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WIND PERSISTENCE AT THE ADRIATIC
Perzistencija vjetra na Jadranu

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Abstract: Using anemograph data from 8 stations in the Adriatic area and two stations in the interior of Croatia the main characteristics of wind persistence were delineated. For several thresholds of wind speeds the mean duration of continuous wind blowing and values of 90%, 99% and maximal duration of all cases are presented. For all duration of wind runs the simple function y = A + B/x could be used which connects the probability of occurrence y with the chosen duration of wind run x in hours, and coefficients A and B may be determined by several nomograms and by the annual wind speed. In the last chapter of the work results on wind direction persistence are also presented.

Key words: Wind persistence, Adriatic

Sažetak: Na temelju anemografskih podataka 8 stranica na Jadranu i dvije stanice u unutrašnjosti Hrvatske nađene su osnovne karakteristike perzistencije vjetra. Za nekoliko pragova brzine vjetra predstavljeni su srednje trajanje neprekidnog puhanja vjetra kao i vrijednosti 90%, 99% te maksimalno trajanje za sve slučajeve. Za sva trajanja kontinuiranog puhanja vjetra nađena je jednostavna funkcija y = A + B/x, koja povezuje vjerojatnost pojave y s izabranim trajanjem kontinuiranog puhanja x u satima. Upotrebom nekoliko nomograma mogu se odrediti koeficijenti A i B pomoću srednje godišnje brzine vjetra. U zadnjem poglavlju rada iznose se neki rezultati perzistencije vjetra po smjeru.

Ključne riječi: Perzistencija vjetra, Jadran

1. INTRODUCTION

In the scope of large investigations on the eolian potential in Croatia which have been carried out lately within the framework of the scientific research project "Utilisation of Solar Energy" the main facts on the possibilities of wind energy utilisation in this part of Yugoslavia were explored. The Socialist Republic of Croatia covers a large part of northern Yugoslavia and the greatest part of Adriatic coast with its islands. As reported in earlier works (1), (2), the eolian potential was exploited only with small wind generators at a few locations, and has only lately been investigated for larger number of locations in Croatia.

The territory of Croatia is situated in a moderate zone with a continental climate in the mainland and a modified Mediterranean climate along the Adriatic coast. This area is frequently under the influence of cyclonic disturbances coming from the W and SW, and of large anticyclones with their center in the NE part of the European continent (3). Under the influence of these baric systems as well of local circulations in the Adriatic basin, wind systems are established which manifest themselves as rather steady winds of moderate force, which may last for several days.

The purpose of this work is to illuminate as completely as possible the problem of wind persistence in the Adriatic space, primarily from the aspect of utilisation of wind energy. In this sense this work is a continuation and supplement to earlier recently published work (4). In our opinion it is necessary for a complete assessment of eolian potential of an area to have not only the facts on wind power but also the knowledge on wind persistence relative to the probability of the number of hours during which the aerogenerator would continuously work under the influence of wind of a specified velocity threshold. Closely connected with this is the question of what the probability is that the aerogenerator will be out of work due to weak wind or calms. The problems caused by these wind conditions could be solved by a special system of energy storage or by a hook-up to other energy sources or connection to the power grid. It is known that in areas where such interruptions of aerogenerator use may be expected longer than 24 hours, existing electricity storing systems are not economicaly justified (5).

2. WIND DATA

As basic data for investigation of wind persistence on the Adriatic, anemographic data were used for comparison from 8 stations on the coast and 2 stations in the interior. The average hourly wind direction and speed data were elaborated and with the exception of the Rijeka station all sets of wind data have a length between 10 and 22 years (see Tab. 1.).

Table 1. Basic data on selected anemograph stations in Croatia.
Tabela 1. Osnovni godišnji statistički podaci o izabranim anemografskim stanicama u Hrvatskoj.

Ord. number	Station	Altitude above sea level m.	Anemograph's height m.	Average wind speed m/s	Data used	Description of location
1.	Slavonski Brod	107	12	2.1	1966-1987	flat, open terrain
2.	Ogulin	328	10	2.0	1965-1984	outskirts, on the roof of a small building
3.	Rijeka-city	120	10	1.9	1979-1986	outskirts, hilly terrain
4.	Pula-airport	67	8	2.9	1968-1985	flat, open terrain
5.	Senj	26	16	5.9	1966-1981	in the city's center on the roof of a large building
6.	Šibenik	77	10	3.4	1977-1986	hilly terrain
7.	Split-Marjan	122	9	4.5	1966-1987	hilly terrain, on the roof
8.	Dubrovnik-Čilipi (airport)	164	10	4.8	1963-1975, 1978	at runway, hilly terrain
9.	Lastovo	186	15	5.8	1975-1986	at the top of a hill by the coast
10.	Palagruža	98	8	6.6	1971-1975, 1978-1982	at the top of a steep hill of a small island

Fig. 1. Locations of anemograph stations used in this paper.
Sl. 1. Lokacije anemografskih stanica, korištenih u ovom radu.

The data of Tab. 1. show that the majority of stations are located at city borders, at exposed locations on islands and airports, respectively. It is therefore impossible to assert that the majority of stations are typical for the wind regime of the larger area. In our opinion however the obtained data may be used for the assessment of wind persistence on the Adriatic, especially for those wind conditions when the wind generator can not operate due to calm or weak wind. In addition, there are interruptions in wind data, but we are not able, as yet, to assess at what measure these discontinuities influence the characteristics of wind persistence. With regard to the fact that all cases of calms and weak winds are covered in one interval i.e. with the set of data of winds v < = 3.0 m/s in our research, the different anemograph sensitivity thresholds should not have any impact on our results.

3. MAIN FEATURES OF WIND PERSISTENCE

Having in mind the selected threshold of aerogenerator (3-3.5 m/s) as well as threshold for the rated power of wind generators the following thresholds of uninterrupted wind run duration are selected: v <= 3.0 m/s, v > 3.0 m/s, v > 5.0 m/s, v > 8.0 m/s, v > 12.0 m/s, v >18.0 m/s. For each of these intervals the well laid-out tables of continuous duration in hours for a year as a whole are calculated by computer for all stations and for the Split-Marjan station for all seasons. An example of a basic wind persistence table for the Šibenik station is given in Tab. 2.

