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Determination of Energy Parameters of Near Surface Wind Field in Transcarpathia (Ukraine)

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Abstract- This research, which is part of a complex wind energy examination, analyses average daily wind speed time series of 9 available meteorological stations. Weibull distribution helps to work out the distribution of daily average wind speeds on levels different from anemometer altitude, then average values are calculated here for the entire period and power law is applied to them. Thus, a correlation between Hellmann's wind profile law and Weibull distribution can be demonstrated. At anemometer altitude and at five chosen altitude levels (20, 40, 60, 80 and 100 m above ground level) other significant parameters from the point of view of wind energy utilization are determined: wind speed mode, its coefficient of variation, wind velocity carrying maximum energy, duration of energetically useful wind speeds, as well as specific wind power. In Transcarpathia, mountain areas have the highest wind power, where the average wind speeds at 100 m above ground level reaches 6-8 m/s, and the specific wind power is 500-700 W/m^2.

Key words: wind energy, wind speed, wind power density, Weibull distribution, Transcarpathia.

1. Introduction

The use of wind energy by humans dates several thousand years back. However, it was in the past four decades that it became the object of intensive research and development as a renewable type of energy and as an alternative of sustainable energy production. Currently wind energy is the leading, most quickly growing, developing energy technology in the world showing the greatest capacity to expand. Since the early 2000s a significant technical and deployed capacity leap could be observed. In the past 20 years the deployed wind park capacity all over the world grew seventyfold, thus, according to Global Wind Energy Council (GWEC) data, the total wind park capacity of the world reached 539.2 GW by the end of 2017 [1].

In the period between 2010 and 2017 Ukraine showed two times quicker development for the renewable type of energy use than that of traditional fossil and thermonuclear energy industry. By the end of 2017 the power plant capacity of only renewable type of energy was 1375.1 MW (in 2016 it was 1117.7 MW) and the amount of electricity grew by 23% compared to the previous year [2]. Energy produced from renewable energy resources (water, wind, sun, geothermal energy and biomass) supplies 7% of the country's power-consumption, wind energy, correspondingly, makes up 0.8% [2]. By the end of 2016 there were 12 functioning wind parks in Ukraine. The biggest among them are Botievska (199,9 MW), Novoasovska-2 (57,5 MW) and Prichornomorska (52,5 MW) [2]. Thus, the total output of all the deployed wind power plants reached 593,6 MW [3]. As a result, the country is 38th in list of countries producing wind energy in the world [1]. In Europe it occupies the 22nd position [3].

The best areas for the development of the wind energy industry – regarding wind speed – have steady wind, i.e. wind speed values have minimal standard deviation and average wind speed equals or exceeds 3 m/s [4]. References [5,6,7,8] state that the following part of the country have favourable conditions for high efficiency energy production of wind power plants: the coasts of the Black Sea and the Sea of Azov, the Podolian Upland, the Donets Upland, as well as the highland regions of the North-eastern Carpathians covering 80% of Transcarpathia. In Ukraine's atlas of the energy potential of renewable and traditional energy resources [9], Transcarpathia occupies sixth place among Ukraine's regions based on the total available wind energy resources. Previous studies [10,11,12] showed that some parts of the highlands have significant wind energy potential. Reference [12] used the data from Subcarpathian meteorological stations and determined specific wind power values for the period between 2005 and 2015. The results show values ranging from 19 W/m^2 (Kolomyia) to 42 W/m^2 (Dolyna) in the case of stations in non-mountainous areas. However, in the highland Pozhyzhevs'ka station it reaches 182 W/m^2. Despite these facts, only two wind parks functioned on the Ukrainian part of the North-eastern Carpathians according to the 2017 UWEA report (WPP Staryi Sambir-1 (with the capacity of 13.2 MW) and WPP Staryi Sambir-2 (with the capacity of 20.7 MW). None was built on the territory of Transcarpathia.

Exploitation of wind energy is a multicomponent process with a multitude of parameters. Output values of local wind conditions and the applied energy conversion system determine the obtainable energy amount. The producible wind energy values can be calculated at meteorological stations on the basis of detailed statistical analysis and/or model calculations of wind data.

This research aims at determining and analysing significant parameters for utilizing wind energy on the basis of wind speed data from Transcarpathian meteorological stations. Small, medium and high output wind turbines have different hub height, thus it seemed plausible to determine energy parameters at these typical altitudes as well. As a result, extra information and wind climate characteristics can be obtained that significantly contribute to determining energy production indices of a given territory, as well as to the choice of location for establishing wind parks. The results hopefully can contribute to spreading wind energy utilization in Transcarpathia in the near future.

2. Material and Method

In this research the daily average wind speed of the meteorological observatories was used. The data series were submitted by the Transcarpathian hydrometeorological centre (KMHMK) based on nine Transcarpathian (Ukraine) functioning meteorological stations (Fig. 1.).

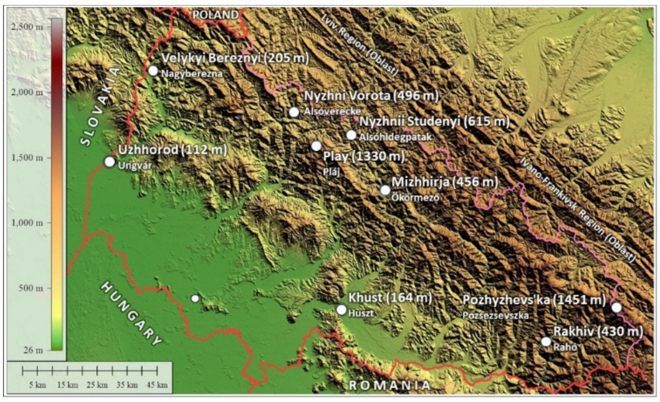

Fig. 1. Geographical locations and altitudes above sea level (m) of the meteorological stations comprising the database.

