5.3 Measurement of speed of rotation

The following methods are used to measure the speed of rotation of an object: -

- Mechanical Tachometer
- Digital Tachometer
- Stroboscopes
- Magnetic Field Angular Position Sensors
- Wheel Encoder

The choice of technique used for measurement is governed by the application range considered, degree of accuracy required, type of installation and original cost. In this section each type will be discussed and an overview of the importance of time measurement will also be discussed.

5.3.1 Mechanical Tachometer

This type of tachometer is a linkage of shafts, gears and rotating weights. When the input shaft which is seen horizontal rotates the vertical shaft it also rotates the weights attached to it which are hinged and free to move inward and outwards. The movement of these flyweights rotates a pointer which is calibrated to give the speed in desired units such as RPM.

Two main drawbacks of this are that the mechanical weights have inertia and hence not very accurate and secondly it does not give an indication of the direction of rotation.

a. Start-up Speed –
This is the speed at which the rotor and blade assembly begins to rotate.

b. Cut-in Speed –
Cut-in speed is the minimum wind speed at which the wind turbine will generate usable power. This wind speed is typically between 7 and 10 mph for most turbines.

c. Rated Speed –
The rated speed is the minimum wind speed at which the wind turbine will generate its designated rated power. For example, a "10 kilowatt" wind turbine may not generate 10 kilowatts until wind speeds reach 25 mph. Rated speed for most machines is in the range of 25 to 35 mph. At wind speeds between cut-in and rated, the power output from a wind turbine increases as the wind increases. The output of most machines levels off above the rated speed. Most manufacturers provide graphs, called "power curves," showing how their wind turbine output varies with wind speed.

d. Cut-out Speed –
At very high wind speeds, typically between 45 and 80 mph, most wind turbines cease power generation and shut down. The wind speed at which shut down occurs is called the cut-out speed, or sometimes the furling speed. Having a cut-out speed is a safety feature which protects the wind turbine from damage. Shut down may occur in one of several ways. In some machines an automatic brake is activated by a wind speed sensor. Some machines twist or "pitch" the blades to spill the wind. Still others use "spoilers," drag flaps mounted on the blades or the hub which are automatically activated by high rotor rpm's, or mechanically activated by a spring loaded device which turns the machine sideways to the wind stream. Normal wind turbine operation usually resumes when the wind drops back to a safe level.