At the Šibenik station on the basis of anemograph records it was ascertained that in extremely rare situations, uninterrupted duration of wind with speed v < = 3.0 m/s may last as many as 7.5 days, at wind speeds over 12.0 m/s up to 14 hours. The basic characteristics of wind persistence may be reviewed on Tab. 3.a) to 3.j). These tables present the mean duration of the winds of the specified intervals when the wind blew at least one or three hours, and futhermore they show data on duration on uninterrupted wind duration, including 90% or 99% of all cases; the absolute longest continuous duration, expressed in hours, is also given.

Tab. 3. shows the mean duration which refers first to the average duration in hours when the wind for the particular speed class had blown continuously at least one hour. The most unfavorable conditions for the work of the aerogenerator (v < = 3 m/s) exist in the area of Rijeka and its immediate vicinity where such wind conditions may last even up to 16 hours. How long these unfavorable conditions for aerogenerators may last is also shown by the statistics of maximal measured "calms" of more than 12 days and the fact that 90% of such wind conditions have uninterrupted

Table 2. Yearly absolute frequencies of continuous wind run duration in hours for selected thresholds of wind velocities, Šibenik, period 1977-1986.
Tabela 2. Godišnje apsolutne čestine neprekidnog puhanja vjetra u satima za izabrane pragove brzine vjetra, Šibenik, period 1977-1986.

Wind speed m/s Run duration hours	<=3.0	> 3.0	> 5.0	> 8.0	> 12.0	> 18.0
1	1311	1321	1236	558	51	0
2	654	681	631	246	26	0
3	454	505	394	131	14	0
4	307	364	267	85	7	0
5	241	321	197	64	2	0
6	202	234	129	35	2	0
7	170	206	102	35	2	0
8	146	161	99	24	1	0
9	128	130	87	32	0	0
10	135	91	56	17	0	0
11	112	80	56	15	0	0
12	87	64	60	13	0	0
13	64	63	47	14	0	0
14	73	46	39	10	1	0
15	79	45	32	10	0	0
.	.	.	.	.	.	.
.	.	.	.	.	.	.
182	0	1	0	0	0	0
Σ	5085	5085	3820	1336	106	0

durations of up to 2 days. Slightly more favorable conditions in the southern part of Istria characterize the mean duration of 9-hours "calms" in Pula, but 90% of such conditions nevertheless achieve the length of up to one day, and in extreme cases in this area a duration as long as 10 days without interruption.

The region of the windier part of the northern part of the Adriatic in regards to the middle and the south has unfavorable conditions for aerogenerators remarkably less pronounced: mean duration of these conditions vary between 3.4 hours (Palagruža) and 8.5 hours (Šibenik), but 90 % of these wind conditions have a duration of up to 1/2 do 3/4 of a day and only on Lastovo island lasted up to 7 hours. Although in extreme cases the continuous duration of these "calms" on the exposed islands of the middle Adriatic may last even 2 to 3 days, our analysis shows that even in 99% of all cases one should expect that such wind conditions on the northern Adriatic (Velebit Channel) will not last more than 1 1/2 days, on the middle Adriatic up to 1 1/2 and 2 days, and at Šibenik, up to 2 1/2 days.

We defined as favorable conditions for the work of aerogenerators those wind conditions when mean wind speeds exceed at least 3 m/s. The aerogenerator at Rijeka could work continuously only 4 hours on the average, in 90 % of all cases only up to 8 hours, and in 99% of cases slightly more than one day continuously. In 8 years of measurements such favorable conditions lasted once as many as 3 days. On the Adriatic coast and islands the continuous duration of these favorable wind conditions vary on the average between 6.2 hours at Pula and 15.8 hours at Palagruža, what undisputably indicates the real constraints to obtaining of electric power in such a way. It should be, however, pointed out that the longest continuous duration of winds with speeds greater than 3 m/s in 90% of cases at all coastal stations (except Rijeka) is more than 12 hours and varies between 14 hours (Pula) and 43 hours (Palagruža). In exceptional cases these wind conditions may last much longer, especially pronounced at localities with frequent and strong bora (Senj even 19 days) but nowhere else shorter than 7 days.

For bigger aerogenerators with cut-in speeds of 5 m/s wind conditions on the Adriatic are less favorable: average durations of such continuous duration wind conditions vary between 3.6 hours (Rijeka) and 11 hours (Palagruža and Senj). The fluctuation of these conditions is illustrated by data that in 90% of all cases such winds do not blow longer than 9 hours in the northern Adriatic and up to 28 hours at most exposed locations of the middle Adriatic. In extreme cases the uninterrupted blow of winds at that region with speeds greater than 5 m/s may achieve a duration of slightly over 50 hours (Rijeka) to 6.5 days (Palagruža).

Of other data presented in Tab 3. will shall comment only statistical indicators of continuous duration of wind speeds greater than 18 m/s (> = 8 Beaufort). Such wind conditions do not occur in the area of Rijeka, and they are extremely rare at the south of the Istrian peninsula. They are most pronounced in the area of Senj, where their average duration is 4.5 hours, and the longest uninterrupted duration of these winds is slightly over 2 days. We should also point out the area of Šibenik, known for its bora winds, but with

Table 3. Basic annual statistical characteristics of wind persistence for different speed thresholds.
Tabela 3. Osnovne godišnje statističke karakteristike perzistencije vjetra za razne pragove brzine vjetra.

a) RIJEKA - city

Speed m/s durat.	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	15.9	3.9	3.6	2.6	1.4	-
Mean durat. >=3 h.	21.9	7.8	7.5	6.1	-	-
Durat.h. 90%	40	8	9	6	-	-
99%	135	28	28	13	-	-
Max.	291	73	51	37	2	-
A	-0.03	-1.92	-3.03	-6.57		
B	20.80	41.55	45.44	58.30		

b) PULA - airport

Speed m/s durat.	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	9.0	6.2	5.5	4.3	2.8	2.5
Mean durat. >=3 h.	13.3	10.1	9.2	7.9	5.7	4.0
Durat.h. 90%	20	14	11	10	6	-
99%	65	50	44	32	17	-
Max.	233	162	133	44	18	4
A	-0.30	-0.60	-0.94	-2.17	-7.49	
B	24.99	30.33	32.79	40.61	52.80	

c) SENJ

Speed m/s durat.	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	5.7	10.2	11.1	12.0	8.0	4.5
Mean durat. >=3 h.	9.3	17.8	19.4	18.5	14.1	8.8
Durat.h. 90%	15	24	28	32	21	9
99%	32	118	118	107	66	36
Max.	116	454	367	311	129	57
A	-0.80	-0.51	-0.66	-0.35	-0.83	-2.82
B	31.19	30.24	30.31	25.89	31.47	43.11

