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Electricity generation using wind energy conversion systems in the area of Western Greece

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Abstract

Weibull parameters estimated by three different methods at four weather stations in the area of central Western Greece were used to estimate wind power potential in this area. A linear correlation was observed between the above mentioned parameters and the measured mean wind speed values. Additionally, analysis of the "unit energy cost", being the specific cost per kilowatt hour, obtained for several wind turbines at different hub heights has been conducted for every station. Our analysis demonstrated that it is possible to profit from electricity generation in Missolonghi and Aktio, especially if larger wind turbines are to be used. The specific cost per kW h decreases as wind turbine size increases for comparable systems made by the same manufacturer with similar performance but with different rated power (size). The observed correlation between these parameters is hyperbolic with the greater decreasing rate in the less windy sites. Moreover, the cost per kilowatt hour increases with hub height due to the increasing tower cost.

Keywords: Wind energy conversion systems; Wind power density; Cost analysis; Specific cost per unit; Present value of costs

1. Introduction

Wind energy potential is not easily estimated because, contrary to solar energy, it depends on the site characteristics and topography to a large degree, as wind speeds are influenced strongly by local topographical features [1]. The classification and characterization of an area as of high or low wind potential requires significant effort, as wind speed and direction present extreme transitions at most sites and demands detailed study of spatial and temporal variations of wind speed values. Cost analysis of the power generated by wind energy conversion systems (WECS) is a rather difficult task requiring the estimation of output power generation as well as the cost of the WECS, apart from the analysis of the wind distribution parameters.

Output power generation of any WECS is closely related not only to the system's performance but also to operating conditions, which means the wind characteristics of the area as well. Furthermore, present values of each annual cost of the WECS must be estimated considering parameters such as inflation and interest rates.

Previous studies of wind energy potential in Western Greece [2–6] have given, generally, promising but widely divergent results due to the inadequate quantity of observations in many areas (three times a day only and no nocturnal observations) or to non-representative station sites leading to an unrealistic estimation of wind power observations [4]. Furthermore, evaluation of cost of electricity produced by WECS has never been performed in this area because of such reasons as indicated above (poor observations and inappropriate station sites) at some locations (i.e.

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Agrinio [4]) or absence of modern weather stations at some others (i.e. Missolonghi). It should be noted that in Missolonghi, a fully computerized automated weather station has been installed from which measurements have been used in the present study [7].

This study, mainly, focuses on the biggest prefecture of Greece, Aitoloakarnania, which lies between 38°16′ to 38°78′ N latitude and between 20°45′ to 22°03′ E longitude, with an area of 5500 km^2 and secondarily on Northwest Peloponnesus. All this area, which represents the central part of Western Greece, is characterized by extremely complex conditions due to its variable topography. The west sides of its territory face the Ionian Sea, with coasts of rather smooth relief. The development of sea breezes could affect the wind potential at these sites, as the Ionian Sea islands, Lefkada, Kefalonia and Zakynthos (Fig. 1), are relatively mountainous and constitute obstacles to W and SW deep sea winds. Patraikos Gulf (Fig. 1) forms a "tunnel" that influences strongly the wind flow because its coasts are mountainous. Several mountains also rise in the interior mainland, so wind conditions differ from site to site.

The present paper has as main objective to examine thoroughly the wind potential in the central part of Western Greece, as being an area with large differences in wind characteristics, even more between two neighbouring sites, by using the studied Weibull parameters of the area [8]. In addition, this study attempts an analysis of the economic viability of several WECS in order to estimate the most promising sites for electricity production in this area. Finally, it deals with the function that describes the variations of the specific cost per kW h as the rated power of the WECS and the hub height changes.

2. Wind characteristics

Studies in the past matched the Weibull distribution and experimental data well [9–14]. Consequently, the Weibull parameters estimated over measured data at Agrinio, Missolonghi, Aktio and Araxos meteorological stations [8] are used for our analysis. All four stations are installed in the area of Western Greece (Fig. 1).

The monthly and annual values of Weibull parameters were calculated using the following three different methods: (i) graphical least square regression method, (ii) relations of mean wind speed and standard deviation and (iii) maximum likelihood method, using a simple estimator. The average values from the above methods, being the most representative ones, are depicted in Table 1.

As scale and shape parameters for wind distribution in every selected site have been calculated, two significant wind speeds for wind energy estimation, the most probable wind speed and the wind speed carrying maximum energy,

Fig. 1. Map of Greece with the sites of the stations: 1. Agrinio, 2. Missolonghi, 3. Aktio and 4. Araxos station. PG, Patraikos Gulf.

Table 1
The three methods average values of the mean monthly Weibull parameters for the four experimental stations

	Agrinio		Missolonghi		Aktio		Araxos	
	k	c (m/s)	k	c (m/s)	k	c (m/s)	k	c (m/s)
January	1.78	1.46	1.65	3.27	1.71	4.53	1.25	3.00
February	1.91	1.78	1.47	4.18	1.77	4.64	1.25	3.15
March	2.18	1.28	1.32	3.92	1.63	4.80	1.25	3.11
April	2.00	1.48	1.41	4.13	1.63	4.36	1.35	2.55
May	2.04	1.28	1.41	3.61	1.62	4.26	1.32	2.71
June	2.05	1.14	1.55	2.80	1.60	4.56	1.39	2.52
July	1.80	1.15	1.50	3.08	1.55	4.46	1.35	2.50
August	1.75	1.25	1.49	2.79	1.59	4.25	1.33	2.52
September	1.91	1.16	1.48	3.31	1.63	4.12	1.34	2.46
October	1.97	1.24	1.32	3.02	1.78	4.10	1.27	2.73
November	2.07	1.41	1.38	3.84	1.79	4.65	1.28	3.29
December	1.88	1.56	1.28	3.90	1.81	4.80	1.28	3.26
Annual	1.89	1.35	1.37	3.50	1.66	3.87	1.41	3.12

can be easily calculated too. The most probable wind speed (v_{mp}), which represents the most frequent wind speed, is expressed by [15]

$$v_{\mathrm{mp}} = c\left(\frac{k-1}{k}\right)^{\frac{1}{k}} \tag{1}$$

The wind speed carrying maximum energy (v_{maxE}) is expressed as

$$v_{\mathrm{maxE}} = c\left(\frac{k+2}{k}\right)^{\frac{1}{k}} \tag{2}$$

The monthly and annual values of v_{mp} and v_{maxE} for the four stations are depicted in Table 2. It is worth noting that Aktio has the significantly highest annual value of v_{mp}, while Agrinio has the lowest one. This does not necessarily mean that Aktio has much higher wind potential than the other sites, as the most probable wind speed is a statistical characteristic not directly connected to wind energy. Moreover, Missolonghi has the highest annual value of v_{maxE} and Agrinio the lowest (classification of the sites according to v_{maxE} is not necessarily similar to the one according to v_{mp}). Finally, higher monthly values of v_{mp} and v_{maxE} are observed during winter, while lower ones are observed during summer. A similar condition characterizes the mean monthly values of wind speed [8].

3. Wind power densities

The instantaneous wind power available in a cross sectional area (A) perpendicular to a wind stream moving at speed v (m/s) with an air density ρ is expressed as follows [1]:

$$P = \frac{E}{\Delta t} = \frac{1}{2}\rho A v^3 \quad (\mathrm{W}) \tag{3}$$

The instantaneous wind power density (per unit area) can be written as follows:

$$P_{\mathrm{d}} = \frac{P}{A} = \frac{1}{2}\rho v^3 \quad (\mathrm{W\,m^{-2}}) \tag{4}$$

Consequently, the mean power density is calculated by

$$\langle P_{\mathrm{d}}\rangle = \langle \tfrac{1}{2}\rho v^3\rangle \quad (\mathrm{W\,m^{-2}}) \tag{5}$$

Wind power estimates have been based on the assumption that the air density is not correlated with wind speed. The error introduced by this assumption on a constant pressure surface is probably less than 5% [16,17]. So, the mean power density is calculated by

Table 2
Monthly and annual values of most probable wind speed (v_{mp}) and wind speed carrying maximum energy (v_{maxE})

	Agrinio		Missolonghi		Aktio		Araxos	
	v_{mp} (m/s)	v_{maxE} (m/s)	v_{mp} (m/s)	v_{maxE} (m/s)	v_{mp} (m/s)	v_{maxE} (m/s)	v_{mp} (m/s)	v_{maxE} (m/s)
January	0.92	2.23	1.86	5.29	2.71	7.13	0.83	6.44
February	1.21	2.59	1.92	7.50	2.90	7.11	0.87	6.77
March	0.97	1.73	1.34	7.88	2.68	7.84	0.86	6.68
April	1.05	2.09	1.72	7.73	2.43	7.13	0.94	5.00
May	0.92	1.79	1.50	6.75	2.35	7.00	0.93	5.45
June	0.82	1.59	1.44	4.78	2.47	7.57	1.01	4.79
July	0.73	1.74	1.48	5.42	2.29	7.61	0.92	4.90
August	0.77	1.93	1.32	4.94	2.28	7.09	0.88	5.02
September	0.79	1.69	1.55	5.90	2.30	6.73	0.88	4.86
October	0.87	1.77	1.03	6.07	2.58	6.26	0.81	5.75
November	1.03	1.95	1.51	7.35	2.94	7.07	1.00	6.86
December	1.04	2.29	1.19	8.13	3.08	7.24	0.99	6.80
Annual	0.91	1.98	1.35	6.75	2.22	6.23	1.30	5.84

$$\langle P_{\mathrm{d}}\rangle = \tfrac{1}{2}\langle\rho\rangle\langle v^3\rangle \quad (\mathrm{W\,m^{-2}}) \tag{6}$$

where $\langle\rho\rangle$ and $\langle v\rangle$ are the mean air density and the mean wind speed value for a given period of time, respectively.

