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DISTRIBUTION FUNCTIONS AND THE ESTIMATION OF WIND POWER

Funkcije razdiobe i procjena energije vjetra

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Abstract — In this paper, different methods of wind speed frequency analysis are discussed, with a view to finding out the most appropriate method for the estimation of wind power potential. It is shown that in areas of pronounced topographic influence and strong Bura winds this estimation may not always be calculated with sufficient precision. Climatic wind data may be generally used for the estimation of wind power potential only with great caution and as a first approximation.

Key words: wind potential, wind speed distribution functions, Bura winds, Croatia

Sažetak — U ovom radu su razmatrane različite metode analize razdiobe brzine vjetra radi pronalaženja najpovoljnije metode za ocjenu vjetrovnog potencijala. Pokazujemo da se u područjima s izraženim orografskim utjecajem na strujanje vjetra i jakom burom takva procjena ne može provesti dovoljno precizno. Podaci klimatoloških postaja o vjetru mogu se za procjenu eolnog potencijala primijeniti samo s velikim oprezom, a tako dobiveni rezultati mogu poslužiti samo kao prva približnost.

Ključne riječi: potencijal energije vjetra, funkcije razdiobe brzine vjetra, bura, Hrvatska

1. INTRODUCTION

In the last several decades, an estimation of wind power potential has been made in many countries using different methods. In this country, as part of the scientific project "Investigation of the Energetic Potential of Wind Power in Croatia", the eolian potential and wind persistence in the mainland and Adriatic areas have been elaborated (D. Poje and B. Cividini, 1988; D. Poje, 1990; D. Poje, 1992; V. Vučetić at all, 1996).

In the process of estimation of wind power most researchers have used the Weibull distribution function for fitting data. The analysis of our wind data, especially of data from Bura[1] wind prone areas shows, however, that a "good" fitting curve can not be always represented by only one frequency distribution curve but by two or even three compound, overlapping curves. Wind power calculated on the basis of only one frequency function curve may sometimes results in quite erroneous values. This becomes even more obvious when usual methods of wind power calculation are used in the areas of strong Bura winds for shorter time intervals (months, seasons) and only one wind direction.

This paper presents the results of research based on a number of Croatian meteorological stations

[1] Bura is the Croatian name for a catabatic wind on the Adriatic coast, known otherwise as *Bora*.

with at least three years of anemograph data records. It is shown that a sufficiently precise estimation of the eolian potential at the investigated locations could not always be achieved with the usual distribution functions. In addition, a comparison of wind power estimation on the basis of three and 24 observations per day for selected stations is presented. Some considerations on interannual wind speed variability are submitted in the last chapter.

2. WIND DATA

In this paper, the hourly and 10-minute average wind speed and direction data from 26 meteorological stations in Croatia with anemograph records are analyzed. At most stations the wind sensor was located at an altitude of 10 m, while in some cases it was placed at the top of higher buildings. The meteorological tower at Konjsko had two measuring levels (at 10 and 50 m above the ground) recording 10-minute interval data. "R.FUESS" mechanical anemographs with a threshold of 1-1.5 ms^{-1} were in use at most stations. At stations no. 4, 11, 12, 21 and 24 (see Tab. 1) "90z" electrical anemographs of the same manufacturer with a threshold speed of 2 ms^{-1} were utilized. Sensitive electrical anemographs of the Slovenian manufacturer "J. Stefan" with a speed threshold of 0.5 ms^{-1} were used at stations no. 7, 8, 9 and 23.

Figure 1. Location of the anemograph stations in Croatia used in this paper.

Slika 1. Lokacije onih anemografskih postaja u Hrvatskoj, čiji su podaci upotrijebljeni u ovom radu.

For this study, data were also used from stations with a shorter period of records in order to get an insight into the wind regime at locations where no regular wind measurements are made and where the stations are representative of wider areas (location map Fig.1.).

Most inland stations are located at the outskirts of towns and are partly under the influence of built-up areas. On the Adriatic coast, the stations are mostly unrepresentative of wider regions due to the complex topography of the area. It should be added that at no location corrections for bad exposure to wind flow due to nearby obstacles were made and that that was one of the reasons for some of the irregularities and difficulties met in the analysis and interpretation of wind data. On the isolated mid-Adriatic islands, the wind sensors are well exposed to wind from all directions.

3. WIND SPEED DISTRIBUTIONS

Fig. 2 depicts the wind speed distribution at the selected stations analyzed in this study. The analyzed diagrams indicate that several types of distribution can be differentiated:

a) the *lowland type*, with a pronounced high percentage of calms and small wind speeds (Varaždin),

b) the *mountain type* of the Gorski kotar and Lika region, with mode values under 2 ms^{-1} and a weak Bura wind influence (Gospić),

c) the *mountain-coastal type*, with mode values under 4 ms^{-1} and a very strong Bura influence (Karlobag),

d) the *mixed type*, with mode values under 5 ms^{-1} and a combined influence of Jugo[2] and Bura winds (Lastovo).

The frequency distribution, especially that of the mountain-coastal type, indicates that at these sites

[2]Strong wind from the southeasterly quadrant on the Adriatic sea, in the Mediterranean area known as *sirocco*

Table 1. Basic data from anemograph stations.

Tablica 1. Osnovni podaci o anemografskim postajama.

