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ASSESSMENT AND ANALYSIS OF WIND ENERGY POTENTIAL IN THE MOUNTAIN AREA AROUND SARAJEVO

Rejhana Blazevic, Halima Hadziahmetovic, Sanda Midzic Kurtagic & Mirela Alispahic

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Abstract

The main goal of this paper is to evaluate and discuss the energy potential of wind in the mountain area around Sarajevo. The analysis of wind energy potential was performed based on measured wind data for Bjelasnica in a period from 2000 to 2017. Measured data for wind velocity were obtained from the Federal Hydrometeorological Institute of Bosnia and Herzegovina. The results of this investigation showed that the analysed place falls under Class 7 according to the international system of wind classification, as the mean long term wind velocity recorded in the analysed area was 11 m/s and the corresponding mean long term power density was estimated about 2013 W/m^2 at 10 m height. Taking into account the power coefficient of the wind turbine as well as the utilization factor of the turbine and generator, it is obtained that the mean long term electrical power density is about 624 W/m^2. For a better insight into the characteristics of the occurrence of high-wind velocity, the calculation of expected maximum wind velocity for a return period of 50 years was carried out. It was shown that for the return period of 50 years, the reference extreme wind velocity is 64.6 m/s.

Keywords: Weibull distribution; renewable energy sources; wind potential; wind power density; wind velocity

1. Introduction

Need to promote and research the possibility of using renewable energy sources has been imposed for a long time as a consequence of the energy crisis, which is reflected in the increasing prices of fossil fuels and the increasing need for additional amounts of energy. One of the strategic goals of the European Union (EU) energy policy is to encourage the use of renewable energy sources with the aim of reducing the negative impact on the environment as well as reducing dependence on energy imports. Renewable energy sources, especially wind energy and solar energy, are playing an increasingly important role in the energy industry considering efforts to reduce the negative impact on nature. According to data from the International Energy Agency (IEA), since 1990 global renewable energy sources have grown at an average annual rate of 2.2% [1]. Only in 2020 renewable energy use increased 3% and the main reason for that is growth in electricity generation from renewable sources. Renewable electricity generation in 2020 has been expanded almost 7% where solar PV and wind represent two-thirds of renewables growth [2].

The International Renewable Energy Agency (IRENA) has established a huge potential for renewable energy sources in the area of Southeast Europe. As part of the report [3], the great technical potential of renewable energy sources in the region, which amounts to 740 GW, was confirmed. It is estimated that 50% of the world's land surface has wind velocities greater than 6 m/s at a height of 10 m, while when it comes to the area of Bosnia and Herzegovina, 10% of the surface has wind velocities greater than 5 m/s at the same height. Fig. 1 and Fig. 2 show the wind atlas for the area of Bosnia and Herzegovina with the average annual wind velocity and average annual wind power density at a height of 100 m.

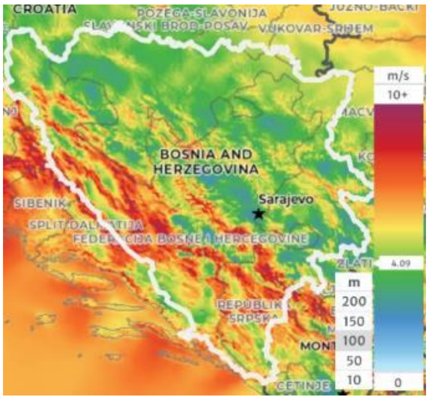

Fig. 1. Mean wind velocity in Bosnia and Herzegovina at 100 m height [4]

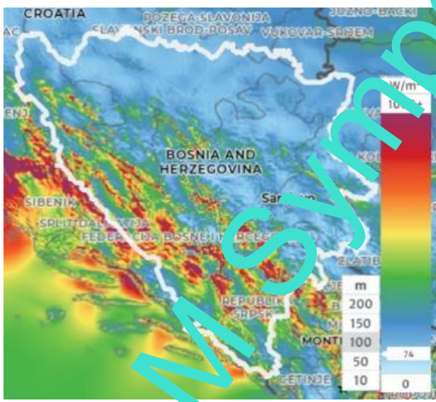

Fig. 2. Mean power density in Bosnia and Herzegovina at 100 m height [4]

From Fig. 1 and Fig. 2 it can be seen that the highest wind potential is located in the southwestern part of the country. Almost 50% of the territory of Bosnia and Herzegovina has a wind velocity of over 6 m/s. For 10% of the area with the highest wind potential, the mean wind power density is estimated to be 7[illegible]7 W/m^2, and the mean wind velocity is estimated to be 7,77 m/s at a height of 100 m, which represent good parameters regarding to qualitative assessment of the quality of wind resources.