d) ŠIBENIK

Speed m/s durat.	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	8.5	8.6	6.0	3.7	2.1	-
Mean durat. >=3 h.	13.1	13.4	10.6	7.5	4.4	-
Durat.h. 90%	20	25	17	10	4	-
99%	62	70	46	24	13	-
Max.	159	182	119	41	14	-
A	-0.40	-0.44	-1.08	-2.35	-6.72	-
B	26.57	27.32	33.70	42.35	56.58	-

e) SPLIT-MARJAN

Speed m/s durat.	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	6.4	8.5	8.4	6.2	3.9	2.5
Mean durat. >=3 h.	10.3	14.4	14.0	11.1	7.6	5.1
Durat.h. 90%	16	21	25	16	9	5
99%	40	80	65	43	26	11
Max.	119	190	117	109	41	12
A	-0.66	-0.57	-0.59	-1.03	-2.11	-3.67
B	29.78	30.42	29.53	33.96	40.77	49.29

f) DUBROVNIK-ČILIPI

Speed m/s durat.	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	4.7	9.0	6.9	5.5	4.0	3.5
Mean durat. >=3 h.	7.9	14.1	10.8	9.0	7.3	6.7
Durat.h. 90%	12	23	16	13	9	7
99%	24	73	46	35	22	-
Max.	106	172	152	73	41	22
A	-1.06	-0.42	-0.54	-0.85	-0.02	-2.39
B	33.48	27.30	28.40	31.41	39.66	42.94

Table 3. Continuation
Tabela 3. Nastavak

g) LASTOVO							h) PALAGRUŽA					
Speed m/s durat.	<=3	>3	>5	>8	>12	>18	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	3.4	15.1	8.8	5.9	4.4	2.6	6.0	15.8	10.9	7.1	5.3	3.3
Mean durat. >=3 h.	6.0	21.0	13.1	10.0	8.2	5.0	7.6	22.5	15.9	11.6	9.1	6.3
Durat.h. 90%	7	40	21	14	10	5	13	43	28	18	13	8
99%	18	110	67	48	30	10	18	108	77	50	35	17
Max.	50	247	118	88	44	12	71	207	158	89	60	23
A	-1.76	-0.09	-0.30	-0.94	-1.70	-4.92	-	-0.11	-0.20	-0.69	-1.05	-3.02
B	38.41	20.82	25.19	32.99	38.09	51.14	-	21.22	23.50	30.00	33.05	44.02

i) SLAVONSKI BROD							j) OGULIN					
Speed m/s durat.	<=3	>3	>5	>8	>12	>18	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	14.0	4.3	3.1	2.3	1.5	-	18.9	3.9	3.0	2.4	1.9	-
Mean durat. >=3 h.	19.9	7.6	6.0	5.0	4.0	-	27.1	7.4	5.9	4.5	4.1	-
Durat.h. 90%	36	10	8	5	2	-	32	9	8	5	3	-
99%	95	17	18	11	5	-	197	21	16	9	6	-
Max.	276	91	56	22	6	-	476	55	31	13	7	-
A	-0.13	-1.20	-2.65	-5.65	-13.67	-	-0.15	-0.17	-2.92	-4.20	-7.35	-
B	21.70	35.74	44.06	54.63	76.50	-	22.09	39.76	44.24	48.58	59.40	-

no registered period of winds of such an intensity. On the exposed islands of the middle Adriatic the average duration of continuous duration of these gale winds is only a few hours and in extreme cases, one day.

Tab. 3. also includes data on continuous duration of winds of different speed intervals for those cases when the duration of such winds is at least 3 hours. For speeds up to 12 m/s the average duration is 20 to 80% greater than for continuous duration which also includes quite short winds of 1 and 2 hours duration and for speeds greater than 18 m/s those durations are nearly twice as long as the winds of a duration of one hour and longer.

On account of comparison of the described wind conditions on the Adriatic with those in the interior of Croatia there are also data in Tab. 3. for the Ogulin station, situated on the fringes of mountain regions of Gorski Kotar and for the Slavonski Brod station situated in the low-lands of Posavina. At these stations the occurrence of "calms" for aerogenerators is considerably greater and the average duration of these conditions exceeds 14 hours and in extreme cases it may last even for 20 days!

In Tab. 4.a)-4.d) the data of wind persistence peculiar for different seasons at the Split-Marjan station are entered. For unfavorable wind conditions the differences in single seasons are not significant. However in summer there are average and maximal duration of wind speeds v > 3.0 m/s more than twice as large as in winter and continuous winds of a speed greater than 18 m/s do not occur at all.

Table 4. Basic seasonal statistical characteristics of wind persistence for different speed thresholds, SPLIT-MARJAN, seasons.
Tabela 4. Osnovne sezonske statističke karakteristike perzistencije vjetra za razne pragove brzine, Split-Marjan.

a) spring							b) summer					
Speed m/s durat.	<=3	>3	>5	>8	>12	>18	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	6.0	8.4	9.1	7.0	4.1	2.4	6.0	5.7	5.3	3.6	2.2	-
Mean durat. >=3 h.	9.9	14.2	15.0	11.9	7.7	4.5	9.4	9.2	9.1	7.3	4.7	-
Durat.h. 90%	16	23	25	17	10	4	16	13	13	8	4	-
99%	36	71	65	53	26	-	29	41	34	23	9	-
Max.	86	137	117	108	39	12	70	84	71	40	12	-

c) fall							d) winter					
Speed m/s durat.	<=3	>3	>5	>8	>12	>18	<=3	>3	>5	>8	>12	>18
Mean durat. >=1 h.	7.0	9.2	9.3	6.3	3.3	2.4	5.7	12.5	10.2	6.8	4.5	2.7
Mean durat. >=3 h.	11.2	16.0	15.1	11.0	6.6	4.7	9.9	21.3	16.6	12.0	8.5	5.6
Durat.h. 90%	17	24	26	16	7	5	13	37	29	18	12	6
99%	53	84	68	44	23	-	42	104	72	44	28	-
Max.	119	145	105	74	33	10	90	190	115	109	41	12

