RESEARCH ARTICLE

Climatic conditions of wind energy use in the Polonyna Borzhava Mountains (Transcarpathia, Ukraine)

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ABSTRACT

This paper deals with the statistical structure, seasonal peculiarities of wind climate at meteorological station Play (in Ukrainian: метеорологічна станція Плай, location: 48°40'1" N; 23°11'51" E, 1330 m above sea level) located in the Polonyna Borzhava Mountain of the North-Eastern Carpathians. Furthermore, it determines significant parameters of exploiting wind energy. Weibull distribution was applied to determine specific wind power and characterize its annual course. Wind speed was analyzed together with the available daily and yearly course of wind power. Wind power density determined by means of distribution parameters at Play is 169.0 W/m^2 and 8.0-9.0 m/s winds yield most energy over the year. The minimum number of energetically utilizable wind hours is in summer, while its maximum is in spring. On the territory represented by the measuring point, a 3 m/s start-up speed wind turbine could operate 63% time over the year. Finally, the periods were specified, and those wind directions were chosen that are richer in wind energy than others. The most frequent characteristic wind direction with the highest mean velocity in each season is south-western; its average relative frequency is 34.4%. Mean speed of characteristic wind directions is 5.8 m/s. South-western wind direction yields 47% of the total energy.

Keywords: wind energy, wind speed, wind direction, wind power density, Weibull distribution, Transcarpathia.

1. Introduction

Among renewable energy resources a very useful and efficiently renewable is wind energy, which is available and significantly contributes to many countries' diversification of energy production. Also, wind energy increases energy security and complies with various ecological commitments. To avoid using hydrocarbon in the energy sector, wind energy utilization is gaining an ever-increasing role worldwide. The possibility, method, territory, and extent of wind energy exploitation are closely related to the prevailing wind conditions, namely wind speed intensity and stability at the respective geographical location. Accessible wind energy values can be calculated at meteorological stations, based on detailed statistical analysis and/or model calculations of wind data.

Nowadays wind energy has become a crucial and dynamically developing branch of industry. According to GWEC (Global Wind Energy Council) (2020) data, at the end of year 2019, the world's cumulated wind park capacity reached 621.4 GW. The global new installations (60.1 GW) in the onshore wind market reached 54.2 GW, while the offshore 6.1 GW. According to EWEA (European Wind Energy Association) report in 2019 15.2 GW new wind turbine capacities were put into operation in Europe (11.6 GW onshore and 3.6 GW offshore). By the end of 2019, the aggregate capacity showed 27.0% increase, reaching 204.6 GW, thus, comprising 32.9% of the world's capacity (EWEA, 2020). The United Kingdom installed the most wind turbines in 2019 (2.4 GW), followed by Spain, Sweden, France, and Germany. According to UWEA (Ukrainian Wind Energy Association) report (2020), the cumulated wind park capacity in Ukraine reached 1.1 GW. The Ukrainian wind power industry should continue growing in the coming years as the country set the official target of 25% of renewable energy share by 2035 (OECD, 2019).

From the wind speed prospective, the best areas for the development of wind energy industry should benefit of steady wind, i.e., wind speed values must have minimal deviation and average wind speed equals or exceeds 3 m/s (Sembery and Tóth, 2004). Ukraine has favorable regional conditions to produce high efficiency electric energy by means of wind power plants: on the coasts of the Black Sea and the Sea of Azov, highland regions of the Ukrainian Carpathians, the Podolian Upland, the Donets Upland, and the Crimean Peninsula, i.e., in the country's southern, south-eastern, central and highland regions. In the northern, north-western regions (Polissia), highland river valleys and the Carpathian lowlands wind speeds will provide for only limited capacity of the wind parks (Kudrya et al., 2001; Dmytrenko and Barandich, 2007; Polishchuk, 2010; Raihenbah, 2010; Ivus et al., 2010; Makarovskiy and Zinych, 2014; Pivnyak and Skrabets, 2015; Moskalchuk and Pryhodko, 2017).

Previously conducted studies (Osadchyi et al., 2014, 2015; Mandryk, 2016; Moskalchuk and Pryhodko, 2017; Hadnagy and Tar, 2019a) show that some parts of the highland, particularly the orographically open mountain ridges of Polonyna and Verkhovyna, possess significant wind energy potential. Our preliminary analyses (Hadnagy and Tar, 2019b) showed that the highland Polonyna Borzhava offers favorable conditions for exploiting wind energy. The wind climatological database necessary for the study comes from Play meteorological station on the north-western ridge of the mountain range. This study aims at analyzing the statistical structure of the measuring point's wind climate, from the standpoint of wind energy. It provides significant data for further wind energy research and for decision-making of investments, as well.