No	Station	Altit. a.s.l. (m)	Height of anem. above gr. (m)	Aver. annual wind speed (m/s)	z_0 (m)	Per- -cen tage of calms (%)	Period of data used	Location description
1.	Osijek-airport	88	10	2,7	0,10	4,4	1980-1988	flat, open country
2.	Sl.Brod-airport	107	10	2,1	0,20	6,7	1966-1987	on the roof of a hangar
3.	Daruvar	161	10	1,4	0,30	10,7	1974-1980	hilly terrain, at outskirts
4.	Varaždin-airport	167	10	2,4	0,02	5,2	1976-1981	flat, open country
5.	Puntijarka	988	23	4,0	2,0	0,4	1975-1980	on a tower above the forested peak of Medvednica mountain
6.	Oborovo	101	12	1,5	0,05	10,7	1975-1987	flat, open country
7.	Jablan	650	10	2,4	0,17	1,4	1984-1985	hilly, forested terrain
8.	Plomin	5	40	4,2	0,17	1,8	1978-1982	at the top of the main building of a power plant
9.	Štrmac	340	33	5,4	0,05	0,03	1980-1983	hilly terrain, on top of a water tower
10.	Parg	863	11	2,3	0,17	0,7	1951-1956	hilly terrain, partly forest
11.	Pula-airport	67	8	3,0	0,02	2,2	1969-1985	flat, open country
12.	Krk-airport	85	9	2,6	0,02	9,1	1979-1986	gently rolling country
13.	Ostrovica	630	6	5,3	0,30	0,2	1976-1982	hilly, forested terrain
14.	Ogulin	328	10	2,1	0,17	2,4	1975-1984	outskirts of a small town
15.	Gospić	564	10	2,0	0,17	6,3	1966-1985	at the town outskirts
16.	Senj	26	16	5,9	0,60	0,1	1966-1981	on the roof of a large building in the city center
17.	Karlobag	30	10	4,0	0,17	0,2	1966-1971	hilly terrain, in a small town
18.	Zadar	5	10	3,3	0,17	0,4	1965-1968	at the town outskirts
19.	Šibenik	77	10	3,4	0,17	9,1	1977-1986	hilly terrain
20.	Split-Marjan	122	9	4,3	0,15	0,01	1966-1980	on the roof of a building on a forested hill
21.	Split-airport	19	7	2,5	0,05	5,7	1976-1985	on the runway, hilly terrain
22.	Sinj	298	10	3,3	0,17	0,1	1954-1960	at the town outskirts
23.	Konjsko	345	10,50	2,7	0,17	-	1989-1981	rolling terrain
24.	Dubrovnik-airport	164	10	4,7	0,02	0,3	1963-1979	on the runway, hilly terrain
25.	Lastovo	186	15	5,9	0,05	0,4	1976-1986	on a small hill top, on the coast
26.	Palagruža	98	8	6,6	0,17	0,5	1971-1982	at the top of a steep rock on a small island

we can discern two, sometimes three, overlapping compound wind speed distributions, which frequently make unsuitable the use of any known distribution function taken for all data combined. This is particularly visible at locations with strong Bura winds: Plomin, Ostrovica, Senj, Karlobag and partly also at Sinj, Konjsko, Split-Marjan and Šibenik.

Most analysts of wind speed data distributions have used different distribution functions, mainly the Weibull and Rayleigh functions, which have been also predominantly applied to the calculations of wind power potential. The basic idea behind the use of distribution functions for the estimation of wind characteristics is to eliminate as much as pos-

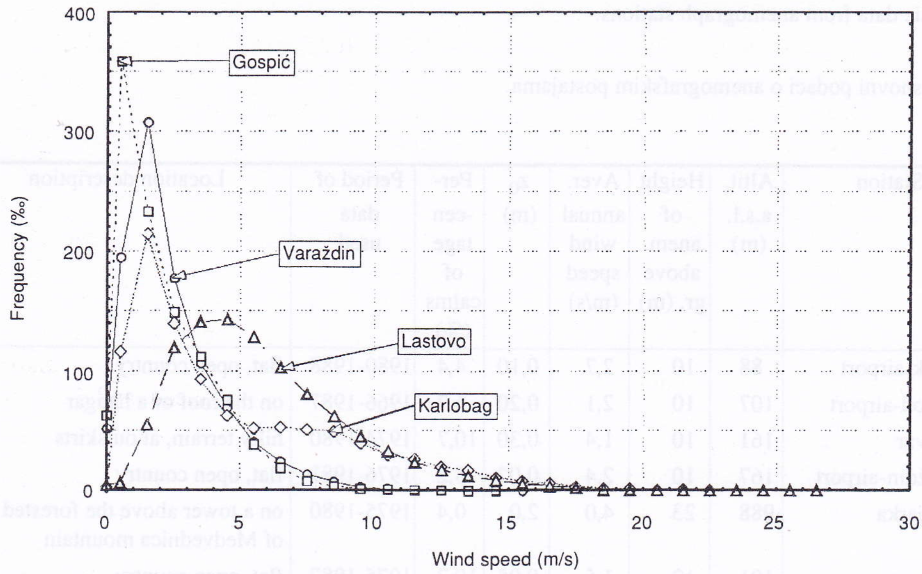

Figure 2. Typical wind speed distribution curves for different parts of Croatia.

Slika 2. Tipične razdiobe brzine vjetra u različitim dijelovima Hrvatske.

sible the irregularities in the measured frequency distribution. These irregularities mainly result from interruptions of measurements, short periods of data, instruments failure or the influence of the surrounding countryside. The other objective is to apply a model to extrapolate the wind characteristics of chosen locations to a wider area as was achieved in the *European Wind Atlas* (1988).