Table 1 shows the exact geographical coordinates of these stations, their altitude above sea level, as well as the altitude of the wind-gauge above ground level. The data were collected in the period from 1 January 2011 to 31 December 2015.

Table 1. Exact geographical coordinates of the meteorological stations and anemometer altitudes (φ: latitude, λ: longitude, h: elevation, h_a: anemometer altitude above ground level)

Meteorological station	Geographical coordinate		h (m)	h_a (m)
	φ (northern)	λ (eastern)	Jan. 2011. – Dec. 2015.	
Uzhhorod	48°38'	22°16'	112	14
Khust	48°11'	23°18'	164	16
Velykyi Bereznyi	48°54'	22°28'	205	10
Rakhiv	48°03'	24°12'	430	10
Mizhhirja	48°31'	23°30'	456	10
Nyzhni Vorota	48°46'	23°06'	496	10
Nyzhnii Studenyi	48°42'	23°22'	615	10
Play	48°40'	23°12'	1330	8
Pozhyzhevs'ka	48°09'	24°32'	1451	11

The basic principle of wind energy utilization is to use the energy of atmospheric movements as direct mechanic energy source or to transform it into electric energy by means of a transformation system. The movement, kinetic energy (E_{kin}) of the wind that flows at speed v (m/s) through a blade sweep area A within a particular period of time t (s) can be calculated by means of the equation (1) [13,14,15]:

$$E_{kin} = \frac{1}{2}mv^2 = \frac{1}{2}\rho A t v^3 \quad (1)$$

where m stands for air mass (kg), and ρ stands for air density (kg/m^3). If normal cross-section of the wind direction and time are taken as a unit, i.e. A = 1 m^2 and t = 1, it will result in specific wind power.

Thus, the index-number of potential wind energy is the kinetic energy of the airflow and wind power density derived from it: energy flowing normally, on a unit of cross-section, and in a unit of time to the direction of the wind [13,14,16], and its unit of measurement will be W/m^2. The available mean wind power density (P_m) of the site can be expressed by the following expression:

$$P_m = \frac{1}{2}\rho v^3 EPF \quad (2)$$

where v is the mean wind speed and EPF is the energy pattern factor. The EPF is related to the averaged data of wind speed and is defined as a ratio between mean of cubic wind speed to cube of mean wind speed [17,18]:

$$EPF = \frac{\frac{1}{n}\sum_{i=1}^{n} v_i^3}{\left(\frac{1}{n}\sum_{i=1}^{n} v_i\right)^3} = \frac{\overline{v^3}}{(\overline{v})^3} \quad (3)$$

where v_i is the wind speed (m/s) for the *ith* observation, n is the number of wind speed samples, and $\overline{v}$ is the annual mean wind speed.

Eq. (2) shows that wind power is proportional to its third power. Thus, it is important to choose high average wind speed points. Equation (2) also shows that wind energy is in proportion with air density, consequently, at higher altitudes above ground level the same wind speed produces less energy [14]. Air density, however, depends on its temperature, pressure, as well as other constituents. That is why, despite identical wind speed, there may be 10-15% seasonal differences in wind power [19]. Taking into account the change of air density, the so-called dynamic specific power function can be noted that takes into account the influence of all the significant physical parameters of the air [14]. Equation (2) accurately determines wind power; however, the condition of its application is that all its variables are to be measured and calculated at the same time. This makes its use more difficult, thus air density is taken as a constant in wind energy calculations (ρ = 1,225 kg/m^3, at 15 °C and 760 mm of atmospheric pressure).

Therefore, wind power density of the flow of air at a particular time moving with v speed can be determined by means of equation (2). Wind power density of a time interval, i.e. of a longer period of time can be determined by exchanging v for the average speed of the period in equation (2). Another possibility is to summarize specific wind power density of a particular period (day, month, season) at a discreet time. This possibility is more practical. In this case, however, the result depends on the number of measurement times. This dependence can be decreased by means of averaging. In this case, however, wind power density is obtained for a measurement point of a given period [20,21,22].

It should be noted that there is a conceptual solution to eliminate this dependence. The area below the curve of the function applied to the daily course of cubed wind speed needs to be determined. If it is multiplied by half (ρ/2) of air density, the exact value of daily total specific wind power is obtained. The calculation can be performed at a given day by means of a numerical integral. However, average wind power density per day of an arbitrary period (e.g. month, season, year) can be calculated by means of the chosen approximation function [21,22].

The knowledge of probability density function is necessary to calculate energy production. It can be estimated by means of relative frequency of the measured wind data. It is definitely not enough to know the relative frequency of wind speeds and their energy parameters close to the ground level, at anemometer altitude. The hub height of mainly industrial wind power plants used nowadays, depending on the type, reaches 80-120 m. From energy point of view, it is important to know some characteristics of wind speeds at these altitudes.