Many articles have been published whose research topic was assessment and statistical analysis of wind velocity data. The most commonly recommended and used probability density functions in the analysis of wind velocities records are Weibull and Rayleigh distributions. For extreme wind analysis the Gumbel and generalized extreme value (GEV) distributions are also widely used. Yan et al. in their investigation [5] were analysed extreme wind velocities based on 40 years of the wind fields from the ERA5 dataset and parametric wind data in the northern South China Sea. They have been calculated extreme wind velocities by different distributions at three sites. The conclusion of their research was that the data have the greatest influence on the calculated result, followed by the distribution function and parameter estimation method. Furthermore, Parajuli [6] used a wider range of the wind data to estimate the wind power density based on Weibull and Rayleigh models of Jumla, Nepal. Similarly, the wind characteristics and wind energy potential on Hatiya Island in Bangladesh were also investigated. The wind characteristics of Antakya area in Hatay province were investigated and statistically analysed by Mert and Karakuş [7]. For mountainous areas, which represent complex terrain areas, relevant investigation has also been carried out in the recent years. Kim et al. presented a methodology for evaluating suitable sites for wind farm development by identifying suitable ridges in mountainous terrain using morphometric analysis [8]. Medugu et al. (2020) analysed and discussed the wind resource potential available in the mountainous region at Mandara [9].

The most important feature of the wind potential at the analysed location is the mean annual wind velocity at a certain height above the ground. However, determining the mean annual wind velocity is only the first step in determining the wind potential [10]. After that, it is necessary to consider wind velocity distribution during the year. For example, the annual average may contain a large number of hours with a wind velocity above 30 m/s or below 3.5 m/s, which is actually not suitable for exploitation. In this paper, data obtained from the Federal Hydrometeorological Institute of Bosnia and Herzegovina related to the wind velocity in the area of Bjelasnica, for the period from 2000 to 2017, were analysed. The obtained data will be used to calculate the mean and maximum monthly and annual wind velocity values, as well as the mean wind power density for the mentioned period. Also, an assessment of the extreme wind velocity at the Bjelasnica location for different return periods will be made.

2. Materials and method

2.1. Meteorological station Bjelasnica

Bjelasnica is a mountain in the central part of Bosnia and Herzegovina, which belongs to the Dinaric mountain system, and is located southwest of the city of Sarajevo. Bjelasnica is covered with snow from November to May, and sometimes also in the summer months. Since the Mediterranean and continental climates meet in Bjelasnica, it is very interesting for meteorological observations. Meteorological station Bjelasnica is located at 43º43" latitude and 18º16" longitude, Fig. 3.

Fig. 3. Meteorological station Bjelasnica [11]

The meteorological station Bjelasnica started operating in 1895 and observes and measures temperature, precipitation, wind velocity, cloudiness, air pressure, relative humidity and insolation. Measurements at the station are made in term observations at 07:00, 14:00 and 21:00 during the day. Given that the measuring station is placed at an altitude of 2067 m above sea level, during the late autumn, winter period and early spring, the measuring poles and mounted equipment are exposed to low temperatures, snow blows and ice deposits. The average annual temperature in Bjelasnica is 0.7°C due to extremely low winter temperatures.

2.2. Wind potential analysis

The variation of wind velocity in a certain area is usually described by the Weibull and Rayleigh distributions. Weibull probability density function and cumulative density function as a function of wind velocity v are given as follows:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \cdot e^{-\left(\frac{v}{c}\right)^k} \qquad (1)$$

$$F(v) = \int_0^v f(v)dv = 1 - e^{-\left(\frac{v}{c}\right)^k} \qquad (2)$$

Where k is the dimensionless shape factor, and c is the Weibull scale factor with units of velocity (m/s).

Energy Pattern Factor Method was used to determine the parameters k and c. To find these parameters, the first thing to find is the energy pattern factor from the expression (3) [6], [7], [12], [13]:

$$E_{pf} = \frac{(v^3)_m}{(v_m)^3} = \frac{\Gamma\left(1+\frac{3}{k}\right)}{\Gamma\left(1+\frac{1}{k}\right)^3} \qquad (3)$$

where $(v^3)_m$ represents the mean of the cube of wind velocity and $(v_m)^3$ represents the cube of the mean wind velocity.