The seperation of wind data sets to multiple distribution wind subsets has first been realized by Essenwanger (1956). More recently Lisac (1984) applied his method to the wind direction data of the Zagreb-Grič observatory using the Gauss distribution function. Tabony (1983), in his wind data analysis in hurricane prone areas separates the parent and extreme value distributions which partially overlap. Essenwanger's method requires a lot of manipulating and fitting of data and could be hardly applied to a large number of separate wind data sets. In this work, we used the commercial PC program *Peakfit*[3] for, (hereinafter referred to as "*Peak.*"), which, generally rather simply and quickly automatically separates the wind speed data frequency curve into one, or two and more overlapping individual frequency curves. The data are sorted in speed classes of 1 ms^{-1}. This program operates with the Levenberg-Marquardt algorithm (D.W. Marquart, 1963) for a very efficient non-linear fitting and besides the coefficients for every function, calculates also the values of ρ^2, χ^2 and F statistics as measures of fitting efficiency. The program provides for the Weibull distribution function following characteristic parameters:

a) a_0 value of amplitude (highest value in the point of mode)

b) a_1 value of center (abscisse value of the point of mode)

c) a_2 value of with1 (measure of the width of the curve)

d) a_3 value of with2 (measure of the width of the curve)

and the Weibull function has the following form:

$$f(x) = a_0\left[\frac{a_3-1}{a_3}\right]^{\frac{a_3-1}{a_3}}\left[\left(\frac{x-a_1}{a_2}\right)+\left(\frac{a_3-1}{a_3}\right)^{\frac{1}{a_3}}\right]^{a_3-1} exp\left[-\left[\left(\frac{x-a_1}{a_2}\right)+\left(\frac{a_3-1}{a_3}\right)^{\frac{1}{a_3}}\right]^{a_3}+\left[\frac{a_3-1}{a_3}\right]\right] \quad (1)$$

[3] Jandel Scientific, microcomputer tools for scientists, USA

The "classical" two-parameter Weibull distribution function is used in the expression:

$$f(x)=\frac{k}{a}\left(\frac{x}{a}\right)^{k-1} exp\left[-\left(\frac{x}{a}\right)^{k}\right] \quad (2)$$

where k stands as the shape factor and a as a scale factor (according to the notation in the *European Wind Atlas*).

Of this program, we used the following statistical distribution functions: the Gaussian, Log-normal, Weibull, Extreme-value, Gamma and Beta functions. We found which function best fits the wind speed data frequencies for each of the 26 sets of yearly wind speed distributions with or without separating the data into two or three frequency distributions subsets.

Table 2 reveals that the best fitting of wind speed data, when taking in the account only one distribution, was achieved at 11 stations with the Gama function and at 8 stations with the Log-normal function. If the wind data are separated by the *Peak.* program into two separate overlapping distributions, the best results in fitting data can be accomplished by the Weibull and Gama functions. For locations with generally low wind speeds, good results can be obtained by the Log-normal function. It should be noticed, however, that in general the difference in fitting efficiency expressed as ρ^2 is quite small, while it is sufficiently great for χ^2 (Table 3.). Having in mind that at nearly all coastal locations (where the greatest wind potential can be expected) a negligible number of calms occurs, we did not try to implement the hybrid Weibull distribution function as proposed by Takle and Brown (1978). In the case of the lowland station of Slav. Brod (with a small wind potential) the difference between the distribution functions is very pronounced, and there such procedure would probably be justified.

In the course of data fitting we sometimes had to smooth the frequency distribution to some degree by polynomial interpolation in order to eliminate small secondary peaks which originate mainly at locations with short record periods of or with interruptions in wind data set.

In our earlier investigations of the eolian potential we used the *Maxfit* program (T. Fitz-Simons, D.M. Holland, 1979) to determine the k and a coefficients in the Weibull distribution function. This programme uses the maximum likelihood approach to fit the Weibull function to the data (K. Conradsen,

Table 2. Fitting efficiency for different distribution functions for the annual wind speed frequency distributions at selected Croatian stations.

Tablica 2. Uspješnost prilagodbe pojedinih funkcija razdiobe za godišnje čestine brzine vjetra izabranih hrvatskih postaja.

	Gaussian	Log-norm.	Weibull	Extr. value	Gama	Beta
One distribution	-	8	2	-	11	6
Two distribution	-	4	7	3	5	3

Table 3. Statistics of fitting efficiency for the annual frequency of wind speed distribution at the Slavonski Brod station.

Tablica 3. Statistika uspješnosti prilagodbe za godišnju čestinu razdiobe brzine vjetra za postaju Slavonski Brod.

	Statistics	Gauss	Log-n.	Weibull	Extreme	Gamma	Beta
One distrib.	χ^2	998,4	710,6	156,2	273,6	133,7	101,0
	ρ^2	0,9931	0,9951	0,9989	0,9981	0,9991	0,9993
Two distrib.	χ^2	71,9	7,6	0,41	17,6	0,15	50,9
	ρ^2	0,9995	0,9999	1,0	0,9999	1,0	0,9996

L.B. Nielsen, 1984) and estimates in particular coefficients for only one frequency distribution. As a result, in some cases, when there are undoubtedly at least two subsets of wind speed data in measured frequencies, a large difference occurs in certain speed classes between the calculated and measured frequencies. This can be best illustrated by an example based on the Senj station data to which both the *Peak* and *Maxfit* programs have been applied for one and two distributions (Fig. 3, Fig. 4.)

Figure 3. depicts the measured and *Maxfit*- and *Peak*. calculated annual wind speed frequencies for the Senj station in speed classes of 1 ms^{-1}. It can be noticed that in the area of weak winds the fitting of data is poor for both programs and the same is true also for the speed range between 9 and 16 ms^{-1}, where both programs give too low frequency values. On the other hand, in the range of 5 to 7 ms^{-1}, Maxfit results in frequency values over 20% higher than the measured values. In the area of very great speeds (>17 ms^{-1}) both programs come quite near to the measured values.

