period. Also useful are reduced data, such as monthly averages, diurnal patterns, etc. This type of data may be obtained from meteorological stations, airports, or a wind atlas. However, great caution is needed as data usually are not very reliable and sometimes even in contradiction. Still, they may be useful as a first estimate to decide whether a project might be feasible or not (and in a first stage, it is the only thing we can do).

As a second problem, wind data generally just do not exist for the exact site for a future wind energy project. This means that we should make an estimate of the local wind speed distribution on the site, based upon wind data from a distant meteo station, of which the reliability still is questionable. This is a far from simple task.

To carry out measurements oneself does not solve this problem, as average wind speed distributions are derived from accumulated measurements over a very long time (several decades). Also, it is not easy at all to measure wind speeds, and an extensive wind speed measuring programme would lead to additional costs too.
Therefore a viable strategy could be:

- use existing data
- examine the site and surroundings in order to:
  - choose the best possible location
  - correct distant meteo data for topographical conditions
- carry out additional measurements (if necessary) to obtain:
  - specific site data
  - correlate with existing wind data to create a wind map of the region

3.2 Evaluating wind data

A brief description of possibilities for wind resource assessments has been given in a paper prepared under the Global Wind Pump Evaluation Programme (GWEP) [4].

The first approach to wind assessment should be to use existing information. In most countries data may be obtained from the climatological department of the national meteorological service. Airports are also a useful source of data. They collect data which are often quite useful since airport wind is normally measured at 10m height above flat, open terrain.

It is not generally advisable to take data from agro-meteorological services. Much of their wind data are normally of little interest for wind energy applications since measurements are performed at 2m height or lower at sites that are not always well exposed to the wind.

While available data on a region or country is useful for a first impression of wind resources, one should be careful not to draw detailed conclusions from these data. In practically all detailed surveys of wind regimes carried out in industrialized and developing countries, reliability and accuracy of data proved to be limited or even poor. Errors occur related to the exposure of the anemometer (buildings, trees). calibration and functioning of the anemometer, and to data collection.

For more reliable information a wind energy expert should be asked to perform a detailed survey. The work would include:

- Desk study of type of climate, seasonal variations to be expected, overall movements of air masses, contour maps.
- Field trips to study landscape features relevant for wind flow such as hills, plains, valleys, ridges and biological indicators of wind speed such as bending trees; and to talk with local people.
- Visits to meteorological stations, paying attention to the exposure of the anemometer to the wind, condition of the equipment, and methods of data collection used.
- Collection of data from selected meteorological stations, either from the stations themselves or some supervisory service.
- Analysis and interpretation of data.

Usually, sufficient information is obtained from the survey for a general feasibility study and to permit a decision on whether to initiate a pilot project. Also, it is desirable to take new measurements to verify existing data, to investigate specific or representative sites, and to collect data in a more suitable format.

The contents of any measuring program will depend strongly on the situation and for which purpose the information will be used. Some general features of such a program are:

- Classification of typical regions and landscapes according to the type of wind regime.
- Detailed (time sequential) measurements at a limited number of sites characteristic for the typical regions or landscapes.
- Simple cumulative measurements at a larger number of sites, representative for future wind pump installations.
- Comparison of data with data obtained from existing meteorological stations that have acquired records over a long period of time.

In order to obtain complete and accurate measurements, a period of several years would be required. Of course, this is not always feasible. However, it is important to obtain the most accurate information possible. This is why it is best to consult a wind energy expert.

3.3 Site selection

The power output of a wind rotor increases with the cube of the wind speed as we have seen in a former Section. This means that the site for a windmill must be chosen very carefully to ensure that the location with the highest wind speed in the area is selected. The site selection is rather easy in flat terrain but much more complicated in hilly or mountainous terrains.

An excellent text book on siting of small wind machines is the handbook by H.L. Wegley [5].

When selecting a site for installation of a wind pump, one should, besides selecting the windiest site possible, make shore that there is an adequate source of water at the site location. An existing well may be used, or a new one may be constructed.