After calculating energy pattern factor, k and c can be determined by the following expressions [6], [7], [12], [13]:

$$k = 1 + \frac{3.69}{{E_{pf}}^2} \qquad (4)$$

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

Rayleigh's distribution is a simplified case of the Weibull distribution in which the shape factor is taken as $k = 2$.

The general equation relating wind power density is [6], [7], [12], [13]:

$$\bar{P} = \frac{1}{2}\rho_m (v^3)_m \qquad (6)$$

where P represents the mean wind power density, ρ is the air density values (a value of 1,225 kg/m^3 is used in this work), and v is the wind velocity.

When it comes to electricity production, only a certain proportion of the kinetic energy of the wind can be converted into electric. Electric power generated can be expressed as:

$$\bar{P}_{el} = \eta_{el}\eta_m C_p \bar{P} \tag{7}$$

where $\bar{P}_{el}$ represent the amount of electric power generated, η_{el} is the electric conversion efficiency of the wind turbine, η_m is the mechanical efficiency, and C_p is the power coefficient [12].

2.3. Assessment of extreme wind velocities

In order to make the correct selection and foundation of wind turbines, it is very important to consider as precisely as possible the extreme winds that can occur in the location where the construction of the wind power plant is planned [13].
The Gumbel distribution is often used to describe the statistics of extreme wind velocity values. Gumbel's function of probability density distribution of extreme wind velocities $F(v)$ is given by the following expression [13]:

$$F(v_R) = exp\left\{-exp\left[-\frac{v_R - b}{a}\right]\right\} \tag{8}$$

Where v_R is extreme wind velocity that occurs on average once every R year (usually said with a return period of R years), b is the location parameter, a is the scaling parameter.

The previous expression can be written in the following mathematical form:

$$v_R = a \cdot \{-ln[-\ln(F(v_R))]\} + b \tag{9}$$

Parameters a and b are determined by linear regression, i.e. by the method of least squares based on multi-year data on extreme wind velocities.
The relationship between the return period R of the occurrence of extreme wind velocities v_R and the corresponding probability is given by the following expression:

$$R = \frac{1}{1 - F(v_R)} \tag{10}$$

Combining relations (9) and (10), an explicit expression can be obtained for the calculation of the reference wind velocity v_R which occurs on average once every R year:

$$v_R = -a \cdot ln\left[-ln\left(1 - \frac{1}{R}\right)\right] + b. \tag{11}$$

The reference wind velocity v_R can be calculated according to the expression (11) for any return period. Of a particular interest for the selection of wind turbines is the return period of 50 years (assumed minimum lifetime of the structure). A return period of 50 years is prescribed as a standard in European norms that define the wind load on building structures [14].
The basic task of the statistical analysis of extreme wind velocities is to calculate the parameters a and b based on the available set of measurement data, and then, using expression (11), to calculate the requested reference extreme wind velocity. There are several methods used to estimate the coefficient of the Gumbel statistical function, one of the most common methods is the annual maximum method [13]. This method requires wind velocity measured data for a period of at least ten years. From the data set for each year, which is available for 365 days, the time interval in which the maximum wind velocity occurred in that year is selected. That data is declared as extreme velocity in that year. Such a procedure is carried out for all years in the available set of measurement data covering N years, and based on this, a corresponding table with extreme values of wind velocities is formed [13]. After creating a table with extreme values of wind velocities, it is necessary to sort these data by placing them in descending order and each type is assigned the corresponding rank m=1,2,..,N. For each type, the corresponding value of the cumulative probability distribution function can be estimated according to the following relation [13], [15], [16]:

$$F(v_R) = \frac{m}{N + 1} \tag{12}$$

In practice, it has been shown that a lower dispersity of points, i.e. a better fit, can be achieved if instead of relation (12) relation (13) is used, which was proposed by Gringorten (1963) [17], [18]:

$$F(v_R) = \frac{m - 0{,}44}{N + 1 - 0{,}88} = \frac{m - 0{,}44}{N + 0{,}12}. \tag{13}$$

3. Results and discussion

One of the most important parameters in determining the energy power obtained from the wind is wind velocity. Fig. 4 and 5 show the mean monthly wind velocity values as well as the extreme wind velocity values that occurred at least one day during the considered period.