The monthly mean air density $\langle\rho\rangle$ ($\mathrm{kg\,m^{-3}}$) is calculated as follows [18]:

$$\langle\rho\rangle = 0.0034843\frac{\langle P\rangle}{\langle T\rangle} \quad (\mathrm{kg\,m^{-3}}) \tag{7}$$

where $\langle P\rangle$ is the monthly average air pressure ($\mathrm{N\,m^{-2}}$) and $\langle T\rangle$ is the monthly average air temperature (K).

It had been shown [19] that $\langle v^3\rangle$, that is the third moment of the distribution for the Weibull probability model, is

$$\langle v^3\rangle_{\mathrm{Weibull}} = \left[\frac{\Gamma\left(1+\frac{3}{k}\right)}{\Gamma^3\left(1+\frac{1}{k}\right)}\right]\langle v\rangle^3$$

Since: $\langle v\rangle = c\Gamma\left(1+\frac{1}{k}\right)$,

we have : $\langle v^3\rangle_{\mathrm{Weibull}} = c^3\Gamma\left(1+\dfrac{3}{k}\right)$ (8)

in accordance to the general equation: $\langle v^a\rangle = c^a\Gamma\left(1+\frac{a}{k}\right)$.

Finally, taking into consideration Eqs. (6)–(8), the mean power density can be calculated by

$$\langle P_{\mathrm{d}}\rangle = 0.0017421\frac{\langle P\rangle}{\langle T\rangle}c^3\Gamma\left(1+\frac{3}{k}\right) \quad (\mathrm{W\,m^{-2}}) \tag{9}$$

Using the monthly mean values of P and T for the four selected sites and the Weibull parameters at the 10 m height, the above equation gives the monthly mean power densities at this height. These values for the four selected stations are presented in Fig. 2. As shown, Aktio has the highest power densities in the area, with limited fluctuations over the year. Missolonghi has also high power densities but presents significant fluctuations between seasons. Besides, Araxos presents rather lower power densities, while Agrinio is the least windy site.

The variation of monthly mean power densities with measured monthly mean wind speed is depicted in Fig. 3a for Agrinio and Fig. 3b for Missolonghi, Aktio and Araxos stations, respectively. As can be seen, there is a strong correlation, $R^2 > 0.91$, between the monthly mean power densities and the measured monthly mean wind speeds. Although the instantaneous power density is given by the third moment of wind speed {as indicated in Eq. (6)}, the probability density function $f(v)$ of the Weibull distribution, which is involved in the expression of $\langle v^3\rangle$, results in a linear correlation with the first moment [20,21].

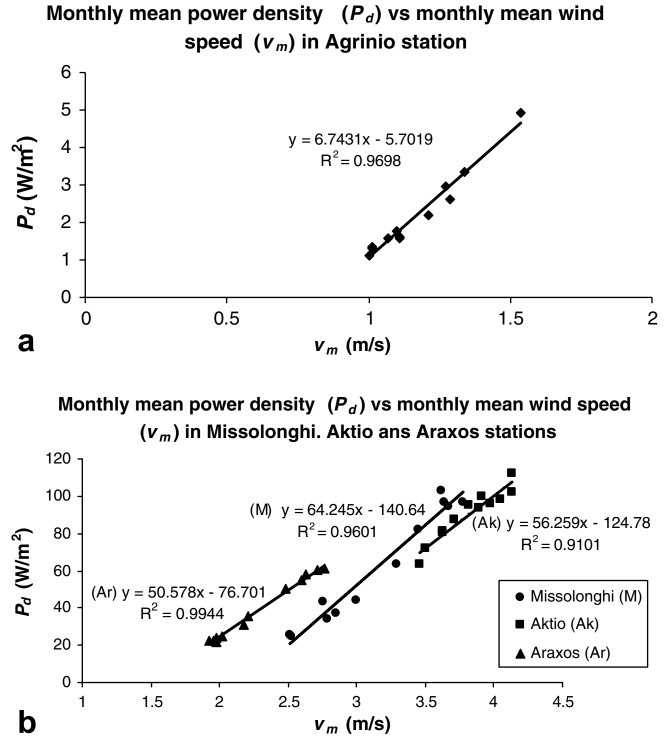

Fig. 3. Monthly mean power density (P_{d}) as a function of measured monthly mean wind speed (v_{m}) in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

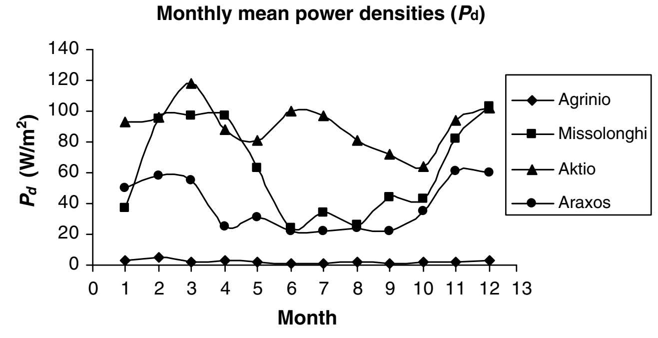

Fig. 2. Fluctuations of monthly mean wind power densities (P_{d}) in the selected stations.

The slopes of the straight lines in Fig. 3a and b, being abrupt, are in strong proportion to the quantity "c/k" for each site, as shown by the linearity in Fig. 4.

4. Cost analysis and theoretical curves

The economic viability of WECS, which is mainly judged by a cost analysis for the system over its expected lifetime, should be considered before the system's installation [22]. The two most appropriate methods for economic analysis of the WECS are the "net present value" method

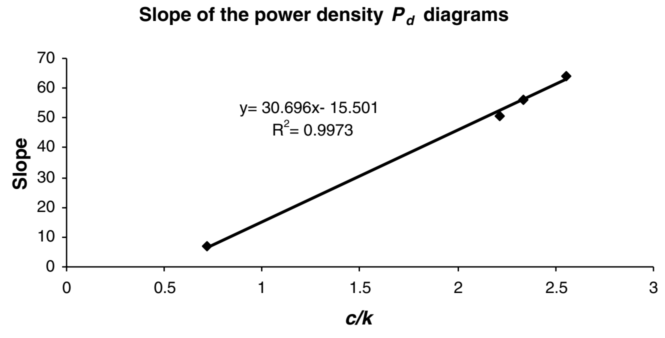

Fig. 4. Representation of the relationship of the power density diagrams' slopes of Fig. 3 as a function of the quantity c/k.

Table 3
Cost analysis per kW h for $(\mathrm{WECS})_{\mathrm{I}}$ in Agrinio (Panel A), in Missolonghi (Panel B), in Aktio (Panel C) and in Araxos (Panel D)