In complex terrain (valleys, mountains, etc) one should consider the general flow of air over the terrain in order to find the windiest sites. For example the middle of a valley may be a good site. If some kind of remote transmission is applied, the top of a smooth hill can be a good site.

For site selection in complex terrain a number of effects have to be considered [5]:

1. *windshear*: the wind slows down, near the ground, to an extent determined by the surface roughness.
2. *turbulence*: behind building, tress, ridges, etc.....
3. *acceleration*: (or retardation) on the top of hill, ridges etc.

These effects will be discussed in the following sections.

3.3.1 Wind shear

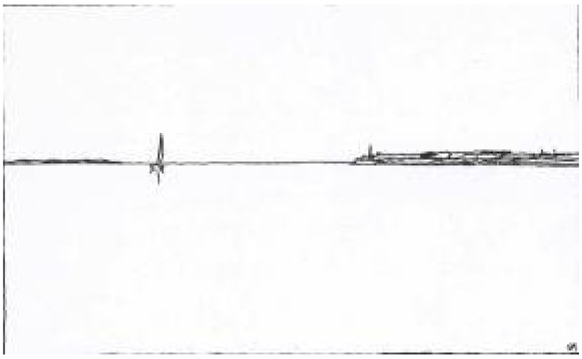
The effect of surface roughness is important. A high roughness tends to decrease wind speed. One should try and install a wind pump in flat terrain that is open up to a distance of 1 or 2 km, especially in the main wind direction.

Vegetation, buildings and the ground itself cause the wind to slow down near the ground or, vice versa, the wind speed increases with increasing height. The rate of the wind speed increase with height strongly depends upon the roughness of the terrain and the changes in this roughness.

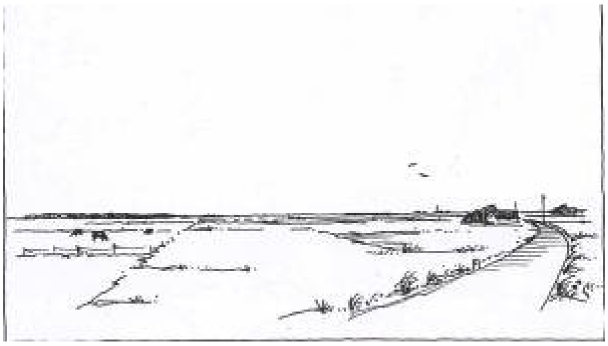
Typical values of roughness length z_0

(roughness classes as defined in the Danish norm, see also European Wind Atlas)

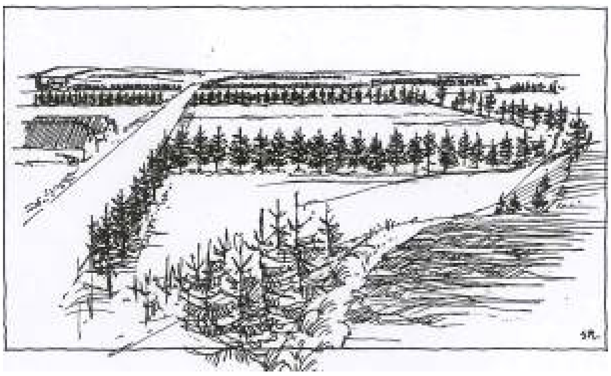
Terrain class 0.001
z_0 ~ 0.001-0.004



Terrain class 0.01
z_0 ~ 0.01



Terrain class 0.05
z_0 ~ 0.05



Terrain class 0.3
z_0 ~ 0.3

For various types of terrain the "roughness height" z_0 can be determined, usually by means of a gust analysis [6].

flat	:	beach, ice, snow landscape, ocean	z_0 1	=	0.005
open	:	low grass, airports, empty crop	z_0 2	=	0.03
	:	land, high grass, low crops	z_0 3	=	0.10
rough	:	tall row crops, low woods	z_0 4	=	0.25
very rough	:	forests, orchards	z_0 5	=	0.50
closed	:	villages, suburbs	z_0 6	=	1.0
towns	:	town centres, open spaces in forests	z_0 7	>	2

