WIND POWER POTENTIAL OF THE VOLGA FEDERAL DISTRICT AND RATIONALE OF THE USE OF LOW-POWER WIND-DRIVEN POWER-PLANTS

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ABSTRACT

A considerable enough attention is paid to the issues of wind energy resources assessment in various countries around the world, especially in Western Europe, USA, Japan, and China. In Russia there was developed an energy strategy for the development of the country until 2030, where it has also paid attention to the development of wind power engineering. This paper describes the wind conditions in the vast territory of the Volga Federal District and considers the possibility of using wind energy with a uniform measurement material, as well as evaluates the wind power potential of the Volga Federal District. The paper discusses the wind regime in the territory of the Volga Federal District using time series of mean monthly wind speeds at 183 meteorological stations in the period 1966-2009. There were analyzed the mean values, measures of variability, anomalies of wind speeds, linear trends, correlations between points, etc. We have revealed an inhomogeneous distribution of the mean monthly wind speeds (MMWS) in the territory, and the general trend of lowering wind flows. The wind power potential of the Volga Federal District in the atmosphere layer of 10-150 m was assessed. The analysis led to the conclusion that one of the priority directions of development of wind power in the near future will be a stand-alone use of small and medium-sized wind-driven power plants in remote areas where the population density is low, there is no large electrical networks, and it is appropriate to use wind-powered generating plants for energy supply purposes.

Key Words: *Wind Speed, Wind Speed Variability, Linear Trend, Wind Power Potential, Possible Wind Power Resources*

INTRODUCTION

By definition, wind is an air movement relative to the earth surface that depends on the circulation of the atmosphere and terrain features. Flows pattern is largely determined by a baric field and its gradients. Direction and speed of wind, and its gusts should be known when making the weather forecast, assessing pollution transport, for the purposes of aviation security, for construction needs, and for the needs of wind power (Huber et al, 2014.; Guo, He, 2012). Characteristics of wind are calculated both for the low heights starting from 10-12m - mounting height of a wind vane within the range of surface and boundary layers of the atmosphere, and for the free atmosphere.

This paper describes the wind conditions in the vast territory of the Volga Federal District and considers the possibility of using wind energy with the use of a uniform measurement material, as well as gives an assessment of the wind power potential of the Volga Federal District.

Source Material and the Methods of Calculation

In the capacity of a source material we have used data of meteorological observations from the database of All-Russian Research Institute of Hydro meteorological Information International Data Center for wind speed at 183 stations of the Volga Federal District in the period of 1966-2009 spaced evenly enough on the territory, the statistical series of wind observations data with prefix of time at 20 stations evenly covering the territory of the District during 1966-2011, as well as statistical series of NCEP / NCAR reanalysis for the period of 1948-2013, distributed by NOAA / OAR / ESRLPSD, Boulder, Colorado, USA.

We have calculated long-term monthly mean values of wind speed, standard deviations σ, coefficients of variation Cv, linear trend slope coefficients (LTSC).

The known formula was used for calculation of wind power potential:

$$N_{уд} = \frac{1}{2}\rho(\bar{v})^3(1 + 3C_v^2 + AC_v^3), (1)$$

Where N $_{ud}$ - specific power of the wind flow, ρ - air density, $\bar{v}$ - average speed, Cv - coefficient of variation, A - skewness coefficient.

Calculation of the wind speed at different heights z greater than the height of the weather vane installation h was carried out by the power formula:

$$\frac{\bar{v}_z}{\bar{v}_h} = \left(\frac{z}{h}\right)^m, (2)$$

Where $\bar{v}_z$ and $\bar{v}_h$ - mean wind speeds at heights z and h, respectively, m - dimensionless parameter depending on the state of turbulence, thermal stratification, and local physical and geographical conditions.

In the calculations values m should be assumed equal to: m = 0.864exp (-0.31$\overline{v_h}$) for the average annual wind speed, for the period September-May m = 0.798exp (-0.28$\overline{v_h}$), and for the period July-August when convection in lowest atmospheric layers is the most developed, m = 0.911exp (-0.35$\overline{v_h}$).