Model	H_{hub} (m)	v_{i} (m/s)	v_{r} (m/s)	v_{o} (m/s)	P_{r} (W)	k	c (m/s)	C_{f}	PVC (€)	Cost (€)/kW h
Panel A										
23–10	24.38	3.58	11.18	53.64	1500	1.89	1.53	0.0014	39334.2	105.303
	30.48	3.58	11.18	53.64	1500		1.58	0.0020	41760.9	81.049
	36.58	3.58	11.18	53.64	1500		1.62	0.0025	43084.5	65.109
23–12.5	24.38	3.58	12.07	53.64	1500		1.53	0.0013	39334.2	117.692
	30.48	3.58	12.07	53.64	1500		1.58	0.0018	41760.9	90.584
	36.58	3.58	12.07	53.64	1500		1.62	0.0023	43084.5	72.769
26–15	24.38	3.58	11.62	53.64	3000		1.53	0.0013	39775.4	56.374
	30.48	3.58	11.62	53.64	3000		1.58	0.0019	42202.1	43.361
	36.58	3.58	11.62	53.64	3000		1.62	0.0024	43525.7	34.822
26–17.5	24.38	3.58	12.07	53.64	3000		1.53	0.0013	39775.4	59.506
	30.48	3.58	12.07	53.64	3000		1.58	0.0018	42202.1	45.770
	36.58	3.58	12.07	53.64	3000		1.62	0.0023	43525.7	36.757
31–20	24.38	3.58	11.62	53.64	4500		1.53	0.0013	40150.4	37.937
	30.48	3.58	11.62	53.64	4500		1.58	0.0019	42577.1	29.164
	36.58	3.58	11.62	53.64	4500		1.62	0.0024	43900.7	23.415
Panel B										
23–10	24.38	3.58	11.18	53.64	1500	1.37	3.98	0.2117	39334.2	0.706
	30.48	3.58	11.18	53.64	1500		4.10	0.2255	41760.9	0.704
	36.58	3.58	11.18	53.64	1500		4.21	0.2370	43084.5	0.691
23–12.5	24.38	3.58	12.07	53.64	1500		3.98	0.1922	39334.2	0.778
	30.48	3.58	12.07	53.64	1500		4.10	0.2051	41760.9	0.774
	36.58	3.58	12.07	53.64	1500		4.21	0.2158	43084.5	0.759
26–15	24.38	3.58	11.62	53.64	3000		3.98	0.2016	39775.4	0.375
	30.48	3.58	11.62	53.64	3000		4.10	0.2149	42202.1	0.373
	36.58	3.58	11.62	53.64	3000		4.21	0.2260	43525.7	0.366
26–17.5	24.38	3.58	12.07	53.64	3000		3.98	0.1922	39775.4	0.393
	30.48	3.58	12.07	53.64	3000		4.10	0.2051	42202.1	0.391
	36.58	3.58	12.07	53.64	3000		4.21	0.2158	43525.7	0.383
31–20	24.38	3.58	11.62	53.64	4500		3.98	0.2016	40150.4	0.252
	30.48	3.58	11.62	53.64	4500		4.10	0.2149	42577.1	0.251
	36.58	3.58	11.62	53.64	4500		4.21	0.2260	43900.7	0.246
Panel C										
23–10	24.38	3.58	11.18	53.64	1500	1.66	4.40	0.2791	39334.2	0.536
	30.48	3.58	11.18	53.64	1500		4.54	0.2976	41760.9	0.534
	36.58	3.58	11.18	53.64	1500		4.66	0.3130	43084.5	0.523
23–12.5	24.38	3.58	12.07	53.64	1500		4.40	0.2519	39334.2	0.594
	30.48	3.58	12.07	53.64	1500		4.54	0.2691	41760.9	0.590
	36.58	3.58	12.07	53.64	1500		4.66	0.2835	43084.5	0.578
26–15	24.38	3.58	11.62	53.64	3000		4.40	0.2649	39775.4	0.285
	30.48	3.58	11.62	53.64	3000		4.54	0.2828	42202.1	0.284
	36.58	3.58	11.62	53.64	3000		4.66	0.2977	43525.7	0.278
26–17.5	24.38	3.58	12.07	53.64	3000		4.40	0.2519	39775.4	0.300
	30.48	3.58	12.07	53.64	3000		4.54	0.2691	42202.1	0.298
	36.58	3.58	12.07	53.64	3000		4.66	0.2835	43525.7	0.292
31–20	24.38	3.58	11.62	53.64	4500		4.40	0.2649	40150.4	0.192
	30.48	3.58	11.62	53.64	4500		4.54	0.2828	42577.1	0.191
	36.58	3.58	11.62	53.64	4500		4.66	0.2977	43900.7	0.187
Panel D										
23–10	24.38	3.58	11.18	53.64	1500	1.41	3.54	0.1663	39334.2	0.899
	30.48	3.58	11.18	53.64	1500		3.66	0.1789	41760.9	0.888
	36.58	3.58	11.18	53.64	1500		3.76	0.1896	43084.5	0.864
23–12.5	24.38	3.58	12.07	53.64	1500		3.54	0.1500	39334.2	0.997
	30.48	3.58	12.07	53.64	1500		3.66	0.1615	41760.9	0.983
	36.58	3.58	12.07	53.64	1500		3.76	0.1713	43084.5	0.956
26–15	24.38	3.58	11.62	53.64	3000		3.54	0.1578	39775.4	0.479
	30.48	3.58	11.62	53.64	3000		3.66	0.1698	42202.1	0.472
	36.58	3.58	11.62	53.64	3000		3.76	0.1801	43525.7	0.460
26–17.5	24.38	3.58	12.07	53.64	3000		3.54	0.1500	39775.4	0.504
	30.48	3.58	12.07	53.64	3000		3.66	0.1615	42202.1	0.497
	36.58	3.58	12.07	53.64	3000		3.76	0.1713	43525.7	0.483
31–20	24.38	3.58	11.62	53.64	4500		3.54	0.1578	40150.4	0.323
	30.48	3.58	11.62	53.64	4500		3.66	0.1698	42577.1	0.318
	36.58	3.58	11.62	53.64	4500		3.76	0.1801	43900.7	0.309

Table 4
Cost analysis per kW h for $(\mathrm{WECS})_{\mathrm{II}}$ in Agrinio (Panel A), in Missolonghi (Panel B), in Aktio (Panel C) and in Araxos (Panel D)

Model	H_{hub} (m)	v_{i} (m/s)	v_{r} (m/s)	v_{o} (m/s)	P_{r} (W)	k	c (m/s)	C_{f}	PVC (€)	Cost (€)/kW h
Panel A										
WT600	5.5	2.5	12	65	600	1.89	1.24	0.0030	14990.1	47.190
	12	2.5	12	65	600		1.39	0.0069	15470.5	21.306
WT2500	6.5	2.5	12	65	2500		1.27	0.0037	21139.9	13.209
	11	2.5	12	65	2500		1.37	0.0063	23830.4	8.575
WT6000	9	2.5	12	65	6000		1.33	0.0052	35169.0	6.457
	15	2.5	12	65	6000		1.43	0.0085	36706.5	4.097
WT15000	15	2.5	12	65	15000		1.43	0.0085	76872.2	3.432
	25	2.5	12	65	15000		1.54	0.0133	84559.5	2.424
Panel B										
WT600	5.5	2.5	12	65	600	1.37	3.21	0.1657	14990.1	0.860
	12	2.5	12	65	600		3.59	0.2037	15470.5	0.722
WT2500	6.5	2.5	12	65	2500		3.29	0.1735	21139.9	0.278
	11	2.5	12	65	2500		3.55	0.1993	23830.4	0.273
WT6000	9	2.5	12	65	6000		3.45	0.1892	35169.0	0.177
	15	2.5	12	65	6000		3.71	0.2154	36706.5	0.162
WT15000	15	2.5	12	65	15000		3.71	0.2154	76872.2	0.136
	25	2.5	12	65	15000		3.99	0.2433	84559.5	0.132
Panel C										
WT600	5.5	2.5	12	65	600	1.66	3.55	0.2139	14990.1	0.666
	12	2.5	12	65	600		3.97	0.2622	15470.5	0.561
WT2500	6.5	2.5	12	65	2500		3.64	0.2238	21139.9	0.216
	11	2.5	12	65	2500		3.92	0.2566	23830.4	0.212
WT6000	9	2.5	12	65	6000		3.81	0.2438	35169.0	0.137
	15	2.5	12	65	6000		4.10	0.2769	36706.5	0.126
WT15000	15	2.5	12	65	15000		4.10	0.2769	76872.2	0.106
	25	2.5	12	65	15000		4.41	0.3121	84559.5	0.103
Panel D										
WT600	5.5	2.5	12	65	600	1.41	2.86	0.1319	12917.8	0.931
	12	2.5	12	65	600		3.20	0.1660	13331.8	0.764
WT2500	6.5	2.5	12	65	2500		2.93	0.1388	18217.4	0.299
	11	2.5	12	65	2500		3.16	0.1619	20535.9	0.289
WT6000	9	2.5	12	65	6000		3.07	0.1529	30307.1	0.188
	15	2.5	12	65	6000		3.31	0.1766	31632.0	0.170
WT15000	15	2.5	12	65	15000		3.31	0.1766	66244.9	0.143
	25	2.5	12	65	15000		3.56	0.2023	72869.4	0.137

and the "unit energy cost" method [9]. The latter one was adopted here to estimate the cost per unit, (CPU), in every studied site, since it is mainly used worldwide [18]. Two factors are necessary, the capital investment and the capacity factor of the WECS in the particular site [9]. The "capacity factor (C_{f})" is defined as the ratio of the total energy E_{out} generated by the WECS per year under the wind conditions at that site to the energy E_{rated} generated per year if the WECS is operating at its rated capacity all the time and is given by

$$C_{\mathrm{f}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{rated}}} \tag{10}$$

Estimation of the capacity factor C_{f} is a rather complicated task, as it is a function of both site and turbine characteristics.

Estimation of the CPU is made by estimating the specific cost per kilowatt hour, which is expressed as the present value of costs (PVC) of the investment divided by the energy output during the wind turbine's lifetime [18,22,23]:

$$\mathrm{CPU} = \frac{\mathrm{PVC}}{E_{\mathrm{out}}} \quad (€/\mathrm{kW\,h}) \tag{11}$$

PVC calculation can be made by the formula [18,22–24]:

$$\mathrm{PVC} = I + C_{\mathrm{omr}}\left[\frac{1+i}{r-i}\right]\cdot\left[1-\left(\frac{1+i}{1+r}\right)^{t}\right] - S\left(\frac{1+i}{1+r}\right)^{t} \tag{12}$$

where I is the investment cost, C_{omr} is the operation, maintenance and repair cost, i is the inflation rate, r is the interest rate, t is the lifetime of the machine (in years) and S is the scrap value.

The following assumptions are usually considered [18,22,23]:

(a) The investment cost (I) consists of the wind turbine's price plus the cost of civil work and the connection cables to the grid (20% of the price).
(b) Operation, maintenance and repair cost (C_{omr}) was considered to be 25% of the annual cost of the turbine (machine price/lifetime) and must be escalated with the general inflation rate.

