SMALL WIND TURBINE: POWER CURVES AND ANNUAL ENERGY OUTPUT

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Abstract. *Currently, there are many manufacturers for small wind turbine machines. To size a system it is necessary to have available the power output curve of these machines. Here we present a recompilation of 23 machines available commercially from different manufacturers from North America and Europe. The turbines were studied according to their nominal power output in three groups: turbines with a power output ranging from 25 to 280W, turbines with power output from 400W to 1500W and turbines with power output from 2500W to 10kW. To each one of the turbines, the power output curve was adjusted with polynomial expressions. The energy generated by the machines for different wind speeds is presented. Simplified models with analytical expressions that allow to determine the energy of these machines are presented as well. The results presented by the 23 machines permitted to help the users with the choice of the machine that best adapts to their energy demand. To compare the quality of the machines, the concept of specific energy, which substitutes the conventional concept for power pattern factor, was used.*

Keywords*. Renewable Energy, Small Wind Turbine, Wind Turbine Power Curve, Energy Output.*

1. Introduction

The Small Wind Turbines (SWT) are a great option for supplying energy in small scale especially in remote areas without utility power. It is, therefore, an option that is fundamental for developing countries such as Brazil. Currently, there are about 200.000 units available worldwide (AWEA,2001) in Mongol (China), where more than 100.000 small wind generators are employed for domestic use in Europe where they are employed for tourism purposes mainly in boats and camping. At the present time, there are around 50 manufacturers for small wind turbines around the world with 100 different models of turbines (Gipe,1993). To the sizing of the system it is fundamental that the manufacturer supplies the power output curve for the models they make. With such information the energy output necessary to the sizing of wind systems can be estimated. The simplified methods for the sizing of the systems as well as the method that employs the power output curve supplied by the manufacturer are presented in this work. 23 models from different manufacturers included in a power output range from 25 W to 10 kW were employed here.

2. Methodology

To the sizing a wind system it is fundamental to determine the amount of energy generated by the wind turbines. Several methods are possible to be employed (Balouktsis et all., 2002). For this research, the three methods described below were employed to determine the annual energy output generated by the small wind turbines.

(A) Power Density Method

- In this method the *Annual Energy Output* (AEO) Eq. (4) is obtained by employing the power density *(DP)* which depends on de average wind speed *(Vm)* and the energy pattern factor *(Ke)*. It is necessary to adopt a global conversion efficiency rate for the turbine *(η)* and take into consideration the diameter of the rotor to determine the area swept by the turbine *(A).* This procedure is called the simplified method.

$$AEO \Rightarrow \phi\{V_m, Ke, A, \eta\} \quad (1)$$

For the present work it was determined an AEO for a SWT from 25W to 10kW. The results show an AEO for this range of turbines considering an average wind speed between 4.0 to 7.0m/s.

(B) Analytical Average Power Output Method

- This method (Powell,1981) determines the AEO using a function that represents the power output curve for the turbine together with a Rayleigh distribution function. Here, it is necessary to define the annual average wind speed *(Vm)* and the project speeds for the turbine: cut-in wind speed *(Vin)*, nominal speed *(Vr)* and cut-out wind speed for that turbine *(Vco).*

$$AEO \Rightarrow \phi\{P(V)_{analytical}, f(V)\} \quad (2)$$

Here we employ this method in two ways:
(1) Assuming a analytical *P(V)* with the same project wind speeds in all turbines.
(2) Employing analytical *P(V)* with different project wind speeds from commercial turbines.
Both results show an AEO for the turbines from de 25W to 10kW considering areas with annual average wind speed ranging from 4.5 to 7.5m/s.

(C) Manufacturer Output Power Curve Method
• For this method 23 commercial turbines are selected after the characteristic power output curve for each one of them is adjusted. The AEO for the 23 machines is obtained by employing the Rayleigh distribution for the annual average wind speeds from 4.0 to 7.0m/s.

$$AEO \Rightarrow \phi\{P(V)_{Manufacturer}, f(V)\} \quad (3)$$

2.1. Power Density Method

It is a simplified method (Gipe, 1993) which employs the power density and the global conversion efficiency of the machine to determine e annual energy output generated:

$$AEO = DPA_t \eta_G T \quad (4)$$

Where A_t is the area swept by the turbine *(πR^2)*, η_G is the global conversion efficiency of the turbine which ranges from 15 to 30%. *T* represents the number of hours in a year (*T*=8760h). The *DP* term represents the power density (W/m^2) given here as:

$$DP = \frac{1}{2}\rho k_e \overline{V}^3 \quad (5)$$

Where ρ is the air density (1,223 kg/m3); k_e is the energy pattern factor, which depends on the local distribution of speed. For the Rayleigh distribution k_e =1,9. Fig 1. and Fig.2 show de AEO obtained with this method using η_G =23% , k_e =1,9 and average wind speed between 4.5 to 7.5m/s.