These values can be used in the standard formula for the logarithmic profile of the windshear:

$$\frac{V(z)}{V(z_r)} = \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \qquad \mathbf{20}$$

For a reference height of z_r = 10 m this formula is shown in *Figure 10* for different values of the roughness height z_0. The graph can be used in areas where there are no large hills or other large obstructions within a range of 1 to 2 km from the windmill.†

† *Equation 5 gives the windshear in one location. In case one wants to compare two locations, each with its own roughness height then Wieringa's assumption [6] that the wind speed at 60 m height is unaffected by the roughness, leads to the formula: (5a)*

$$\frac{V(z)}{V(z_r)} = \frac{\ln(60/z_{0r})\ln(z/z_0)}{\ln(60/z_0)\ln(z_r/z_0 r)}$$

with z_{0r} *the roughness height at the reference location, for example a meteorological station, where the wind speed is being measured at a reference height* z_r

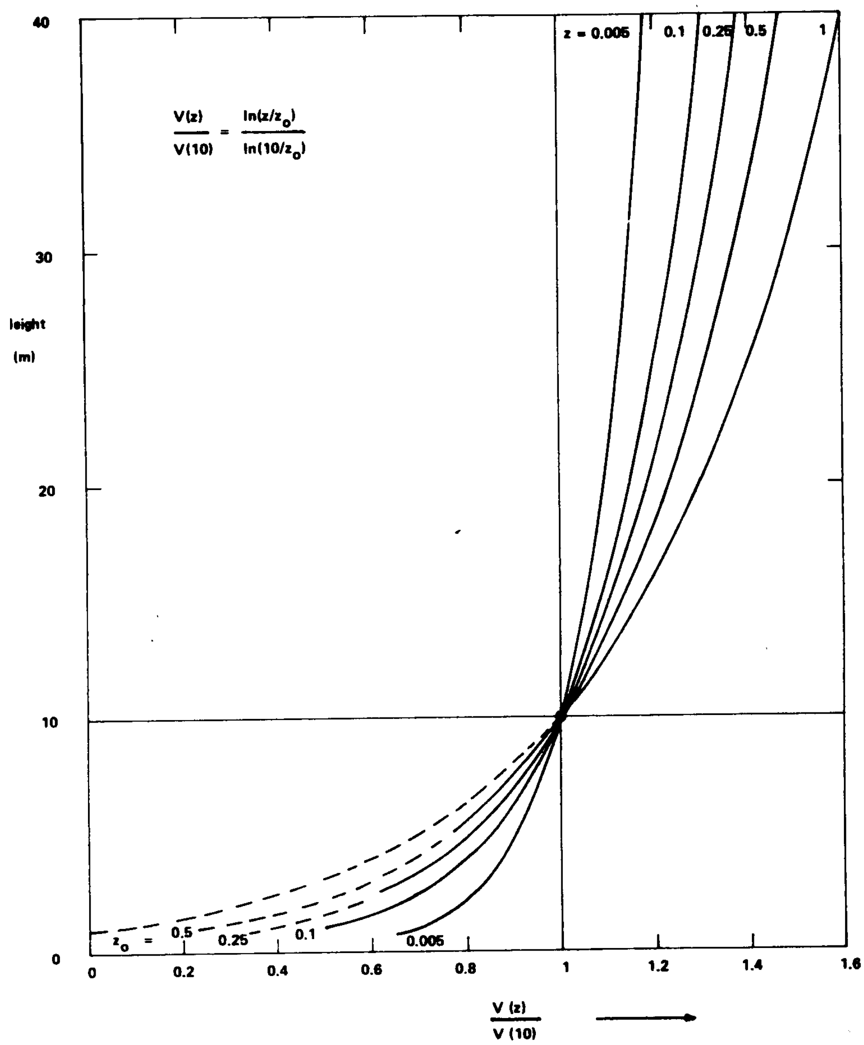


Figure 10 Windshear related to a reference height of 10m, for various roughness heights z_0.