The capability of *Peak.* to separate wind speed subsets is well illustrated in Fig. 4. The first subset covers the range between 0 and 11 ms^{-1} and the second one the range between 3.5 and 22.5 ms^{-1}. The sum of both subsets results in a frequency curve which almost completely approximates the measured frequencies.

The procedure of separating wind speed frequencies into separate frequency subsets has been applied also to sets of wind speed frequencies from other stations and many interesting features of wind regime could be discerned. We pointed out the results of this technique in the study on Bura and Burin at Split (D. Poje, 1996).

It should be mentioned here that at locations with stronger winds, and where there are no distinctive topographic influences, the frequency distributions can be highly effectively fitted with only *one* Weibull distribution function. A typical example of this are the data of the Lastovo station, which is situated on a hill on a small island in the southern Adriatic, where calculated data almost do not differ from the measured ones.

4. WIND POWER

Due to its high degree of fitting to measured data, the Weibull distribution function is widely

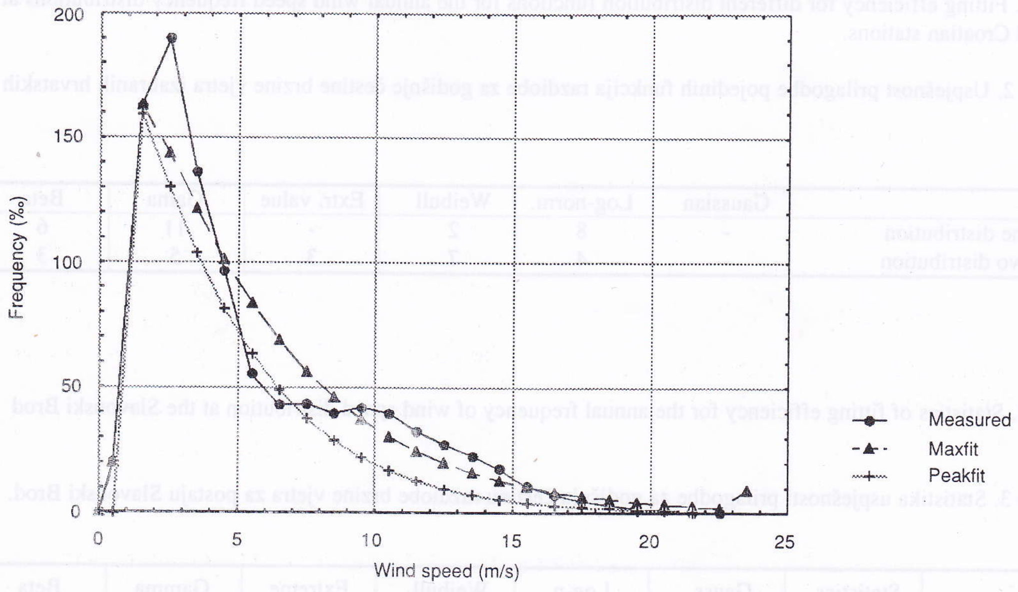

Figure 3. The fitting of annual wind speed frequency data from the Senj station using the *Maxfit* and *Peakfit* programs.

Slika 3. Prilagođavanje podataka godišnje čestine brzine vjetra postaje Senj upotrebom programa *Maxfit* i *Peakfit*.

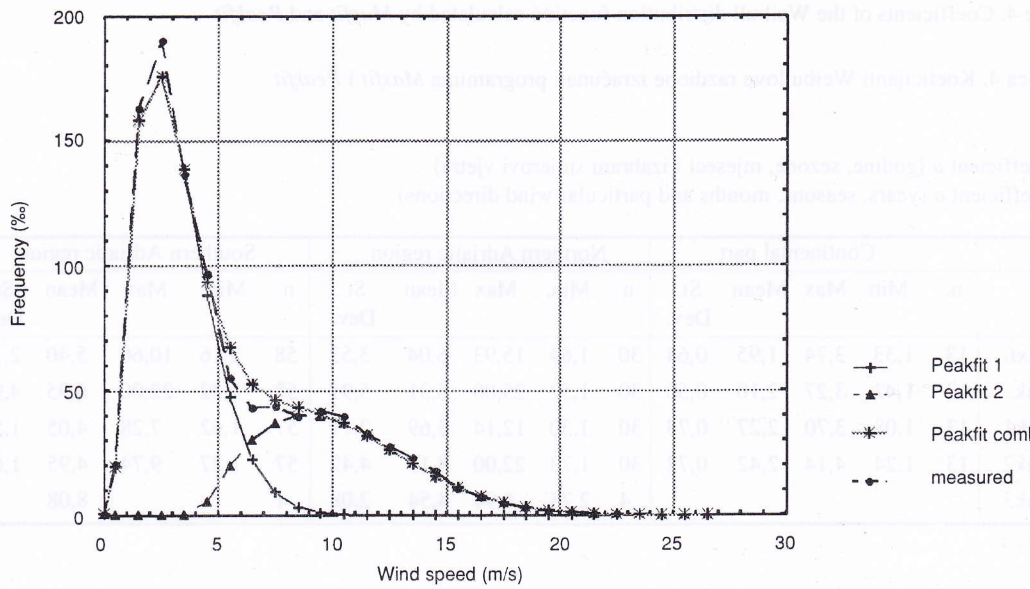

Figure 4 as Fig. 3 but with *Peak* - calculated frequencies for two separate overlapping curves, and the curve combining the two separate frequency curves.