4. STATISTICAL MODELS OF WIND PERSISTENCE

The data on continuous duration of wind of different thresholds are investigated with regard to their fitting to specific functions, as done by other authors (5). The possibility of fitting the data was examined by the following functions:

$$y = A + B \cdot x \quad (1)$$
$$y = a + B \cdot \ln x \quad (2)$$
$$y = A + B \cdot x^2 \quad (3)$$
$$y = A + B/x \quad (4)$$
$$1/y = A + B \cdot x \quad (5)$$
$$y = A + B^x \quad (6)$$
$$y = A + x^B \quad (7)$$
$$y = A \cdot e^{B.x} \quad (8)$$

and by the method of least squares it was found that function (4) shows the highest degree of fitting. The complete material of computerized tables of continuous wind duration of different speed intervals for all 10 stations was examined by the same programe. In the lower part of Tab. 3. the values of coefficients A and B for different speed intervals are quoted and on Fig. 2. the curves of wind persistence based on the same function for yearly data for the Šibenik station and speed intervals v < = 3 m/s, v > 5.0 m/s, v > 8.0 m/s and v > 12.0 m/s are depicted.

From Fig. 2. one could easily determine that e.g. in the case when in Šibenik wind blew with speeds v < = 3.0 m/s the probability of uninterrupted duration of such a winds of 10 hours is 0.022, for wind v > 8.0 m/s the corresponding probability of 10 hours duration is only 0.019. The yearly values of probabilities of occurence of winds for the same 4 intervals are also entered in Fig 2., so we can find for the aforementioned examples that the probability of occurrence of wind speeds v < = 3.0 m/s and of 10 hours duration is only 0.0088 (0.022 x 0.400 = 0.0088) and for winds v > 8.0 m/s and duration of 10 hours only 0.0012.

Insertion of coefficients A and B from Tab. 3. into

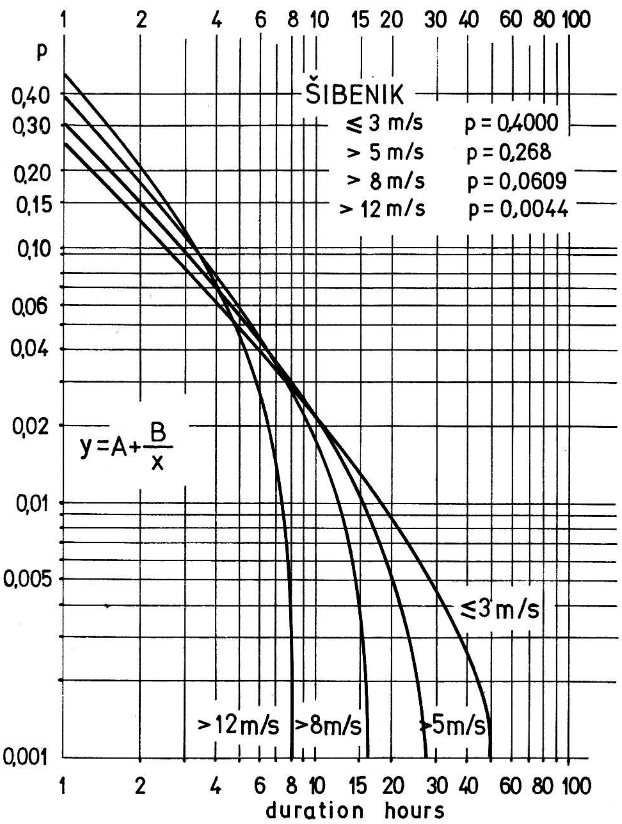

Fig. 2. Curves of wind persistence (yearly values) for the Šibenik station for speed intervals v ≤ 3.0 m/s, v > 5.0 m/s, v > 8.0 m/s and v > 12.0 m/s. Probabilities p refer to the probability of occurrence of wind speeds in the annual average for the same speed intervals.

Sl. 2. Krivulje perzistencije vjetra (godišnje vrijednosti) za stanicu Šibenik u 4 intervala brzina. Vjerojatnosti p odnose se na vjerojatnosti pojave brzina vjetra u godišnjem prosjeku za iste intervale brzina.

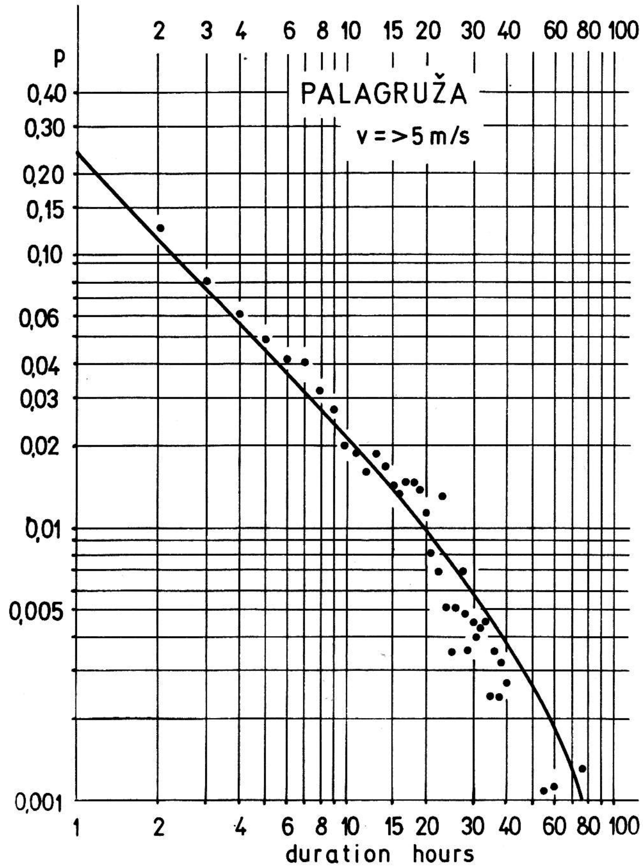

Fig.3. The wind persistence curve based on function (4) and probabilities of measured wind speed values for Palagruža station for v > 5.0 m/s, yearly values.

Sl. 3. Krivulja perzistencije vjetra bazirana na funkciji (4) i vjerojatnostima mjerenih vrijednosti brzine vjetra za stanicu Palagruža za v > 5,0 m/s, godišnje vrijednosti.

expression $y = A + B/x$ makes it possible to find out for any convenient number of hours of continuous wind duration x the probability of occurrence of wind runs for four selected speed intervals.