3.3.2 Turbulence

Wind flowing around buildings or over very rough surfaces exhibits rapid changes in speed and/or direction, called turbulence. This turbulence decreases the power output of the windmill and can also lead to undesirable vibrations of the machine.

Thus the site should be free of large obstacles. "Behind" an obstacle, as seen from the main wind direction, the wind flow is disturbed in an area twice as high as the obstacle and extending horizontally 10 or 20 times the obstacle height. In this area the wind speed is lower and wind turbulence (rapid variations of wind speed and direction) is strong. The lower wind speed reduces output, while turbulence shortens lifetime. If possible, one should install any windmill in such a way that the rotor is completely clear from the region of disturbed flow, as indicated in *Figure 11*.

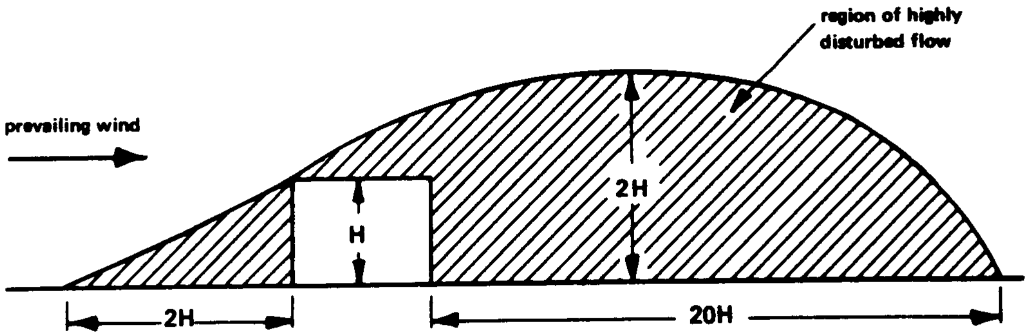


Figure 11 Zone of turbulence over a small building.

For trees the situation is even worse. Near shelterbelts of trees the turbulence is felt up to a leeward distance of at least 10-15 times the height of the trees. The region of turbulence also extends windward about five times the height of the obstruction [5].

A simple method to detect turbulence and the height to which it extends, is by means of a 1m. long ribbon tied to a long pole or a kite. The flapping of the ribbon indicates the amount of turbulence.

3.3.3 Acceleration on ridges

Apart from the fact that tops of ridges experience higher wind speeds due to the effect of windshear (section 3.3.1), the ridge also acts as a sort of concentrator for the air stream, causing the air to accelerate nearby the top (*Figure 12*).