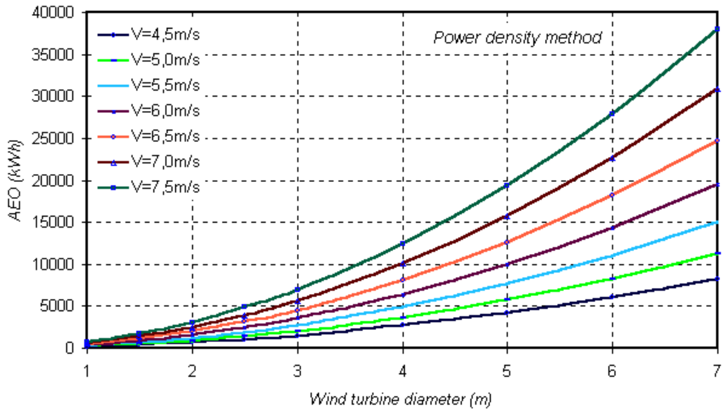


Figure 1. Power density method - AEO for different diameter

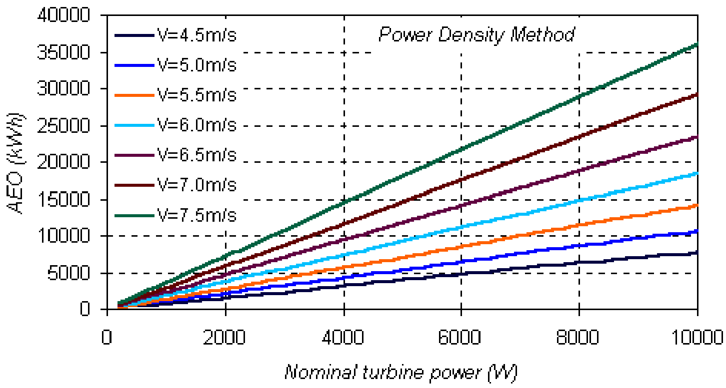


Figure 2. Power density method - AEO for different nominal power

2.2. Analytical Average Output Power Curve Method

In this method (Powell, 1981) the annual energy output is given by:

$$AEO = \overline{P}T \tag{6}$$

T is the number of hours in a year (T=8760h) and $\overline{P}$ is the average power output represented by:

$$\overline{P} = \int_{Vci}^{Vco} P(V)\, f(V) dV \tag{7}$$

The average power output can be obtained by employing an analytical expression for the power output curve of the turbine *P(V)* . For the speed distribution function *f(V)* the Rayleigh distribution is adopted. By doing so we have:

$$\overline{P} = P_r \left[\frac{\left\{ \exp(-v_{ci}^2) - \exp(-v_r^2) \right\}}{\left(v_r^2 - v_{ci}^2 \right)} - \left\{ \exp(-v_{co}^2) \right\} \right] \tag{8}$$

where *Pr* is rated power, V_r is the nominal wind turbine speed; V_{ci} is the cut-in wind speed and V_{co} is the cut-out wind speed. These speeds are represented in a non-dimensional form employing the average speed.

$$v_{ci} = \frac{V_{ci}}{\overline{V}} \sqrt{\frac{\pi}{4}} \qquad v_r = \frac{V_r}{\overline{V}} \sqrt{\frac{\pi}{4}} \qquad v_{co} = \frac{V_{co}}{\overline{V}} \sqrt{\frac{\pi}{4}} \tag{9}$$

Figure (3) show de AEO obtained with this method assuming the same machine project speeds in all turbines *Vci*=4,0m/s *Vr*=12,5m/s and *Vco*=22m/s. This values represent the mean of the SWT manufacturers design velocities.