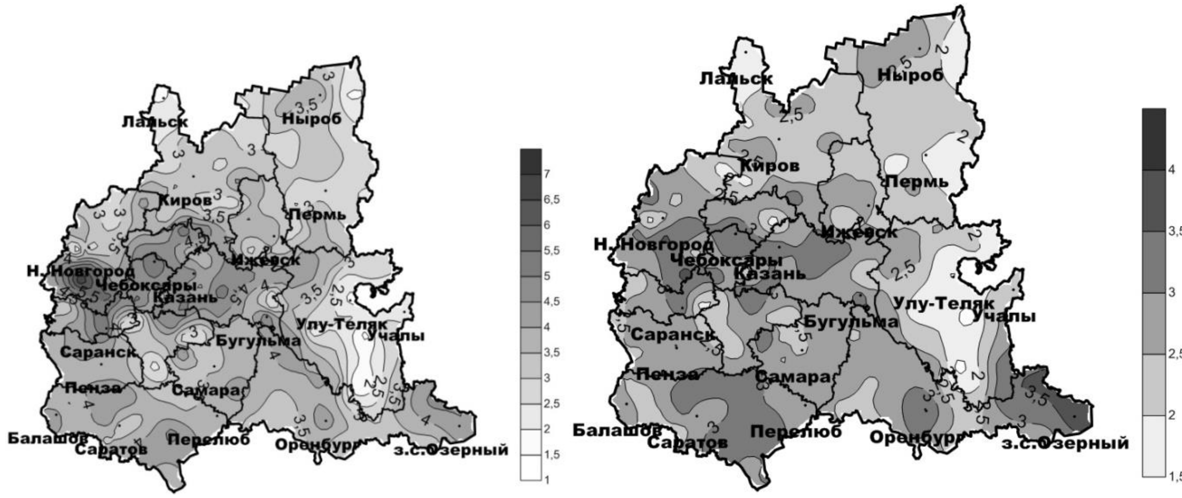
The calculations performed in this study are presented in the form of numerous charts and tables. Naturally, the limits of this paper do not allow us to include all the material in it.

Distribution of Mean Monthly Wind Speeds in the Territory of the Volga Federal District

Let's consider the climatic distribution of wind speeds in the territory of the Volga Federal District. Results of calculations are presented in the form of maps and tables. It should be noted that the territory of the Volga Federal District is a fairly heterogeneous in physical and geographical terms, it has a series of hills with the valleys of large rivers; East of the region is occupied by the Ural foothills. Three vegetation zones are located in the territory of the region: forest, forest-steppe, and steppe.

According to Fig. 1**,** the monthly mean wind speed at a height of 10-12m from the earth's surface are characterized by the lowest values in summer (1.3-4.1 m / s) and high values more frequently in winter (up to 5.1-5.6 m / s) due to an increase in the pressure gradient from summer to winter. The spatial distribution of wind speeds is non-uniform: highest values are found in the central part of the region in Saransk, Cheboksary, Kazan, Bugulma, Izhevsk, as well as in the south-east of the Orenburg region. Maximum average speed in January (≈7m / s) was identified at the Arzamas station (Nizhny Novgorod region), in the north of the Volga Federal District in the forest zone (the average speed in the order of 3 m / s), in the east within Bashkortostan (the Cis-Ural region) speeds drop up to 2 m / s, and significantly increase at the border with Kazakhstan (up to 4.5 m /s).

Figure 1
AVERAGE MANY-YEAR WIND SPEED (M / S) AT A WEATHER VANE LEVEL: A - JANUARY; B – JULY



a) b)

The spatial pattern of average speeds distribution is very diverse (mosaic) what is determined by the nature of atmospheric circulation and topography. In July, at the most stations the speed is 0.9-1.3 m / s lower than in January what leads to the annual variation. It should be noted that in the summer in the southern part of the district in the afternoon an intense convection develops that contributes to increase of wind near the ground.

During the year, the location of foci with high and low velocity values is preserved. For many years the map of the average annual wind speed makes an emphasis on the station Bugulma (4.4 m / s) with a maximum value and the station Tukan with a minimum value (1.3 m / s). Note that the station Bugulma is located on the Bugulma-Bebeley upland.

The resulting climatic wind distribution is influenced by the structure of the baric field (its gradient), atmospheric circulation, terrain, and local specifics. In general, a latitudinal zoning manifests itself except for the eastern regions where a significant effect of the terrain is shown.