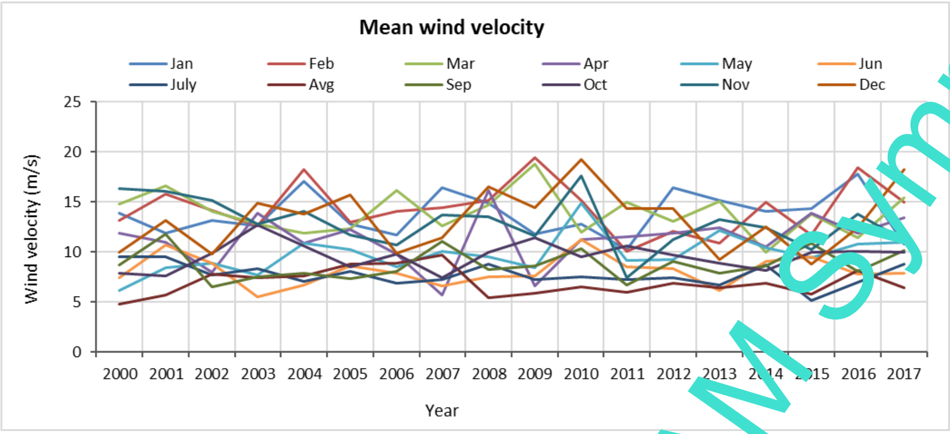

Fig. 4. Mean monthly wind velocities in the area of Bjelasnica for the period from 2000 to 2017

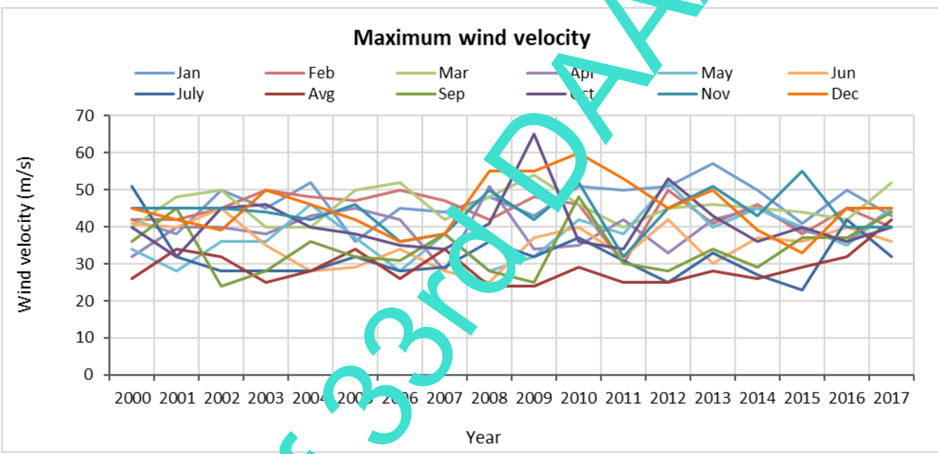

Fig. 5. Maximum monthly wind velocities in the area of Bjelasnica for the period from 2000 to 2017

From Fig. 4, it can be concluded that the values of the mean wind velocity range from 4,8 m/s to 19,4 m/s, which is a sufficient condition for the continuous operation of the wind turbine and the production of the maximum amount of electricity. On the other hand, when it comes to the maximum wind velocity, it ranges from 23 m/s to 65 m/s, which occurred in October 2009 and only for one day. When extreme wind velocities occur, i.e. velocities that exceed the permitted threshold, which usually ranges from 25 m/s to 30 m/s, it is necessary to ensure that the operation of the wind turbine is stopped in order to prevent damage to some of its parts. Maximum wind velocities that exceed the value of 30 m/s occur every year, however, when looking at the number of days during the year when these extremes occur, it is an average of 60 days a year. Which means that for the remaining 305 days of the year, the maximum wind velocities do not exceed 30 m/s.

When assessing the long-term potential of wind in a certain area, it is not enough to include only seasonal variations in wind velocity, because it is necessary to take into account that every year is not equally windy. For this reason, it is very important to take into account the variability of wind energy potential at the analysed location from year to year. Fig. 6 and 7 show the mean annual wind velocities as well as the deviation of the mean annual wind velocities from the long term average wind velocity in the Bjelasnica area.