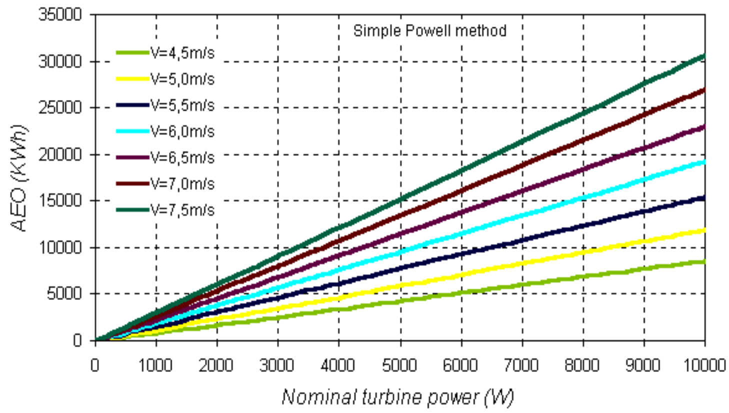


Figure 3. Analytical Average Output Power Curve Method - AEO

3. Manufacturer Output Power Curve Method

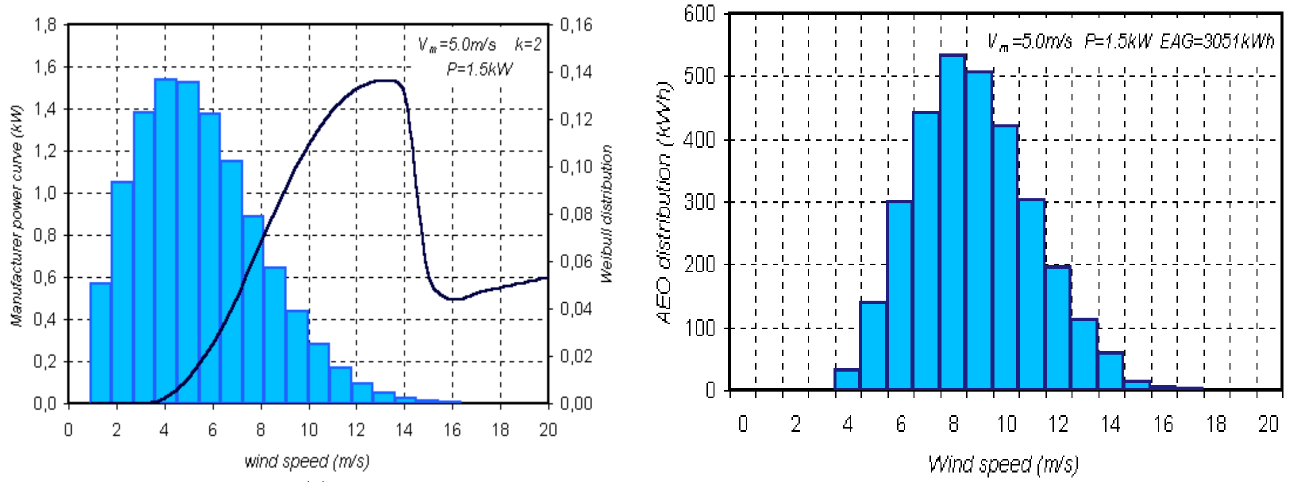
The annual energy output (AEO) is one of the main information that can be determined by identifying the average annual energy output supplied by the turbine. We can represent this energy by the following expression:

$$AEO_{manuf} = \overline{P}_{manuf} T \tag{10}$$

where T is the number of hours in a year (T=8760h) and $\overline{P}$ is the average power output given by:

$$\overline{P}_{manuf} = \int_{Vci}^{Vco} P(V)_{adjusted}\, f(V) dV \tag{11}$$

P(V) represents the power output curve of the turbine. *f(V)* represents the function of distribution of the wind speed. *Vci* is cut-in wind speed and *Vco* is cut-out wind speed. Figure (4) show the typical *P(V)* of a small wind turbine and the typical curve of the speed distribution *f(V)*. Figure (5) shows the result of the method obtaining the annual energy output for the turbine.



(a) (b)

Figure 4. (a)Probabiliy density function of the wind speed and turbine power curve; (b) Annual energy output example.