Table 5
Cost analysis per kW h for $(\text{WECS})_{\text{III}}$ in Agrinio (Panel A), in Missolonghi (Panel B), in Aktio (Panel C) and in Araxos (Panel D)

Model	H_{hub} (m)	v_{i} (m/s)	v_{r} (m/s)	v_{o} (m/s)	P_{r} (W)	k	c (m/s)	C_{f}	PVC (€)	Cost (€)/kW h
Panel A										
T330	6	2.1	11.6	40	1500	1.89	1.25	0.0094	5813.0	2.358
	9	2.1	11.6	40	1500		1.33	0.0131	6557.5	1.908
	12	2.1	11.6	40	1500		1.39	0.0163	7517.2	1.759
	15	2.1	11.6	40	1500		1.43	0.0191	8929.1	1.780
	18	2.1	11.6	40	1500		1.47	0.0216	10305.6	1.812
	24	2.1	11.6	40	1500		1.53	0.0261	13308.1	1.939
T460	9	2.1	11.6	40	3000		1.33	0.0131	9220.3	1.342
	12	2.1	11.6	40	3000		1.39	0.0163	10328.8	1.208
	15	2.1	11.6	40	3000		1.43	0.0191	11690.0	1.165
	18	2.1	11.6	40	3000		1.47	0.0216	13245.2	1.165
	24	2.1	11.6	40	3000		1.53	0.0261	16529.0	1.204
	30	2.1	11.6	40	3000		1.58	0.0300	21095.5	1.338
T550	12	2.1	12.0	40	4500		1.39	0.0156	13843.1	1.125
	15	2.1	12.0	40	4500		1.43	0.0183	15398.4	1.066
	18	2.1	12.0	40	4500		1.47	0.0208	16906.2	1.033
	24	2.1	12.0	40	4500		1.53	0.0250	20726.0	1.049
	30	2.1	12.0	40	4500		1.58	0.0288	24487.3	1.079
T780	15	2.1	12.0	40	10000		1.43	0.0183	26748.6	0.833
	18	2.1	12.0	40	10000		1.47	0.0208	28447.2	0.782
	24	2.1	12.0	40	10000		1.53	0.0250	32131.4	0.732
	30	2.1	12.0	40	10000		1.58	0.0288	37117.1	0.736
	39	2.1	12.0	40	10000		1.64	0.0336	42124.9	0.716
T1100	24	2.1	12.0	40	20000		1.53	0.0250	48742.0	0.555
	30	2.1	12.0	40	20000		1.58	0.0288	55276.3	0.548
	39	2.1	12.0	40	20000		1.64	0.0336	65012.8	0.552
Panel B										
T330	6	2.1	11.6	40	1500	1.37	3.25	0.1967	5813.0	0.112
	9	2.1	11.6	40	1500		3.45	0.2167	6557.5	0.115
	12	2.1	11.6	40	1500		3.59	0.2316	7517.2	0.123
	15	2.1	11.6	40	1500		3.71	0.2434	8929.1	0.139
	18	2.1	11.6	40	1500		3.81	0.2533	10305.6	0.155
	24	2.1	11.6	40	1500		3.97	0.2694	13308.1	0.188
T460	9	2.1	11.6	40	3000		3.45	0.2167	9220.3	0.081
	12	2.1	11.6	40	3000		3.59	0.2316	10328.8	0.085
	15	2.1	11.6	40	3000		3.71	0.2434	11690.0	0.091
	18	2.1	11.6	40	3000		3.81	0.2533	13245.2	0.099
	24	2.1	11.6	40	3000		3.97	0.2694	16529.0	0.117
	30	2.1	11.6	40	3000		4.09	0.2821	21095.5	0.142
T550	12	2.1	12.0	40	4500		3.59	0.2227	13843.1	0.079
	15	2.1	12.0	40	4500		3.71	0.2342	15398.4	0.083
	18	2.1	12.0	40	4500		3.81	0.2439	16906.2	0.088
	24	2.1	12.0	40	4500		3.97	0.2594	20726.0	0.101
	30	2.1	12.0	40	4500		4.09	0.2718	24487.3	0.114
T780	15	2.1	12.0	40	10000		3.71	0.2342	26748.6	0.065
	18	2.1	12.0	40	10000		3.81	0.2439	28447.2	0.067
	24	2.1	12.0	40	10000		3.97	0.2594	32131.4	0.071
	30	2.1	12.0	40	10000		4.09	0.2718	37117.1	0.078
	39	2.1	12.0	40	10000		4.25	0.2867	42124.9	0.084
T1100	24	2.1	12.0	40	20000		3.97	0.2594	48742.0	0.054
	30	2.1	12.0	40	20000		4.09	0.2718	55276.3	0.058
	39	2.1	12.0	40	20000		4.25	0.2867	65012.8	0.065
Panel C										
T330	6	2.1	11.6	40	1500	1.66	3.60	0.2512	5813.0	0.088
	9	2.1	11.6	40	1500		3.81	0.2760	6557.5	0.090
	12	2.1	11.6	40	1500		3.97	0.2944	7517.2	0.097
	15	2.1	11.6	40	1500		4.10	0.3090	8929.1	0.110
	18	2.1	11.6	40	1500		4.21	0.3212	10305.6	0.122
	24	2.1	11.6	40	1500		4.39	0.3408	13308.1	0.148
T460	9	2.1	11.6	40	3000		3.81	0.2760	9220.3	0.064
	12	2.1	11.6	40	3000		3.97	0.2944	10328.8	0.067
	15	2.1	11.6	40	3000		4.10	0.3090	11690.0	0.072
	18	2.1	11.6	40	3000		4.21	0.3212	13245.2	0.078

Table 5 (*continued*)

Model	H_{hub} (m)	v_{i} (m/s)	v_{r} (m/s)	v_{o} (m/s)	P_{r} (W)	k	c (m/s)	C_{f}	PVC (€)	Cost (€)/kW h
	24	2.1	11.6	40	3000		4.39	0.3408	16529.0	0.092
	30	2.1	11.6	40	3000		4.53	0.3564	21095.5	0.113
T550	12	2.1	12.0	40	4500		3.97	0.2828	13843.1	0.062
	15	2.1	12.0	40	4500		4.10	0.2969	15398.4	0.066
	18	2.1	12.0	40	4500		4.21	0.3087	16906.2	0.069
	24	2.1	12.0	40	4500		4.39	0.3278	20726.0	0.080
	30	2.1	12.0	40	4500		4.53	0.3429	24487.3	0.091
T780	15	2.1	12.0	40	10000		4.10	0.2969	26748.6	0.051
	18	2.1	12.0	40	10000		4.21	0.3087	28447.2	0.053
	24	2.1	12.0	40	10000		4.39	0.3278	32131.4	0.056
	30	2.1	12.0	40	10000		4.53	0.3429	37117.1	0.062
	39	2.1	12.0	40	10000		4.70	0.3610	42124.9	0.067
T1100	24	2.1	12.0	40	20000		4.39	0.3278	48742.0	0.042
	30	2.1	12.0	40	20000		4.53	0.3429	55276.3	0.046
	39	2.1	12.0	40	20000		4.70	0.3610	65012.8	0.051
Panel D										
T330	6	2.1	11.6	40	1500	1.41	2.90	0.1617	5813.0	0.137
	9	2.1	11.6	40	1500		3.07	0.1798	6557.5	0.139
	12	2.1	11.6	40	1500		3.20	0.1934	7517.2	0.148
	15	2.1	11.6	40	1500		3.31	0.2044	8929.1	0.166
	18	2.1	11.6	40	1500		3.39	0.2136	10305.6	0.183
	24	2.1	11.6	40	1500		3.54	0.2286	13308.1	0.221
T460	9	2.1	11.6	40	3000		3.07	0.1798	9220.3	0.097
	12	2.1	11.6	40	3000		3.20	0.1934	10328.8	0.102
	15	2.1	11.6	40	3000		3.31	0.2044	11690.0	0.109
	18	2.1	11.6	40	3000		3.39	0.2136	13245.2	0.118
	24	2.1	11.6	40	3000		3.54	0.2286	16529.0	0.137
	30	2.1	11.6	40	3000		3.65	0.2406	21095.5	0.167
T550	12	2.1	12.0	40	4500		3.20	0.1858	13843.1	0.094
	15	2.1	12.0	40	4500		3.31	0.1964	15398.4	0.099
	18	2.1	12.0	40	4500		3.39	0.2053	16906.2	0.104
	24	2.1	12.0	40	4500		3.54	0.2197	20726.0	0.120
	30	2.1	12.0	40	4500		3.65	0.2313	24487.3	0.134
T780	15	2.1	12.0	40	10000		3.31	0.1964	26748.6	0.078
	18	2.1	12.0	40	10000		3.39	0.2053	28447.2	0.079
	24	2.1	12.0	40	10000		3.54	0.2197	32131.4	0.083
	30	2.1	12.0	40	10000		3.65	0.2313	37117.1	0.092
	39	2.1	12.0	40	10000		3.79	0.2454	42124.9	0.098
T1100	24	2.1	12.0	40	20000		3.54	0.2197	48742.0	0.063
	30	2.1	12.0	40	20000		3.65	0.2313	55276.3	0.068
	39	2.1	12.0	40	20000		3.79	0.2454	65012.8	0.076

(c) Inflation rate (i) and interest rate (r) are taken as 0.035 and 0.045, respectively, which, at the present circumstances, are fair values for the European Community.

(d) The machine is assumed to have only a 20 year lifetime (t).

(e) Scrap value (S) is taken as 10% of the investment (machine and civil work).