From Fig. 6 and 7, it can be concluded that the measurements carried out during one year cannot be a reliable representative for the long-term period for which the wind power plant is designed. For example, for the analysed location, if the conclusion about the wind potential was made on the basis of the measurements carried out in 2011, the estimate of the wind energy potential would be lower than the long term average, because the average annual wind velocity in that year was about 12% lower than the long term average wind velocity. If 2010 were to be considered as the reference year when assessing the wind potential, since the average annual wind velocity in that year was about 12% higher than the long term average, the wind potential would be overestimated.

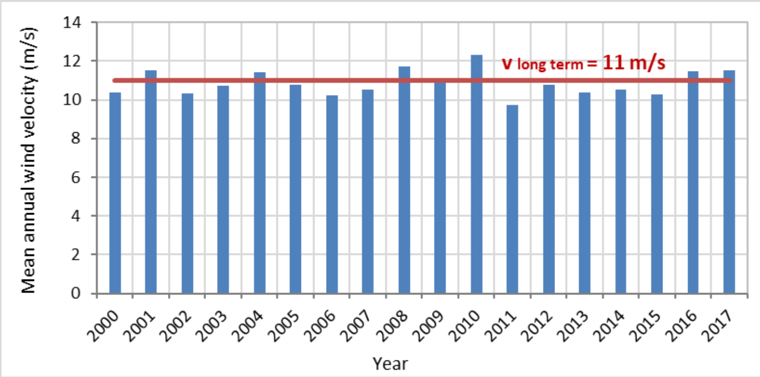

Fig. 6. Mean annual wind velocities in the area of Bjelasnica for the period from 2000 to 2017 with long term wind velocity indicated

Fig. 7. Deviation of mean annual wind velocities from the long term average wind velocity in the area of Bjelasnica

Different types of wind dominate in Bosnia and Herzegovina, depending on the climate area. The shape of the wind rose (frequency, direction and mean wind velocity) depends on the orography of the terrain, so it is different for each station. The wind frequency rose and the mean wind velocity rose for the weather station Bjelasnica for the period 2000 to 2017 are shown in Fig. 8. From Fig. 8 it can be seen that the prevailing wind directions are north (N) in 31,2% of cases with a calculated wind velocity of 12,1 m/s, south (S) with a share of 16,5% and south-southwest (SSW) with a share of 16,8%.

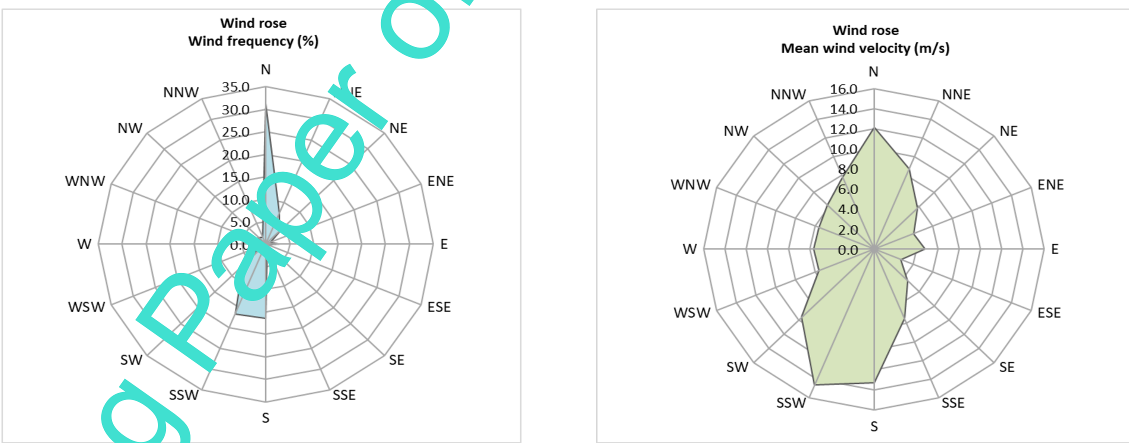

Fig. 8. Wind rose for meteorological station from 2000 to 2017 in the area of Bjelasnica

The long term average wind velocity is the basic indicator of the wind energy potential at a location, however, it is not sufficient to estimate the possible electricity production of a wind turbine. It is very important to know the wind velocity distribution, i.e. how long the wind blows at a certain intensity. This information is provided by the histogram of wind velocity duration. Fig. 9 shows a normalized histogram of wind velocities for the Bjelasnica area, obtained on the basis of eighteen-year measurements of daily wind velocities.