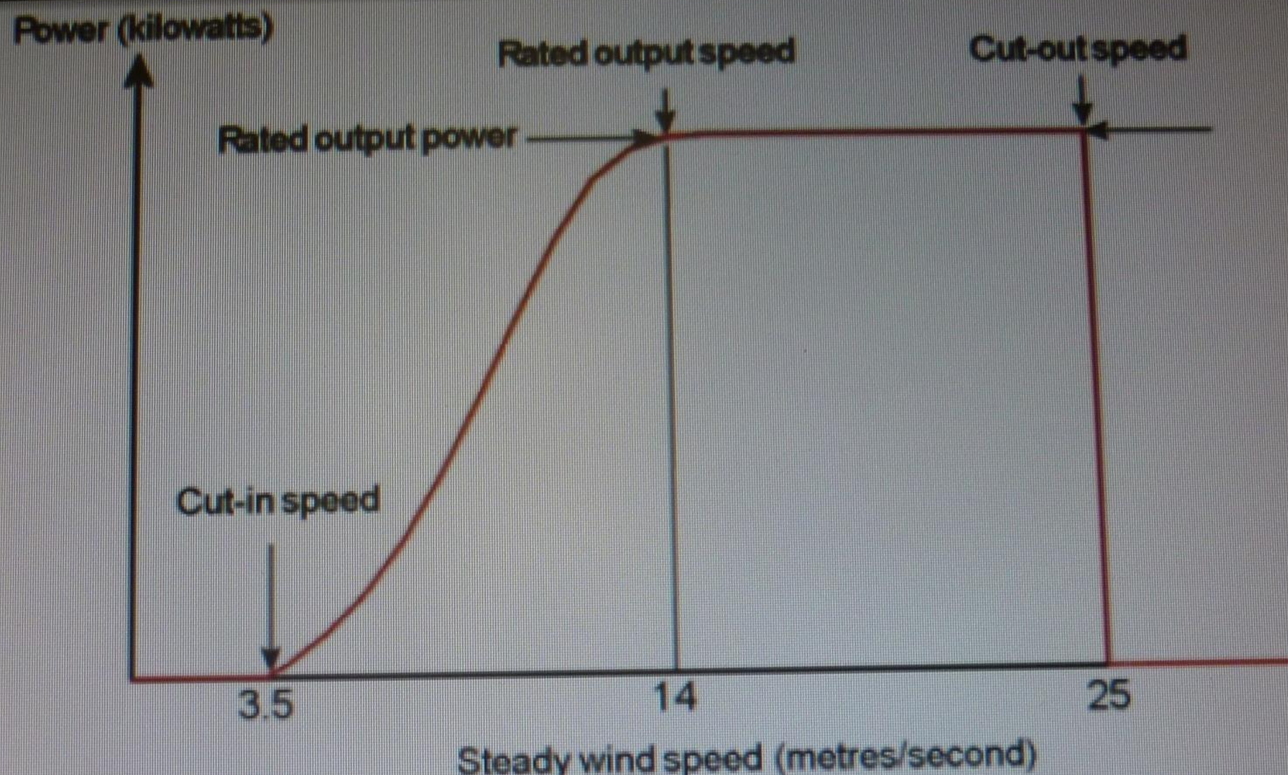

Figure 5.13 Wind speeds for a wind turbine

6 Worked Examples

Worked Example 6.1

The table below summarises the data for a wind turbine to be installed. Determine the annual power output for this turbine on this particular site.

Set	Wind Speed (m/sec)	Turbine Output (kW)	No of hours per year at given wind speed
(a)	(b)	(c)	(d)
1	4	2	1100
2	5	4	1100
3	6	6	1000
4	7	8	900
5	8	10	800
6	9	10	600
7	10	10	400
8	11	10	300
9	12	10	200
10	13	10	100

Solution:

First calculate the power output for each speed group, and then add them up as shown below. Hence the annual output is calculated as 43.8 MWh per year

Set	Wind Speed (m/sec)	Turbine Output (kW)	No of hours per year at given wind speed	Power output kWh (c x d)
(a)	(b)	(c)	(d)	(e)
1	4	2	1100	2200
2	5	4	1100	4400
3	6	6	1000	6000
4	7	8	900	7200
5	8	10	800	8000
6	9	10	600	6000
7	10	10	400	4000
8	11	10	300	3000
9	12	10	200	2000
10	13	10	100	1000
				43800

Worked Example 6.2

If the average wind speed of 10 mph which yields 100 watts per square meter, Determine the power produced by a wind mill when the wind speed is 40 mph.

Solution:

The change in wind speed means that wind blows at the ratio of

(40/10 = 4) times

Since the power is proportional to wind speed to power 3,

Hence an increase in wind velocity of 4 times, implies that the power will be increased by a factor of:

$4^3 = 64$

Therefore, if a 10 mph wind gives you 100 watts

Then a 40 mph wind gives you 64 times more power

=64x100 = 6400 watts

= 6.4 kW.

Worked Example 6.3

The following specifications for two HAWT are supplied by the manufacturers.

Item	Turbine A	Turbine B
Rotor diameter	25m	28m
Power coefficient	38	35
Gearbox efficiency	90	88
Generator efficiency	98	95
Capital cost	£99,000	£103,000
Maintenance cost/year	£4,000	£4,000

a. draw up a table for the performance of each turbine for wind speeds 4-12 m/s in intervals of 2 m/s
b. Assume the site wind availability to be 2000 hours per year, and average wind speed of 6 m/s, select the wind turbine which will be most economical. Assume life expectancy for each to be 20 years, and the unit cost of power to be 6 pence per kWh to remain constant.