Variability of Wind Speed

We have calculated a set of parameters to characterize the temporal variability of wind speed. Let's consider their spatial and temporal distribution. The value of the standard deviation (SD) σ characterizes inter annual variability of wind speeds. The value of standard deviation varies with the annual course from the minimum values in summer (0.3-0.9 m / s) up to a maximum in winter reaching 0.6-1.7 m / s.

Also, in order to identify trends in wind speed over time we have calculated linear trend slope coefficients (LTSC) ((m / s) / 10 years) for each station. Analysis of the results shows that for the entire territory of the Volga Federal District, the sign of the slope of the trend line is negative indicating a widespread lowering of the wind speed. In January, the value of the linear trend slope coefficient ranges from -0.2 ((m / s) / 10 years) in the north of the District to -0.6 ((m / s) / 10 years) in the south. A similar picture emerges in the other months of the year; the picture in the space is also non-uniform. The fact of lowering wind speeds in the European territory of Russia in the last decade has been also pointed out in other works.

It is known that the intensity of the wind flows determines the dynamics of pollutant transport in the lower layer of the atmosphere, and also affects the evaporation of moisture from the underlying surface, particularly from the water surface what affects the hydrological regime of the territory and other natural processes. Perhaps one reason of attenuation of the wind regime in the region is a global warming at which meridional thermal contrasts are faded what affects the pressure field (attenuation of pressure gradients) and hence reduces the wind speed. In addition, in the summer period blockings began to appear more frequently that also contributes to the lowering of the wind and create calm situations.

Evaluation of Wind Power Potential of the Volga Federal District

A considerable enough attention is paid to the issues of wind energy resources assessment in various countries around the world, especially in Western Europe, USA, Japan, and China. (Yao et.al, 2014; Hallgren et al, 2014.; Adaramola et al, 2012.; Gökçek et al, 2009). In Russia there was developed an energy strategy for the development of the country until 2030, where it has also paid attention to the development of wind power engineering.

The advantage of wind-powered generating plants (WPGP) over conventional energy sources is a fast capacity commissioning, the ability to build up power of wind farms on a modular scheme, and significant economic efficiency. The installed capacity of wind power in the world has increased from 6.2 MW in 1996 to 94.3 MW in 2007. Over the past 25 years, the basic cost parameters of wind power have lowered significantly and now account for 4.5 eurocents per 1kW.

Energy wind areas, i.e., the areas where the use of wind power is clearly appropriate, are also located in areas of the Arctic coast and the Far East, Middle and Lower Volga, the Caspian Sea, etc.

Natural wind power potential is a long-term average value of wind energy of air masses motion over a territory. Gross potential of wind energy resources is calculated as the power of a wind flow excluding the properties and capabilities of wind motors by the formula:

$$N = \frac{1}{2}\rho v^3 S, \quad (3)$$

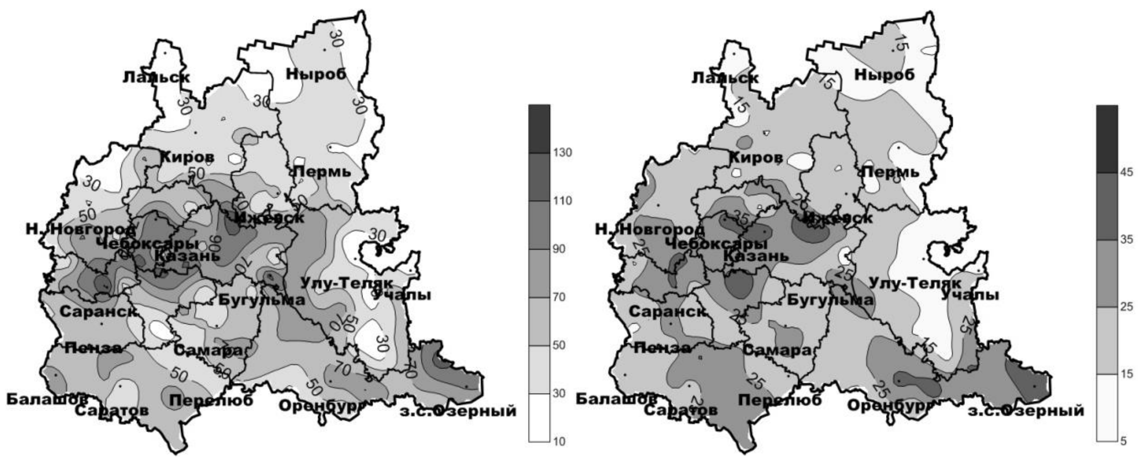
where N - overall power of total (full) wind flow; ρ - air density; v - wind speed; S - area perpendicular to the wind flow.