The characteristics of Weibull distribution belonging to the gamma function family are applied for this purpose in wind climatology [23,24,25]. Distribution parameters can be determined from wind speed values at anemometer altitude. Parameters for other altitudes can be calculated on the basis of measurement level values, i.e. Weibull distribution helps describe frequency distribution of wind speed at various altitudes.

Weibull distribution is a double-parameter (k and c) asymmetrical distribution, whose distribution density can be easily described in the following way (4) [26,27]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (4)$$

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. The Weibull shape parameter k is a very important factor to know about the characteristics of the wind wave of a particular wind site. The Weibull scale factor c indicates the potentiality of the wind power of that site. The greater the value of c is, the higher the potential of wind sites is. Parameters k and c that are valid at anemometer altitude can be determined in several ways [23,25,26,28,29,30]. That method we chosen, where parameters k and c in the previously conducted test yielded best approximation at 5% significance level.

The chosen method (5), (6) can be traced back to the estimation of momentum [23,25,28,31]. If average wind speed (v_m) and standard deviation (σ) are known, then

$$k = \left(\frac{\sigma}{v_m}\right)^{-1,086} \quad (5)$$

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

where σ/v_m is the coefficient of variation and $\Gamma(x)$ is the gamma function which is defined by the following integral form as follows [29]:

$$\Gamma(x) = \int_0^{\infty} t^{x-1} \exp(-t)\, dt \quad (7)$$

The gamma function is often used for wind energy analysis. This integral function is a component in various probability-distribution functions, for example, the gamma distribution. The gamma distribution can be used to describe the frequency distribution of wind speeds.

However, if we proceed from this and want to give distributions at different altitudes, then the distribution parameters for other altitudes can be calculated on the basis of the values related to the measurement level. If the value of parameters at anemometer z_a altitude are c_a and k_a then at a $z \neq z_a$ level [17,29]:

$$c_z = c_a \left(\frac{z}{z_a}\right)^n \quad (8)$$

$$k_z = \frac{k_a\left[1-0,088\, ln\left(\frac{z_a}{10}\right)\right]}{\left[1-0,088\, ln\left(\frac{z}{10}\right)\right]} \quad (9)$$

The n exponent is:

$$n = \frac{[0,37-0,088 \ln c_a]}{\left[1-0,088\, ln\left(\frac{z_a}{10}\right)\right]} \quad (10)$$

By working out daily average wind speed distribution at a level different from anemometer altitude, knowing the scale- and shape parameter at this altitude, average wind speed, standard deviation, mode, coefficient of variation, mean power density (P_m) can be calculated by means of the gamma function.

The average v_m sample taken from the probability variable of Weibull distribution can be determined in the following way (11) [17,32]:

$$v_m = c\Gamma\left(1+\frac{1}{k}\right) \tag{11}$$

where c and k are parameters of the distribution at a given altitude.

Its standard deviation (12) is [17]:

$$\sigma = c\left[\Gamma\left(1+\frac{1}{k}\right) - \Gamma^2\left(1+\frac{1}{k}\right)\right]^{\frac{1}{2}} \tag{12}$$

Distribution mode (13) will be its most probable value [33,34]:

$$M_0 = c\left(1-\frac{1}{k}\right)^{\frac{1}{k}} \tag{13}$$

Wind velocity carrying maximum energy (14) will yield maximum efficiency under optimal conditions [32,34]:

$$v_{maxE} = c\left(1+\frac{2}{k}\right)^{\frac{1}{k}} \tag{14}$$

This generally equals 1.4-2.0 times the average wind speed [32].

Power estimation approximated by means of Weibull distribution is based on the above-mentioned characteristic of the distribution, i.e. if v wind speed can be described by means of parameters k and c Weibull distribution, then at v^m level it can be described by means of Weibull distribution parameters k^m and c^m [24,31,32]. Specific wind power can be defined by means of gamma function $\Gamma(x)$ in the following way (15) [32,35,36]:

$$P_m = \frac{1}{2}\rho c^3 \Gamma\left(1+\frac{3}{k}\right) \tag{15}$$

where c and k are Weibull distribution parameters.

Specific wind power can be determined by means of relative frequency distributions (16) as well that have been worked out at various altitude levels [10,12,13]

$$P_m = \frac{1}{2}\rho \sum_{i=1}^{n} v_i^3 p_i \tag{16}$$

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 is the number of speed intervals. As far as formula (16) is based on frequency distribution of wind speeds, it yields the same result as formula (15).

3. Results

The frequency distribution of daily mean wind speeds was described by the Weibull distribution. The reliability of distribution matching was checked by means of χ^2-test. Each case, except Khust, resulted in matching at 5% significance level. Then equations (8), (9) and (10) were used to determine parameters k and c of the distribution at levels (z) differing from anemometer altitude (z_a) as well. Its z_a values were taken from Table 1. The chosen altitudes are z=20, 40, 60, 80 and 100 m above ground level. In Khust they are best approximated, however, Weibull parameters below 0.90 acceptance level were used. These helped work out the distributions at z altitudes. At some levels average values, standard deviation, mode, coefficient of variation and distribution parameters are presented in Table 2. At higher levels equations (11), (12) and (13) were applied to determine these. Further on in the research energy parameters of the wind field will be analysed and Transcarpathian territorial differences regarding wind energy exploitation will be revealed.

Table 2. Parameters and basic statistical data of the Weibull distribution which describes the distribution of daily average wind speeds at z_a anemometer altitude and at five other levels in the period between 2011 and 2015.