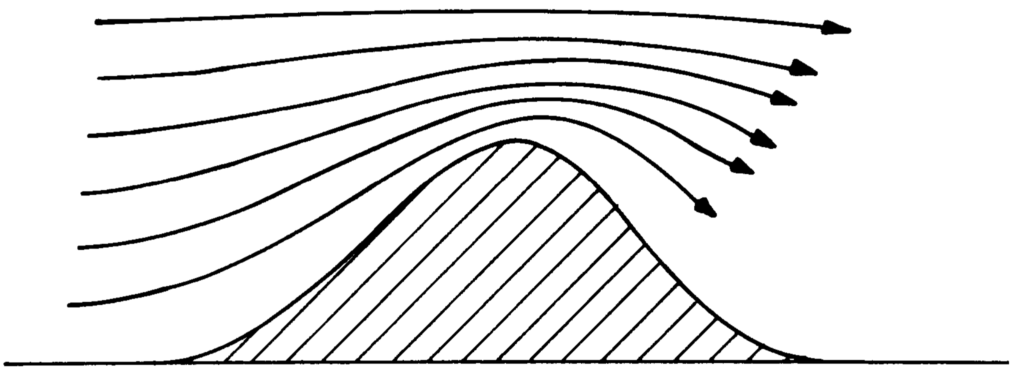


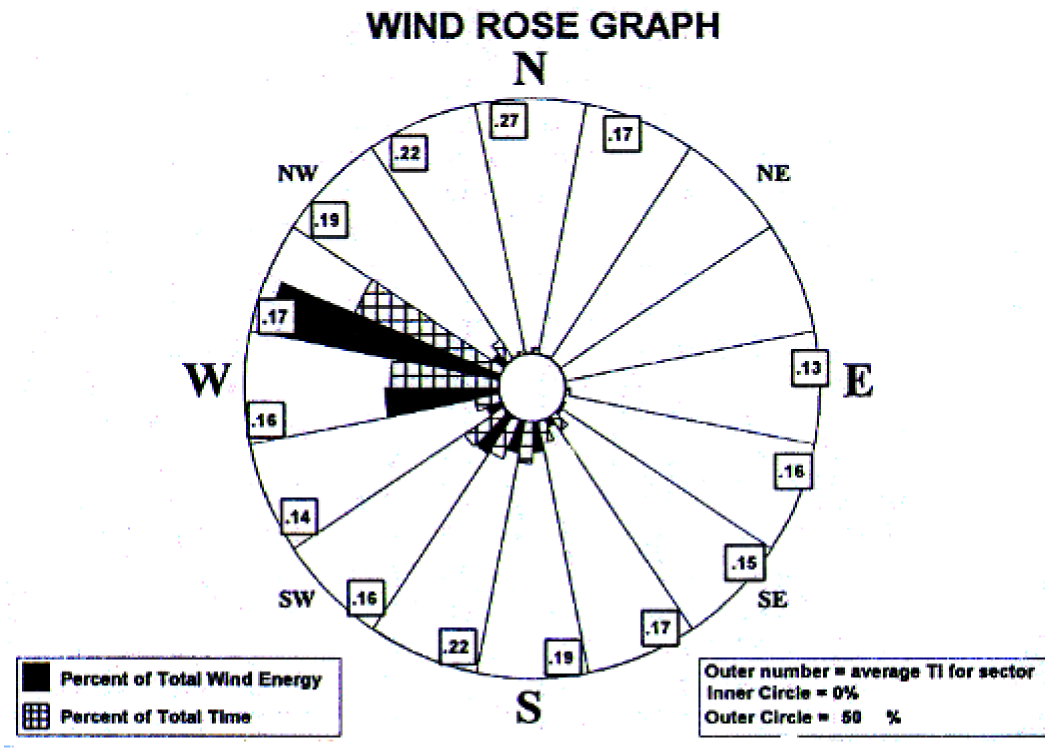
Figure 12 Acceleration of the wind over a ridge.

Generally, it can be said that the effect is stronger when the ridge is rather smooth and not too steep nor too flat. The ideal slope angle is said to be 16° (29m rise per 100m horizontal distance) but angles between 6° and 16° are good [5]. Angles greater than 27° should be avoided. Triangular shaped ridges are even better than rounded ridges.

The orientation of the ridge should preferably be perpendicular to the prevailing wind direction. If the ridge is curved it is best if the wind blows in the concave side of the ridge. A quantitative estimate of the acceleration effect is difficult to give, but increases of 10% to 20% in wind speed are easily attained.

Isolated hills give less acceleration than ridges, because the air tends to flow around the hill. This means that in some cases the hill sides, perpendicular to the prevailing wind, are better locations than the top. For specific cases, such as passes and saddles, valleys and hills, the reader is referred to the Siting Handbook [5] and Golding's book [7].