The energy output E_{out} of the wind turbine in its lifetime (20 years) can be estimated from the lifetime rated energy E_{rated} and the factor capacity C_{f} of the wind turbine from Eq. (10):

$$E_{\mathrm{out}} = C_{\mathrm{f}} \cdot E_{\mathrm{rated}} \tag{13}$$

The capacity factor C_{f} for a WECS in its particular location is calculated by the following formula [25–28]:

$$C_{\mathrm{f}} = \frac{\exp\left(-\left(\frac{v_{\mathrm{i}}}{c}\right)^{k}\right) - \exp\left(-\left(\frac{v_{\mathrm{r}}}{c}\right)^{k}\right)}{\left(\frac{v_{\mathrm{r}}}{c}\right)^{k} - \left(\frac{v_{\mathrm{i}}}{c}\right)^{k}} - \exp\left[-\left(\frac{v_{\mathrm{o}}}{c}\right)^{k}\right] \tag{14}$$

where v_{i}, v_{r} and v_{o} are the cut in, rated and cut off wind speeds, respectively (WECS's characteristics) and k and c are the Weibull parameters at hub height (site characteristics). The problem of transformation of Weibull parameters at the hub heights of the wind turbines can be easily solved due to the features of the Weibull distribution. One of the advantages of the choice of the Weibull function for presentation of the wind speed distribution is that it makes it possible to transform the wind speed distribution at 10 m height to the distribution at any other height. This is done by applying the so called one seventh power law [29–31]:

$$\frac{c_2}{c_1} = \left(\frac{z_2}{z_1}\right)^{1/7} \tag{15}$$

where c_2 and c_1 are the Weibull scale parameters at heights z_2 and z_1, respectively. Even if the Weibull shape parameter, k, varies with height, the variation is small, and for the present analysis, the shape factor is assumed to be independent of the height.

With the use of Eq. (15), one can estimate the Weibull parameter c for the various hub heights that should be used to calculate the mean wind speed at that height.

The rated energy E_{rated} for this wind turbine is calculated from the expression

$$E_{\text{rated}} = 20\ \text{years} \cdot 365.25 \cdot 24\ \text{h} \cdot P_{\text{out}} \quad (\text{kW h}) \tag{16}$$

Finally, the CPU can be estimated with the help of Eqs. (11)–(14) and (16). As was shown in a previous study [8], the selected area has rather low to moderate wind energy potential. Thus, it is rather more appropriate to examine mainly small (up to 2 kW) and medium size (2–100 kW) WECS than large size (100 kW and up) ones [32,33]. In order to investigate the relationship between CPU and only the size of the WECS, we examined several wind turbines manufactured by the same company, taking care that the other possible variables that could influence CPU, (cut in, rated and cut off wind speed) remain stable. This is necessary because the capacity factor mainly depends on the cut in and rated wind speed [34].

The specific cost per kW h is estimated for the following wind turbines:

(i) Five Jacobs turbines $\{(\text{WECS})_{\text{I}}\}$ with rated power from 1500 to 4500 W [35].
(ii) Four Proven turbines $\{(\text{WECS})_{\text{II}}\}$ with rated power from 600 to 15000 W [36].
(iii) Five Turbex turbines $\{(\text{WECS})_{\text{III}}\}$ with rated power from 1500 to 20000 W [37].
(iv) Five Fortis turbines $\{(\text{WECS})_{\text{IV}}\}$ with rated power from 800 to 30000 W [38].
(v) Five Bonus turbines $\{(\text{WECS})_{\text{V}}\}$ with rated power from 600 to 2300 kW [39,40].

The prices of the wind machines and their characteristics can be found from the official sites of the manufacturers. In order to express all prices in euros, the exchange rates of the 25th March of 2006 were used for USD and GBP:

$$1\ \text{USD} = 0.831015\ €, \quad 1\ \text{GBP} = 1.44787\ €$$

The turbines' characteristics and the cost analysis are shown in Tables 3–7, respectively. The values of the Weibull parameters k and c that were used are the annual ones, transformed to the hub height $\{k$ being independent of hub height while c follows Eq. (15)$\}$. In case of the WECS with several hub heights H_{hub} at standard rated power, the value of PVC used at every rated power was the average of those of all the hub heights.

For the various turbines to be installed in a particular site, made by the same manufacturer, the fluctuation of the calculated values of CPU (specific cost per kW h) with

Table 6
Cost analysis per kW h for $(\text{WECS})_{\text{IV}}$ in Agrinio (Panel A), in Missolonghi (Panel B), in Aktio (Panel C) and in Araxos (Panel D)

Model	H_{hub} (m)	v_{i} (m/s)	v_{r} (m/s)	v_{o} (m/s)	P_{r} (W)	k	c (m/s)	C_{f}	PVC (€)	Cost (€)/kW h
Panel A										
ESPADA	12	3	16	25	800	1.89	1.39	0.0014	6391.1	31.690
PASSAAT	12	3	16	25	1400		1.39	0.0014	7591.0	21.508
MONTANA	18	3	17	25	5800		1.47	0.0022	18582.7	8.265
ALIZE	24	3	12	25	10000		1.53	0.0048	37165.3	4.433
BOREAS	30	3	9	25	30000		1.58	0.0091	117800.8	2.455
Panel B										
ESPADA	12	3	16	25	800	1.37	3.59	0.1264	6391.1	0.361
PASSAAT	12	3	16	25	1400		3.59	0.1264	7591.0	0.245
MONTANA	18	3	17	25	5800		3.81	0.1320	18582.7	0.138
ALIZE	24	3	12	25	10000		3.97	0.2182	37165.3	0.097
BOREAS	30	3	9	25	30000		4.09	0.3192	117800.8	0.070
Panel C										
ESPADA	12	3	16	25	800	1.66	3.97	0.1631	6391.1	0.279
PASSAAT	12	3	16	25	1400		3.97	0.1631	7591.0	0.190
MONTANA	18	3	17	25	5800		4.21	0.1700	18582.7	0.107
ALIZE	24	3	12	25	10000		4.39	0.2837	37165.3	0.075
BOREAS	30	3	9	25	30000		4.53	0.4224	117800.8	0.053
Panel D										
ESPADA	12	3	16	25	800	1.41	3.20	0.0989	6391.1	0.461
PASSAAT	12	3	16	25	1400		3.20	0.0989	7591.0	0.313
MONTANA	18	3	17	25	5800		3.39	0.1046	18582.7	0.175
ALIZE	24	3	12	25	10000		3.54	0.1763	37165.3	0.120
BOREAS	30	3	9	25	30000		3.65	0.2678	117800.8	0.084

the size (rated power P_r) are well represented by the hyperbolic curves of Figs. 5–9. These curves are a good match to the theoretically calculated values of CPU (in many occasions $R^2 = .99$) and demonstrate that for a specific manufacturer, the specific cost per kW h as the rated power increases follows the expression:

$$(\mathrm{CPU}) = a \cdot P_r^b \tag{17}$$

Table 7
Cost analysis per kW h for $(\mathrm{WECS})_V$ in Agrinio (Panel A), in Missolonghi (Panel B), in Aktio (Panel C) and in Araxos (Panel D)

Model	H_{hub} (m)	v_i (m/s)	v_r (m/s)	v_o (m/s)	P_r (W)	k	c (m/s)	C_f	PVC (€)	Cost (€)/kW h
Panel A										
AN 0.6 MW/44-3	42	3	15	25	600	1.89	1.66	0.0064	630483.2	0.929
	50	3	15	25	600		1.70	0.0076	650393.2	0.817
	55	3	15	25	600		1.72	0.0083	671630.5	0.773
	58	3	15	25	600		1.74	0.0087	684903.9	0.751
AN 1 MW/54	50	3	15	25	1000		1.70	0.0076	1099031.8	0.828
	60	3	15	25	1000		1.74	0.0089	1138851.8	0.726
	70	3	15	25	1000		1.78	0.0102	1193272.5	0.665
AN 1.3 MW	60	3	15	25	1300		1.74	0.0089	1417591.7	0.696
	68	3	15	25	1300		1.78	0.0100	1546343.1	0.679
	80	3	15	25	1300		1.82	0.0115	1668457.7	0.638
	90	3	15	25	1300		1.85	0.0127	1797209.0	0.623
AN 2 MW	60	3	15	25	2000		1.74	0.0089	2203372.9	0.703
	80	3	15	25	2000		1.82	0.0115	2374598.9	0.590
	90	3	15	25	2000		1.85	0.0127	2521932.9	0.569
AN 2.3 MW	80	3	15	25	2300		1.82	0.0115	2561752.9	0.554
	90	3	15	25	2300		1.85	0.0127	2721032.8	0.533
	100	3	15	25	2300		1.88	0.0138	2860402.8	0.515
Panel B										
AN 0.6 MW/44-3	42	3	15	25	600	1.37	4.30	0.1932	630483.2	0.031
	50	3	15	25	600		4.40	0.2016	650393.2	0.031
	55	3	15	25	600		4.47	0.2064	671630.5	0.031
	58	3	15	25	600		4.50	0.2091	684903.9	0.031
AN 1 MW/54	50	3	15	25	1000		4.40	0.2016	1099031.8	0.031
	60	3	15	25	1000		4.52	0.2109	1138851.8	0.031
	70	3	15	25	1000		4.62	0.2189	1193272.5	0.031
AN 1.3 MW	60	3	15	25	1300		4.52	0.2109	1417591.7	0.029
	68	3	15	25	1300		4.60	0.2174	1546343.1	0.031
	80	3	15	25	1300		4.71	0.2260	1668457.7	0.032
	90	3	15	25	1300		4.79	0.2324	1797209.0	0.034
AN 2 MW	60	3	15	25	2000		4.52	0.2109	2203372.9	0.030
	80	3	15	25	2000		4.71	0.2260	2374598.9	0.030
	90	3	15	25	2000		4.79	0.2324	2521932.9	0.031
AN 2.3 MW	80	3	15	25	2300		4.71	0.2260	2561752.9	0.028
	90	3	15	25	2300		4.79	0.2324	2721032.8	0.029
	100	3	15	25	2300		4.86	0.2382	2860402.8	0.030
Panel C										
AN 0.6 MW/44-3	42	3	15	25	600	1.66	4.76	0.2483	630483.2	0.024
	50	3	15	25	600		4.87	0.2588	650393.2	0.024
	55	3	15	25	600		4.94	0.2649	671630.5	0.024
	58	3	15	25	600		4.97	0.2684	684903.9	0.024
AN 1 MW/54	50	3	15	25	1000		4.87	0.2588	1099031.8	0.024
	60	3	15	25	1000		5.00	0.2706	1138851.8	0.024
	70	3	15	25	1000		5.11	0.2807	1193272.5	0.024
AN 1.3 MW	60	3	15	25	1300		5.00	0.2706	1417591.7	0.023
	68	3	15	25	1300		5.09	0.2788	1546343.1	0.024
	80	3	15	25	1300		5.21	0.2896	1668457.7	0.025
	90	3	15	25	1300		5.30	0.2975	1797209.0	0.027
AN 2 MW	60	3	15	25	2000		5.00	0.2706	2203372.9	0.023
	80	3	15	25	2000		5.21	0.2896	2374598.9	0.023
	90	3	15	25	2000		5.30	0.2975	2521932.9	0.024
AN 2.3 MW	80	3	15	25	2300		5.21	0.2896	2561752.9	0.022
	90	3	15	25	2300		5.30	0.2975	2721032.8	0.023
	100	3	15	25	2300		5.38	0.3047	2860402.8	0.023