Altitude	Parameter	Uzhhorod (112 m)	Khust (164 m)	Velykyi Bereznyi (205 m)	Rakhiv (430 m)	Mizhhirja (456 m)	Nyzhni Vorota (496 m)	Nyzhnii Studenyi (615 m)	Play (1330 m)	Pozhyzhevs'ka (1451 m)
	z_a	14	16	10	10	10	10	10	8	11
	n	0.31	**0.38**	**0.34**	0.34	**0.35**	0.31	0.33	*0.22*	0.26
z_a m	k_a	**1.82**	**2.71**	1.32	*1.02*	1.48	1.59	**2.19**	1.65	1.15
	c_a (m/s)	**2.30**	*1.03*	1.42	1.44	1.30	2.02	1.66	**5.23**	**3.59**
	average (m/s)	**2.05**	*0.92*	1.30	1.43	1.18	1.82	1.47	**4.68**	**3.41**
	stand. deviation (m/s)	1.17	*0.37*	1.00	1.40	0.81	**1.18**	0.71	**2.92**	**2.97**

	mode (m/s)	**1.49**	0.87	0.48	*0.03*	0.61	1.09	**1.26**	**2.97**	0.62
	coefficient of variation	0.57	*0.40*	**0.77**	**0.98**	0.69	0.65	0.48	0.62	**0.87**
20 m	k_z	**1.88**	**2.77**	1.40	*1.07*	1.58	1.70	**2.34**	1.79	1.22
	c_z (m/s)	**2.85**	*1.35*	1.79	1.82	1.66	2.51	2.08	**6.10**	**4.29**
	average (m/s)	**2.53**	*1.20*	1.63	1.77	1.49	2.24	1.84	**5.42**	**4.02**
	stand. deviation (m/s)	1.40	*0.47*	1.18	**1.67**	0.96	1.36	0.84	**3.14**	**3.32**
	mode (m/s)	**1.90**	1.14	0.74	*0.13*	0.88	1.48	**1.64**	**3.85**	1.04
	coefficient of variation	0.55	*0.39*	**0.72**	**0.94**	0.65	0.61	0.45	0.58	**0.83**
40 m	k_z	**2.01**	**2.96**	1.50	*1.14*	1.69	1.81	**2.60**	1.91	1.30
	c_z (m/s)	**3.52**	*1.75*	2.27	2.30	2.11	3.10	2.97	**7.10**	**5.14**
	average (m/s)	**3.12**	*1.57*	2.05	2.19	1.88	2.76	2.64	**6.30**	**4.75**
	stand. deviation (m/s)	1.62	*0.58*	1.39	**1.93**	1.15	1.57	1.09	**3.43**	**3.68**
	mode (m/s)	**2.50**	1.53	1.09	*0.37*	1.24	1.99	**2.47**	**4.82**	1.67
	coefficient of variation	0.52	*0.37*	**0.68**	**0.88**	0.61	0.57	0.41	0.54	**0.77**
60 m	k_z	**2.10**	**3.09**	1.56	*1.19*	1.76	1.89	**2.68**	1.99	1.36
	c_z (m/s)	**3.98**	*2.05*	2.60	2.64	2.43	3.51	3.27	**7.76**	**5.71**
	average (m/s)	**3.53**	*1.83*	2.34	2.49	2.16	3.12	2.90	**6.88**	**5.23**
	stand. deviation (m/s)	1.77	*0.65*	1.53	**2.10**	1.21	1.72	1.17	**3.61**	**3.90**
	mode (m/s)	**2.92**	1.80	1.35	*0.56*	1.51	2.36	**2.74**	**5.47**	2.13
	coefficient of variation	0.50	*0.35*	**0.65**	**0.84**	0.59	0.55	0.40	0.52	**0.75**
80 m	k_z	**2.16**	**3.18**	1.61	*1.23*	1.82	1.95	**2.68**	2.06	1.40
	c_z (m/s)	**4.35**	*2.29*	2.87	2.91	2.68	3.84	3.27	**8.27**	**6.15**
	average (m/s)	**3.85**	*2.05*	2.57	2.72	2.38	3.40	2.90	**7.33**	**5.61**
	stand. deviation (m/s)	1.88	*0.71*	1.63	**2.23**	1.36	1.82	1.17	**3.74**	**4.06**
	mode (m/s)	**3.26**	2.03	1.57	*0.73*	1.73	2.65	**2.74**	**5.98**	2.51
	coefficient of variation	0.49	*0.34*	**0.64**	**0.82**	0.57	0.54	0.40	0.51	**0.72**
100 m	k_z	**2.21**	**3.26**	1.65	*1.26*	1.86	2.00	**2.75**	2.11	1.43
	c_z (m/s)	**4.66**	*2.49*	3.09	3.13	2.90	4.11	3.51	**8.69**	**6.52**
	average (m/s)	**4.12**	*2.23*	2.77	2.92	2.57	3.64	3.12	**7.69**	**5.92**
	stand. deviation (m/s)	**1.97**	*0.75*	1.72	2.34	1.44	1.91	1.23	**3.84**	**4.19**
	mode (m/s)	**3.55**	2.23	1.76	*0.88*	1.91	2.90	**2.98**	**6.40**	2.83
	coefficient of variation	0.48	*0.34*	**0.62**	**0.80**	0.56	0.52	0.39	0.50	**0.71**