3.3.4 *Wind direction*



3.4 Evaluation of wind speed at a site

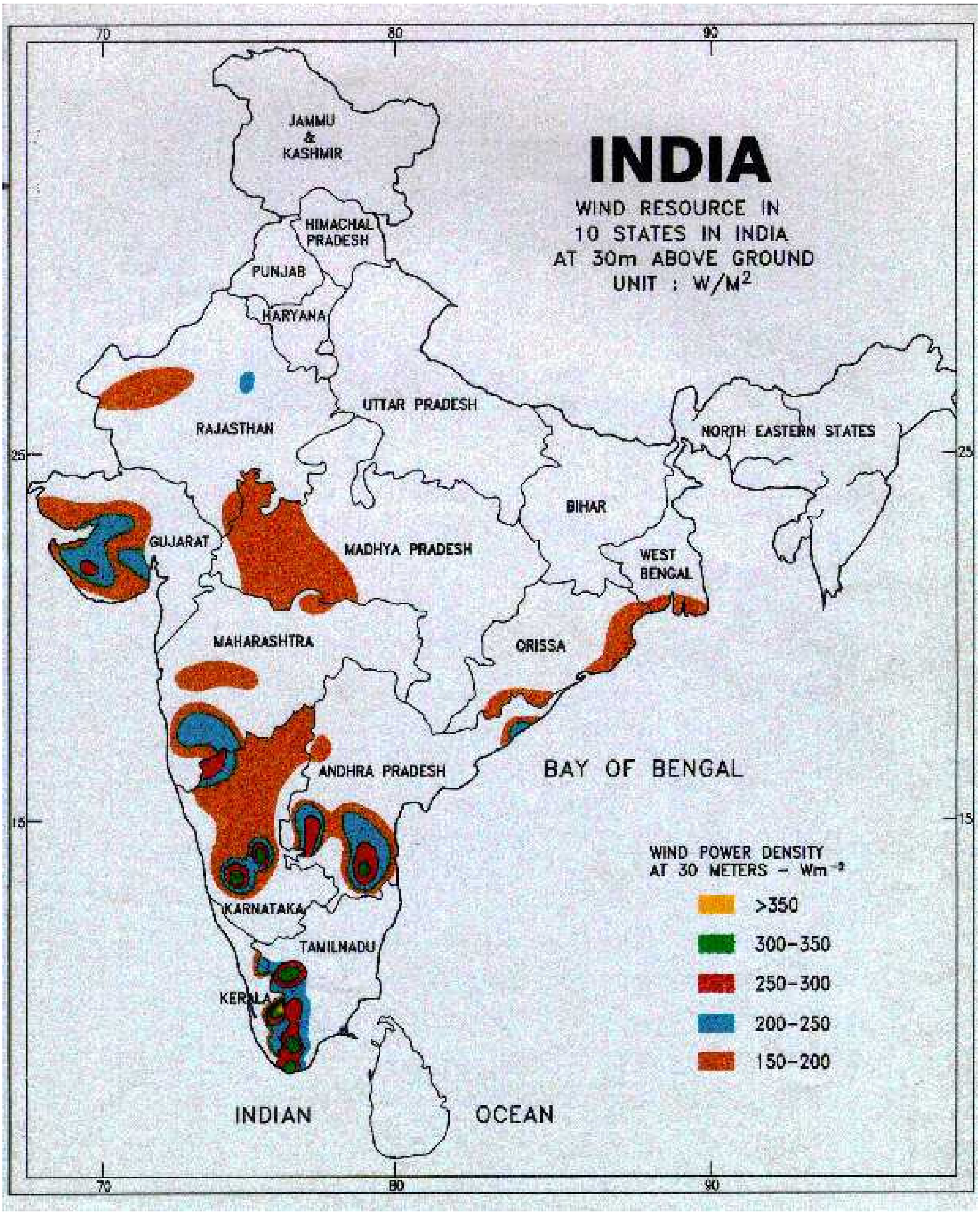
Once a site has been selected, the wind potential of the site should be evaluated.

In *flat terrain*, ideally, a wind map would be available. By studying detailed maps and by visiting the site it should be possible to establish its roughness characteristics. The appropriate corrections can then be applied in order to find the site's wind characteristics.

Often no windmap will be available, and one will have to use data from nearby meteorological stations. In this case on should estimate the potential wind speed using the roughness characteristics of the meteorological station, and convert it to the site's wind speed using the roughness characteristics of the site. If large distances are involved, one will have to consider the problem on a meso scale. For example, at an inland site the wind speed is generally lower than at a meterological station situated near the coast.