Slika 4. Kao na sl. 3, no čestine su izračunate programom *Peakfit* za dvije odvojene preklapajuće krivulje; krivulja koja kombinira te dvije posebne krivulje čestina.

used in the estimation of wind power. Wind power is usually expressed as:

$$\frac{P}{At} = \frac{1}{2}\frac{mv^2}{At} = \frac{1}{2}\rho v^3 \qquad (3)$$

where P = instantaneous or hourly power density in Wm^{-2}

A = swept area of wind generator in m^2

v = instantaneous or average hourly wind speed in ms^{-1}

ρ = air density in kgm^{-3}.

The Weibull distribution function is widely used for the determination of wind power with the following expression:

$$P = \frac{1}{2}\rho a^3 \Gamma\left(1+\frac{3}{k}\right) \quad (W\,m^{-2}) \qquad (4)$$

where Γ stands for the Gama function and the a and k coefficients are estimated by some fitting procedure of the Weibull function to measured data. Both the *Maxfit* and *Peak.* programs were used to estimate these coefficients in 101 sets of frequency distribution data including also seasonal, monthly, and for Bura characteristic wind speed data from several stations.

In expression (4) the air density was ascertained by the following expression:

$$\rho = \frac{0.384p}{T} \qquad (5)$$

where p stands for the average air pressure in hPa and T is the absolute temperature in °K. These values were calculated as mean values for the same periods for which the wind data were elaborated. To find out if air density depends on wind speed, the January 1977 wind speed data set of the Lastovo station were tested and no dependence was found. For all 744 average hourly wind speed data the following relation was found:

$$\rho = 1.632 - 0.002\,v \qquad (6)$$

where v stands for average hourly wind speed; $r = -0.390$; $p = 0.000$. An even smaller interdependence was found in the set of average yearly and monthly data of the Croatian stations considered in this work (84 cases),:

$$\rho = 1.320 + 0.003\,v\,,\quad r = 0.119,\quad p = 0.072 \qquad (7)$$

Table 4. Coefficients of the Weibull distribution function calculated by *Maxfit* and *Peakfit*

Tablica 4. Koeficijenti Weibullove razdiobe izračunati programima *Maxfit* i *Peakfit*

a) koefficient *a* (godine, sezone, mjeseci i izabrani smjerovi vjetra)
a) coefficient *a* (years, seasons, months and particular wind directions)

	Continental part					Northern Adriatic region					Southern Adriatic region				
	n.	Min	Max	Mean	St. Dev.	n	Min.	Max	Mean	St. Dev.	n	Min.	Max	Mean	St. Dev.
Maxf.	13	1,33	3,74	1,95	0,64	30	1,64	15,93	6,04	3,53	58	2,16	10,60	5,40	2,14
Peak.	13	1,42	3,27	2,10	0,50	30	1,52	25,00	6,31	5,91	58	1,32	22,00	6,95	4,90
Peak1	13	1,08	3,70	2,27	0,73	30	1,30	12,14	3,69	2,11	57	1,62	7,28	4,05	1,56
Peak2	13	1,24	4,14	2,42	0,72	30	1,73	22,00	8,13	4,42	57	1,27	9,74	4,95	1,63
Peak3						4	2,73	6,94	4,54	2,08	1			8,08	

b) koefficient *k* (godine, sezone, mjeseci i izabrani smjerovi vjetra)
b) coefficient *k* (years, seasons, months and particular wind directions)

	Continental part					Northern Adriatic region					Southern Adriatic region				
	n.	Min	Max	Mean	St. Dev.	n	Min.	Max	Mean	St. Dev.	n	Min.	Max	Mean	St. Dev.
Maxf.	13	0,93	1,53	1,14	0,16	30	0,80	3,28	1,33	0,62	58	0,86	3,12	1,61	0,48
Peak.	13	1,01	1,67	1,29	0,20	30	1,03	3,99	1,145	0,80	58	0,72	5,40	2,04	1,24
Peak1	13	1,86	2,98	2,09	0,72	30	1,40	3,12	1,97	0,52	57	1,19	5,03	2,26	0,75
Peak2	13	1,12	2,10	1,52	0,30	30	1,07	10,74	2,76	1,96	57	1,28	7,27	2,17	1,15
Peak3						4	1,53	2,87	2,10	0,56				1,86	

The Weibull function coefficients in any one frequency wind speed data set were determined by *Peak.* by fitting to this data set one or two or even three frequency subsets, whichever gave the best results. As opposed to the *Maxfit* program, where the determination of coefficients is simple and unambiguous, the *Peak.* procedure is sometimes tedious and may produce unrealistic results, especially for locations with strong topographic influence and for shorter observation periods. We determined the *a* and *k* coefficients for the three main parts of the country and found a rather large range of these coefficients on the Adriatic coast and on the islands.

In Tab. 4 the values of the *a* and *k* Weibull's coefficients calculated by *Maxfit* and *Peak.* (for the whole set and subsets 1, 2 and 3) are presented. The inland regions of Croatia show a small differences in the *a* and *k* coefficient values estimated by *Maxfit* and *Peak.* Larger differences in a values occur in the southern Adriatic regions with stronger winds. Very high values of this coefficient (up to 25.0) have been found at locations with strong Bura winds during the winter months. In the southern Adriatic region the mean annual value of coefficient *a*, as estimated by *Peak.*, is somewhat greater than the one estimated by the *Maxfit* program and its maximal value may attain 22.0.