The use of alternative energy sources is crucial, including with due account for the sustainable development of the territory (Gabdrakhmanov, 2014, Rubtsov, 2015). For economic reasons, it is advisable to develop wind power only in those areas where the mean monthly wind speed is not less than 3-5 m / s. At a wind speed of 7 m / s installation of high wind-driven power plants (WDPP) becomes expedient [Herbert et al, 2007].

Favorable conditions for choosing a site for the construction of wind-driven power plants are high wind power potential (mean monthly wind speed of 5 m / s, a relatively large duration of the operating speed from 9 to 25 m / s, the energy lulls repeatability (less than 3 m / s) is 20-30%, lower variation coefficient values (preferably less than 0.3), the absence or low repeatability of occurrence of "windstorm" (more than 20 m / s) and "hurricane" (more than 33 m / s) wind speeds (Li et al, 2008).

Using the formula (1) calculations of wind energy resources at the level of the weather vane (10 m) and at altitudes of 50, 100 and 150 m for which the wind speeds have been pre-calculated according to power law (equation (2)) were carried out for the Volga Federal District. Some calculation results are presented in Fig.2. As can be seen, the most favorable conditions for the development of wind power are in the central part of the Volga Federal District and in the southeast region. With increasing height a marked increase in wind speed (wind speed at altitude of 100m is in 1.5-1.7 times higher its value at altitude of 10 m) and hence the generating capacity of the wind flow, as cube power of speed value is used in the calculation.

Figure 2
SPECIFIC POWER OF THE WIND FLOW (W / M $^{2)}$ AT AN ALTITUDE OF 100M: A - JANUARY; B – JULY



a) b)

On The Effectiveness of the Use of Low-Power Wind-Driven Power Plants at the Territory of the Volga Federal District

The priority direction of development of wind power industry in the near future will be a stand-alone use of small and medium-sized wind-driven power plants in remote areas where the population density is low, there are no large electrical networks and use of wind-powered generating plants for energy purposes is appropriate (Bett, Thornton, 2016; Snyder, Kaiser, 2009).

Power supply of stand-alone consumers using renewable energy sources, particularly wind energy, in some Russian regions already is economically more viable (new energy policy of Russia, 1995) than the use of liquid fuels, and is more efficient for low-power consumers compared with construction of power lines from centralized energy systems.

The purpose of this study in this section is to find out the possibility of using wind-driven power plants in the Volga Federal District, as well as identification of the types of wind-driven power plants the use of which is possible and appropriate in the district.

According to the standard (GOST R 51990-200), wind-driven power plants are classified into four groups depending on their power: high power - more than 1 MW; average power - from 100 kW to 1 MW; low power - 5 to 99 kW, and a very low power - less than 5 kW.

Let's consider the feasibility of using wind-driven power plants of low and very low power. These wind-driven power plants are used for power supply of small houses and farms.

Today, wind turbine electro-generators are reliable and easy-to-use installations and the only issue to address is "if there are enough wind resources in the area where it was planned to install wind-driven power plants?" One of the goals of this research is to identify the areas where there are sufficient wind resources.

In the regions which are attractive for the use of low-power wind-driven power plants the mean monthly wind speed must be 4 - 6 m / s or more. When considering the average annual wind speed field (Fig. 3a) it is clear that on 87% of the District territory mean monthly wind speed does not exceed the value of 4m / s (Fig. 3b).

The annual course of wind speed means the maximum speed in winter and minimum in summer when the circulating factors are weak. So, in January, the area of the territory on which the monthly mean monthly wind speed exceeds 4 m / s is about a quarter of the District area (Figure 3c, Table 1). Thus, the seasonal use of wind-driven power plants is possible and appropriate in the central part, in the south-west of the District, as well as in the south-east of the Orenburg region.