3.1 Commercial Small Wind Turbines

To study the behavior of small wind turbines, catalogues and information available on internet in the manufacturers' and retailers' websites were employed. The main information employed was nominal power output, nominal speed, nominal rotation, rotor diameter and number of blades. Here we selected 23 turbines Tab. (1) that presented the same characteristics of the turbines that were commercialized. Figure (6) show the results of the efficiency and diameter of the selected wind turbines.

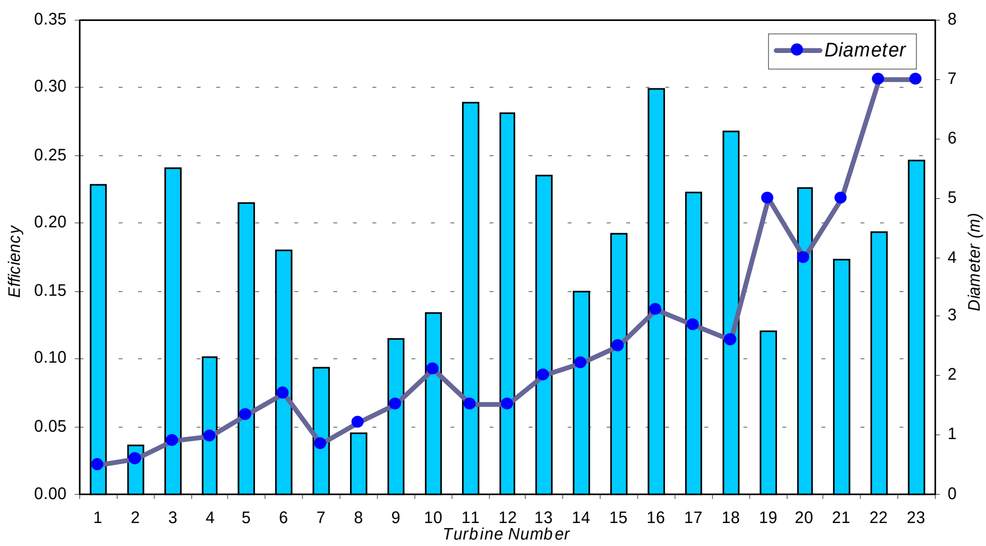
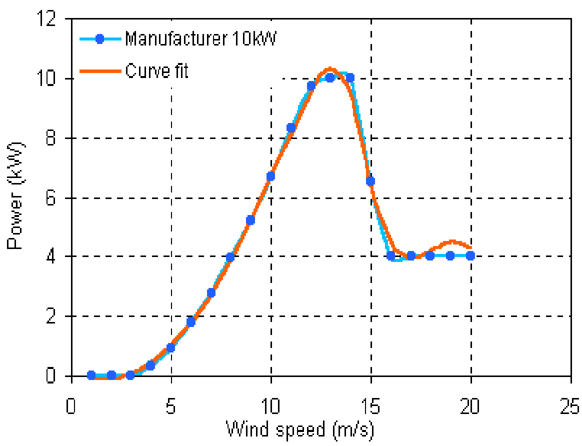


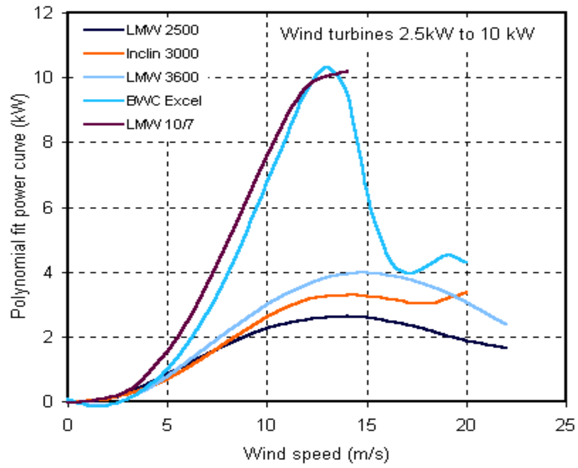
Figure 6. Efficiency and diameter for small wind turbines

3.2 Power Output Curve Adjustment

The manufacturer's power output curves were adjusted by employing the CurveExpert 1.3™ application. The program employs interpolation techniques and linear and non-linear regression models. The interpolation guarantees that the adjusted curve passes by all the points of the inserted data. The regression simply asserts that the difference between the adjusted function and the data is minimum. The program automatically selects the models that best approximated to the original curve data. In Fig. (7a) show an example of the quality of the polynomial adjustment. Figure (7b) show the results obtained for others adjusted curves for the commercial turbines studied.