3.1. Average wind speed

At the 9 stations under analysis average wind speed at anemometer altitude (z_a) varies from 0.92 m/s (in Khust) to 4.68 m/s (in Play). Average wind speed of the area is 2.03 m/s; however, it shows spatial variability. Plains and narrow river valleys are rather characterized by low average wind speeds (1.45 m/s), while mountain ridges and mountain peaks have stronger winds with correspondingly higher average speeds (4.05 m/s). According to average wind speed the ascending order of stations is as follows: Khust, Mizhhirja, Velykyi Bereznyi, Rakhiv, Nyzhnii Studenyi, Nyzhni Vorota, Uzhhorod, Pozhyzhevs'ka, and Play. Average wind speed increases depending on the altitude above ground level. At 100 m above ground level the order of the stations does not change, only the values are higher, with the minimum of 2.23 m/s (Khust) and maximum 7.69 m/s (Play). Its territorial picture at 100 m above ground level is shown in Fig. 2. IDW (Inverse Distance Weighted, weighted arithmetic mean) linear interpolation method offered by the common geomatic software was applied for wind speed interpolation. Here the flow-modifying influence of the terrain was not taken into account. Due to the complex terrain characteristics, one can get a more accurate map by means of significant increase of density of measurement points or by means of dynamic models that take into account surface roughness and turbulence and serve for horizontal and vertical extrapolation of wind data.

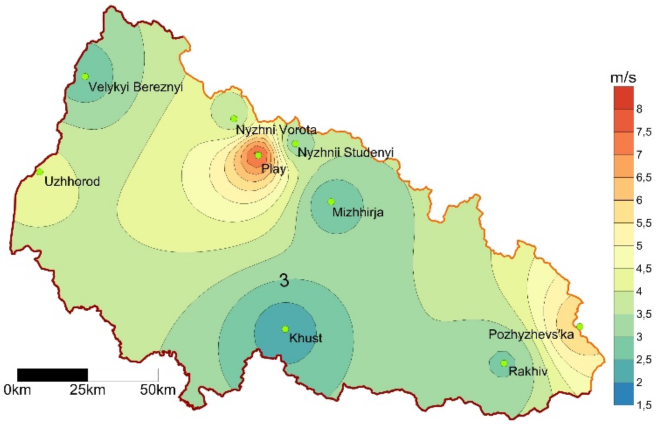

Fig. 2. Average wind speed at 100 m above ground level in Transcarpathia in the period between 2011 and 2015.

Connections were found at all altitude levels between average wind speed of measurement points and altitude above sea level. The average value of the correlation coefficient was 0.851. Reliability of the correlation coefficient was tested by means of T-test and F-test; the latter was applied during analysis of variance (ANOVA). On the basis of two tests it can be stated with a 5% reliability level that there is a reliable connection between the two variables, r significantly deviates from 0.

This study does not research in detail the possible connection between average wind speed and Weibull distribution parameters as well as other characteristics of parameters. Henessey [37] claims that shape parameter allows one to infer specific wind power. Where average wind speed is highest and the shape parameter of Weibull distribution is lowest, specific wind power is greatest. In Transcarpathia the k values are relatively low (Table 2), they are not combined with significant average wind speed, thus wind power density is not high except for the Play station (to be discussed later).

3.2. Dependence of average wind speed on altitude

Fig. 3 illustrates the dependency of average speeds calculated for the whole period (v_{zmean}) on altitude based on the data in Table 2. We fitted a power function on the calculated values at six points, that is $v_{zmean}=az^{\alpha}$. Thus we can formulate the Hellmann relation for v_1 and v_2 average speeds at altitudes z_1 and z_2 in the form conventionally used in wind energy research as:

$$\frac{v_2}{v_1} = \left(\frac{z_2}{z_1}\right)^{\alpha} \quad (17)$$

Eq. (17) and (8) – as far as scale parameters are measured in m/s – are theoretically the same, i.e. $n=\alpha$. The results of α refer to the same application. These are the following: Uzhhorod 0.30, Khust 0.39, Velykyi Bereznyi 0.33, Rakhiv 0.31, Mizhhirja 0.34, Nyzhni Vorota 0.30, Nyzhnii Studenyi, 0.33, Play 0.21 and Pozhyzhevs′ka 0.24; the above values correspond well with data in Table 2 on n. In other words, if a different method is applied, e.g. α value is determined by means of wind speed measurements at different levels, then an important Weibull parameter is obtained.

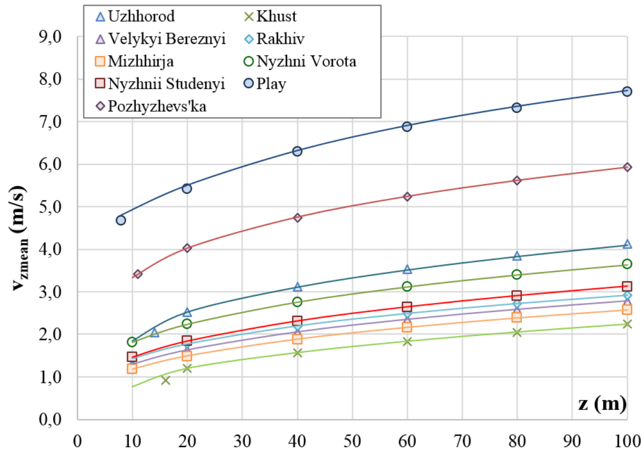

Fig. 3. Average wind speeds (points) calculated for the whole measurement period and the power function fitted on them.