Figure 3
ANNUAL MEAN MONTHLY WIND SPEED AT THE WIND VANE HEIGHT (A), AREAS WITH $V_{AV. ANN.} \geq 4$ M / S (B), STATIONS WITH $V_{JANUARY} \geq 4$ M / S (C)

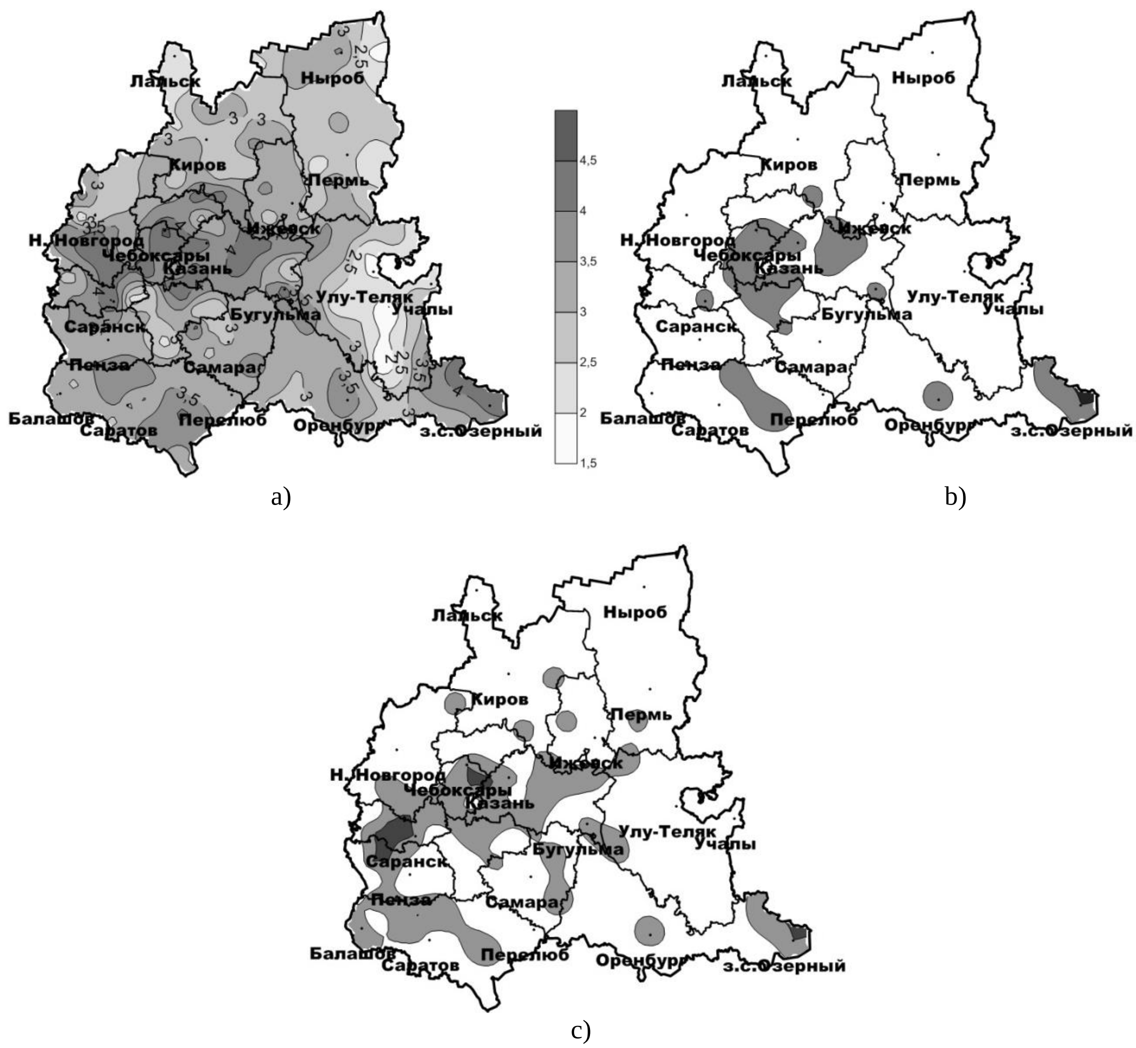


Table 1
THE RATIO (%) OF THE NUMBER OF STATIONS WITH V $_{AV. MONTH.}$≥4 M / S TO THE TOTAL NUMBER OF STATIONS (AT THE HEIGHT OF THE WIND VANE Z = 10M)