(*continued on next page*)

Table 7 (*continued*)

Model	H_{hub} (m)	v_{i} (m/s)	v_{r} (m/s)	v_{o} (m/s)	P_{r} (W)	k	c (m/s)	C_{f}	PVC (€)	Cost (€)/kW h
Panel D										
AN 0.6 MW/44-3	42	3	15	25	600	1.41	3.83	0.1571	630483.2	0.038
	50	3	15	25	600		3.93	0.1646	650393.2	0.038
	55	3	15	25	600		3.98	0.1690	671630.5	0.038
	58	3	15	25	600		4.01	0.1715	684903.9	0.038
AN 1 MW/54	50	3	15	25	1000		3.93	0.1646	1099031.8	0.038
	60	3	15	25	1000		4.03	0.1731	1138851.8	0.038
	70	3	15	25	1000		4.12	0.1804	1193272.5	0.038
AN 1.3 MW	60	3	15	25	1300		4.03	0.1731	1417591.7	0.036
	68	3	15	25	1300		4.10	0.1790	1546343.1	0.038
	80	3	15	25	1300		4.20	0.1869	1668457.7	0.039
	90	3	15	25	1300		4.27	0.1928	1797209.0	0.041
AN 2 MW	60	3	15	25	2000		4.03	0.1731	2203372.9	0.036
	80	3	15	25	2000		4.20	0.1869	2374598.9	0.036
	90	3	15	25	2000		4.27	0.1928	2521932.9	0.037
AN 2.3 MW	80	3	15	25	2300		4.20	0.1869	2561752.9	0.034
	90	3	15	25	2300		4.27	0.1928	2721032.8	0.035
	100	3	15	25	2300		4.34	0.1981	2860402.8	0.036

where α and b are constants, being dependent both on the manufacturer and the characteristics of the selected site. The values of a and b for several types of wind turbines in the four selected stations, as well as the R^2 values, are provided in Table 8. Studying the values of α for each hyperbolic representation of Figs. 5–9 (each different installation site), one realizes that they are proportional to the maximum cost per unit [$(\mathrm{CPU})_0$] for each selected site with a relationship coefficient s that is constant for each manufacturer. The relationship corresponding to the parameter α is expressed as

$$a = s \cdot (\mathrm{CPU})_0 \tag{18}$$

The values of s for each manufacturer studied that are the same for all four sites under investigation are depicted in Table 9.

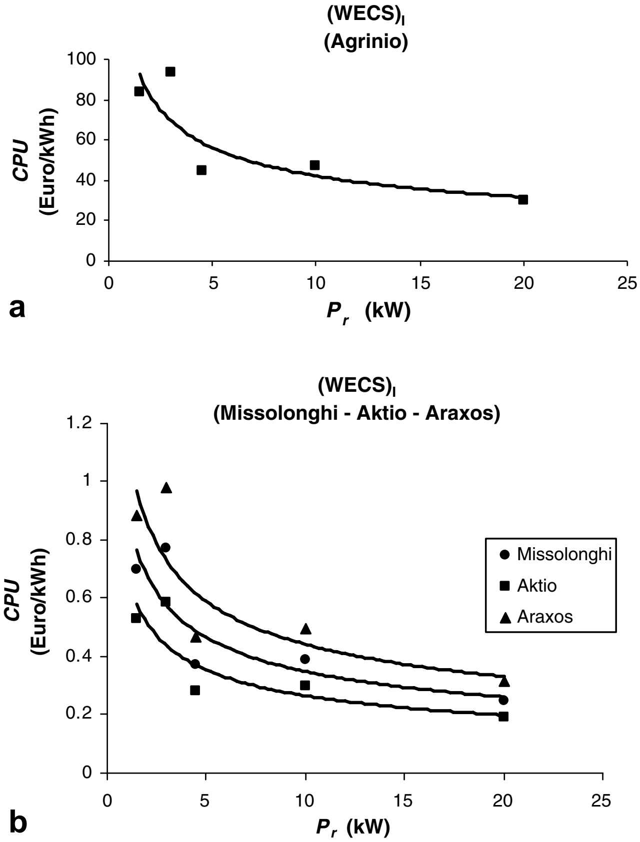

Fig. 5. Cost per unit (CPU) as a function of the rated power (P_{r}) for the Jacobs wind turbines {$(\mathrm{WECS})_{\mathrm{I}}$} in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

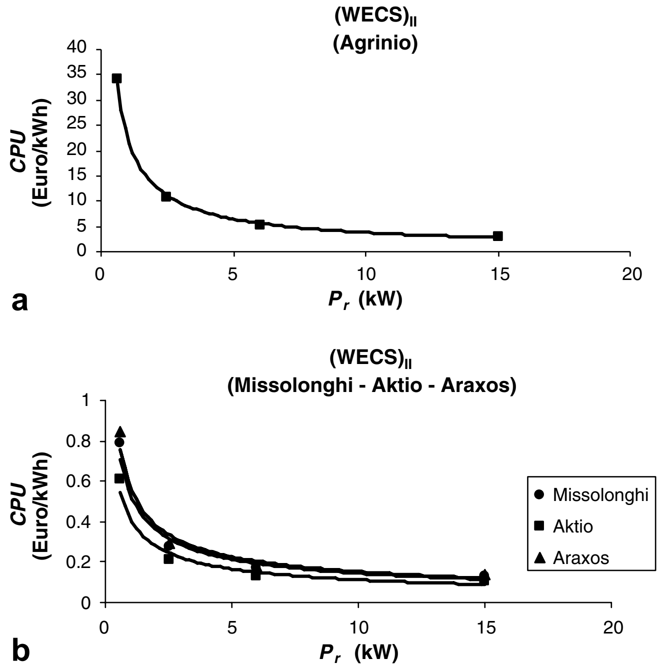

Fig. 6. Cost per unit (CPU) as a function of the rated power (P_{r}) for the Proven wind turbines {$(\mathrm{WECS})_{\mathrm{II}}$} in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

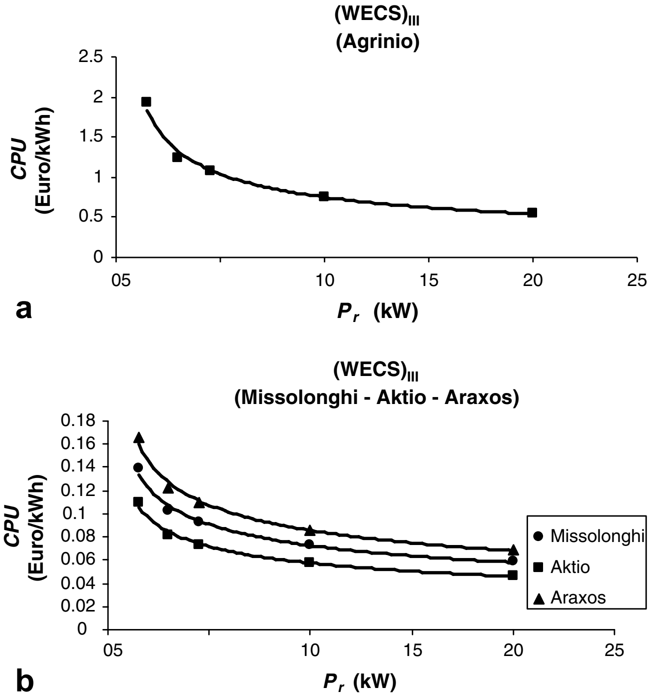

Fig. 7. Cost per unit (CPU) as a function of the rated power (P_r) for the Turbex wind turbines {$(\mathrm{WECS})_{\mathrm{III}}$} in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