2. Methods

The Play meteorological station has the following exact geographical coordinates φ=48°40'1'' N and λ=23°11'51'' E. Its altitude above sea level is 1330 m. Its spatial topographic location is displayed in Figure 1. The meteorological observatory recorded wind speed and direction of wind every 3 h and these data series were used for the study. Data refer to the altitude of 10 m above ground level. The database refers to the period from January 1, 2011 to December 31, 2015. Further on, methods applied in the data analysis are disclosed and results shown.

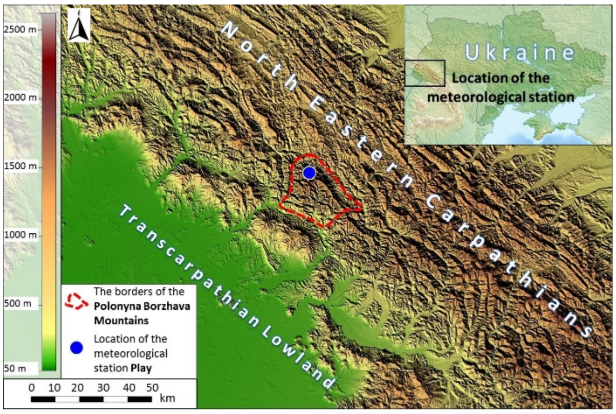

Figure 1. Location of the Play meteorological station in Polonyna Borzhava Mountains

Energy value is an important element of wind fields. It is closely related to the frequency distribution of wind directions and wind speeds both individually and in combination. Thus, modification of any wind field characteristics causes changes in the available wind energy. Wind power density can be determined according to Eq. (1), irrespectively of directions, by means of relative frequency distributions worked out at a given altitude (Osadchyi et al., 2015, Moskalchuk, 2017):

$$P_{f1} = \frac{\rho}{2} \sum_{i=1}^{n} p_i v_i^3 \tag{1}$$

where v_i^3 are cubed values of speed interval ($\Delta x=1$ m/s) midpoints (v_i), p_i is their relative frequency, and n represents the number of wind speed intervals.

Specific wind power can be defined by means of gamma function ($\Gamma(x)$), as shown in Eq. (2) (Troen and Petersen, 1989; Bartholy and Radics, 2000; Ahmed et al., 2013)

$$P_f = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \quad \textbf{(2)}$$

where c and k are Weibull distribution parameters.

Weibull distribution is a double-parameter (k and c) asymmetrical distribution (Justus et al., 1978; Tar, 2008) whose distribution density is given by Eq. (3):

$$f(x) = f(x;k;c) = \frac{k}{c}\left(\frac{x}{c}\right)^{k-1} e^{-\left(\frac{x}{c}\right)^k} \quad \textbf{(3)}$$

where k is the shape parameter (a dimensionless number) and c is the scale parameter (m/s), these can be calculated from the available database. There are several methods to determine the k and c parameters at anemometer altitude (Justus et al., 1978; Tar, 2008; Costa Rocha et al., 2012; Kidmo et al., 2015; Kravchyshyn et al., 2016). We chose the ones, whose k and c parameters yielded best approximation at 5% significance level. A matching study was performed by means of χ^2 test.

The method of choice can be traced back to momentum estimation (Tar, 2008; Costa Rocha et al., 2012; Kravchyshyn et al., 2016). If average wind speed (v_m) and the empirical deviation (s_n) are known, then Equations (4) and (5) can be applied:

$$k = \left(\frac{s_n}{v_m}\right)^{-1{,}086} \quad \textbf{(4)}$$

$$c = \frac{v_m}{\Gamma\left(1+\frac{1}{k}\right)} \quad \textbf{(5)}$$

where s_n/v_m is the coefficient of variation, while $\Gamma(x)$ is the gamma function.

The average v_m sample taken from the probability variable of the Weibull distribution can be determined by Eq. (6) (Troen and Petersen, 1989; Morgan, 1995):

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \quad \textbf{(6)}$$

Weibull distribution is related to other probability distributions. Depending on the k value, distribution density significantly changes, and c takes on the value characteristic of the local wind conditions. In case of $k=1$ distribution, exponential distribution, $k=2$ represents Rayleigh-distribution, while if the value is close to $k=3.5$ the distribution approximates symmetrical, thus being very close to normal distribution (Troen and Petersen, 1989).