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average per year
% of stations	26.1	21.2	17.0	15.8	12.1	1.2	0.0	0.0	4.8	18.8	22.4	24.2	12.7

For the needs of the wind energy industry it is necessary to know the actual frequency of occurrence (%) of wind speed by gradations in order to identify the total time for useful electricity production and time of the forced installation downtime (Askarzadeh, Zebarjadi, 2014).

If we look at the specific models of low power wind units, one of the most efficient wind-driven power plants in this class are wind generators EuroWind 5, EuroWind 10, EuroWind 15) which starting speed is v≥2 m / s (Márqueza et al, 2012).

The data in Table 2 reflect the proportion of the time when rotors of wind-driven power plants will rotate and the installation will produce usable electricity.

Table 2
REPEATABILITY OF WIND SPEEDS V≥2 M / S CALCULATED FROM THE TIME-DEPENDENT DATA FOR THE PERIOD 1966-2010

	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**	**Среднее**
Lalsk	54	54	57	56	61	57	52	52	55	65	61	59	57
Nyrob	81	79	82	82	83	80	74	75	79	86	83	80	80
Kirov	84	82	81	80	79	73	67	70	74	84	84	85	79
Perm	73	68	71	73	71	64	56	60	68	78	75	72	69
Izhevsk	86	84	85	86	86	82	75	78	84	89	89	85	84
Nizhny Novgorod	84	81	84	82	78	75	70	71	76	86	88	86	80
Cheboksary	92	92	92	92	91	88	85	88	91	94	95	93	91
Kazan	75	74	71	74	71	67	62	64	68	76	78	74	71
Saransk	89	86	86	88	86	82	78	79	85	90	92	90	86
Ulyanovsk	89	87	87	87	86	80	80	81	84	89	88	90	86
Bugulma	87	87	86	88	88	82	79	81	85	90	90	86	86
Ulu Telyak	45	46	46	50	52	47	41	38	43	53	51	43	46
Uchaly	48	51	53	61	64	60	55	53	57	64	57	48	56
Penza	77	77	75	74	70	67	61	60	64	75	78	77	71
Samara	83	82	77	70	67	68	72	74	75	76	78	84	75
Balashov	85	85	84	84	78	74	70	72	74	82	85	85	80
Marks	80	81	82	80	77	74	74	71	72	77	83	82	78
Perelyub	76	76	74	75	73	71	68	65	67	74	78	75	73
Orenburg	85	83	85	88	87	85	83	82	82	85	88	86	85
Ozerny	80	82	81	84	86	85	83	81	80	82	83	80	82

High wind speed increases the amount of passing air masses. Therefore, with an increase in wind speed the amount of electricity produced by a wind power plant increases also. Wind energy is proportional to the cube power of the wind speed value. Thus, for example, if the wind speed doubles, the kinetic energy received by the rotor is increased eightfold.

Mean monthly wind speed value is a universal characteristic. However, it does not reflect the length of observations of wind activity. Most information can be obtained by studying the frequency of wind speed repeatability.

Earlier it was also stated that the rationale for the wind power industry development prospects in the region requires knowing the frequency of occurrence of "working" speeds and repeatability of hurricane speeds. All these data could be available if to know the wind speed distribution parameters for gradation. In addition, these data can be used to evaluate the amount of generated electric power for which it is necessary to know the wind speed repeatability by gradations (Table 3, the data obtained by processing the information from observations with prefix of time).