(a)



(b)

Figure 7. Manufacturer power curve – (a) fit curve example, (b) fit power curve for small wind turbines.

Table 1. Show the coefficients of adjustment for the manufacturer power output curve.

	Turbinas		***Coefficients***						
			$P(V)\cdot 1000 = a_0 + a_1V + a_2V^2 + a_3V^3 + a_4V^4 + a_5V^5 + a_6V^6$						
	Name	Rated power (W)	a_0	a_1	a_2	a_3	a_4	a_5	a_6
1	Rutland 503	25	163,636	-1543,969	494,351	-13,087	-	-	-
2	Aero2Gen*	50							
3	Rutland 913	90	-138,528	-1801,267	1162,128	-26,885	-	-	-
4	Aero4Gen-F	140	0,281	-7,436	2,710	-0,179	0,004	-	-
5	Inclin 250	250	-0,802	4,609	-3,943	1,671	-0,161	0,006	-0,0001
6	LMW 250	250	2,780	-32,622	6,686	1,449	-0,138	0,003	-
7	Aero4Gen	280	0,224	-5,135	1,793	-0,074	0,001	-	-
8	Aero6Gen-F*	280							
9	Aero8Gen-F	280	0,042	1,484	-2,117	0,872	-0,047	-	-
10	AIR 403	400	-4,793	21,241	-7,842	1,229	-0,042	-	-
11	Windseeker 502	500	-85,459	111,091	-43,264	7,644	-0,569	0,019	-0,0002
12	Windseeker 503	500	-85,459	111,091	-43,264	7,644	-0,569	0,019	-0,0002
13	Inclin 600	600	17,425	-76,678	29,430	-2,171	0,048	-	-
14	LMW 600	600	5,001	-50,824	17,575	-0,970	0,015	-	-
15	LMW 1000	1000	2,780	-32,622	6,686	1,449	-0,138	0,003	-
16	LMW 1003	1400	9,799	-83,689	34,431	-2,038	0,035	-	-
17	Inclin 1500	1500	-8,689	-34,491	26,600	0,020	-0,152	0,005	-
18	BWC 1500*	1500							
19	LMW 2500	2500	-22,436	-67,341	72,219	-5,358	0,108	-	-
20	Inclin 3000	3000	-14,904	-3,090	9,070	7,280	-0,743	0,019	-
21	LMW 3600	3600	4,006	-263,829	117,596	-7,453	0,131	-	-
22	BWC Excel*	10000							
23	LMW 10/7	10000	-46,139	-4,186	6,885	16,118	-0,918	-	-

(*) The adjustment of the power curve of these turbines is different of the polynomial majority, therefore more information can be found at Alé, Hilbig (2002).

4. Results

In tab. (2) the results of the AEO are shown employing the adjustment of the manufacturers' power output curves using a Rayleigh distribution for annual average speeds from 5.0m/s to 7,0m/s. We observe that machines with the same nominal power output supply different amounts of energy. The results show that the simplified models underestimate the energy that the turbines can supply.

Table 2 - Annual Energy Output - AEO (KWh/year) for different nominal power

V=5m/s	***25W***	***250W***	***500W***	***1000W***	***1500W***	***3000W***	***10000W***
Manufacter Power Curve	46	609	694	2434	3999	7446	18749
Power Density Method	27	266	533	1065	1598	3196	10652
Powell Method (*)	30	297	594	1188	1782	3564	11880
V=6 m/s							
Manufacter Power Curve	73	877	1041	3468	5313	10131	26662
Power Density Method	46	460	920	1841	2761	5522	18407
Powell Method (*)	48	481	962	1924	2887	5773	19244
V=7 m/s							
Manufacter Power Curve	102	1129	1405	4470	6495	12610	33685
Power Density Method	73	731	1461	2923	4384	8769	29230
Powell Method (*)	67	673	1347	2693	4040	8079	26931

(*) Powell Method is the analytical average output power curve method

Figure (8 to 10) show the results of the AEO employing the adjustment of the manufacturers' power output curves using a Rayleigh distribution for annual average speeds from 4.0m/s to 7,5m/s