3.3. Coefficient of variation of wind speeds

Coefficient of variation shows what part and how many per cent experience deviation comprises compared to average value. It enables one to compare relative variability of wind speeds at some measurement points and to single out areas with least and most variable wind. From wind energy production point of view steady wind is most favourable, i.e. when wind speeds are constantly close to average. Territories with favourable wind conditions combine low coefficient of variation and high average wind speed. According to Table 2, coefficient of variation at anemometer altitude ranges from 0.40 (Khust) to 0.98 (Rakhiv). Ascending order of the stations is as follows: Khust, Nyzhnii Studenyi, Uzhhorod, Play, Nyzhni Vorota, Mizhhirja, Velykyi Bereznyi, Pozhyzhevs′ka, Rakhiv. The order stays the same at all altitudes. Average wind speeds are highest in Uzhhorod, Pozhyzhevs′ka, and Play. Among these, Uzhhorod and Play have the least changeable wind. The two stations are situated in two different orographic conditions. Taking into account wind speeds at higher altitude (80, 100 m above ground level), from wind energy exploitation point of view in Transcarpathia, on plains Uzhanska dolyna, while in the highlands Polonyna Borzhava offer the best conditions.

3.4. Wind speed mode

Among statistical average values mode bears important information on the distribution of wind speeds, as far as it is the value occurring most often. Wind speed mode at the stations at z_a altitude varies from 0.03 m/s (Rakhiv) and 2.97 m/s (Play). Ascending order of the stations according to the mode is as follows: Rakhiv, Velykyi Bereznyi, Mizhhirja, Khust, Pozhyzhevs′ka, Nyzhni Vorota, Nyzhnii Studenyi, Uzhhorod, Play. Altitude does not change the mode. Taking into account the mode of Transcarpathian settlements, Uzhhorod and Play are favourable ones for their mode, i.e. the most probable wind speed at 100 m above ground level reaches 3.5 m/s and 6.40 m/s.

Another highland station Pozhyzhevs′ka has relatively high average wind speed (5.92 m/s at 100 m above ground level), however, due to high coefficient of variation (0.71 m/s at 100 m above ground level) and low mode (2.83 m/s at 100 m above ground level) continuous and adjusted functioning of wind turbines is not possible. Compared to the majority of measurement points in the territory, higher average wind speed is probably caused by frequent windless periods followed by short periods of strong winds (v≥10 m/s).

3.5. Frequency distribution of wind speeds

Wind speeds depend on time in their frequency distribution. Distributions help determine the spread of distribution area above the chosen wind speed values. Knowing the reference time of average wind speed, one can calculate the duration of some wind speed ranges. From wind energy point of view, one of the important indices is knowing the spread of wind speed range exceeding the start-up speed of wind turbines, i.e. its average duration. The start-up speed of modern wind turbines is often 3 m/s, thus the knowledge of the cumulated frequency of wind speeds exceeding this value is necessary to determine what part of the year, month, etc. the equipment will theoretically function and produce electricity.

Histograms of wind speed, Δx=1 m/s subdivided into wind speed classes and formed on the basis of data series referring to the entire period, yield a different picture at various stations according to local wind peculiarities. Based on our research results, only the histogram of Uzhhorod and Play at anemometer altitude (z_a) and at other five chosen levels are shown in Fig. 4.

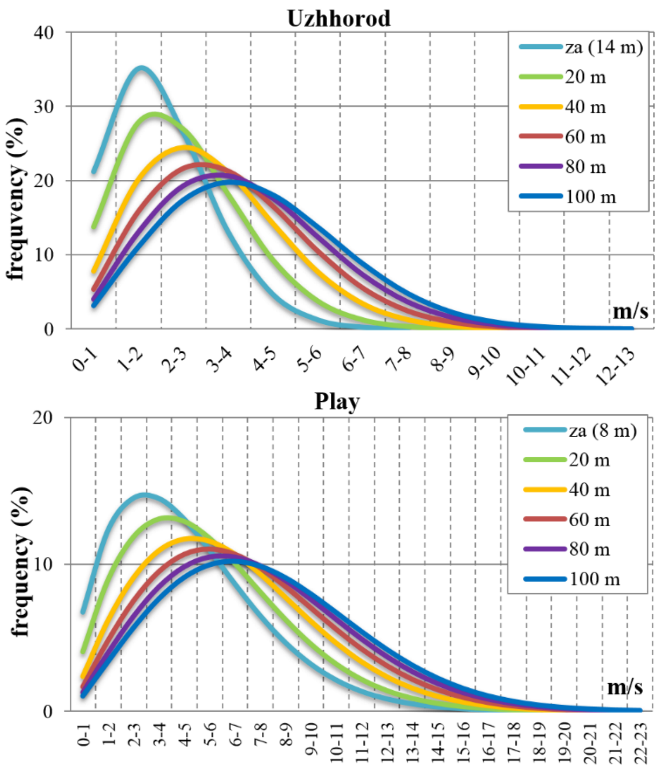

Fig. 4. Distribution of daily average wind speeds at anemometer altitude (z_a) and at five additional levels in the period between 2011 and 2015.

Table 3 shows the cumulated frequency of some wind speed ranges, the wind speeds yielding greatest energy determined by means of equations (14), (15) and (16), as well as the change of wind power density depending on altitude.