Frequency distribution of wind direction related to the season is in close stochastic relation with the relative energy content, average velocity, and average length of time of a certain wind direction. There are also wind directions in which these characteristics significantly differ from other wind directions (Tar, 2007). A transformed statistical test (Vince, 1975) was applied to decide on the equality of probability and to study the wind directions whose frequency is significantly determined, i.e., they do not occur randomly at one particular place in a particular season. According to the statistical test, a critical range with limits h_1 and $h_2>h_1$ can be determined for a given probability level in the following way: if there is a wind direction D, whose frequency g_D will make disparity $g_D>h_2$ true, then the distribution of directions cannot be considered equal. There are, however, multiple similar directions, and these are called characteristic directions for one particular place in a particular period. If $g_D<h_2$, these are called non-characteristic directions (Tar and Verdes, 2003; Tar, 2004). h_1 and h_2 values are given by Equations (7) and (8) (Vince, 1975):

$$h_1 = p_0 n - u_\varepsilon\sqrt{np_0(1-p_0)} \quad \textbf{(7)}$$

$$h_2 = p_0 n + u_\varepsilon\sqrt{np_0(1-p_0)} \quad \textbf{(8)}$$

where, p_0 is the probability of occurrence of a wind direction assuming equal distribution, i.e., now – as far as we distinguish 8 wind directions: p_0=1/8=0.125, n is the total number of occurrences (sample value: 8 [8 measurements per day]×the number of days).

The u_ε can be determined by means of the Eq. (9):

$$2\Phi(u_\varepsilon) - 1 = 1 - \varepsilon \quad \textbf{(9)}$$

where $\Phi(x)$ is the standard normal distribution function of the probability variable. Thus, if ε=0,0027 (Péczely, 1957), then u_ε=2,28.

In energy calculations, side by side with the knowledge of probability density functions of wind data, it is significant to delimit and choose those time periods or wind directions that are richer in wind energy than others. The average energy value of one particular D wind direction in a particular time period (e.g., year, season, or month) can be determined by means of the daily average wind power density; this can be calculated from Eq. (10):

$$P_{f1}(D) = \frac{\rho}{2}\sum_{j=1}^{k}\frac{f_{Dj}}{N}v_j^3 \quad \textbf{(10)}$$

where f_{Dj} is the frequency of D direction wind speed v_j, k represents wind speed intervals, and N is the number of cases within a particular period. If P_{f1} is the daily average wind power density of the period (irrespective of the directions), then the rate provides the relative energy value of the given wind direction *via* Eq. (11):

$$p_D = \frac{P_{f1}(D)}{P_{f1}} \tag{11}$$

The wind direction with the highest energy value is considered the *energetically prevailing direction of wind* (Tar and Verdes, 2003; Tar, 2004).

3. Results and discussion

First, the statistical parameters of wind speed data series were established for the entire period and for several selected seasons, as well. Table 1 reveals that average wind speed has summer minimum and winter maximum values. This seasonal order is followed by standard deviation, mode, and quartiles. Coefficient of variation value except autumn is 0.63, i.e., experimental standard deviations amount to 63% of the average. Standard deviation of average daily wind speeds has been lowest in summer and spring in agreement with the average speed of the given season. Thus, in summer and spring one can positively count on the daily change of wind speed and wind energy to occur more equally, hence their control is facilitated.

Table 1. The basic statistical parameters of the wind speed (m/s) values (10 m above ground level) of the meteorological station (*italics*: a dimensionless number).

Statistical parameter	Year	Seasons			
		winter	spring	summer	autumn
Mean	4.9	5.5	5.1	4.1	4.8
Standard deviation	3.1	3.5	3.1	2.4	3.2
Coeff. of variation	*0.63*	*0.63*	*0.59*	*0.58*	*0.66*
Mode	2.9	4.5	3.4	2.3	2.6
First quartile	2.5	2.7	2.9	2.2	2.4
Median	4.3	5.1	4.4	3.7	4.4
Third quartile	6.6	7.7	7.2	5.4	6.4
Maximum	20.0	20.0	17.9	14.6	16.2
Kurtosis	*1.1*	*0.7*	*0.6*	*1.2*	*0.8*
Skewness	*1.0*	*0.9*	*0.9*	*0.9*	*1.0*

From the standpoint of wind energy utilization, it is favorable for high average wind speed to go with low coefficient of variation. Wind speed mode shows higher values in winter and spring. Maximum wind speed is in the season characterized by highest average speed, i.e., in winter.

The statistical value of kurtosis in case of normal distribution is zero. Positive kurtosis values show that the observations are more pointed and have longer tail as compared to the normal distribution. Skewness is the index-number of distribution asymmetry. Normal distribution is symmetrical, its skewness value is 0. Positive skewness values show that the frequency distribution of wind speeds have long right-wing "tail". In the Carpathian Basin and, consequently, in Transcarpathia meteorological processes over extensive territories, low- or high-pressure atmospheric formations by virtue of their characteristic features significantly affect the local wind field properties. In winter and transitional seasons, the usual cyclone activity significantly decreases over summer (Voropai and Kunitsa, 1996; Justyák, 2002). Thus, wind is mainly formed by the local climatic conditions and summer thunderstorms.