To determine wind power we have applied expression (4) using the estimated values of the *a* and *k* coefficients derived by the *Maxfit* and *Peak.* programs for the wind frequency data as a whole and for two or three overlapping subsets. The obtained values of wind power have been compared with the values of wind power calculated from measured frequency data ("true wind power") using the expression

$$P = \frac{1}{2}\bar{\rho}\frac{1}{n}\sum_{i=1}^{j} f_i v_i^3 \qquad (8)$$

where f_i stands for wind frequencies in the speed classes of 1 ms^{-1}, v_i are the middle values of the speed classes i, n is the total number of data used and $\bar{\rho}$ is the average air density. For the sake of brevity we are presenting here (Table 5) only the main statistical characteristics of the values of wind power at 30 stations in the three main regions of the country.

Table 5 illustrates the basic wind power statistics of elaborated wind speed frequencies with different method data for selected stations in Croatia. The calculated values of wind power at 10 m are in a wide range from a few Wm^{-2} in the lowland continental areas to several thousand Wm^{-2} in the coastal regions, in winter, during strong Bura winds. The *Maxfit* program results show values closer to the measured data (in Table 5 "true windpower") than the results of *Peak.* elaborated data. The values denoted as elaborated by *Peak1*, *Peak2* and *Peak3* are the calculation results for the first, second and third subsets of data in all cases. The values denoted as *PeakΣ* represent the results achieved by the summation of the wind power values of all two or three subsets combined. The difference between the values calculated by different programs which are of greater importance in the evaluation of wind potential can be seen on Tab. 6. This table explains those differences, in all cases, when true wind power at some stations was smaller than 1000 Wm^{-2}. This practically includes all the cases on the Adriatic with the exception of winter cases on the Northern Adriatic region with strong Bura winds.

Generally speaking, and taking into consideration also the cases with stronger katabatic winds and smaller time intervals, the *Maxfit* program calculations result in values closer to the realistic wind power values defined by expression (8). If one calculate only one distribution curve in *Peak* the results may be quite errenous, especially in strong Bura prone areas.

Table 5. Wind power (Wm^{-2}) at selected stations in Croatia calculated by different methods (years, seasons, months, Bura wind directions).

Tablica 5. Snaga vjetra (Wm^{-2}) na izabranim postajama u Hrvatskoj izračunata različitim metodama (godine, sezone, mjeseci, smjerovi vjetra bure).

	n	Min.	Max.	Mean	St. dev.
Maxfit	103	6,3	2714,9	364,3	516,9
Peak	103	6,2	9943,3	782,6	1683,7
Peak1	102	1,9	1296,8	90,2	157,3
Peak2	102	0,1	6661,3	340,6	922,5
Peak3	1	19,2	230,9	110,1	102,5
PeakΣ	103	13,4	7958,2	435,1	1045,4
True power	103	7,6	1237,5	296,4	274,3
Rev. Peak.	103	11,1	7916,1	430,7	1040,3

Table 6. Differences betweenvalues calculated by *Maxfit* and *Peakfit* and "true" wind power values (Wm^{-2}).

Tablica 6. Razlike između vrijednosti izračunatih programima *Maxfit* i *Peakfit* i "prave" vrijednosti snage vjetra (Wm^{-2}).

	N	Min.	Max.	Mean	St. dev.
Maxfit	96	-286,8	117,2	3,4	58,5
Maxfit%	96	-110,5	46,9	6,1	23,7
Peak	96	-6117,1	503,1	-251,9	1042,7
Peak%	96	-2202,1	88,4	-1345,0	481,8
Peak.Σ	96	-151,5	145,8	-5,1	47,2
Peak.Σ%	96	-295,3	36,4	-16,0	46,9

Here are some examples of *Maxfit* results for wind speed frequency cases with Bura wind direction at some Adriatic stations. For Ostrovica, in winter, the difference from "true" wind power value is -880.3 Wm^{-2}, at Senj, in February it is -1215.7 Wm^{-2}, at Karlobag, in winter, the difference is -1604.4 Wm^{-2} and at Lastovo, also in winter, this difference is 117.2 Wm^{-2}. At all other locations the difference is mainly under 50 Wm^{-2}. On the other hand, the difference resulting from the *Peak.* program, including the resolving of data into two subsets are much greater: the average difference amounts to -16.0 Wm^{-2} and the negative difference may reach up to 6117.1 Wm^{-2} i.e. to quite unrealistic result!

Having in mind that for the estimation of wind power at heights above anemograph measuring levels the only known expressions are those which use the a and k coefficients of the Weibull distribution function, we have tried by different methods to combine the values of the subset coefficients a_1 and a_2 into a, as well as k_1 and k_2 into k for all cases when these values were determined by *Peak.*, but no acceptable results were achieved.

In the 96 analyzed cases of wind speed frequency, when the "true" wind power was less than 1000 Wm^{-2} it was possible to improve somewhat the values of wind power estimated by *Maxfit* or *Peak.* by using the following relations:

$$\text{for } Maxfit\text{: } P=-8.122+2.968\ P^{0.822}{}_{(Maxfit)} \qquad (9)$$
$$r = 0.9672$$

$$\text{for } Peak.\text{: } P=-20.687+1.590\ P^{0.930}{}_{(Peak.\ comb.)} \qquad (10)$$
$$r = 0.9647$$

In expression (9) $P_{(Maxfit)}$ stands for the wind power derived first by calculation of the Weibull characteristics by *Maxfit* and then by using relation (4). $P_{(Peak\ comb)}$ is the wind power calculated first by using *Peak* for calculation of the Weibull characteristics of wind data separated in two subsets and then by using relation (4) and summing up the wind power values elaborated for each subset.