Solution:

(a)The shaft power of a wind rotor is given by:

$$P = C_p * 1/2 * \rho * A * V^3 * \eta_{gb} * \eta_{gen}$$

Wind speed m/s	Turbine A Power (kW)=98.713V³	Turbine B Power(kW)=108.101V³
4	6.317	6.918
6	21.322	23.350
8	50.541	55.348
10	98.713	108.101
12	170.576	186.799

(b) at 6 m/s, Turbine B, produce more power

The annual difference = (23.350-21.322)x2000 = 4056 kWh
Cost difference over 20 years = 4056x0.06x20 = £4867

Hence Turbine B is chosen even though it is £4000 more expensive to buy than A, with a net saving of £867.

8.3 Energy and power in the wind

Kinetic energy of the wind is $\frac{1}{2}\left[\text{mass}\cdot(\text{velocity})^2\right]$ (8.1)

If ρ = density of air, V = relative velocity of the wind and A = flow - swept area through which the wind stream passes, then the mass flow rate of air is ρAV. Hence the kinetic energy from equation (8.1) is rewritten as:

$$P_w = \frac{1}{2}\rho A V^3 \qquad (8.2)$$

Note that this is the ideal power available (P_w), in the wind. Only a fraction of this power can actually be extracted, because of losses that incurred in the energy conversion process.
Useful power which can be extracted by the turbine rotor is given by multiplying the available power by a coefficient of performance C_p for the particular turbine. C_p has a maximum theoretical value of 0.593 (Betz' law). Other losses incurred in conversion through the gearbox and generator..
Thus the actual power output ($P_{w/t}$) of a wind turbine rotor is:

$$P_{w/t} = C_p \cdot \eta_{gen} \cdot \eta_{gb} \cdot \frac{1}{2}\rho A V^3 \qquad (8.3)$$

η_{gen} = generator efficiency (50% for car alternator, 80% or possibly more for a permanent magnet generator or grid-connected induction generator)

η_{gb} = gearbox / bearings efficiency (depends, could be as high as 95% if good)

The wind variation for a typical site is usually described using the so-called Weibull distribution. The Weibull distribution represents a mathematical distribution which resembles the distribution of different wind speeds throughout the year. It's a statistical model that gives the probability of occurrence. The basic equation is:

$$p(U) = \frac{k}{C} \cdot \left[\frac{U}{C}\right]^{k-1} \cdot \exp\left\{-\left[\frac{U}{C}\right]^{k}\right\} \qquad (8.4)$$

The Rayleigh distribution is a special case of the Weibull distribution in which the shape factor $k = 2$. Thus the Rayleigh equation is:

$$p(U) = \frac{\partial \cdot U}{2 \cdot v^2} \cdot \exp\left[-\frac{\partial \cdot U^2}{4 \cdot v^2}\right] \qquad (8.5)$$

Where v is the annual average wind speed at hub height h above ground level.

Wind turbine manufacturers often present performance figures for their machines using the Rayleigh distribution.

Figures 8.1, and 8.2 depict two different Rayleigh distributions for two different values of wind speeds (3 and 8 m/s respectively).

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Figure 8.1: wind speed v = 3 m/s

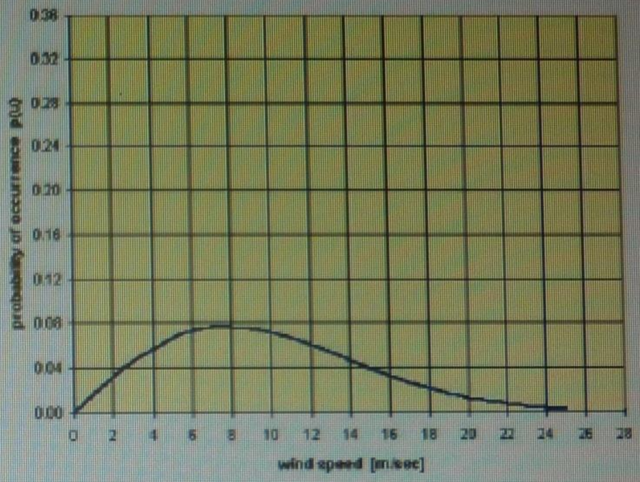

Figure 8.2: wind speed v = 8 m/s

8.4 Estimating the Annual Energy Output (A.E.O.)

wind speed frequency = 8760 x p(U) in [hours/yr] (8.6)

