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Alternative power supply systems for remote industrial customers

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Abstract. The paper addresses the problem of alternative power supply of remote industrial clusters with renewable electric energy generation. As a result of different technologies comparison, consideration is given to wind energy application. The authors present a methodology of mean expected wind generation output calculation, based on Weibull distribution, which provides an effective express-tool for preliminary assessment of required installed generation capacity. The case study is based on real data including database of meteorological information, relief characteristics, power system topology etc. Wind generation feasibility estimation for a specific territory is followed by power flow calculations using Monte Carlo methodology. Finally, the paper provides a set of recommendations to ensure safe and reliable power supply for the final customers and, subsequently, to provide sustainable development of the regions, located far from megalopolises and industrial centres.

1. Introduction

In view of the small capacities developed at the powerhouses with alternative energy in use, renewable energy sources (RES) [1] are most often considered in power industry together with a concept of the distributed generation [2]. Such generation allows providing small consumers including ones working autonomous from the centralized.

The enterprise often needs implementation of additional production capacities for further development. In most cases the enterprise increases the external electric network consumption after receiving specifications of the electric grid company concerning connection of additional electroreceivers. However, in certain cases own source of electrical power is installed to reduce costs of production power supply. Such installations as wind generators, solar batteries and also the generators consuming biofuel as well as with geothermal power in use can act as energy resources.

Expediency of the power sources choice is explained by the fact that there is no fuel component in structure of expenses and also there is no payment for energy transmission on electric network which provides low cost of electric energy production even in case of high capital investments into the power equipment. To choose an optimum resource of renewable power for the objective solution it is expedient to investigate the potential of different types of alternative energy for the considered location area of the generating object.

The limited amount of Russian regions has the sufficient potential for realization of commercial use of sunlight energy. So, for instance, by information from Hevel Solar [3] only in the Far East of Russia, in the areas adjoining to China, the insolation level exceeds 4.5 kWh/sq.m/day. Only Kamchatka and the Kuril Islands territories have sufficient potentials for geothermal energy use due to its terrestrial heat flow corresponding to a geothermal gradient 20 ºC/100 m in comparison with 6 ºC/100 m in the Caucasus and in the Crimea [4] which are also considered as perspective territories for geothermal power exploitation. In different regions this indicator is much lower therefore now use of geothermal energy in Russia in areas besides Kamchatka and the Kuril Islands is inexpedient. According to the national atlas of Russia [5] the average wind speed is sufficient for operation of low-speed wind turbines on the most part of the Russian Federation territory. The paper deals with questions of application of various RES for creation of power supply systems for remote industrial consumers having electrical shortage which is one of the main limiting factors of sustainable development.

2. RES geography in Russia

To suggest a solution of the problem of partial autonomous enterprise power supply it is necessary to consider already available achievements in the field of renewable energy use in Russia.

2.1. Geothermal power

Despite the presence of a certain potential in the North Caucasian, Volga region, East and West Siberian areas the most perspective from the point of view of geothermal resources the Kamchatka Region is considered. In Russia there are only five geothermal generating stations with a overall installed capacity of 80.1 MW and all of them are located in the Kamchatka Region or in the Sakhalin region [6]. At the same time nearly 60% of this value is made by the power of Mutnovsky geothermal power plant of 50 MW [7]. However, this area experience concerning installation of geothermal power plants [8] which have allowed to reduce significantly the region dependence on imported fuel oil and, as a result, to reduce energy prices is rather an exception to the rules.

2.2. Biofuel use

Russia is included into the three of the biofuel exporting countries, however, only 20 % of produced fuel pellets are consumed in domestic market [9]. As biofuel production is closely connected with agriculture, its use is mostly widespread in territories which are historically more populated. Power plants of "Baytsury", "Luchiki" and the first Russian bioreactor in the Doshino village can be examples. Biogas power plants are generally used by agricultural complexes for ensuring own power needs. It should be noted that it is unprofitable for enterprises to sell the energy produced by biofuel in the retail or wholesale markets as unlike the European countries in Russia there are no special tariffs for "bioelectric power".

2.3. Solar power

According to [10] the overall installed capacity of solar and wind power facilities in Russia has to make 1600 MW in ten years [11]. Nevertheless, for today there are only eight large solar power stations which are mainly located at the southern borders of Russia except for solar powerhouse of Batagai in Yakutia with only 1 MW capacity. Practically all solar objects have been implemented within the last several years and average quantity of installed capacity makes about 5 MW [12]. On some solar power stations new stages construction is planned but the maximum installed capacity will not exceed 10 MW after expansion [13] which is in many respects caused by features of a geographical location of Russia and, as a result, the specific climate which is not suitable for mass solar power assimilation.