The cumulated frequency (v_{mean}≥3 m/s) of wind speeds exceeding 3 m/s shows significant territorial variability. At z_a level it varies from 0 days/year (Khust) to 245 days/year (Play), while at 100 m above ground level it varies from 52 days/year to 329 days/year. This means that at Play measurement point, for instance, a 100 m hub height wind turbine with such a start-up speed can function for approximately 90.0% of a year. It is followed by Pozhyzhevs′ka (with 72.0%) and Uzhhorod (with 68.6%). The difference between the previous two at 100 m above ground level is 3.5%, however, at Pozhyzhevs′ka, due to stronger winds, the wind speeds are v_{mean}≥5 m/s in their cumulated frequency (approximately 20% difference), thus causing significant differences in wind power (Figures 5 and 6). At the other 6 stations the v_{mean}≥3 m/s cumulated frequency at z_a altitude does not exceed 15% (55 days/year), while at 100 m above ground level it comprises 39.4% (144 days/year). On the basis of v_{mean}≥3 m/s cumulated frequency, the ascending order of stations at z_a and other z levels is the following: Khust, Nyzhnii Studenyi, Mizhhirja, Velykyi Bereznyi, Rakhiv, Nyzhni Vorota, Uzhhorod, Pozhyzhevs′ka, and Play.

Taking into account wind velocity carrying maximum energy (v_{maxE}), Khust had the expected lowest values at all altitudes (at z_a altitude 8.58 m/s, at 100 m above ground level

11.99 m/s), while Pozhyzhevs′ka had the expected highest values (at z_a altitude 1.26 m/s, at 100 m above ground level 2.89 m/s). Among all the stations Pozhyzhevs′ka has the strongest winds carrying maximum energy, however, their time distribution is not even. Play station has the second highest values (at z_a altitude 8.48 m/s, at 100 m above ground level 11.92 m/s) of wind velocity carrying maximum energy together with relatively low coefficient of variation; the latter is a favourable feature from wind energy exploitation point of view of. Rakhiv has the third highest value having the same wind as in Pozhyzhevs′ka. Rakhiv has lower average wind speed, however, low mode, high standard deviation and coefficient of variation, as well as the average speed of the winds carrying maximum energy testify to the fact that local wind is also characterized by frequent calm followed by strong winds. Rakhiv is situated in the Chorna Tisa valley, and Pozhyzhevs′ka is on the Chornohora massif ridge. Similar wind at two measurement points situated in different terrain conditions is probable. It can be explained by closeness to each other (35 km in a straight line) as well as by North-East-South-West line of bearing. It corresponds to the airflow of the same direction above the mountain ridge. The compass card at Pozhyzhevs′ka station shows the same.

3.6. Specific wind power

Available specific wind power (P_m) was determined for each station. It is a fundamentally important parameter to measure the utilizable wind energy of a measurement point and its close surroundings. In Transcarpathia, specific wind power at z_a levels varies from 0.7 W/m^2 (Khust) to 153.7 W/m^2 (Play), while at 100 m above ground level it is 10.5 W/m^2 (Khust) and 540.4 W/m^2 (Play) and it is a large difference. Characteristic average values at 100 m above ground level are only around 20-80 W/m^2. These average values are relatively very low. The following stations should be highlighted for they have the best conditions for energy exploitation at this altitude in Transcarpathia: Uzhhorod (74.7 W/m^2 at 100 m above ground level), Pozhyzhevs′ka (540.4 W/m^2) and Play (682.0 W/m^2) (Fig. 5).

Table 3. Some energy parameters of the wind field at anemometer (z_a) altitude and at other five levels in the period between 2011 and 2015 (highlighting: **the first three highest** and lowest values)

Altitude	Parameter	Uzhhorod (112 m)	Khust (164 m)	Velykyi Bereznyi (205 m)	Rakhiv (430 m)	Mizhhirja (456 m)	Nyzhni Vorota (496 m)	Nyzhnii Studenyi (615 m)	Play (1330 m)	Pozhyzhevs′ka (1451 m)
z_a m	v_{mean}≥3 m/s (days/year)	**70**	0	24	43	10	54	7	**245**	**161**
	≥3 m/s (%)	**19.3**	0.0	6.5	11.8	2.9	14.9	1.9	**67.0**	**44.2**
	≥5 m/s (%)	1.5	0.0	0.5	**2.8**	0.1	1.4	0.0	**39.4**	**23.0**
	v_{maxE} (m/s)	3.46	1.26	2.86	**4.17**	2.32	3.37	2.23	**8.48**	**8.58**
	P_m (W/m^2)	**11.5**	0.7	4.8	10.3	3.0	9.6	3.5	**153.7**	**103.3**
20 m	v_{mean}≥3 m/s (days/year)	**120**	0	45	65	27	92	31	**276**	**191**
	≥3 m/s (%)	**32.8**	0.0	12.3	17.9	7.3	25.3	8.5	**75.5**	**52.3**
	≥5 m/s (%)	**5.4**	0.0	1.4	5.2	0.3	3.8	0.0	**49.5**	**29.9**
	v_{maxE} (m/s)	4.19	1.64	3.37	**4.90**	2.78	3.97	2.71	**9.28**	**9.54**
	P_m (W/m^2)	**21.6**	1.6	9.4	19.4	6.0	18.0	6.9	**238.8**	**169.2**
40 m	v_{mean}≥3 m/s (days/year)	**176**	1	78	93	58	141	85	**302**	**222**
	≥3 m/s (%)	**48.6**	0.3	21.4	25.6	15.8	38.7	23.2	**82.6**	**60.8**
	≥5 m/s (%)	**12.9**	0.0	3.7	8.7	1.3	9.0	0.5	**60.0**	**38.0**
	v_{maxE} (m/s)	4.96	2.09	3.99	**5.59**	3.35	4.67	3.30	**10.32**	**10.50**
	P_m (W/m^2)	**40.5**	3.7	18.6	36.8	12.0	33.6	20.4	**375.0**	**279.2**
60 m	v_{mean}≥3 m/s (days/year)	**210**	9	103	113	84	173	129	**315**	**240**
	≥3 m/s (%)	**57.6**	2.5	28.3	30.9	22.9	47.5	35.4	**86.1**	**65.8**
	≥5 m/s (%)	**19.7**	0.0	6.1	11.7	2.7	14.0	1.8	**66.0**	**43.3**
	v_{maxE} (m/s)	5.49	2.41	4.41	**6.05**	3.74	5.15	3.70	**11.00**	**11.13**
	P_m (W/m^2)	**58.6**	5.8	27.7	54.1	18.2	48.5	27.0	**488.4**	**372.6**
80 m	v_{mean}≥3 m/s (days/year)	**233**	27	124	128	106	196	164	**323**	**253**
	≥3 m/s (%)	**63.9**	7.4	33.8	35.1	28.9	53.8	44.9	**88.4**	**69.3**
	≥5 m/s (%)	**25.7**	0.0	8.5	14.2	4.3	18.5	3.9	**70.1**	**47.3**