Then the wind speed frequency is matching with the power curve to estimate the Annual Energy Output (AEO). Thus:

(AEO) = power x wind speed frequency in [kWh/yr] (8.7)

Finally the total annual energy output (AEO) is calculated by summing the energy produced (kWh/yr) at all wind speeds within the operating range of each wind turbine, and divining by 10^6 to get results in [GWh/yr]

$$\text{Total (AEO)} = \sum \frac{(\text{AEO})}{10^6} \quad \text{in [GWh/yr]} \qquad (8.8)$$

8.5 The Software Package

The aim of this study is to present a software package especially written using the Microsoft Excel program for Windows. The user is able to use the availability of wind energy on a given site under given wind conditions in order to evaluate the pattern and amount of energy possible to collect at any time during the year.

However, this software has the ability to examine any given site throughout the U.K.

In this software package there is available a database, of seven (7) different manufacturers and twenty eight (28) different models of various sizes covering a wide range from 0.5 kW to 2500 kW.

Finally, the software package is quite friendly to the user because requires just 5 simple steps before the user can get the desirable output.

At the sheet named 'Calculations', [Figure 8.3] the user should enter the following inputs:

1. the annual average wind speed u at standard height z = 10 m
2. the index a which is a parameter relative to surface roughness
   The user can find a Table indicating the values to be expected to certain types of terrain at the sheet named 'Help Menu'.
3. the hub height h. In this software package there are available eight different values of height h i.e. h = 10 m, 20 m, 30 m, 40 m, 50 m, 60 m, 70 m, 80 m.
   Height requirements for medium and large wind turbines are 20 - 80 m.
   Height requirements for small wind turbines are up to 20 m.
4. the name of the manufacturer
5. the name of the model
   In this software package there is available a database of seven different manufacturers and twenty eight different models of various sizes (from 0,5 kW - 2500 kW)

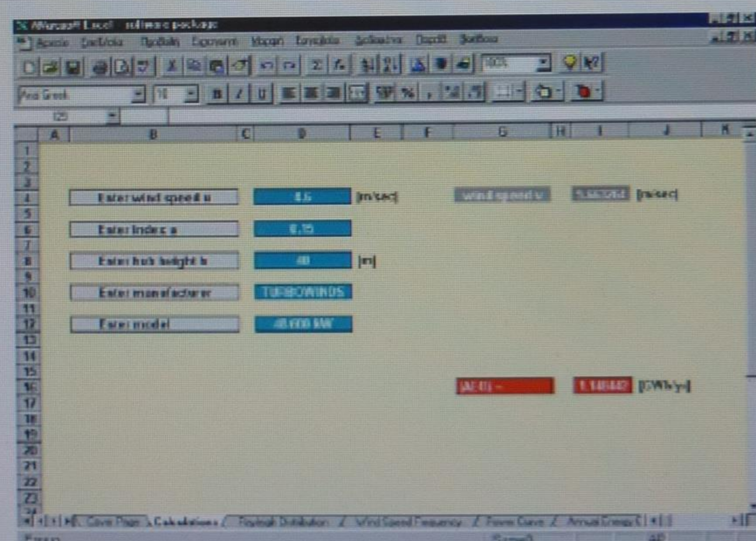

Figure 8.3: Main menu

Figure 8.3: Main menu

The user then get the following output:

1. the annual average wind speed v at hub height for the above 8 different values of height h
2. the total Annual Energy Output (AEO) in [GWh/yr]

The 'Rayleigh Distribution', [Figure 8.4] shows a graph of a mathematical distribution called the Rayleigh distribution which resembles the distribution of different wind speeds throughout the year.

The 'Wind Speed Frequency', [Figure 8.5] is showing the number of hours for which the wind blows at different wind speeds, during a given period of time.

The 'Power Curve', [Figure 8.6] displays the values of instantaneous power in [kW] given from manufacturers for each model of the database of this software package.