2.4. Wind power

The major wind power stations of Russia are in the Crimea. These are Donuzlavsky, Ostaninsky, Tarkhankutsky and East Crimean wind generating stations. Similar objects are operating in the Kaliningrad region (the Zelenograd WDPP), at Chukotka (the Anadyr WPS), in the Republic of Bashkortostan (Tyupkilda WPS), Kalmykia, at Bering Island of the Commander Islands and at the Kola Peninsula [14]. There is also a number of projects in other regions but they are in a development stage. Design capacities of the developed WPS can reach 75 MW [15] nonetheless the capacity of already operating power plants, except for the Crimea, does not exceed 5 MW [16].

Nevertheless, many steppe regions of Russia have sufficient potential from the point of view of speed and constancy of wind flows (for example, Kurgan and Tyumen regions) in total with high concentration of the industrial enterprises in these areas. These factors combination provides profitable wind power use for power supply of remote industrial consumers.

3. Assessment of expediency of wind power generation use

The expediency of the suggested solution is estimated on a practical example. The first step is the choice of the optimum place for WPS placement within the Kurgan region. This area was chosen because of the combination of a plain terrain, high concentration of the industrial enterprises and relative remoteness from the large cities, which had been described above.

3.1. The settlement choice

The first step is the choice of the optimum place for placement of wind power station within the Kurgan region on the map based on meteorological data [17, 18]. This area was chosen because of the combination of a plain terrain, high concentration of the industrial enterprises and relative remoteness from the large cities, which had been described above.

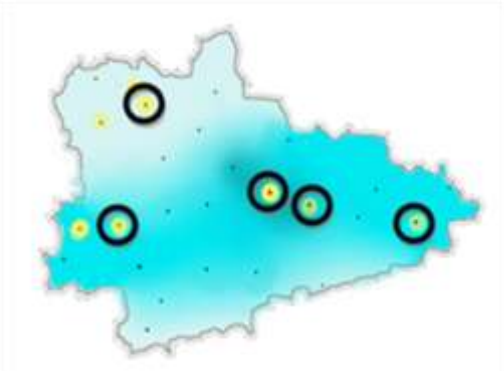

Figure 1. The map of average wind speed at the height of 10 m above ground, m/s:
– more than 5.5; – from 3 to 5.5; – less than 3.
The number of the industrial enterprises in the settlement:
– more than 5; – from 3 to 5; – 2 and less.
• – designation of the settlement, – the chosen location

3.2. Assessment of expediency of wind power plants construction

The first step is the choice of the optimum place for placement of wind power station within the Kurgan region on the map based on meteorological data [17, 18]. This area was chosen because of the effective combination of a plain terrain, high concentration of the industrial enterprises and relative remoteness from the large cities.

Calculation is made on the basis of Weibull distribution function [19, 20] as the way of an assessment of wind speed change in the medium-term period, i.e. in one year. Integral Weibull distribution function represents the probability density distribution of wind speed presented by the expression:

$$P(v) = 1 - e^{-\left(\frac{v}{c}\right)^k}, \quad (1)$$

where P is the probability of occurrence of a wind flow with a speed not lower than v; c is the scale factor, k is the shape factor.

In each case the system of nonlinear equations with P and v found in result of averaging of observation results [17, 18] was solved for c and k by means of the Mathcad software package. Calculation for Kurgan is given as an example.

Table I. Probability of wind occurrence in the given speeds range, where v_0-v, m/s is the range of wind speeds

v_0-v_i, m/s	Possibility of wind speed accessory to this interval v_0-v,%											
	Jan.	***Feb.***	***Mar.***	***Apr.***	***May***	***June***	***July***	***Aug.***	***Sept.***	***Oct.***	***Nov.***	***Dec.***
0-3	19	21	3	0	3	0	6	3	7	6	0	13
3-6	52	54	37	20	19	47	58	55	33	36	23	42
6-10	26	21	37	53	75	40	33	39	53	39	50	36
10-14	3	4	23	20	3	13	3	6	7	19	24	3
14-16.5	0	0	0	7	0	0	0	0	0	0	3	6

The probability of average daily wind speed v in the range (v_0,v_i) for calendar year is calculated as follows:

$$P(v=v_i)=\frac{\sum_{1}^{12}P\left(v\in(v_0,v_i)\right)}{12}\cdot 100\% \tag{2}$$

The probability of average daily wind speed v in the range (v_0,v_i) for calendar month is calculated as follows:

$$P\left(v\in(v_0,v)\right)=\frac{n\left(v\in(v_0,v_i)\right)}{n} \tag{3}$$

where $n\left(v \in (v_0, v_i)\right)$ is the number of days in a month when average daily wind speed v belongs to the range (v_0,v_i), n is the number of days in a month.