At the analysed location, according to the Fig.9, the most frequent wind velocity is around 4 m/s, i.e. 7,06% of the time (about 464 days during the analysed period of 18 years, i.e. an average of 26 days per year), and velocity of 6 m/s, i.e. 6,9% of the time (about 455 days during the analysed period of 18 years, i.e. an average of 25 days per year). The total duration of silence ($v \leq 0,5\ m/s$) is 0,58%, that is, about 38 days in the analysed period of 18 years, which is an average of 2 days per year. One of the ways of statistical representation of the wind potential is the arranged diagram of the cumulative duration of wind velocities. Fig.9 shows, also, the normalized diagram of the cumulative duration of wind velocities obtained on the basis of eighteen-year measurements of wind velocities in the analysed area at a height of 10 m above the ground. The cumulative probability distribution of wind velocities shows the percentage of time or probability that the wind velocity is less than or equal to v.

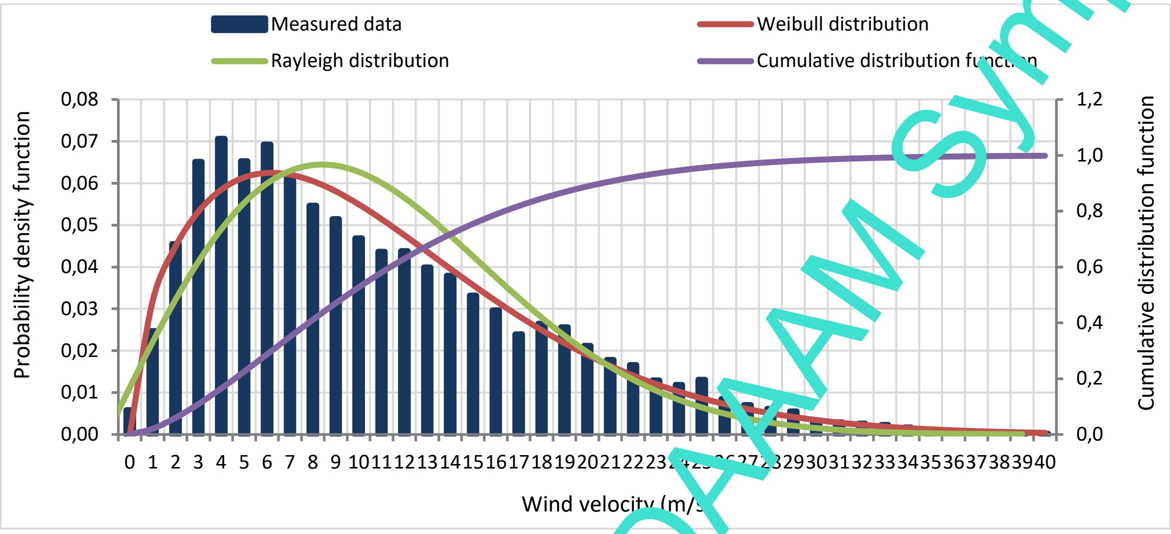

Fig. 9. Probability density distribution and cumulative distribution function of the of annual wind velocities

From Fig. 9 it can be seen that approximately 90% of the recorded wind velocities are below 21 m/s, and the frequency of occurrence of wind velocities greater than 25 m/s, i.e. the cut-out wind velocity is about 5%. The probability of occurrence of velocities below 3,5 m/s is about 10%.

For assessment the maximum theoretical wind power density, it is necessary to take into account the power coefficient of the wind turbine, and maximum utilization rate of turbine and generator which is about 0,65 and 0,8, respectively, to determine the maximum electrical wind power density. Taking into account all the above coefficients, it is possible to use about 31% of the total wind energy for electricity production. Fig.10 show the mean wind power obtained from the wind flow, the maximum theoretical power that can be obtained taking into account the upper limit for the power coefficient and electric power depending on the wind velocity for an area of 1 m^2.