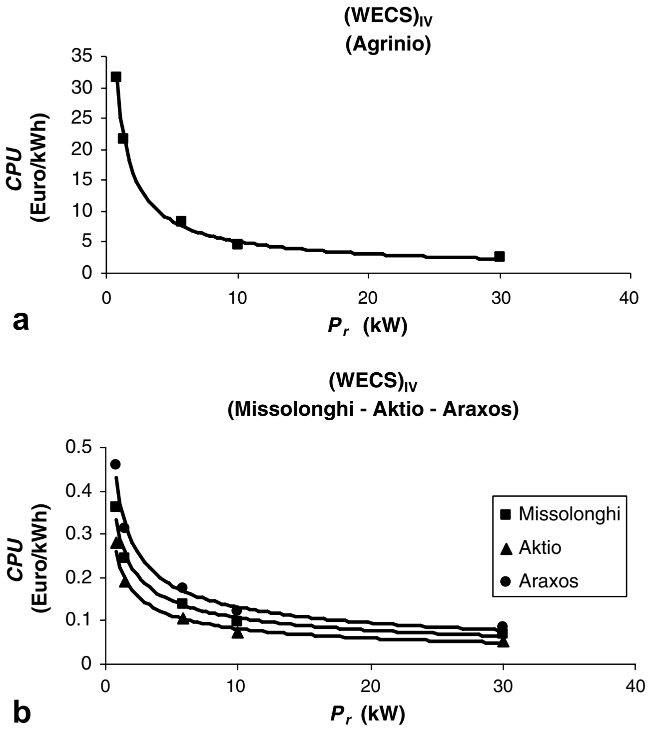

Fig. 8. Cost per unit (CPU) as a function of the rated power (P_r) for the Fortis wind turbines {$(\mathrm{WECS})_{\mathrm{IV}}$} in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

Combining Eqs. (17) and (18), we have

$$(\mathrm{CPU}) = s \cdot (\mathrm{CPU})_0 \cdot P_{\mathrm{r}}^{b} \tag{19}$$

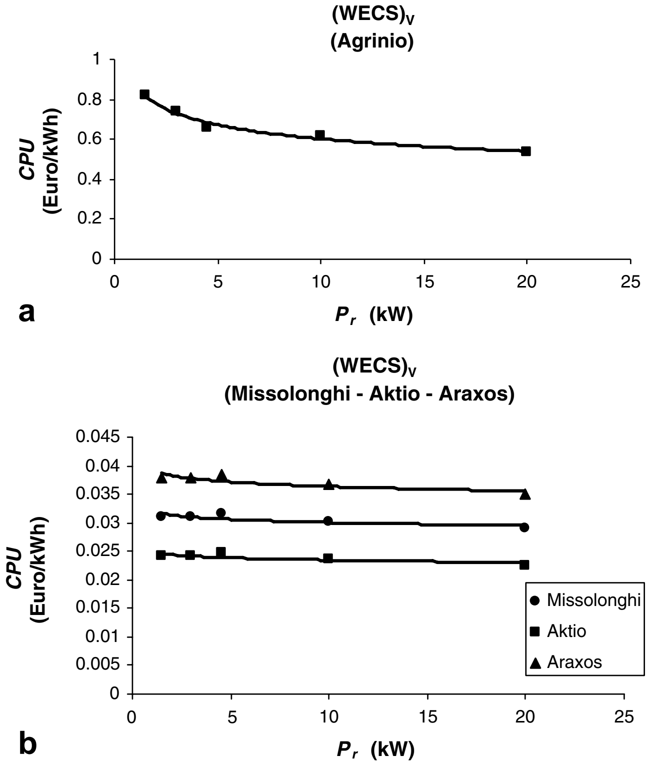

Fig. 9. Cost per unit (CPU) as a function of the rated power (P_r) for the Bonus wind turbines {$(\mathrm{WECS})_{\mathrm{V}}$} in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

Eq. (19) has the form of an expression resulting from experience curves that describe the cost per unit of wind generated electricity [41,42]. Experience curves, generally, depict how this cost declines with cumulative production and are used as an approximation, emerging from the accumulated experience in producing and employing technology [43–45]. Of course, in this study, instead of cumulative production, we consider the rated power of the wind turbine that can be taken as a special characteristic of cumulative production for a single WECS.

In order to picture the rate by which the cost per unit declines, it is essential to calculate the relative cost reduction (RCR) when doubling the rated power of the wind turbine. This can be performed using Eq. (19):

$$\begin{aligned}(\mathrm{RCR}) &= \frac{(\mathrm{CPU})_1 - (\mathrm{CPU})_2}{(\mathrm{CPU})_1} \\ &= \frac{s \cdot (\mathrm{CPU})_0 \cdot P_{\mathrm{r}}^{b} - s \cdot (\mathrm{CPU})_0 \cdot (2P_{\mathrm{r}})^{b}}{s \cdot (\mathrm{CPU}h)_0 \cdot P_{\mathrm{r}}^{b}} \\ &= 1 - 2^{b}\end{aligned} \tag{20}$$

The previous expression of RCR is the same as that in the experience curves. Consequently, in order to express the progress of cost reduction, a useful quantity is the progress ratio (PR), represented by the value 2^b, which is inversely related toRCR. A progress ratio of 85%, for example, means that the cost is reduced by 15% each time

Table 8
Values of a, b, PR and R^2 of the wind turbines for the selected stations

Wind turbine	Agrinio				Missolonghi			
	a	b	PR	R^2	a	b	PR	R^2
$(WECS)_{I}$	3463	−1.5464	34.24	0.8097	29.609	−1.5586	33.95	0.8203
$(WECS)_{II}$	22.459	−0.7722	58.55	0.9976	0.5296	−0.5642	67.63	0.9616
$(WECS)_{III}$	2.2047	−0.4678	72.31	0.9914	0.1527	−0.3231	79.94	0.9921
$(WECS)_{IV}$	27.075	−0.7221	60.62	0.993	0.3023	−0.4505	73.18	0.9865
$(WECS)_{V}$	0.7184	−0.2906	81.76	0.9313	0.0309	−0.041	97.20	0.4143
	Aktio				Araxos			
$(WECS)_{I}$	22.269	−1.5545	34.04	0.8165	36.989	−1.5534	34.07	0.8156
$(WECS)_{II}$	0.4108	−0.5631	67.68	0.9611	0.5671	−0.5719	67.27	0.9647
$(WECS)_{III}$	0.1201	−0.3204	80.08	0.992	0.1826	−0.3291	79.60	0.9921
$(WECS)_{IV}$	0.235	−0.4566	72.87	0.9878	0.3883	−0.4689	72.25	0.9893
$(WECS)_{V}$	0.0241	−0.0389	97.34	0.389	0.0376	−0.0514	96.50	0.5304

Table 9
s values for each manufacturer that are constant for all installation sites

Turbine manufacturer	s
Jacobs	41.84418
Proven	0.666071
Turbex	1.111385
Fortis	0.844308
Bonus	0.967774

the rated power is doubled. The PR values are also depicted in Table 8. We observe that the smallest wind turbine, $(WECS)_{I}$, has the lowest values of PR (which means the higher value in cost reduction), while $(WECS)_{V}$ has the highest value in every selected station. In experience curves, there is not a clear demonstration of the cost per unit as many different parameters are involved (rated power, characteristic velocities, manufacturer's standards, site wind potential, etc.) [41,42]. In the present study, the "behavior" of the specific costs per kW h is a function of the rated power of the WECS only, without interference of other parameters.

In the above cost analysis, the values of the specific costs per kW h were averaged for several hub heights. The variations of the cost per unit in relation to the hub height (H_{hub}) of the $WECS_{III}$ wind turbines are depicted in Figs. 10–14. As shown, the specific cost per kW h increases with hub height.

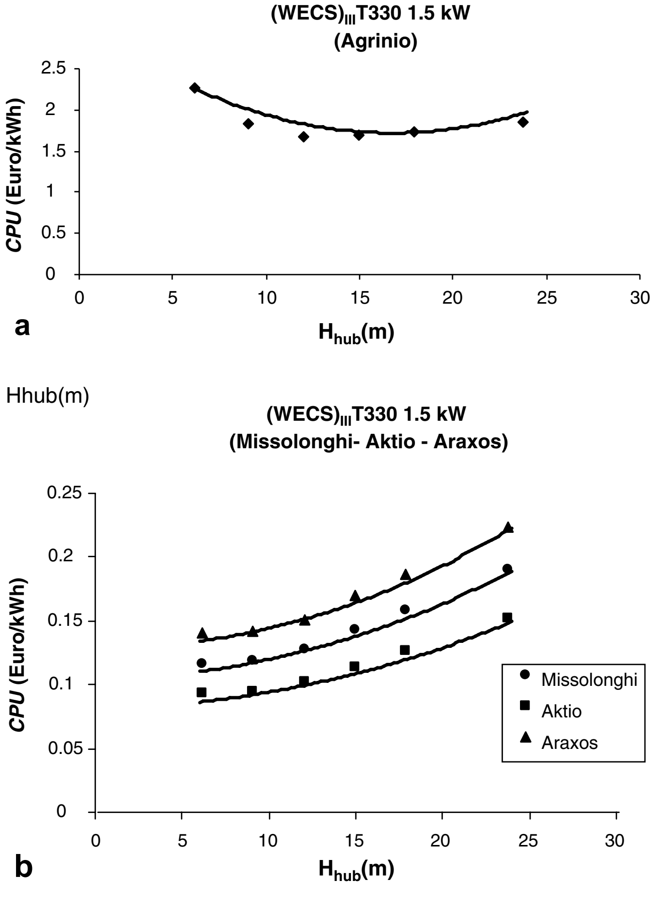

Fig. 10. Cost per unit (CPU) as a function of the hub height for the Turbex T330 1.5 kW wind turbines in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

5. Results and discussion

Weibull parameters, obtained and tested by different methods, at four selected sites in the central area of Western Greece were used in order to estimate wind power densities. The results indicated that coastal regions might be suitable for wind power utilization, while the inland locations are inappropriate. The most promising site, according to our study, Aktio, has power densities ranging from 60 to 120 W m^{-2}. Data analysis demonstrated a linear correlation between the monthly mean power density and the measured monthly mean wind speed, while the slope is proportional to the quantity "c/k" for all studied sites.