	v_{maxE} (m/s)	5.89	2.67	4.73	**6.40**	4.04	5.52	4.02	**11.51**	**11.61**
	P_m (W/m^2)	**76.0**	8.2	36.7	70.6	24.4	62.8	27.0	**590.6**	**459.9**
100 m	v_{mean}≥3 m/s (days/year)	**251**	52	140	141	124	214	191	**329**	**263**
	≥3 m/s (%)	**68.6**	14.2	38.4	38.6	34.0	58.7	52.2	**90.0**	**72.0**
	≥5 m/s (%)	**30.8**	0.0	10.8	16.4	6.1	22.6	6.6	**73.2**	**50.4**
	v_{maxE} (m/s)	6.23	2.89	5.00	**6.69**	4.29	5.82	4.28	**11.92**	**11.99**
	P_m (W/m^2)	**93.1**	10.5	46.0	87.3	30.7	77.1	33.6	**682.0**	**540.4**

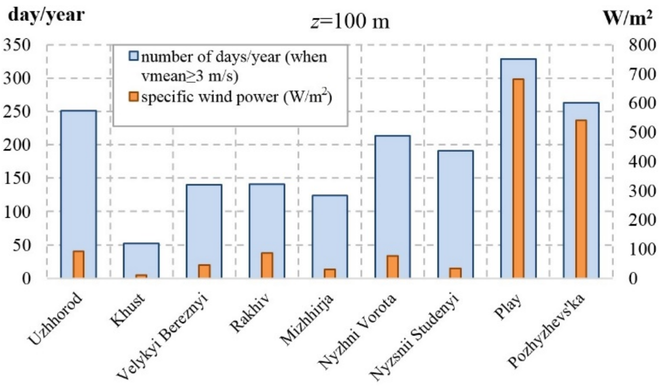

Fig. 5. The number of days (days/year) with average wind speed v≥3 m/s and specific wind power (W/m^2) at 100 m above ground level in the period between 2011 and 2015.

Fig. 6 shows available wind power field at 100 m above ground level. The map clearly shows the extremely huge territorial differences that may be caused by terrain conditions.

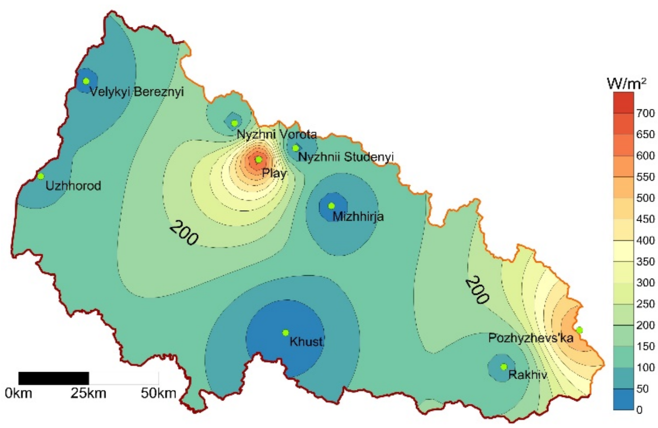

Fig. 6. Available wind power-field in Transcarpathia without taking into account the flow-modifying effect of the terrain at 100 m above ground level in the period between 2011 and 2015.

4. Conclusion

In Transcarpathia, wind energy exploitation conditions are most favourable in the highland regions and in open mountain ridges. On plain territories, in highland river valleys and in small basins wind energy exploitation conditions are unfavourable.

Transcarpathia needs significantly more measurement points than available for the territorial depiction of wind maps and wind power with proper resolution. Without these it is impossible to elaborate a wind potential map with proper resolution covering the entire territory of Transcarpathia. Taking into account the above-mentioned deficiencies of the database, the obtained wind map has limited applicability, mainly in highland regions where due to terrain characteristics there may be large differences in wind speed and thus in wind power even on a small territory.

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