The analysis of measured data of wind duration fitted by function (4) shows a high degree of fitting : the coefficients of correlation r lie inside of limits r = 0.9649 - 0.9949, and 80% od correlation coefficients data A and B have r > 0.99. Due to a large number of wind run data, these correlation coefficients are highly significant. An example of data fitting by function (4) is depicted on Fig. 3. for station Palagruža and for v > 5.0 m/s. The best fitting of data lies inside the interval of continuous duration which is less than 10 hours. It is further evident that in the area of probability less than 0.01 more considerable deviation of measured data may occur from those calculated by function (4). For the time being it is not possible to assess to what degree these deviations are the result of real conditions at specific locations, respectively of the choice of simple function (4) or if these differences should be assigned to individual shorter or longer interruptionns of measurements at certain stations.

The next step in consideration of the chosen model has brought us to the linking of model (4) with the mean annual wind speed. Such a connection would provide an opportunity for determining wind persistence at the stations where we possess only the average annual wind speed and not the individual values of mean hourly wind speeds. We also figured out that the function $y = A + B/x$ best fits the annual wind speed values to the coefficients A and B (Fig. 4).

In Fig. 4. the depicted dependence of mean annual wind speeds on coefficients A and B enables us to determine the values of wind persistence for selected lengths of continuous wind duration. As an example we could for the average annual wind speed of 3.0 m/s from the graph 3a) find the values A = -0.85, and B = 32.0, and with their insertion into expression (4) for a requested number hours of continuous wind duration x the probability of occurrence p. A larger number of analysed stations would undoubtedly make possible more reliable determination of coefficients A and

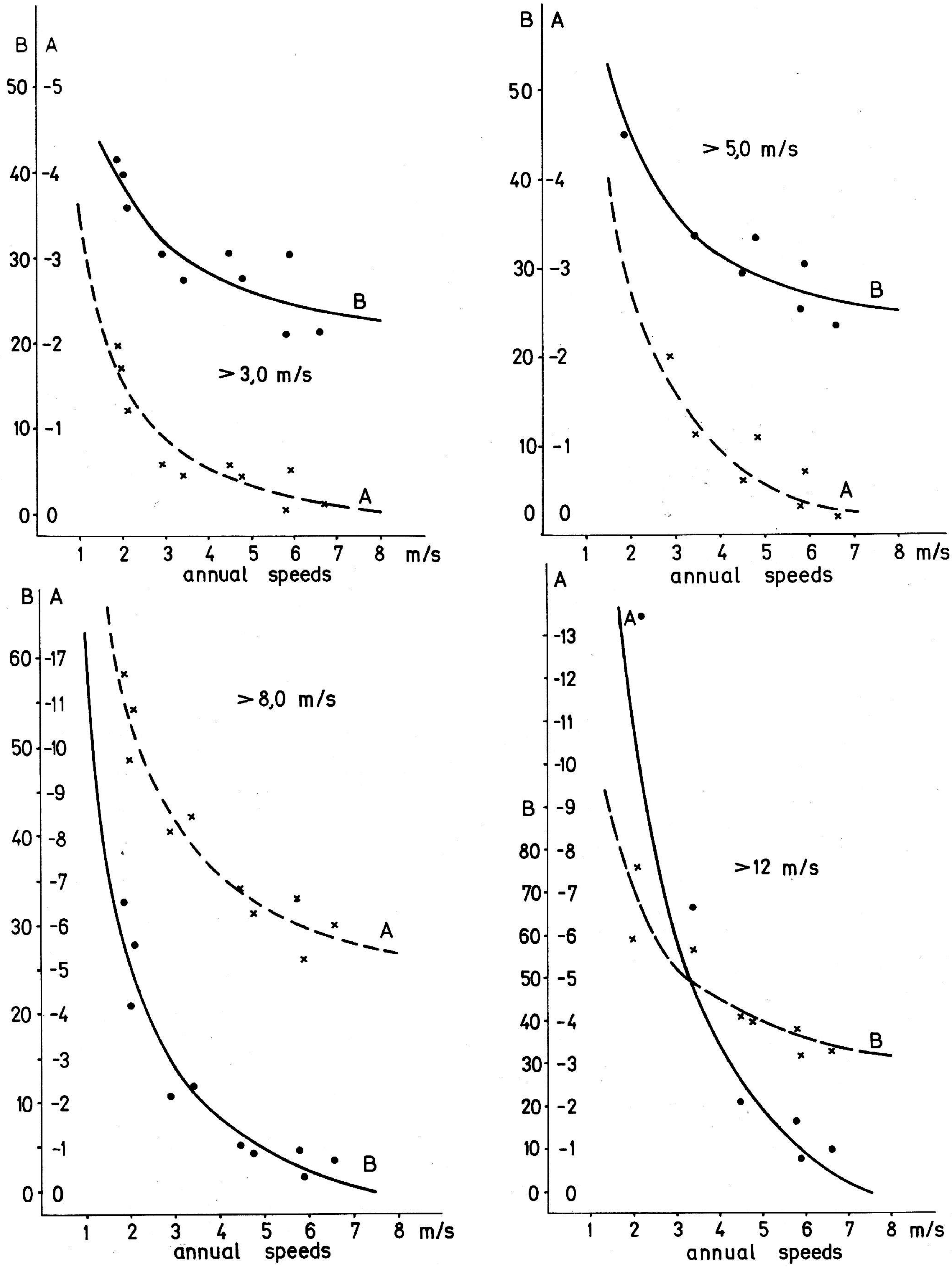

Fig. 4. Nomograms for determination of coefficients A and B from the annual mean wind speed for different speed intervals: v > 3.0 m/s, v > 5.0 m/s, v > 8.0 m/s, v > 12.0 m/s.

Sl. 4. Nomogrami za određivanje koeficijenata A i B iz srednje godišnje brzine vjetra za različite intervale brzine vjetra: v > 3,0 m/s, v > 5,0 m/s, v > 8,0 m/s, v > 12,0 m/s.