Then, a cost analysis was performed for the selected locations in order to estimate the specific cost per kilowatt hour. This analysis showed that for a specific manufacturer, the cost per unit decreases as the rated power of the wind turbine increases. The calculated values of the cost per kW h are described by a hyperbolic function of

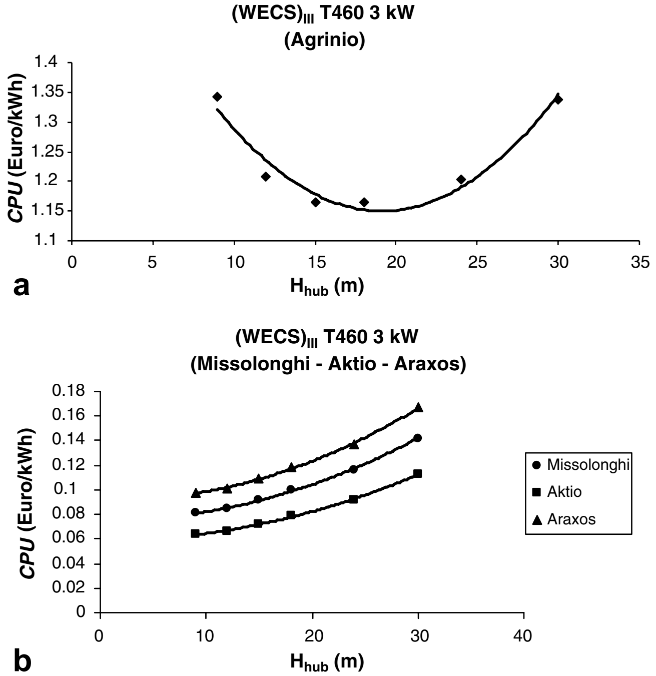

Fig. 11. Cost per unit (CPU) as a function of the hub height for the Turbex T460 3 kW wind turbines in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

the rated power of the WECS and are in complete agreement with the experience curves.

The above results of the cost analysis are explained by the lower costs per kilowatt installed for small wind machines [46,47] (a fact that is based on the assumption that there are economies of scaling up to a certain point in several of the costs in wind turbine manufacturing). For instance, the amount of manpower involved in building a 150 kW machine is not very different from the

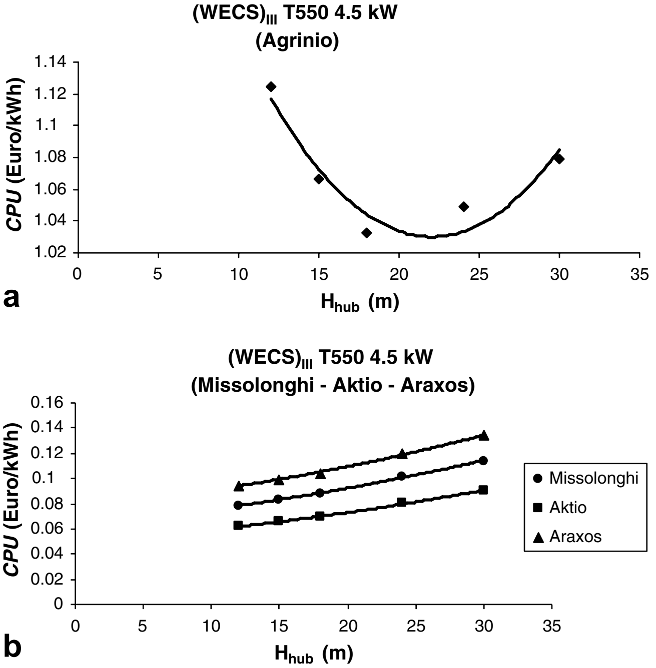

Fig. 12. Cost per unit (CPU) as a function of the hub height for the Turbex T550 4.5 kW wind turbines in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

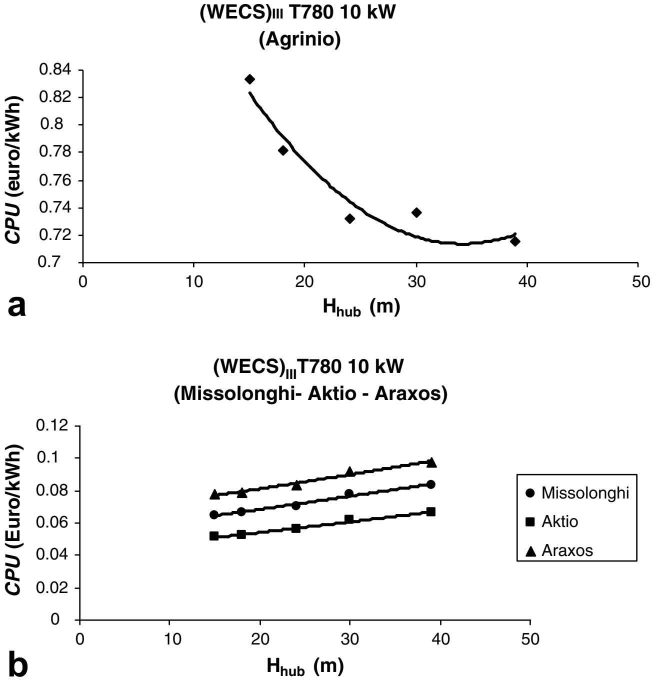

Fig. 13. Cost per unit (CPU) as a function of the hub height for the Turbex T780 10 kW wind turbines in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

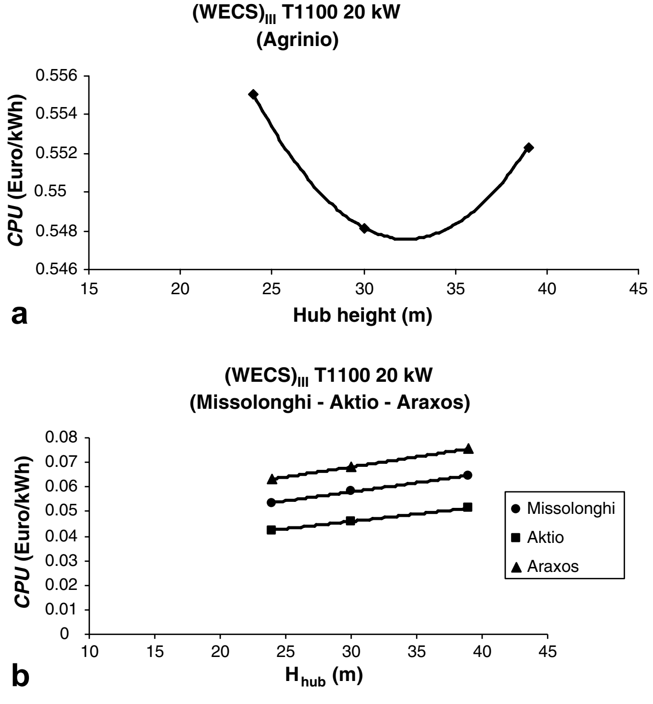

Fig. 14. Cost per unit (CPU) as a function of the hub height for the Turbex T1100 20 kW wind turbines in (a) Agrinio and (b) Missolonghi, Aktio and Araxos stations.

amount required to build a 600 kW machine. Moreover, the safety features and the amount of electronics required in running a small or a large machine are roughly the same. From the above remarks, moving from a 150 kW machine to a 600 kW machine, we observe that the price may approximately triple, rather than quadruple [47].

By installing large scale wind turbines in Missolonghi and Aktio, one may profit from electrical power production, as the cost of the kW h produced by WECS was found to be comparable to the cost of the kW h produced by the Hellenic Public Power Corporation. The specific cost per unit for Bonus turbines is comparable to the cost for a kW h production of the Public Power Corporation (PPC) in this area, which is 0.0367 €/kW h. Besides, there is a margin for profit by selling energy to the PPC, as the market price for every kW h given is 0.063 €/kW h (90% of the current price per kW h).

Finally, it was observed that for a specific manufacturer, it is beneficial to have smaller hub heights, despite the facts that the capacity factor increases as the hub height increases and the wind power densities increase with hub height as the wind speed increases. This is because the higher cost of the WECS with higher towers overcomes the benefit of greater capacity factors and wind power densities. Moreover, although the capacity factor is larger in small WECS than that in large ones [48], the specific cost per kW h is less in large systems due to the greater rated power that covers the loss in capacity factors.

6. Concluding remarks

A linear relation was observed between mean monthly power densities and the measured mean monthly wind speeds. Analysis of the “unit energy cost”, obtained for several wind turbines of different sizes and performed for every station, indicated that the cost per unit decreases hyperbolically as the rated power of the wind turbine increases. Finally, WECS with lower towers have a greater margin for profit.

Acknowledgement

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