The 'Annual Energy Output', [Figure 8.7] graph displays values of energy in [kWh/yr] for all the wind speeds in the range of 0 - 25 m/sec.

The 'Wind Speed Vertical Profile', is shown in [Figure 8.8].

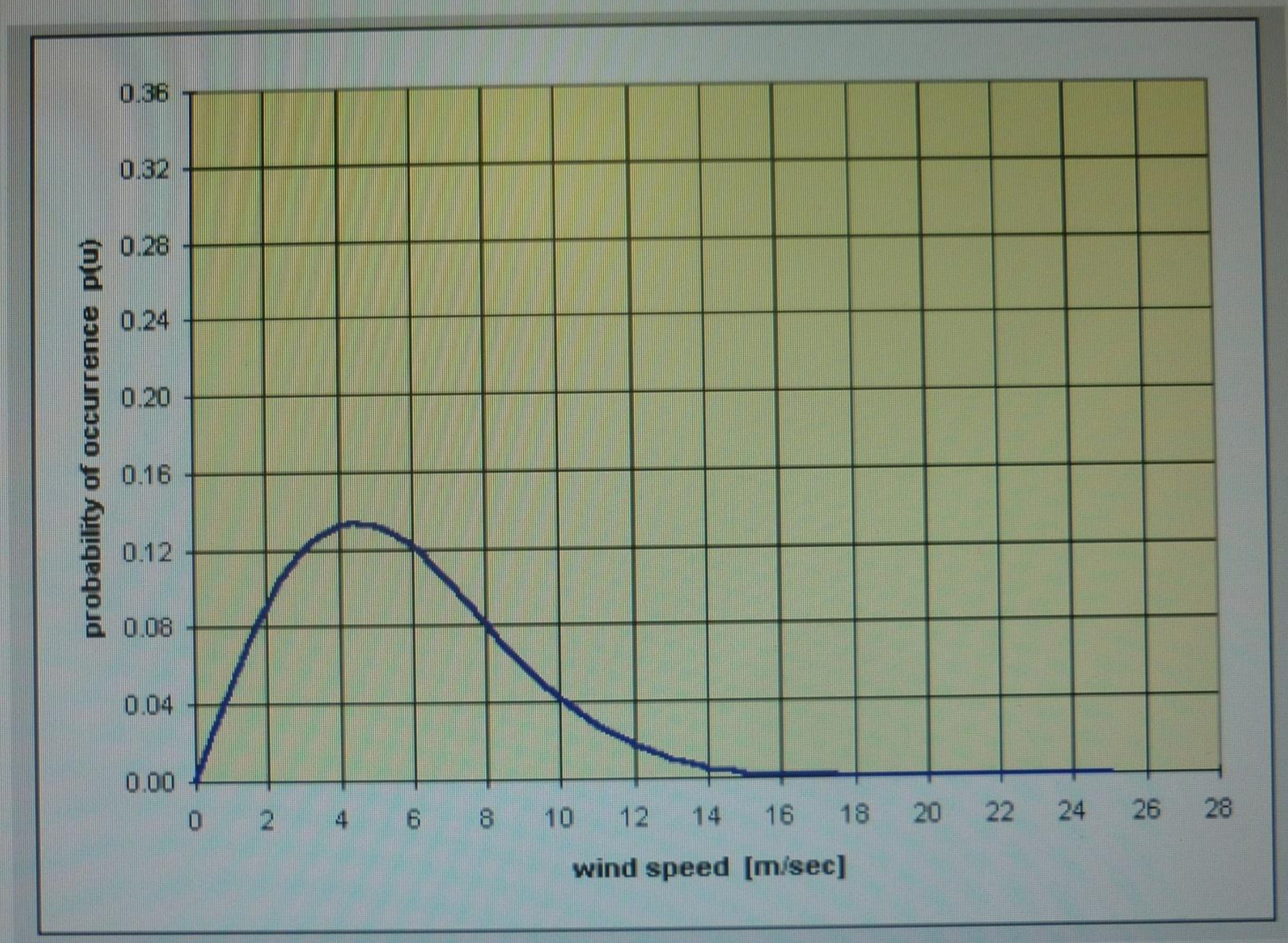

Figure 8.4: The 'Rayleigh Distribution'