Table 5.Probability of occurrence of specified categories of continuous wind duration (v ≤ 3.0 m/s, v > 3.0 m/s, v > 5.0 m/s, v > 8.0 m/s, v > 12.0 m/s, v >18.0 m/s).
Tabela 5. Vjerojatnost pojave specificiranih kategorija kontinuiranog trajanja puhanja vjetra (v ≤ 3,0 m/s, v > 3,0 m/s, v > 5,0 m/s, v > 8,0 m/s, v > 12,0 m/s, v >18,0 m/s).

	a) v < = 3,0 m/s					b) v > 3,0 m/s				
Duration h. station	1-2	3-8	9-24	25-192	>192	1-2	3-8	9-24	25-192	>192
Sl. Brod	22.7	59.5	271.8	399.3	9.9	37.4	92.6	79.5	27.2	-
Ogulin	18.6	53.4	167.4	469.2	120.3	32.6	64.9	60.0	13.6	-
Rijeka	20.1	68.3	191.9	495.3	32.3	38.3	67.1	57.6	29.1	-
Pula	31.9	101.6	256.0	201.1	1.5	39.1	113.6	140.5	114.7	-
Senj	37.3	100.8	172.7	47.8	-	38.3	87.3	113.1	325.5	-
Šibenik	29.9	84.2	228.7	152.9	-	30.7	99.6	138.1	235.9	-
Split - M	38.3	108.9	196.7	87.0	-	39.9	98.1	142.4	288.6	-
Dubrovnik	45.6	119.4	158.2	22.7	-	37.1	118.5	195.3	303.2	-
Lastovo	40.0	91.8	48.0	6.4	-	21.5	65.2	224.6	491.6	-
Palagruža	16.4	82.1	69.3	20.6	-	25.1	67.1	184.1	291.1	-

	c) v > 5,0 m/s					d) v > 8,0 m/s				
Duration h. station	1-2	3-8	9-24	25-192	>192	1-2	3-8	9-24	25-192	>192
Sl. Brod	16.3	29.1	15.2	2.4	-	3.7	4.6	1.2	-	-
Ogulin	12.3	22.1	11.0	1.0	-	2.4	3.6	0.5	-	-
Rijeka	11.5	19.7	17.2	6.5	-	1.9	2.1	1.4	0.6	-
Pula	16.9	45.2	52.8	34.2	-	6.2	12.7	11.2	5.8	-
Senj	22.3	47.6	88.7	239.6	19.7	11.4	32.1	74.1	156.4	8.4
Šibenik	28.6	63.0	97.6	75.3	-	12.0	19.3	21.9	4.8	-
Split-M.	22.3	51.8	104.1	149.5	-	17.1	34.4	60.8	47.6	-
Dubrovnik	28.7	84.1	135.6	103.1	-	18.0	50.1	67.6	27.3	-
Lastovo	29.9	99.1	189.5	211.2	-	23.1	59.3	73.4	61.4	-
Palagruža	25.1	67.1	184.5	291.1	-	32.9	66.2	166.3	110.9	-

	e) v > 12,0 m/s					f) v > 18,0 m/s				
Duration h. station	1-2	3-8	9-24	25-192	>192	1-2	3-8	9-24	25-192	>192
Sl. Brod	0.5	0.2	-	-	-	-	-	-	-	-
Ogulin	0.4	0.3	-	-	-	-	-	-	-	-
Rijeka	0.1	-	-	-	-	-	-	-	-	-
Pula	0.7	1.2	0.6	-	-	-	-	-	-	-
Senj	8.9	21.3	36.0	58.7	-	1.9	3.9	2.9	3.3	-
Šibenik	1.2	1.3	0.2	-	-	-	-	-	-	-
Split-M.	7.3	12.9	13.4	3.6	-	0.8	1.1	0.4	-	-
Dubrovnik	6.4	14.8	13.6	2.5	-	0.4	0.9	0.6	-	-
Lastovo	9.0	16.3	20.4	6.8	-	0.7	1.2	0.5	-	-
Palagruža	14.6	34.4	52.8	17.0	-	4.3	8.3	5.8	-	-

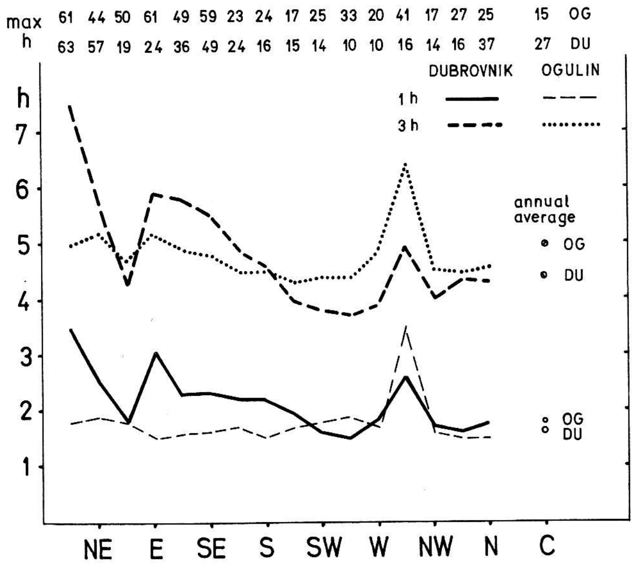

Fig. 5. Average and maximal wind duration by direction of at least one and three-hour duration, Dubrovnik-Čilipi and Ogulin stations.

Sl. 5. Prosječno i maksimalno trajanje puhanja vjetra od barem jednog i tri sata trajanja, stanice Dubrovnik-Čilipi i Ogulin.

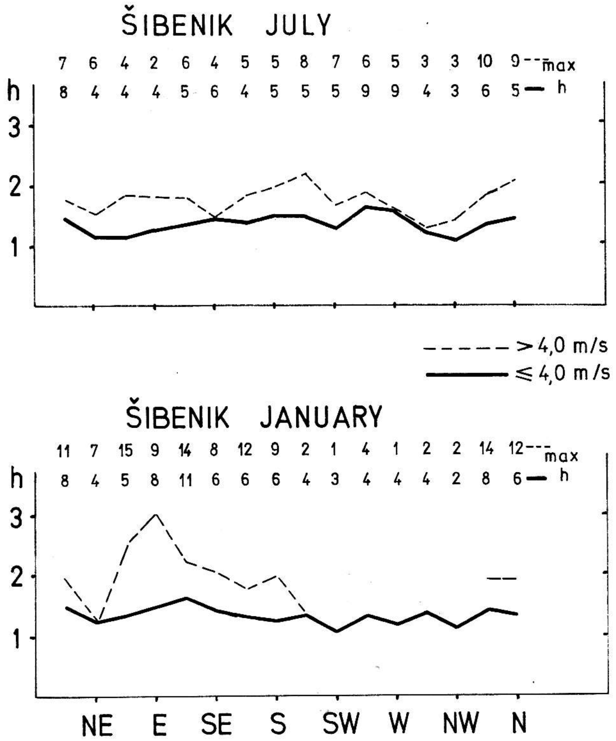

Fig. 6. Average and maximal continuous wind duration by directions for speeds v < = 4.0 m/s and v > 4.0 m/s, Šibenik station, January and July.