As a result, during summer months wind is much steadier as compared to winter months and the other transitional seasons. Isopleth diagram (Figure 2) shows the annual wind speed course at the measuring station with the winter maximum and the summer minimum.

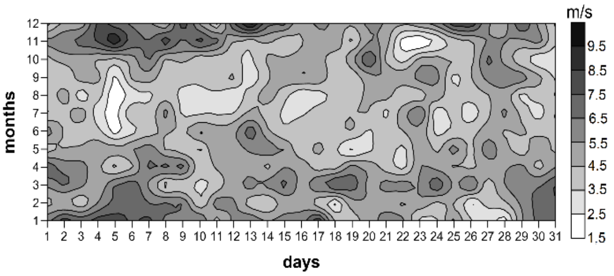

Figure 2. Daily means of wind speed (m/s) in the period 2011-2015

According to Figure 3, wind speeds are higher at night and lower over daytime. Average monthly speed at night varies from 4.2 m/s (August) to 6.2 m/s (December). Average monthly speed daytime values vary from 3.2 m/s (August) to 5.8 m/s (January). Separating daytime and night measurements of wind velocity, one can determine that minimum and maximum wind speed difference during the day is the largest in summer (e.g., in August 1.0 m/s) and in fall; it is smaller in spring, while in winter it is the smallest (e.g., in January 0.1 m/s).

This is also proven by monthly coefficient of variations of wind speeds that occur within one day. It varies from 0.03 (February) to 0.15 (August).

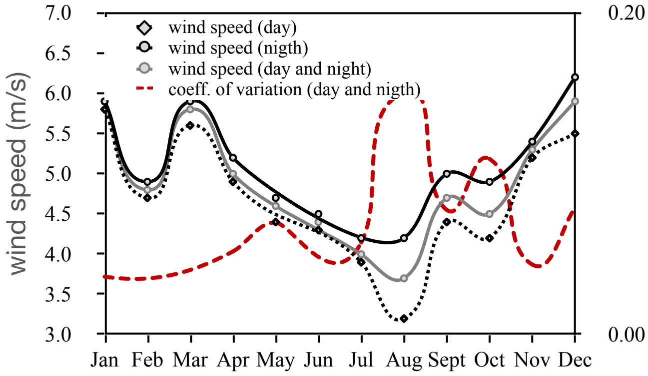

Figure 3. Monthly means of wind speed (m/s)

In the daily wind speed course at Play measuring point there is one maximum (Figure 4) at midnight and early dawn, at 2 AM. The minimum is being recorded at 11:00 AM. This corresponds to observations reported in specialized literature (Mezősi and Simon, 1981; Lysen, 1982; Patay, 2003), i.e., moving away from the ground level, wind speeds exhibit reverse daily course, characterized by minimum values at daytime and maximum values by night. Average wind speed varies within the range from 4.5 to 5.2 m/s, the relative standard deviation of values being about 10%. The low daily oscillation in the process of wind energy utilization is a positive characteristic for energy system control. Variability of wind speed is greater at daytime than by night. The coefficient of variation of deadline average monthly wind speeds varied between 0.13 (5:00 AM) and 0.19 (11:00 AM).

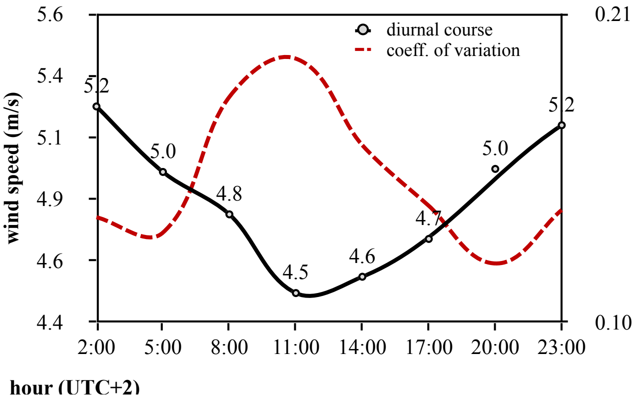

Figure 4. The entire period average (m/s) and the daily course of the coefficient of variation

Table 2 shows that in the daily course of wind speed the minimum is from April to September at 11:00 AM, with the average wind speed of 3.9 m/s. Nevertheless, from October to March the minimum mostly occurs at 5:00 PM with the average wind speed of about 5.0 m/s. Maximum values from March to June are experienced at 2:00 AM with the average wind speed of 5.3 m/s. From July to February they mostly occur at 11:00 PM, with an average wind speed of 5.5 m/s.