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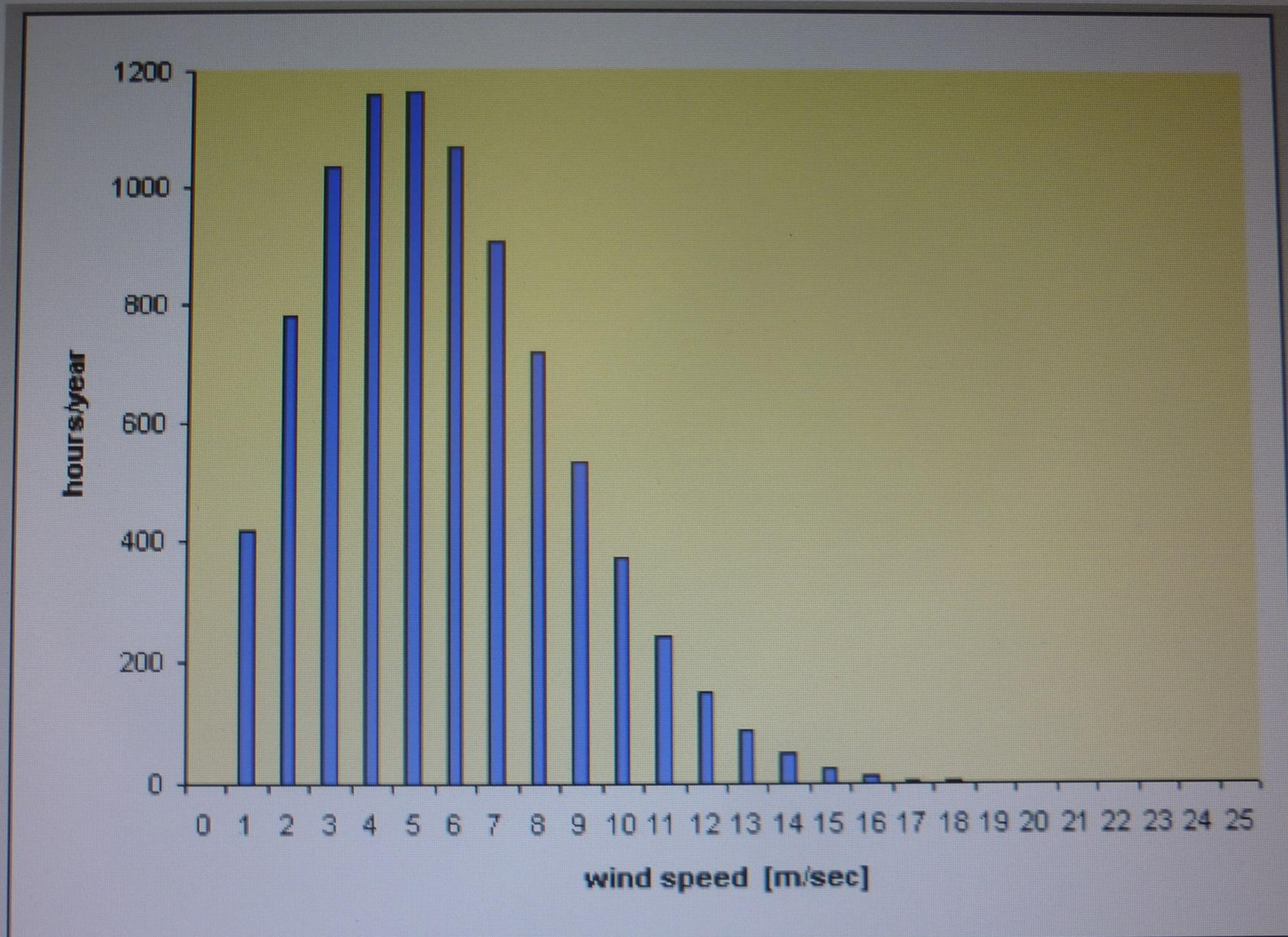