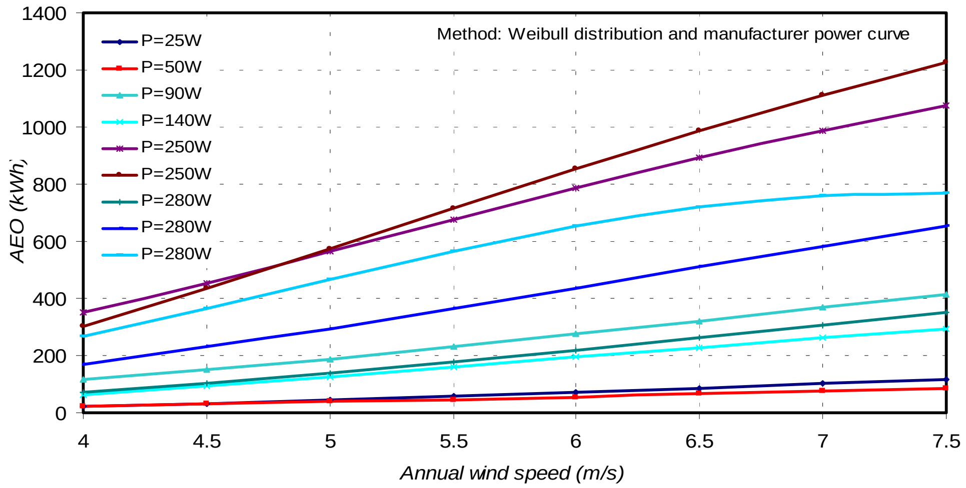


Figure 8. Annual energy output - 25W to 280W

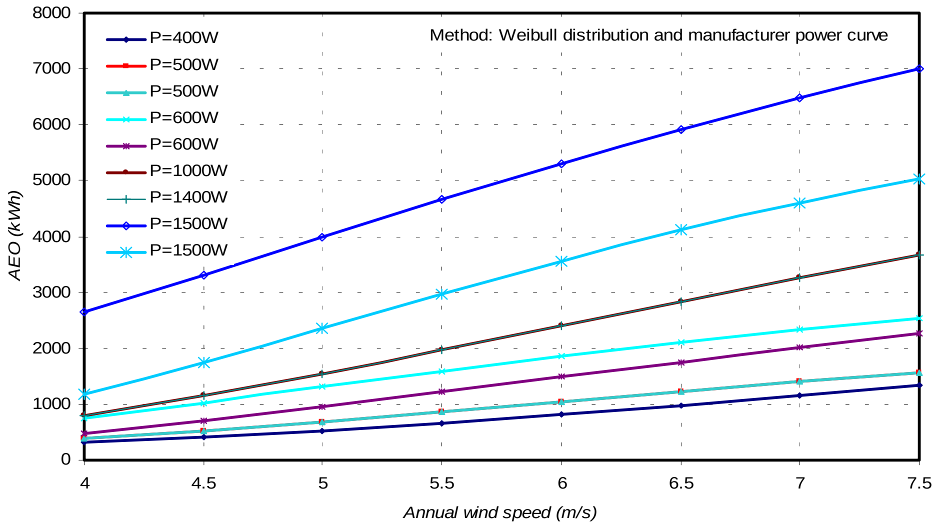


Figure 9. Annual energy output - 400W to 1500W

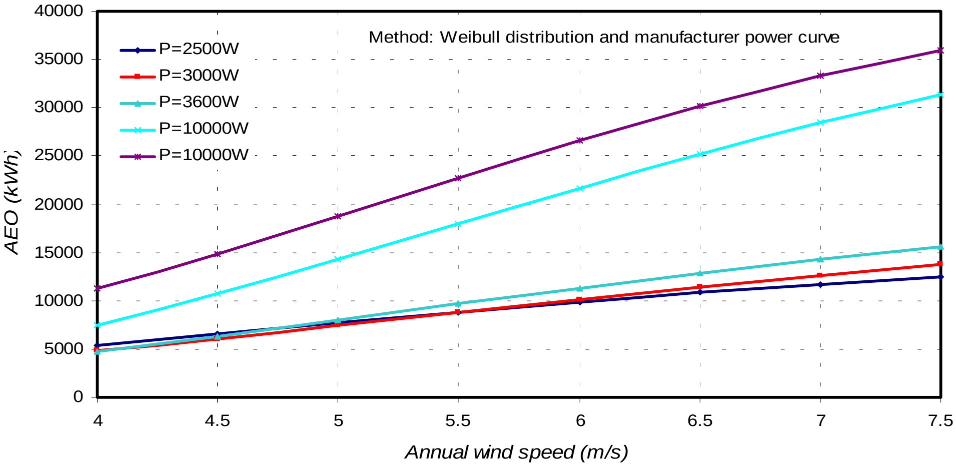


Figure 10. Annual energy output - 2500W to 10kW

4.1. Specific Energy of the Turbines

To study the performance of hydroelectric and thermoelectric plants we adopt the capacity factor concept *(Fc)* that relates the annual energy output to the energy that could be generated in the nominal power output of the machines. Such concept has also been adopted in the wind turbines (Cavallo, 1997) however, this factor does not represent effectively the quality of the energy output by the wind conversion systems since the available wind energy cannot be considered a conventional firm energy. Here we have adopted, as a parameter, to study the quality of the machines from different manufacturers, the so called specific energy. Such concept relates the annual energy output divided by the area swept by the turbine.

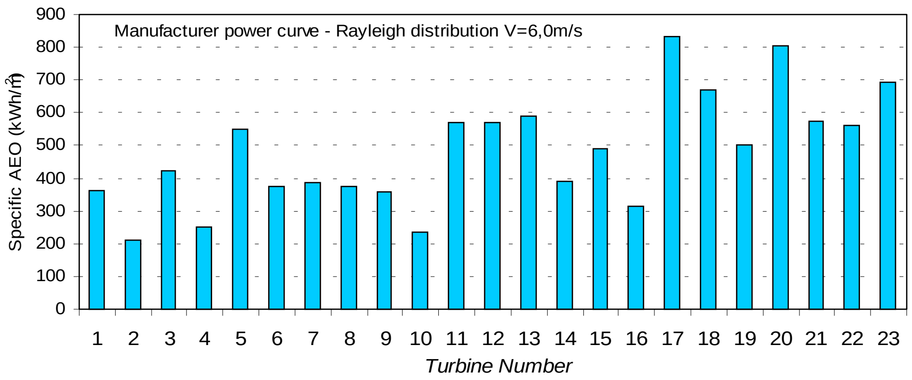


Figure 11. Specific energy for different nominal power output

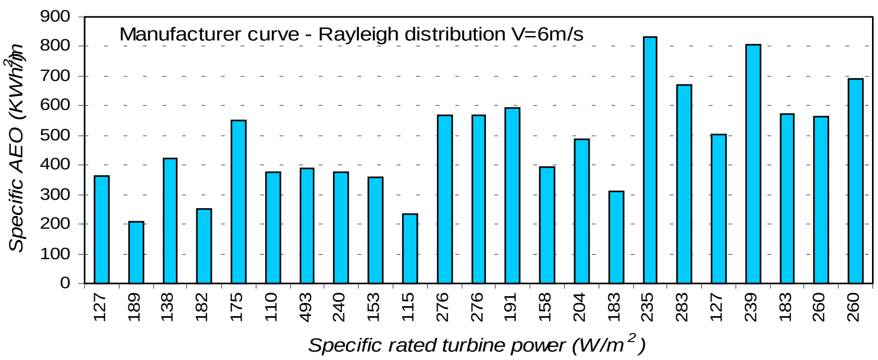


Figure 12. Specific energy for different specific power output

In Fig.(11) and Fig.(12) show that machines with the same nominal power present a different specific energy. This is a good procedure that allows to determine the quality of the machines presented by the various manufacturers that could have the same nominal power output.

5. Conclusions

Here we presented three models that allow to determine the energy generated by small wind turbines. The results show that the most simplified models underestimate the energy that the turbines can supply. It emphasizes the importance of counting with the manufacturer's curve to have the appropriate sizing of the small wind systems. In the research the curves of the manufacturers' turbines were adjusted. Some of the adjusted curves must be improved in order to approximate them to the original manufacturer's curve so as to better represent the energy generated by the turbine. The results also show that wind turbines with the same nominal power output present different performances. In a preliminary selection it cannot be easily detected by a user, running the risk to select a less efficient machine. The representation of the specific energy as a parameter to evaluate the quality of the wind systems is shown to be adequate to substitute the traditional concept of the capacity factor. The tables and graphics shown here make it easier for the users to choose the airgenerators that best adapt to their energy demand.

6. Acknowledgement

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