If the estimate obtained is considered to be insufficiently accurate, one may wish to perform on-site measurements for a short period, e.g. a few months. Comparing the data thus obtained with simultaneous data of a nearby meteorological station, one may try to find a correlation (which may be different for different wind directions!). If a consistent correlation is found, one may estimate the long-term wind characteristics at the site using long-term data from the meteorological station and the correlation derived from the short-term measurements.

In *complex terrain*, it is much more difficult to make any general estimates. One may use data from comparable sites, although it will be difficult to asses what a "comparable" site is. Short-term measurements may be useful, trying to establish a correlation with a nearby meteorological station, as indicated above. A problem may be that the wind direction is affected by the topography of the terrain.



Wind Map of India

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5 ANNEX

This section contains the following information needed for wind evaluation:

- Conversion of units
- The Beaufort scale
- Density of air
- Blank sheet of Weibull paper

Conversion of units

	m/s	km/hr	mph	knots
1 m/s	1.000	3.600	2.237	1.944
1 km/hr	0.278	1.000	0.622	0.540
1 mph	0.447	1.609	1.000	0.869
1 knot	0.514	1.852	1.151	1.000

Figure 13 Conversion of units of wind velocity.

The Beaufort scale

Beaufort number	knots	mph	m/s	km/hour	seaman's term	World Meteorological Organization	estimating wind speed by effects observed on land
0	under 1	under 1	0.0-0.2	under 1	calm	calm	Calm; smoke rises vertically
1	1-3	1-3	0.3-1.5	1-5	light air	light air	Smoke drift indicates direction, vanes do not move.
2	4-6	4-7	1.6-3.3	6-11	light breeze	light breeze	Wind felt on face; leaves in rustle; vanes begin to move.
3	7-10	8-12	3.4-5.4	12-19	gentle breeze	gentle breeze	Leaves, small twigs in constant motion; light flags extended
4	11-16	13-18	5.5-7.9	20-28	moderate breeze	moderate breeze	Dust, leaves and loose paper raised up; small branches move.
5	17-21	19-24	8.0-10.7	29-38	fresh breeze	fresh breeze	Small trees in leaf begin to sway.
6	22-27	25-31	10.8-13.8	39-49	strong breeze	strong breeze	Larger branches of trees in motion; whistling heard in wires.
7	28-33	32-38	13.9-17.1	50-61	moderate gale	near gale	Whole trees in motion; resistance felt in walking against the wind.
8	34-40	39-46	17.2-20.7	62-74	fresh gale	gale	Twigs and small branches broken off trees; progress generally impeded.
9	41-47	47-54	20.8-24.4	85-88	strong gale	strong gale	Sligh structural damage occurs; slate blown from roofs.
10	48-55	55-63	24.5-28.4	89-102	whole gale	storm	Seldom experienced on land; trees broken or uprooted; considerable structural damage occurs.
11	56-63	64-72	28.5-32.6	103-117	storm	violent storm	
12	64-71	73-82	32.7-36.9	118-133			Very rarely experienced on land; usually accompanied by widespread damage.
13	72-80	83-92	37.0-41.4	134-149			
14	81-89	93-102	41.5-46.1	150-166			
15	90-99	104-114	46.2-50.9	167-183	hurricane	hurricane	
16	100-108	115-125	51.0-56.0	184.201			
17	109-118	126-136	56.1-61.2	202-220			

Figure 14 Beaufort classification of wind speeds.

Density of air

Height above sea level	Density of dry air at 20^oC	Density of air at 0^oC
0	1.204	1.292
500	1.134	1.217
1000	1.068	1.146
1500	1.005	1.078
2000	0.945	1.014
2500	0.887	0.952
3000	0.833	0.894
3500	0.781	0.839
4000	0.732	0.786
4500	0.686	0.736
5000	0.642	0.689

Figure 15 Density of dry air at different altitudes under standard conditions.