Table 2. The monthly minimum and maximum time (T, h) and the corresponding average wind speed (V, m/s) in the daily course of wind speed

Months	The time and value of the minimum		The time and value of the maximum	
	T	V	T	V
January	17	5.6	2	6.2
February	8	4.5	23	5.0
March	17	5.4	2	6.1
April	11	4.6	2	5.4
May	11	4.1	2	5.0
June	11	4.0	2	4.6
July	11	3.7	23	4.3
August	11	3.0	2	4.3
September	11	4.1	23	5.1
October	17	3.9	23	5.2
November	17	5.1	8	5.7
December	11	5.3	23	6.5

After the analysis of basic statistic indices, daily average wind speed data series were used to determine Weibull distribution parameters that are indispensable for the generation of the distribution. Then, wind speed data were divided into 1 m/s intervals (Morgan, 1995; Reiszadeh and Motahar, 2011; Costa Rocha et al., 2012; Xydis, 2012; Kidmo et al., 2015) and the relative frequency distribution of the measured wind data was calculated. A matching study at 5% significance level was conducted by means of χ^2 test among derived and observed values. Weibull distribution offered acceptable matching (Figure 5) for the frequency distribution of daily average velocity at the Play meteorological station for the entire period and separate seasons at a given significance level.

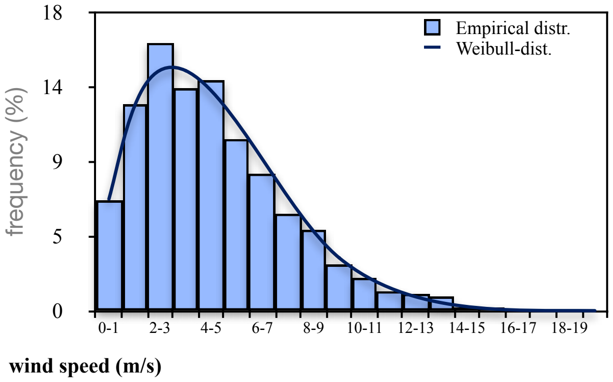

Figure 5. Frequency distribution of daily average wind speeds (m/s) and the Weibull distribution providing significant matching in the 2011-2015 period

Thus, the method applied to determine distribution parameters can be traced back to the evaluation of momentum. The latter requires the knowledge of mean wind speed, its standard deviation, and the characteristics of the gamma function. Table 3 shows the annual and seasonal values of *k* and *c* parameters. These two parameters affect the form of distribution density. Kircsi and Tar (2008) studied the change of scale- and shape parameters of Weibull distribution at different altitudes, and found that shape parameter can be considered constant up to the altitude of 120 m, while the scale parameter is influenced by the change of altitude and the increase of mean wind speed. Thus, wind energy is determined by the scale parameter. Seasonal values of the scale parameter follow the seasonal average values of wind speed. In summer, because of lower wind velocity, the distribution curve achieves kurtosis in the lower 2-3 m/s wind speed class (Figure 6). In winter, the distribution is flatter than the mode in the 4-5 m/s wind velocity class. In spring and fall, the distribution between the two extreme seasons is approximately the same.

Table 3. The annual and seasonal values of the shape parameter *(k)* and scale parameter *(c)*

Period	Weibull distribution parameter	
	K	***ºC***
Year	1.65	5.23
Winter	1.65	5.91
Spring	1.76	5.54
Summer	1.81	4.36
Autumn	1.58	5.16

Henessey (1977) claims that where average wind speed is the highest and the shape parameter of Weibull distribution is the lowest, the entire specific wind power is at its maximum value. In Play, *k* values are relatively low with means of 4.0-5.5 m/s, therefore, the available wind power density cannot be neglected. High *k* values may mean low variability of wind power, though this is less common for this area.

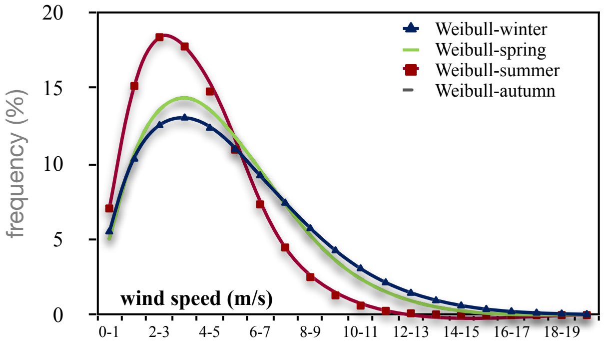

Figure 6. Frequency distributions of wind speed (m/s) based on Weibull distribution in some seasons

It is essential to know the cumulated frequency of wind speeds in some speed classes, in a particular geographical location side by side with the frequency distribution of wind speeds from the standpoint of wind energy utilization and planning. With regard to wind parks, it is important to know the frequency of productive wind velocity and its duration. It is an energetically utilizable wind speed range, which most wind turbines corresponds to the $3 \le v < 25$ m/s interval (Sembery and Tóth, 2004). It is an operating wind speed range of the work hours of the wind turbine. This can be determined by means of Eq. (12):

$$OH=\sum_{i=1}^{n} x_i t \tag{12}$$

where: x_i is the number of cases $3 \le v < 25$ m/s wind speeds occur during the day, *t* is the reference time (h) of the wind velocity value, in this case 3 h. Table 4 summarizes the statistical indices of utilizable hours of operation.