Calculation of probability that the average daily wind speed v is less than speed v_i is made according to the formula (Results of calculations are presented in the table II):

$$P(v_i>v)k=\sum_{1}^{k}P(v_i=v) \tag{4}$$

Table II. Probability of wind distribution

v, m/s	Probability of wind speed	
	P (v_i=v), %	**P (v_i<v),%**
0-3	6.750	6.750
3-6	39.667	46.417
6-10	41.833	88.200
10-14	10.667	98.917
14-16	0.833	99.750
>16	0.500	100

On the basis of the obtained data the system of equations is set:

$$\begin{cases} 0.0675 = 1 - e^{-\left(\frac{3}{c}\right)^k} \\ 0.4640 = 1 - e^{-\left(\frac{6}{c}\right)^k} \end{cases}$$

The equations for two other settlements have been set in the same way. As a result of its solution the values presented in the table have been received III.

Table III. Determination of the scale factor *c* and shape factor *k*

Name of the settlement	Kurgan	Shchuch'ye	Lebyazh'ye	Kataysk	Zverinogolovsk
Scale factor, *c*	7.603	4.49	5.057	3.501	4.149
Shape factor, *k*	1.993	2.903	2.768	2.326	2.347

On the basis of parameters from the table III and a formula (1) the Weibull function diagram is created. In the same coordinates the diagram displaying meteorological observations for the same period is constructed. Blue color is used to indicate temperature change according to weather services, light-blue is used for Weibull distribution on wind speeds.

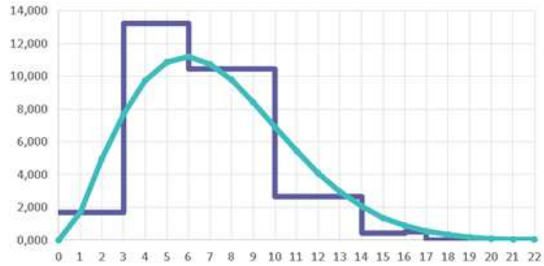

Figure 2. Weibull distribution and weather data, Kurgan

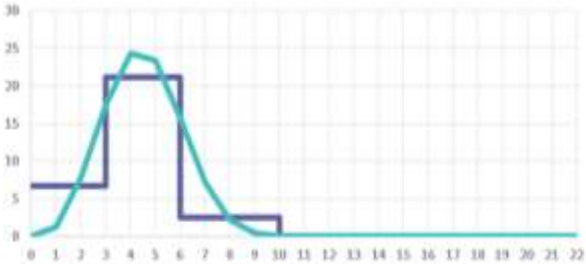

Figure 3. Weibull distribution and weather data, Shchuch'ye

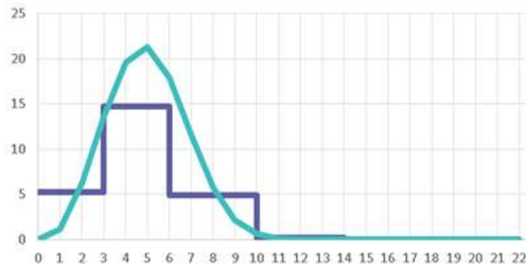

Figure 4. Weibull distribution and weather data, Lebyazh'ye

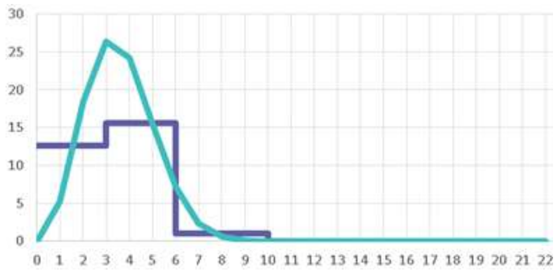

Figure 5. Weibull distribution and weather data, Kataysk

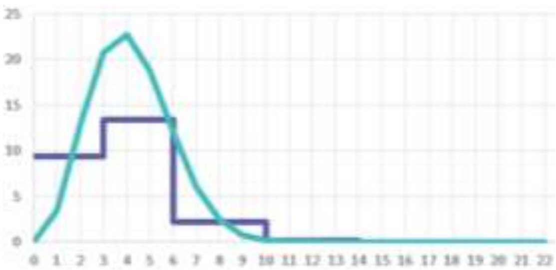

Figure 6. Weibull distribution and weather data, Zverinogolovsk

3.3. Calculation of wind parameters for the considered area

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On the basis of the obtained data calculation of parameters which allowed estimating expediency of wind power stations use in these areas has been made. Calculations were made on the formulas listed below and the received values are given in the table IV. Calculation for Kurgan is given as an example.