Weibull paper

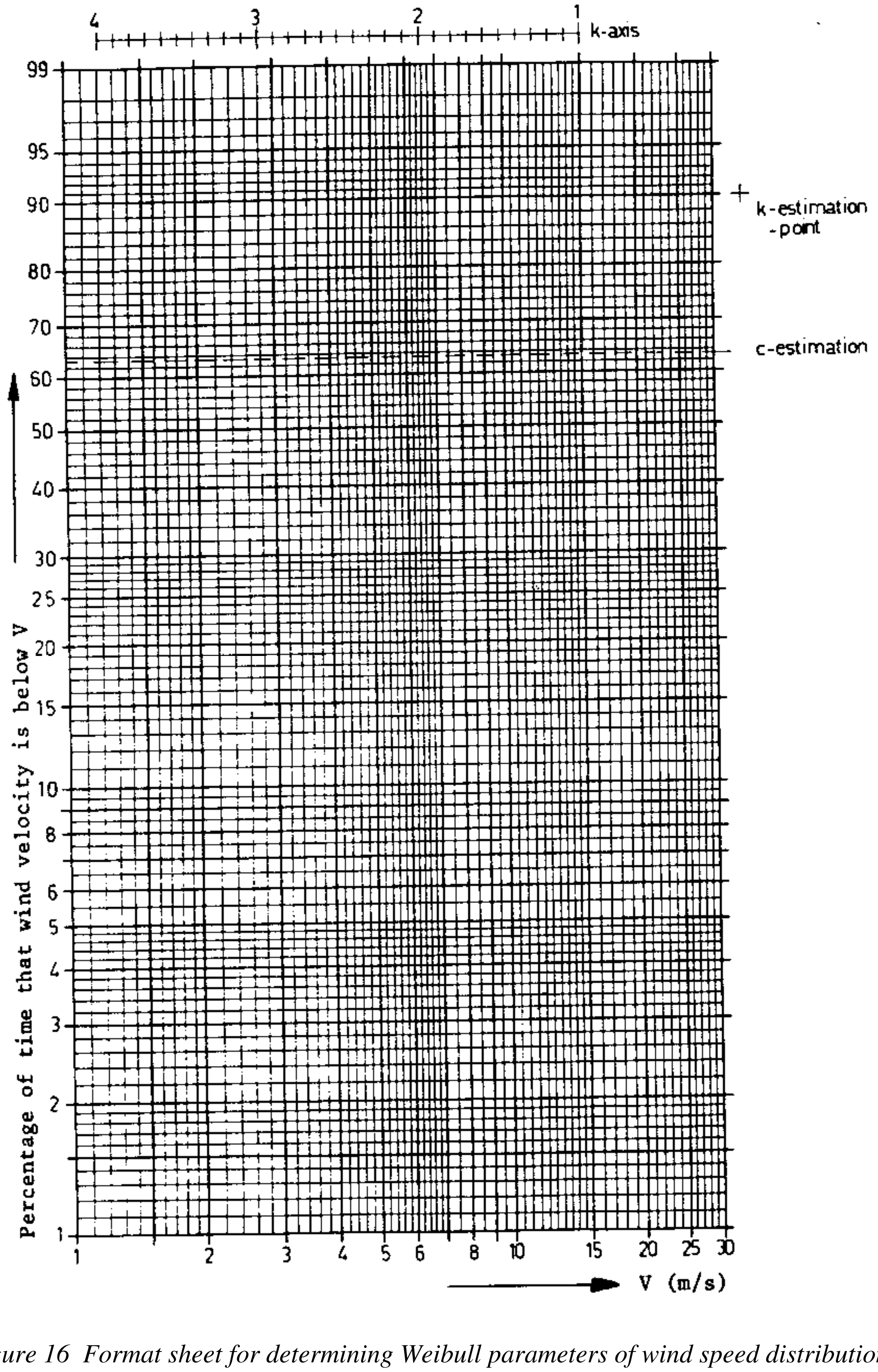

Figure 16 Format sheet for determining Weibull parameters of wind speed distribution.