Table 4. Some duration parameters of wind speeds (m/s) that can be used for energy production (10 m above ground level)

Statistical parameter	Year	Seasons			
		winter	spring	summer	autumn
$OH_{empirical}$ (h)	5495	1412	1450	1284	1350
$OH_{relative}$ (%)	62.7	65.4	65.7	58.2	61.8
$OH_{continuous,}$ average (h)	16.7	23.1	16.8	12.6	16.2
$OH_{continuous,}$ coeff. of variation	1.4	1.2	1.4	1.3	1.5
$OH_{continuous,}$ Maximum	246.0	246.0	219.0	108.0	246.0
$OH_{continuous,}$ month of max. value	Jan, Nov	Jan	Mar	Aug	Nov
$OH_{continuous}$ >3 hour (%)	93.5	96.6	92.9	90.3	92.8
$v \ge 25$ m/s duration	18.0	10.8	2.4	1.2	3.6

The first row in Table 4 represents the annual and seasonal duration (h) of $3 \le v < 25$ m/s speed interval. Its minimum is in summer, while its maximum occurs in spring. The second row shows the relative hours of operation of wind turbines. In Play. a 3 m/s starter speed and 25 m/s highest allowed speed wind turbine would work in average 62.7% time of the year. From the third row onwards one can see continuity characteristics of utilizable wind hours. Optimal operation of a wind turbine requires the highest possible degree of operating wind speed continuity. Average length of time ($3 \leq v < 25$) of continuously operating wind speeds varies from 12.6 h (summer) and 23.1 h (winter), its standard deviation and coefficient of variation are high, corresponding to an annual value of 1.4. This variability is also supported by the low value of the Weibull distribution's k parameter.

Table 5 lists monthly relative values of operating hours. The maximum continuous operation periods are in January and November. These are the months when wind turbines can function more steadily. The percentage rate of occurrence of continuous uptime exceeding 3 h is between 92.3% (summer) and 96.6% (winter). In average, annually 93.5% of time the wind turbine will operate continuously over 3 h and produce energy. At the station wind speeds above the operating range also occur; they have restricted usage; however, these make up only 18 h per year.

Table 5. Monthly relative values of the duration of wind speeds (m/s) that can be used for energy production ($t_{(3 \leq vn \geq 25)relative}$, %)

Months	$t_{(3 \leq vn \geq 25)relative}$ (%)
January	64.5
February	61.9
March	69.8
April	65.8
May	61.4
June	63.0
July	55.7
August	55.9
September	62.0
October	59.0
November	64.6
December	69.4

Equation (2) shows that by knowing Weibull distribution parameters, wind power density at a measuring point for a particular period can be determined by means of the gamma function. At Play station the available wind power density constitutes 169.0 W/m². As it was expected, it is highest in winter, approximately 237.5 W/m², in spring it drops to 180.3 W/m², in autumn it amounts to 174.3 W/m², while in summer it gets the lowest, 83.9 W/m². Monthly values of specific wind power can be seen in Figure 7. Over summer the values are characteristically low, while in autumn specific wind power together with wind velocity are gradually increasing until mid-winter; then, in March the second largest value is reached.

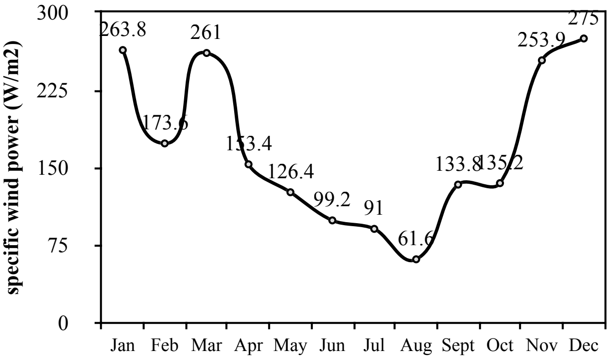

Figure 7. Monthly values of specific wind power (W/m²)

Table 6 reveals that the wind speeds bearing greatest energy in winter and spring fall into the 8.0-9.0 m/s class. In summer, due to lower wind speeds, they fall into the 6.0-7.0 m/s class, while in fall, due to the greater variability of wind, they fall into the 10.0-11.0 m/s class. 8.0-9.0 m/s winds in winter yield the highest mean energy, approximately 122.1 kWh/m².