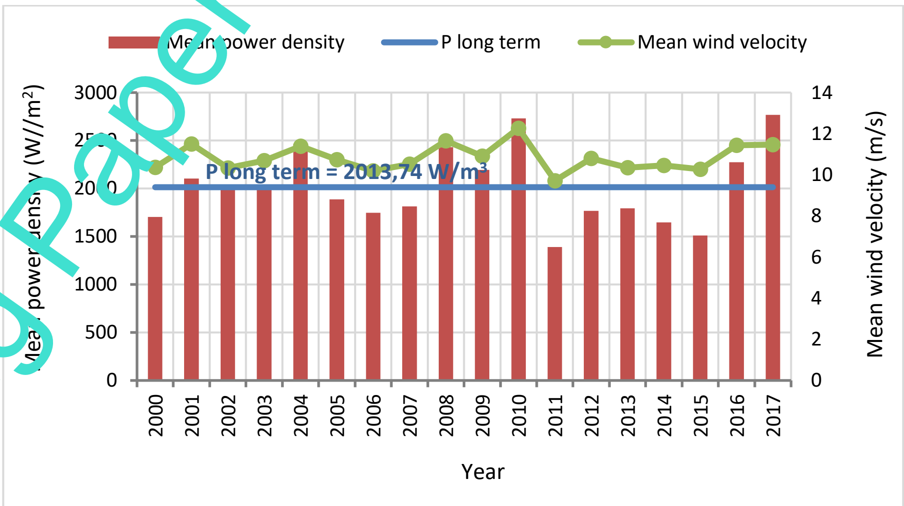

Fig. 10. Yearly variation of the mean power densities and mean wind velocity

Based on the calculated maximum theoretical wind power density in the Bjelasnica area for the period from 2000 to 2017, it is obtained that the long term average theoretical wind power density is 1194 W/m^2, while the long term average electrical wind power density is 624 W/m^2.

Considering that wind turbine safety design and wind turbine selection are primarily based on the annual average wind velocity, turbulence intensity and extreme wind condition it is very important to look more precisely at the extreme winds, that can occur at the location, where the construction of the wind power plant is planned. Table 6 shows the number of days with strong, stormy and strong stormy wind at the analysed location.

Year	Date of appearance	Maximum annual wind velocities (m/s)	Direction of maximum wind	Number of days with strong wind (10,8-17,1 m/s))	Number of days with stormy wind (>=17,2 m/s)	Number of days with strong stormy wind (>=2? m/s)
2000	13.07.2000.	51	N	265	189	100
2001	04.03.2001.	48	S	309	220	127
2002	06.01.2002.	50	N	280	[illegible]	105
2003	04.02.2003.	50	SSW	285	186	114
2004	17.01.2004.	52	SSW	285	[illegible]	118
2005	11.03.2005.	50	SSW	284	[illegible]	117
2006	05.03.2006.	52	SSW	292	170	80
2007	13.02.2007.	47	N	278	173	104
2008	01.12.2008.	55	SSW	295	210	122
2009	13.10.2009.	65	S	[illegible]	188	114
2010	06.12.2010.	60	SSW	305	229	152
2011	16.12.2011.	53	SSW	283	170	84
2012	27.10.2012.	53	S	325	200	107
2013	25.09.2013.	57	S	297	194	130
2014	26.01.2014.	50	NE	313	204	119
2015	20.11.2015.	55	S	308	196	114
2016	11.01.2016.	50	SSW, S	305	211	138
2017	05.03.2017.	52	SSW	296	192	144

Table 1. Number of days with strong, stormy and strong stormy wind at the analysed location

Based on the available measurement data for N=18 years, data and calculated values of statistical parameters of extreme wind velocities were sorted and presented in Table 1.

Year	Extreme wind velocity v_R (m/s)	Rank, m	$F(v_R) = \frac{m - 0,44}{N + 0,12}$	$-ln\,(-\,ln(F(v_R)))$
2000	47	1	0,031	-1,246
2007	48	2	0,086	-0,897
2001	50	3	0,141	-0,671
2006	50	4	0,196	-0,487
2003	50	5	0,252	-0,322
2002	50	6	0,307	-0,167
2009	50	7	0,362	-0,016
2008	51	8	0,417	0,135
2005	52	9	0,472	0,288
2004	52	10	0,528	0,447
2010	52	11	0,583	0,616
2011	53	12	0,638	0,800
2012	53	13	0,693	1,004
2013	55	14	0,748	1,238
2014	55	15	0,804	1,520
2015	57	16	0,859	1,882
2016	60	17	0,914	2,408
2017	65	18	0,969	3,461

Table 2. Statistical data for the calculation of Gumbel parameters of extreme wind velocities at the location of Bjelasnica using the annual maximum method

Based on the data from Table 2, more precisely the data from the second and last column, a linear regression diagram can be drawn, Fig. 11, and determine the parameters of the linear regression using the method of least squares, which is mathematically defined by expression (9).