Figure 8.5: The 'Wind speed frequency' menu

Figure 8.6: The 'Power curve' menu

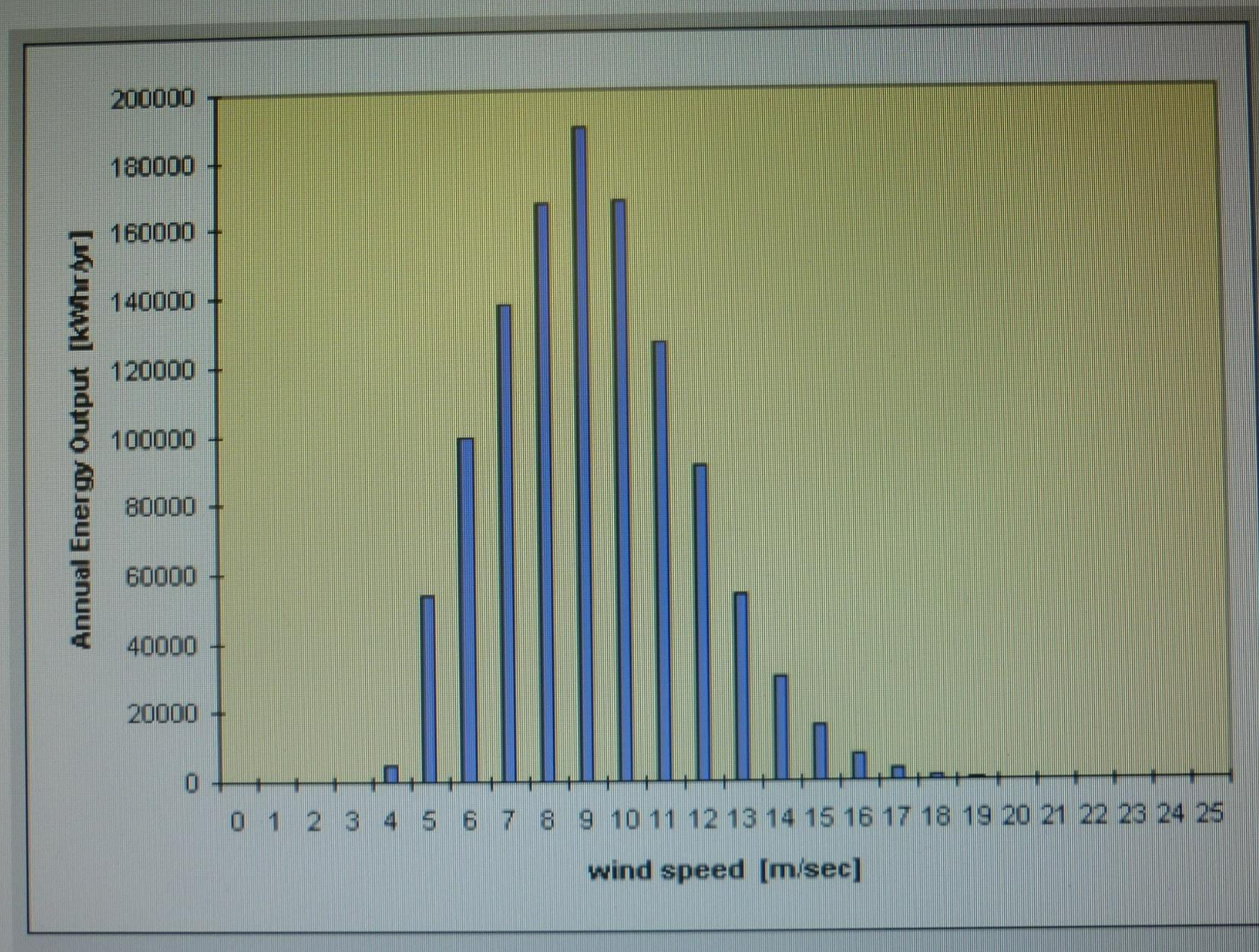