Table 6. Average length of time ($T_{Emax\Delta x}$), specific wind power (P_f), total and relative energy (E és E_1) of the wind speed class ($E_{fmax\Delta x}$) yielding greatest energy (10 m above ground level)

Statistical parameter	Year	Seasons			
		winter	spring	summer	autumn
$E_{max}\Delta x$ (m/s)	8.0-9.0	8.0-9.0	8.0-9.0	6.0-7.0	10.0-11.0
$T_{Emax\Delta x}$ (h/year)	408.9	514.2	571.3	647.5	209.5
P_f (W/m²)	169.0	237.5	180.3	83.9	174.3
E (kWh/m²)	69.1	122.1	103.0	54.3	36.5
E_1 (%)	11.7	10.5	15.3	16.4	11.2

It does not seem reasonable to state that on the entire territory of the highland region mountain ridge or a peak the available wind power is higher than in the lowland areas. Due to the mesoscale baric field interactions, there can be significant differences between some seasons in the highland region and they must be considered in the process of planning of wind energy utilization.

An important segment of wind climatology and wind energy studies is to reveal characteristic features and connections of wind directions. Orographic and terrain setting of the measuring point (buildings, trees) significantly affect wind direction, creating leeward territories, and influence the available wind power in a particular area. The next step was to work out the empirical relative frequency of wind directions for the entire period and for each season (Figure 8). In case disparity $g_D > h_2$ was achieved, characteristic wind directions were chosen.

One can see that seasonally only 1-2 characteristic wind direction(s) can be singled out. The most frequent characteristic wind direction in each season is south-western; another characteristic direction in spring and summer is north-eastern, while in autumn it is southern. Average relative frequency of characteristic directions is 34.4%, however, it varies from 21.4% (over summer) to 44.6% (in winter). Mean wind velocity of some directions varies from 4.4 m/s (south-eastern) to 6.3 m/s (south-western). Average velocity of characteristic directions is 5.8 m/s, while the speed of non-characteristic directions is 4.8 m/s. Velocity distribution of wind directions is displayed in Figure 9.

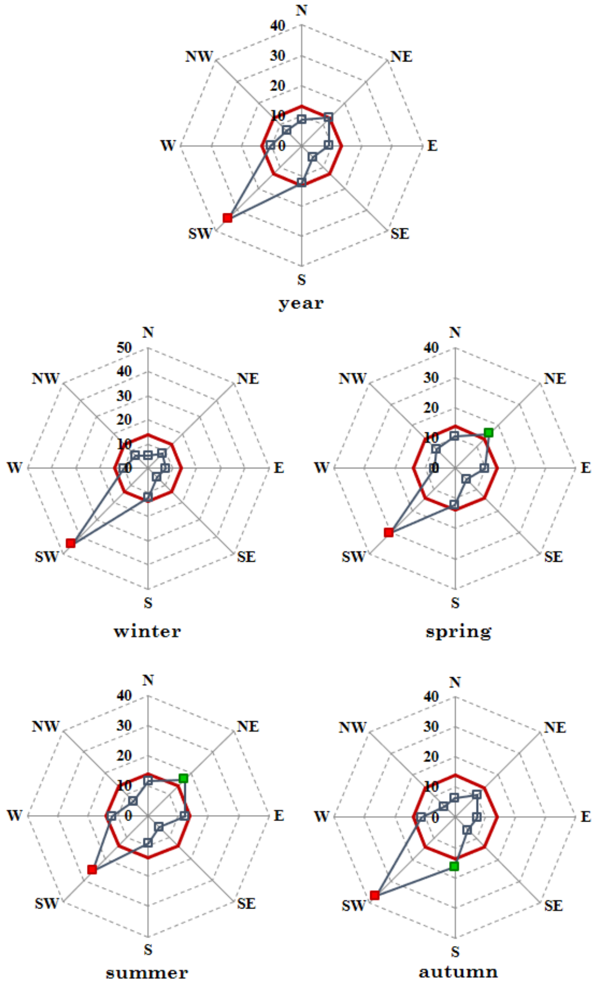

Figure 8. Relative frequency of wind directions and characteristic directions of wind (red markers indicate the most frequent characteristic wind direction, while green markers show all the other characteristic wind directions)

The 27.4% of $v \geq 3$ m/s wind speeds belong to the south-western wind direction, 9.9% to the north-eastern (is characteristic for spring and summer) and 8.5% to the southern (is characteristic for fall) wind direction. Non-characteristic wind directions are characterized in average by the 5.9% of $v \geq 3$ m/s wind speeds.