Sl. 6. Prosječno i maksimalno kontinuirano trajanje puhanja vjetra po smjerovima za brzine v ≤ 4,0 m/s i v > 4,0 m/s, stanica Šibenik, siječanj i srpanj.

B, but with the nomograms presented here it is evident that in the region of annual wind speeds smaller than 2 m/s this dependence is weaker than at greater speeds. The verification of the reliability of matching calculated values A and B with function Y = A + B/x indicated a rather high degree of correlation: the mean value of r for all intervals comes to r = 0.9329 (min. value 0.9012 for A) and r = 0.9489 (min. value 0.8816 for B). For the speed interval v < = 3.0 m/s the corresponding value was not found and for speeds greater than 18.0 m/s there was not a sufficient number of data.

5. WIND PERSISTENCE FOR SELECTED PERIODS OF WIND DURATION

Having in mind the different possibilities of electric energy storage gained by aerogenerators it is useful to investigate also the probability of certain periods of wind duration when there is a wind of a given speed category. For already treated thresholds of wind speeds we calculated probabilities of continuous wind duration of 1-2, 3-8, 9-24, 25-192 hours and over 192 hours (8 days).

For a significant category of conditionally "calms" for aerogenerators Tables 5. show that at all coastal stations one could expect that such wind conditions would occur most freguently with a duration between 9 and 24 hours. The measurements at Rijeka indicate that this station regarding its wind persistence characteristics nearly corresponds to the regime of continental stations, at which the most probable "calm" has a duration of 1 to 8 days. At all stations south of Rijeka such wind conditions do not occur with continuous duration longer than 8 days.

Further analysis of Tab. 5 shows that in relation to the periods of possible use of aerogenerators (v > 3.0 m/s) at all stations south of Rijeka the most probable are the periods of 1 to 8 day durations; at the uttermost exposed islands of the middle Adriatic this probability is between 30 and 50%. Here, too, the location of Senj stands out, where one can also expect with small probability periods of continuous duration even longer than 8 days (bora). We assess the inland of Croatia on the basis of 2 stations, elaborating that it is most probable to expect periods favorable for windgenerators of only 3 to 8 hours.

6. PERSISTENCE OF WIND DIRECTION

The persistence of winds of given direction could be so far examined only on the basis of data of the Dubrovnik, Ogulin and Šibenik stations. For the first two stations the mean duration for every direction was determined with regards to those cases when this duration was at least 1 and 3 hours respectively.

For the period of one hour and more of continuous duration regardless to speed (Fig. 5) very small differences in wind directions are noticeable; average duration is in the range of 1.5 to 1.9 hours, except for the WNW direction for which the mean duration is no less than 3.5 hours. At Dubrovnik the variations of mean durations by wind directions are considerably pronounced and increased wind runs are primarily connected with developed systems of bora, easterly and westnorthwesterly winds.

Winds of a particular direction and of at least 3 hours duration show considerably larger variations in average duration: at Ogulin these limits are in a range of 4.3 to 6.4 hours and at Dubrovnik in a range of 3.7 to 7.5 hours. At Dubrovnik the much more pronounced duration of bora and "scirocco" wind are to be noticed, and at Ogulin only the WNW wind direction caused by local topography is remarkable. It should be mentioned further that average duration of "calms" at Ogulin and Dubrovnik is only 1.7 hours, but the longest unwindy situation at Ogulin may attain 15, and at Dubrovnik even 27 hours.

Continuous duration of particular wind directions for determined speed thresholds is for the time being examined only on wind data of the Šibenik station and for speeds v < = 4.0 m/s and v > 4.0 m/s. On January at Šibenik (Fig. 6) no significant change of average continuous duration for different directions and for speeds v < = 4.0 m/s could be noticed. For greater speeds the longest mean duration have winds from easterly and southeasterly quadrants, with the longest duration of 3 hours (E winds). Winds which blow in the sector from SW to NW do not occur with speeds greater than 4 m/s.

In a typical summer month the differences in mean duration between wind directions are small and speeds up to 4.0 m/s are in the range of 1.1 to 1.6 hours, speeds greater than 4.0 m/s in the range of 1.3 to 2.2 hours. For directions of bora and landward breeze the greatest average duration is 2.2 hours.

The longest registered continuous duration by directions amounts at Šibenik on January only to 11 hours for speeds smaller than 4.0 m/s and 14 hours for speeds greater than 4.0 m/s. In July the longest duration for any direction does not exceed 10 hours.

In regards to the fact that during one hour greater or smaller fluctuations of wind direction occur in dependence of atmospheric stability and the character of the ground surface, the presented statistics, which relate only to separate wind directions, has a limited value and so it is planned to elaborate such a statistics for groups of three directions which overlap (e.g. group N, NNE, NE; group NNE, NE,ENE etc.). In this way one could get a more realistic picture on the blowing of the characteristic wind systems on the Adriatic (e.g. bora, scirocco, landward breeze etc.). This may be of special importance for locations where implementation of aerogenerators with directional usage of wind power is planned (region of Senj for bora).

7. CONCLUSION

Wind persistence in the Adriatic region as well as at selected locations in the interior of Croatia is examined on the basis of anemograph data lasting several years. For selected thresholds of wind speeds mean duration of at least one respectively for 3 hours of continuous duration are determined. The duration in hours of 90% and 99% of all cases is also included. Unfavorable periods for the work of aerogenerators (v < = 3.0 m/s) have, in that region a mean duration of 14 to 19 hours (interior of Croatia) and 3 to 9 hours (Adriatic region). The longest continuous duration of such winds may in extreme cases exceed 10 days. Models of probability function of wind persistence are found for all stations as well as the connection of coefficients of that function with the mean annual wind speed. The probability of longer favorable wind conditions for aerogenerators is rather small, especially at the uppermost northern part of Adriatic. Only in the middle Adriatic are favorable periods for the work of windgenerators (v > 3.0 m/s) exceptionally longer than 8 days.