Figure 8.7: The (A.E.O.) menu

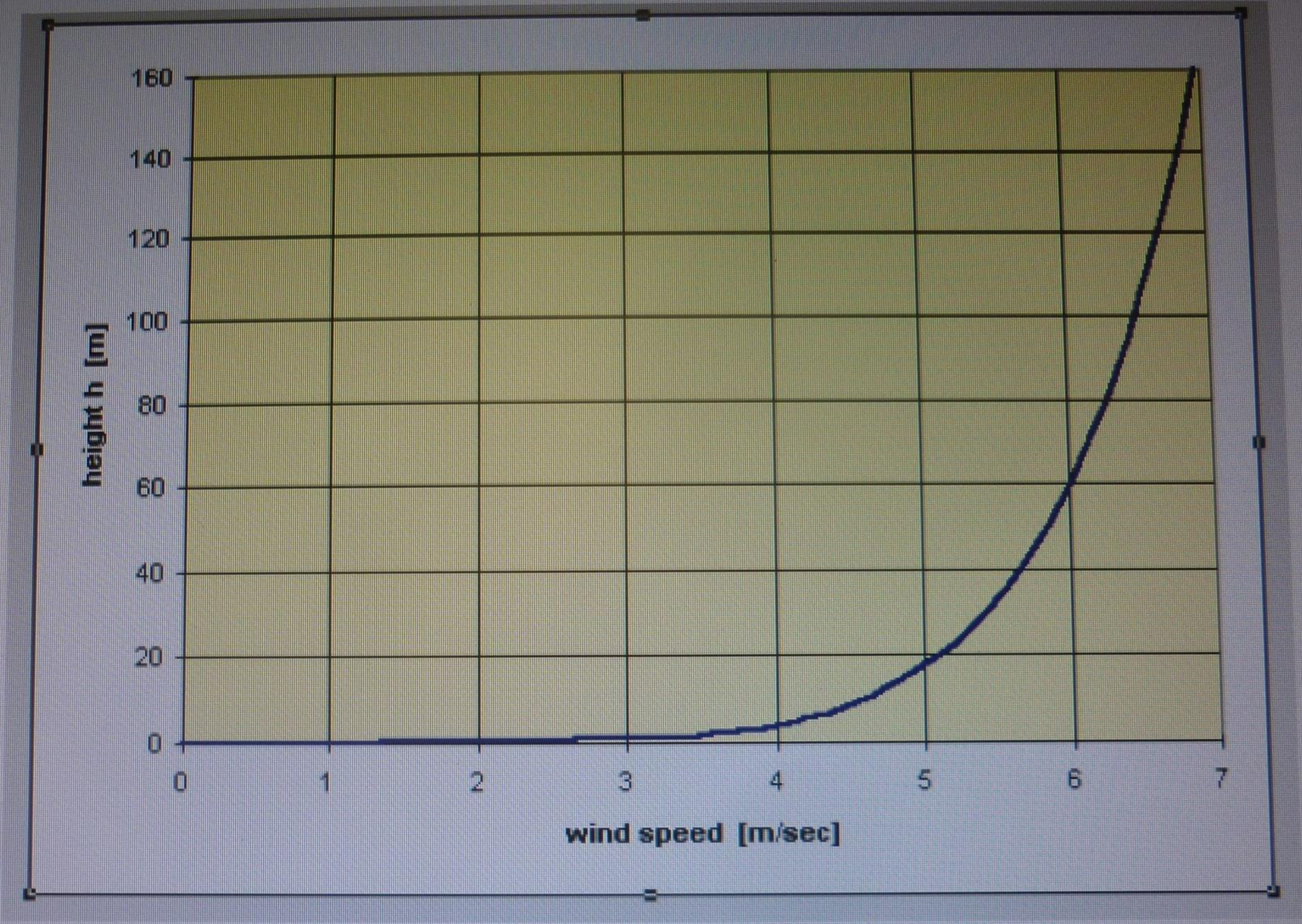

Figure 8.8: The 'Wind speed vertical profile'