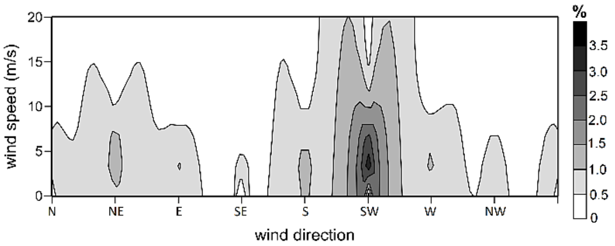

Figure 9. Speed distribution of wind directions at the measuring station

South-western characteristic wind direction yields the highest mean velocity. As far as wind power is in proportion with the third power of wind speed (Patay, 2003), this wind direction yields the greatest energy content. According to the above-mentioned definition south-western direction can be considered the energetically prevailing wind direction. In Play this direction yields 47% of the total energy (Figure 10) including 63% in winter, 35% in spring, 29% in summer, and 49% in fall. A characteristic wind direction in winter yields 12.2 times, in spring – 3.7 times, in summer – 2.5 times, and in fall – 6.6 times more energy than a non-characteristic wind direction.

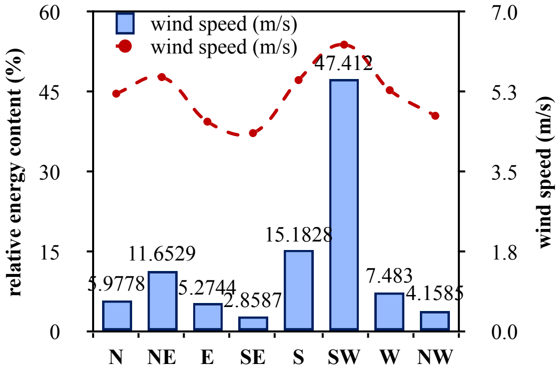

Figure 10. Relative energy content (%) of various wind directions and their average velocity (m/s) (green column is the energetically prevailing wind direction)

The relation between the frequency, velocity of wind directions and their relative energy content was studied by means of linear correlation and regression. Table 7 includes linear correlation coefficient and regression coefficient values. In this case, the critical value of the 0.05 significance level of the correlation coefficient is (n=8) $r_{0.05}$=0.63, i.e., the relation is significant; both the wind speed and the relative energy content are in connection with the frequency distribution of wind directions. Nevertheless, correlation coefficients of relative energy are higher, therefore, the relation in case of relative energy content can be considered determined in a statistical manner. It means that the energy content of wind directions is mostly determined by their frequency of occurrence, rather than by their speed.

Table 7. Linear correlation (*r*) and regression (*b*) between the relative frequency of wind directions, mean velocity of wind, and the relative energy content

Statistical parameter	Average Speed		Relative energy	
	R	***B***	***r***	***b***
Correlation and regression	0.85	0.73	0.99	0.99

In the $y = a + bx$ equation b regression coefficient also shows sensitiveness to the change of the independent variable value of the dependent variable (Obádovics, 2003). The value of almost 1 proves that essentially the frequency and relative energy content of wind directions vary together.

4. Conclusions

Summarizing our results, the following significant conclusions can be drawn:

Average wind speeds with their winter maximums and summer minimums run a definite yearly course. Thus, annual wind climate cannot be considered equal. There are 2.2 m/s between the mean velocity of the windiest January and the least windy August.

The daily course of wind speeds is also determined by night maximum and daily minimum.

Taking into account the annual and the daily course of the wind speed, it can be determined that available wind power at midday hours in summer and early autumn is the smallest and most changing, while at midnight hours of winter and in early spring it is the greatest and steadiest.

The frequency distribution at 5% significance level of daily average wind speeds at Play measuring point can be described by means of Weibull distribution in all seasons. Wind power density determined by means of distribution parameters at Play is 169.0 W/m^2 and 8.0-9.0 m/s winds yield most energy during the year.

In summer, a minimum number of energetically utilizable wind hours are available, while the maximum number of hours is in spring. On the territory represented by the measuring point a 3 m/s start-up speed wind turbine could operate 63% time of the year. Maximum continuous operation periods are in January and November. The average length of continuous operation time in winter exceeds 23 h, while the total utilizable wind hours amount to over 1400 h, averaging 20 days of operation per month.

The most frequent characteristic wind direction with the highest mean velocity in each season is south-western; its average relative frequency is 34.4%. Mean velocity of characteristic wind directions is 5.8 m/s. South-western wind direction yields 47% of the total energy. A characteristic wind direction yields in average 6.3 times more energy than a non-characteristic wind direction. The linear correlation and regression between the relative frequency of wind directions, average wind speed, and relative energy content testify to the fact that the energy value of wind directions is mainly determined by the frequency of occurrence.

A dense measuring point network is needed for the wind climatological characterization of Polonyna Borzhava or any other highland territory, as well as for the mapping of wind energy resources. Terrain differences and relief conditions significantly affect the available wind power, even in small horizontal areas.

Our results verify that the territory around the measuring point can yield wind energy. In Transcarpathia, utilization of renewable energy resources like wind energy, solar power, hydropower, and biomass energy can play an important role in the future.

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