In the last chapter examples of persistence of wind speed and direction are presented for selected stations on the Adriatic and in the interior which indicate a relatively low dependence of wind persistence on direction.

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KRATAK SADRŽAJ

U prvom dijelu ovog rada naveden je ukratko položaj Hrvatske u okviru opće cirkulacije atmosfere, posebno u vezi s nastankom onih vjetrovnih sistema koji dovede do dugotrajnijeg puhanja na Jadranskom prostoru. Istaknuta je važnost poznavanja perzistencije vjetra u svrhu ocjene opravdanosti postavljanja aerogeneratora, posebno s aspekta određivanja vjerojatnosti razdoblja u kojem takav uređaj zbog slabih vjetrova ili tišina uopće neće moći raditi.

U drugom poglavlju dani su osnovni podaci o stanicama na temelju kojih je ovaj rad izrađen (Tab. 1). Duljina nizova anemografskih podataka je bar deset godina sa iznimkom stanice Rijeka-grad, no imajući u vidu specifičnosti lokaliteta pojedinih stanica, ne može se tvrditi da se dobiveni rezultati u pogledu perzistencije mogu primijeniti i za šire područje oko pojedine stanice. Isto tako za sada nije moguće reći u kojoj mjeri prekidi u nizovima podataka imaju utjecaja na dobivene rezultate.

Treće poglavlje donosi osnovne podatke o perzistenciji vjetra za različite pragove brzina. Uzeta je granica od v < = 3,0 m/s, kao donja početna granica za rad aerogeneratora i u taj interval uvrštena i tišina. U tabeli 2 dan je primjer dijela takve obrade za stanicu Šibenik iz koje su vidljive učestalosti kontinuiranog trajanja određenih intervala brzina dok su u tabelama 3.a) do 3.j) prikazane osnovne statističke veličine perzistencije vjetra za svih deset stanica (stanice Ogulin i Slavonski Brod uzete su u svrhu ilustracije vjetrovnih prilika u unutrašnjosti Hrvatske). U prvom retku svake tabele dano je srednje trajanje puhanja vjetra po intervalima, ako je vjetar puhao bar jedan sat, drugi podatak ispod njega predstavlja analogni podatak za slučajeve ako je puhanje vjetra trajalo 3 sata ili dulje. Podaci koji slijede odnose se na podatke koji obuhvaćaju 90% odnosno 99% svih slučajeva, te apsolutno najduže registrirano trajanje - sve izraženo u

satima. Tako npr. za stanicu Pula možemo iz tabele 3.b) lako očitati podatak da za brzine vjetra veće od 3,0 m/s u 90% slučajeva trajanje ne prelazi 14 sati, te da najdulje registrirano trajanje za taj interval brzina, odnosno praktički za rad aerogeneratora ne prelazi 162 sata. U tabelama 4.a) do 4.b) prikazani su isti podaci za stanicu Split-Marjan i to za sva četiri godišnja doba da bi se pokazale posebnosti.

Iz ovih tabela mogu se ocijeniti vjetrovne prilike na 8 lokacija na Jadranu i dvije stanice u unutrašnjosti u pogledu perzistencije vjetra, pa je očito da su na visini od 10 m nad tlom, na koju se odnose dobiveni podaci, u unutrašnjosti vjetrovni uvjeti za rad aerogeneratora vrlo nepovoljni, a isto se može reći i za uže područje Rijeke. Vjetrovne prilike u Velebitskom kanalu i obalnom području južno od Senja, te na izloženim otocima srednjeg i južnog Jadrana, odnosno uvjeti za rad aerogeneratora su mnogo povoljniji iako i na tom području postoje znatne razlike između pojedinih lokaliteta čak i na malim razdaljinama.

U četvrtom poglavlju prezentirani su rezultati statističke analize podataka o neprekinutom trajanju puhanja vjetra određenih pragova brzine (tab. 2). Nađeno je da se najbolja prilagodba dobivenih rezultata može dobiti funkcijom oblika $y = A + B/x$ za koju je realiziran vrlo visok stupanj koeficijenta korelacije unutar granica $r = 0,9649$-$0,9949$.

Na sl. 2. prikazane su adekvatne krivulje funkcije y za 4 intervala brzine vjetra, tako da se iz nomograma može za svako izabrano trajanje odrediti vjerojatnost takve pojave. Na slici su uneseni i podaci o vjerojatnosti pojave određenih brzina, a korištenjem obaju podataka dade se odrediti vjerojatnost puhanja vjetra određenog intervala. Za stanicu Šibenik izlazi da je vjerojatnost pojave vjetrova $v <= 3,0$ m/s, a trajanja 10 sati svega 0,0088 (=0,022 x 0,400). Uvršavanjem koeficijenata A i B iz tabela 2. u izraz $y = A + B/x$, može se za svaki povoljan broj sati traženog trajanja x izračunati vjerojatnost pojave puhanja vjetra za 4 određena intervala brzine i trajanja.

Analiza podataka pokazala je i mogućnost povezivanja srednje godišnje brzine vjetra sa koeficijentima A i B što je prikazano na slici 4. Korištenjem nomograma na toj slici daju se lako odrediti iz poznate srednje brzine vjetra koeficijenti A i B a preko jednostavnog izraza (4) i vjerojatnost pojave trajanja određenog intervala brzine izabrane stanice.

U petom poglavlju prikazane su vjerojatnosti pojavljivanja u promilima određenih kategorija neprekidnog trajanja puhanja vjetra (1 do 2 sata, 3 do 8 sati, 9 do 24 sata, 25 do 192 sata i preko 192 sata) za ranije odabrane intervale brzina.

Zadnje poglavlje ilustrira početne rezultate ispitivanja perzistencije vjetra i ovisnost smjera vjetra za dvije stanice i dva intervala brzina. Na sl. 5.prikazani su rezultati takvog ispitivanja koje obuhvaća prosječno i maksimalno trajanje puhanja vjetra od bar jedno i bar tri sata trajanja za Dubrovnik i Ogulin za svih 16 smjerova vjetra, dok sl. 6 ilustrira prosječno i maksimalno neprekidno trajanje po smjerovima za brzine vjetra $v <= 4,0$ m/s i $v > 4,0$ m/s i to za mjesece siječanj i srpanj za stanicu Šibenik. U daljem radu predviđeno je ispitivanje perzistencije vjetra po grupama od po tri susjedna smjera da bi se ustanovila i mogućnost korištenja aerogeneratora definiranog usmjerenja.