The difference between the values elaborated in such a manner and the values of "true" wind power thus become much smaller in average, although in some cases they may attain unacceptable high values. (See Tab. 7).

The analysis of all 15 cases estimated by *Maxfit* where the difference was greater than $|50|$ Wm^{-2} indicates that such distributions occur in winter in areas with Bura winds (6 cases) and also at other locations with stronger winds in the colder part of the year (winter months in Lastovo and Senj - 5 cases). Such differences were also found in the annual frequencies of Konjsko and Plomin, regardless of wind direction. This suggests that, in some cases, the estimation of wind power in areas with strong Bura winds can not always be reliably elaborated by this program. The same is even more true for *Peak*.

5. DISCUSSION

The applicability of the Weibull distribution function to the fitting of wind speed data has been analyzed by many authors. In our opinion, for most purposes, the use of the Weibull distribution function could well serve for the estimation of wind power potential although there are locations at or near the Adriatic coast where its use may sometimes, even for a large wind data set, result in unacceptably large errors. Even though one could

Table 7. Differences between wind power values estimated by *Maxfit* and *Peakfit* and "true" wind power values (all cases with "true" wind power less than 1000 Wm^{-2}).

Tablica 7. Razlike između vrijednosti snage vjetra procjenjene programima *Maxfit* i *Peakfit* i pravih vrijednosti snage vjetra (svi slučajevi s pravom snagom vjetra manjom od 1000 Wm^{-2}).

	n	Min.	Max.	Mean	St. dev.	p= 0.9500 Upper limit	p=0.9500 Lower limit
Maxfit	96	-225,9	104,0	-0,04	51,3	10,4	-10,4
Maxfit%	96	-106,5	38,3	-3,96	23,7	0,8	-8,8
Peak.Σ	96	-151,4	148,0	-0,004	46,9	9,4	-9,4
PeakΣ%	96	-223,2	137,9	-3,75	45,7	5,5	-13,0

Table 8. Fitting efficiency of different distribution functions, Ostrovica, winter, Bura winds (ENE), 10% smoothed, (the "true" wind power is 1237 Wm^{-2}).

Tablica 8. Uspješnost prilagodbe različitih funkcija razdiobe, Ostrovica, zima, za puhanja bure (ENE), 10% glađeno ("prava" vrijednost snage vjetra jest 1237 Wm^{-2}).

	Gauss	Log. norm.	Weibull	Weibull Peak comb.	Extreme	Gama	Beta	Weibull (revis. Maxfit)
χ^2	975,91	1710,13	974,69	19,145	1262,6	1084,50	**636,80**	
r^2	0,68432	0,44681	0,68471	0,99381	0,59157	0,64919	**0,7940**	
P (Wm^{-2})	1974,7	1061,5	1796,2	2612,6	1377,4	2309,7	**1262,1**	1595,0

achieve better fitting to measured data by resolving the wind distributions into several subsets by using the *Peak.*, this does not mean that a better estimation can generally be achieved by this method. Although we have found that the use of the Gama and Beta distribution functions in the estimation of wind potential may sometimes result in better fitting efficiency, in general the results were not promising and no sound evidence could be found for the preference of using these two functions. We shall illustrate this with the case of the Ostrovica station, for ENE winds in winter (Bura), with data smoothed by 10%.

The application of different distribution functions may sometimes result into quite divergent values of wind power. In this case, the best fitting of data was achieved by the Beta function, and the sum of the wind power values of three subsets determined by Weibull coefficients gave a quite unrealistic value of 2613 Wm^{-2}! Similar results were also found in some cases of other Bura influenced regions, which again indicates that it is not always possible to get realistic results by the discussed methods. In our opinion, the estimation of wind power for selected directions in complex terrain or at locations with pronounced Bura winds can be problematic and should be done with the greatest care.

6. INTERANNUAL WIND SPEED CHANGES

In the period considered in this study (1950-1986) the wind data sets were of different length and from different parts of that time interval. For the stations in the continental part of Croatia, the interannual changes of average wind speed are relatively small, up to 0.5 ms^{-1}. At the stations on the Adriatic coast or in its the vicinity, at stations which are exposed to the influence of Bura winds, these changes may attain values of 1.6 ms^{-1} but most of them lie in the range between 0.7 and 1.1 ms^{-1}. In the southern Adriatic area, these changes are much smaller and rarely attain 0.9 ms^{-1}. Having in mind that wind power depends on the cube of the mean wind speed, a greater interannual difference in wind speed mean also greater changes of mean wind power. It is reasonable, therefore, to suppose that in the continental part of Croatia wind power potential can be estimated from a shorter period of wind speed data (a few years) while in areas of stronger winds, especially in the areas of strong Bura and Jugo winds, longer periods of wind data are needed -at least 5 years. If the mean annual wind speed in the chosen period is by only 1 ms^{-1} stronger than the speed in the longer period, we may get a wind power by 100 Wm^{-2} greater than if it were calculated on the basis of a "normal" period, let us say 10 years.