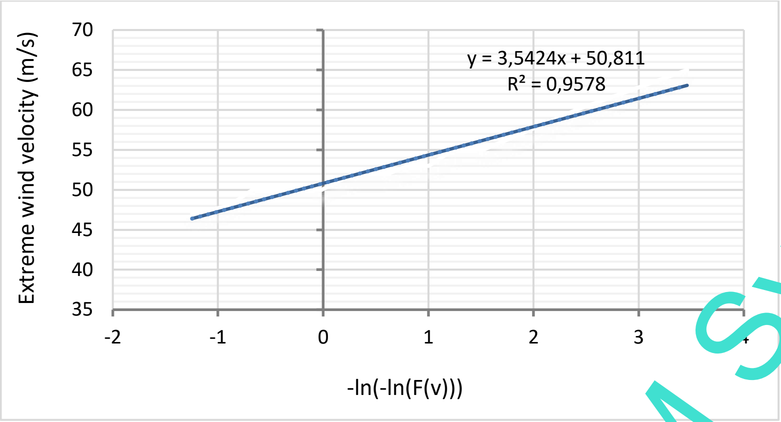

Fig. 11. Estimation of the parameters of the Gumbel distribution of extreme wind velocities using the annual maximum method for the analysed location

The analytical expression for the linear regression from Fig. 11 is:

$$v_R = -3{,}5424\ln\left[-\ln\left(1-\frac{1}{R}\right)\right] + 50{,}811. \quad (14)$$

Using relation (14), the extreme value of the wind velocity for any return period can be calculated. Fig. 12 graphically shows the value of extreme wind velocity for the return period from 1 to 100 years.

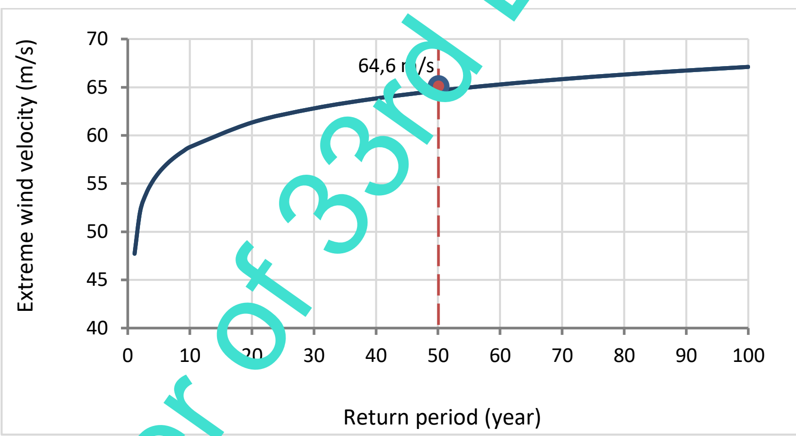

Fig. 12. Estimated extreme wind velocities at the Bjelasnica location for different return periods

For the return period of 50 years, the reference extreme velocity is 64,6 m/s, i.e., it can be expected that once in 50 years the wind velocity exceeds the value of 64,6 m/s, while the maximum average daily wind velocity that occurs on average once a year is around 47 m/s.

4. Conclusion

In this paper, it was analysed wind energy potential in the mountain area around Sarajevo. For that purpose, wind power density and wind velocity distribution parameters were investigated using wind velocity data obtained from the Federal Hydrometeorological Institute of Bosnia and Herzegovina. The measured data used to analyse the wind energy potential in this paper refer to an eighteen-year measurement period. The seasonal wind velocity profile was drawn and mean long term wind velocity was found to be 11 m/s at 10 m height. The mean wind power depending on the wind velocity for an area of 1 m^2 obtained from the wind flow was estimated to be 2013 w/m^2, the maximum theoretical power that can be obtained taking into account the upper limit for the power coefficient and electrical power were estimated to be 1194 w/m^2 and 624 w/m^2, respectively.

The results show that the available wind energy potential to generate electricity in Bjelasnica is high. However, due to the small number of observations it was not possible obtain comprehensive data for wind velocity. In this sense, it can be concluded that the available measurement data provide the possibility of roughly locating and estimating the potential of wind energy at the analyzed location, so they can serve for indicative purposes. Therefore, the assessment of possible electricity production can be considered as an indicative result that points to the existence of wind potential in the analyzed area, and not a reliable data on how much of this potential can be used. The next step of this work would be achieving more accurate results for wind power potential, and giving more insight of the power output reduction of wind farm under extreme wind condition. In order to achieve better and more accurate results it is necessary to have measured data in shorter time intervals, minimum 10-minute wind velocity values.

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