Table 3
REPEATABILITY OF WIND SPEED (IN %) BY GRADATIONS AVERAGED OVER THE TERRITORY OF THE DISTRICT (FOR THE PERIOD 1966-2010)

Wind speed (m / s)	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
0-1	22	23	23	22	23	27	31	30	27	20	20	22
2-3	31	31	33	34	35	38	39	38	37	35	34	32
4-5	24	24	24	25	24	23	21	21	22	25	26	24
6-7	13	12	12	12	11	9	7	7	9	12	12	13
8-9	6	5	5	5	4	3	2	2	3	5	5	5
10-11	3	2	2	2	2	1	1	1	1	2	2	3
12-13	1	1	1	1	1	0	0	0	0	1	1	1
14-15	-	-	-	-	-	-	-	-	-	-	-	-
16-17	-	-	-	-	-	-	-	-	-	-	-	-
18-21	-	-	-	-	-	-	-	-	-	-	-	-
22-25	-	-	-	-	-	-	-	-	-	-	-	-

Along with high repeatability of "working" wind speeds, the speed in the installation place of a wind-driven power plant should have a low frequency of occurrence of high (critical) wind speeds at which the installation goes into idle rotation mode and dangerous to set the speed (in which can occur the destruction of the wind generator). These values differ for different models. For most models of low-power wind-driven power plants this value is 20 m / s.

Repeatability of "dangerous wind speeds for the plant" can be selected from the data of the wind gusts. On the average for the District, repeatability of dangerous speeds does not exceed 1%. When considering the field of this indicator, Bugulma (1.5%), Orenburg (1.0%), and Ozerniy (1.1%) stations stand out.

Data from tables and maps presented above are valid for the altitudes of 10 m/s (height of wind vane installation) in the network of meteorological stations. While the standard height of the low-power wind-driven power plant installation is 18m.

Taking into account the fact that wind-driven power plants do not always set at the height of a wind vane, wind speeds were calculated using power law for all stations in the District for heights other than the height of a weather vane installation (Formula 2).

Based on the obtained wind speed values at the height of installation of the wind power plant rotor, we carried out the approximate estimation of the number of stations (in a rough approximation - an equivalent to a land area) with favorable conditions for electricity generation (Table 4).

Table 4
THE RATIO (%) OF THE NUMBER OF STATIONS WITH V $_{AV. MONTH.}$ ≥4 M / S TO THE TOTAL NUMBER OF STATIONS (AT THE HEIGHT OF THE WIND-DRIVEN POWER PLANTS ROTOR Z = 18M)

Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average per year
% of stations	2.	2.	2.	2.	43.0	14.5	4.8	8.5	20.0	49.1	54.5	52.1	39.0

The circumstances that the maximum monthly average speeds are accounted for the cold season and coincide with the seasonal peak of heat and electricity consumption says in favor of rationality of wind energy industry implementation. At the same time it coincides with a minimum annual flow of local rivers, i.e. makes it possible to compensate for the seasonal shortage of hydropower. It was revealed that the daily change in the average speed in the Volga Federal District is significant in a summer period; with speed in the afternoon is by an average of 1-2 m/s higher than at night what is favorable for efficient use of the wind because the maximum power consumption also falls in the daytime.

CONCLUSIONS

1. We have revealed spatiotemporal heterogeneity in the distribution of wind speeds in the territory of the Volga Federal District: average speeds vary during the year within the limits of 1ю8-5ю6 m / s. The highest wind speeds occur in the area of Bugulma-Bebeley uphill and Orenburg region. With trend-analysis, we have determine the speed of attenuation of wind movements in the territory during the year that reach their peak in January (0.2-0.6 m / s / 10 s);
2. Trend analysis has showed a temporary trend of lowering wind speed on the whole territory of the district at a speed within the wide range of values depending on the location of a station and the months of the year -0,2-0,5 (m / s) / 10 years;
3. Maps of the mean monthly wind speeds distribution at 50, 100 and 150m levels were plotted. Vertical gradients of the mean monthly wind speed were defined. The wind speed at altitude of 100 m is in 1.5-1.7 times higher than at the level of 10 m;
4. Maps of the mean monthly wind speeds distribution at 50, 100 and 150m levels were plotted. Vertical gradients of the mean monthly wind speeds were defined. The wind speed at a height of 100m is in 1.5-1.7 times higher than at the level of 10 m.
5. Wind power potential of the Volga Federal District at 100m varies throughout the year in the district territory within 10-140 W / m ^{2} and is determined by local conditions and features of wind regime. The most favorable conditions for the operation of wind-driven power plants are developed in January in central part of the district, in the south-west, and extreme southeast;

6. Favourable conditions for the use of wind-driven power plants and wind energy utilization on the dominant part of the district territory may be in winter period.

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