7. ESTIMATION OF WIND POWER WITH FEW DAILY WIND OBSERVATIONS

The possibility of determination od the average wind speed, and thereby of wind power with a limited number of daily wind observations is of primary importance in those areas where there are no continuous, 24-hour wind measurements. Corotis (1977) has shown that the amount of wind data for the calculation of average wind speed may be considerably smaller than a set of hourly or 3-hourly wind speed data. Jong and Thoman (1981) have considered the difference between mean wind speeds on the basis of only two (6 and 15 hour) and one (6 or 15 hour) observation per day. They have found that calculations based on only one observation per day differ from the "true" mean by as much as 17%, while a mean combined from two observations results in a difference of only 2%. If a combined mean is at disposal for every three hours then the application of such a mean results in the required accuracy of 5%. A recent study by Katsoulis (1993) is based on three daily climatological data from 42 Greek meteorological stations and it ends with the statement that the mean wind speed based on three daily observations is smaller than the true mean by 10% at all stations and therefore that climatological data may be used for the estimation of wind potential.

Although there is a large number of climatological stations in the Adriatic area, we considered it necessary to investigate first, on the basis of a limited number of anemograph stations, the difference between the mean annual wind speed based on three mean hourly observations per day (7, 14 and 21 hour) and the "true" mean wind speed based on 24 hour observations. The analysis included inland stations (Sl. Brod, Oborovo, Ogulin) and stations on the Adriatic area (Senj, Zadar, Šibenik, Split-Marjan, Dubrovnik-airport, Lastovo). For most stations the difference found is ± 0.1 ms^{-1} (- 0.2 ms^{-1} - only at Dubrovnik and Lastovo) and this difference may be considered as negligible. We further investigated by *Maxfit* the annual wind power values for the Senj station for all data for three different wind speed class divisions: 1 ms^{-1}, 2 ms^{-1} and the wind speed classes according to the Beaufort scale. The result showed no difference from the "true" value of wind power of 430 Wm^{-2} for the data set in the Beaufort speed classes; a 10 Wm^{-2} smaller value was found for the data set in the 2 ms^{-1} classes, and a 30 Wm^{-2} lesser value for the set in 1 ms^{-1} classes. There is, however, no indication that this result is generally valid.

The application of mean wind speed based on three observations per day instead of 24-hour mean wind speed values increases the difference between the "true" wind power values and those values estimated by a modified *Maxfit* program from 15.9% to 23.9% at continental stations and from 10.0 to 10.9% in the Adriatic area. The maximal absolute differences amount to 28.3% in the interior of Croatia and to 35% in the Adriatic area. The results achieved by the use of a modified *Peak* expression for wind power are significantly worse: in the Adriatic area the differences lie between 51.5% and 96.8% and the maximal differences may attain 167%. Having in mind that at climatological stations wind force is estimated subjectively by means of the Beaufort scale, *it is justified to assume that the evaluation of wind power potential on the basis of climatological data in our country may produce errors much greater than the acceptable 5% and may therefore be applied only as a preliminary and approximative procedure.*

8. CONCLUSION

The estimation of wind power potential on the basis of a large number of anemograph stations in Croatia revealed that in the areas with strong Bura winds there is no unique procedure of computation by existing methods and that no method can be generally used to achieve satisfactory results. An analysis of the possible use of several distribution functions in the determination of wind power potential indicates that the Weibull function is the appropriate choice in most cases but may sometimes lead to a large difference from the "true" wind potential. **The application of the *Maxfit* program for the determination of Weibull coefficients and, further, for the estimation of wind power potential gives better results than the application of the *Peakfit* program, even if two or three subsetwind frequencies are determined. Climatological wind data may be used only for an approximative estimation of wind power potential.**

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REFERENCES

Poje D. and B. Cividini,1988: Assessment of the wind energy potential in Croatia *Solar Energy*, **41**, 543-554.

Poje D., 1990: Wind persistence on the Adriatic *Papers* of Republ. Hydrometeor. Institute, Zagreb **25**, 49-60.

Poje D., 1992: Wind persistence in Croatia *Int. Journal of Climatology*, **12**, 569-589.

Vučetić V., A. Bajić, M. Viher, 1996: Local winds in the mountain area of Croatia, ICAM 96, Bled, 217-224.

Essenwanger O., 1956: Neue Methode der Zerlegung von Häufigkeitsverteilungen in Gaussschen

Normalkurven und ihre Anwendung in der Meteorologie *Berichte des Deutschen Wetterdienstes*, Nr. 10. 11 pp.

Lisac I., 1984: Vjetar u Zagrebu (Wind in Zagreb) *Geofizika*, **1**, 47-134

European Wind Atlas, 1988: Roskilde, 600 pp.

Tabony R.C., 1983: Extreme value analysis in meteorology, *The meteorooogical magazine*, 77-98.

Marquart D.W., 1963: An algorithm for least square estimation of nonlinear parameters, Journal of the Society for industrial and applied mathematics, **2**, 431-441.

Takle E.S., J.M. Brown, 1978: Note on the use of Weibull statistics to characterize wind speed data, *Journal of applied meteorokogy*, **17**, 556-559.

Fitz-Simons T. and D.M. Holland, 1979: The maximum likelihood approach to probabilistic modeling of air quality data, EPA-600/4-79-044, p. 33.

Conradsen K., L.B. Nielsen, 1984: Review of Weibull statistics for estimation of wind speed distributions, *Journal of climate and applied meteorology*, **23**, 1173-1183.

Poje D., 1996: Bura (Bora) and Burin at Split *Hrvatski meteorološki časopis*, **30**, 1-19.

Corotis R.B., A.B. Sigl, M.P. Cohen, 1977: Variance analysis of wind characteristics for energy conversion *Journal of applied meteorology*, **16**, 1149-1157.

Jong M. and G. Thoman, 1981: Sampling wind data for mean wind speed estimation *Journal of applied Meteorology*, **20**, 323-327.

Katsoulis B., 1993: An approach of wind energy along the Greek coasts and islands *Meteorologische Zeitschrift*, 220-223.