1. Determination of wind speed at z height knowing wind speed v_0 at z_0 height can be made according to a formula:

$$v = v_0 \cdot \frac{z}{z_0} \tag{5}$$

2. Expectation of average wind speed at the height of 10 m for Kurgan:

$$\bar{v} = c \cdot \Gamma(1 + 1/k) = 7.603 \cdot 0.891 = 6.774 \text{ m/s} \tag{6}$$

3. The most probable wind speed at the height of 10 m (mode) at $k > 1$ is calculated on the expression:

$$v_{p\max} = \frac{c \cdot (k-1)^{(1/k)}}{k^{(1/k)}} = \frac{7.603 \cdot (1.993 - 1)^{(1/1.998)}}{1.993^{(1/1.998)}} = 5.360 \text{ m/s} \tag{7}$$

4. Wind turbulence at the height of 50 m (a mean square deviation) is defined as follows:

$$\sigma_v = \sqrt{c^2 \cdot \Gamma(1 + 2/k) - (\bar{v})^2} = \sqrt{7.603^2 \cdot 1.001 - (8.485)^2} = 4.300 \text{ m/s} \tag{8}$$

5. Probability of occurrence of a wind flow with the speed not exceeding 3 m/s:

$$\exp\left[-\left(\frac{v}{c}\right)^k\right] = 1 - \exp\left[-\left(\frac{3}{7.603}\right)^{1.993}\right] = 14.414\% \tag{9}$$

6. Calculation of average capacity of wind power generation:

$$P(\bar{v}) = \Delta v \cdot \left(\sum_{n=0}^{50} p(n) \cdot P(n) - 0.5 \cdot p(50) \cdot p(50)\right) \tag{10}$$

Table IV. Results of calculation of wind power parameters

Name of the settlement	**Wind parameters**										
	c	***k***	***$C_{exp.}$***	***$V_{av.}$*, m/s**	***$V_{av.}$*, m/s**	***P(v≤3)*, %**	***$v_{p\,max}$*, m/s**	***$σ_v$***	***$P_{av.}$*, %**	***$V_{av.exp.}$*, m/s, *h=50 m***	***v_{max}*, m/s, *h=50 m***
Kurgan	7.603	1.993	7.295	6.500	6.774	14.410	5.360	4.340	23.355	8.485	20.043
Shchuch'ye	4.490	2.903	4.607	4.100	3.996	26.520	3.882	1.519	6.430	5.136	12.527
Lebyazh'ye	5.057	2.768	5.505	4.900	4.501	20.870	4.300	1.758	9.442	6.138	17.538

Name of the settlement	Wind parameters										
	c	k	$C_{exp.}$	$V_{av.}$, m/s	$V_{av.}$, m/s	$P(v\leq 3)$, %	$v_{p\ max}$, m/s	σ_v	$P_{av.}$,%	$V_{av.exp.}$, m/s, h=50 m	v_{max}, m/s, h=50 m
Kataysk	3.501	2.326	4.606	3.865	3.967	50.020	2.750	1.217	3.244	5.219	12.731
Zverinogolovsk	4.149	2.347	5.505	4.600	4.589	37.126	3.275	1.442	5.658	6.089	16.155

3.4. Analysis of average capacities of wind power generation in the Kurgan region

The obtained data have been plotted on the map for simplification of the analysis. According to this map it is possible to draw a conclusion on what part of installed capacity of the wind generator will be developed on average in standard conditions taking into account Weibull distribution and terrain features.

In practice the received results can be used for both the preliminary analysis of expediency of wind power stations use at the existing enterprises and the choice of optimum location of the new enterprise taking into account a possibility of its partial power supply by wind power.

For descriptive reasons the calculation is made to define what average capacity will be given by one wind generator with the installed capacity of P_{inst} = 2500 kW according to data for Kurgan [16].

$$P_{av.} = \frac{P_{inst.} \cdot P_{av.\%} \cdot \cos\beta}{100} = \frac{2500 \cdot 23.355 \cdot 0.819}{100} = 478.194 \text{ kW}, \qquad (11)$$

where β = 270°-10°-$C_{av.}$=270°-10°-225° = 35°. (12)

At that β is the same for all the area as the prevailing wind direction according to data [10] is southeast for all territory.

Thus it is possible to calculate average efficiency of power use:

$$K_{\exp.av.} = \frac{P_{av.}}{P_{inst.}} = \frac{P_{av.\%} \cdot \cos\beta}{100}, \qquad (13)$$

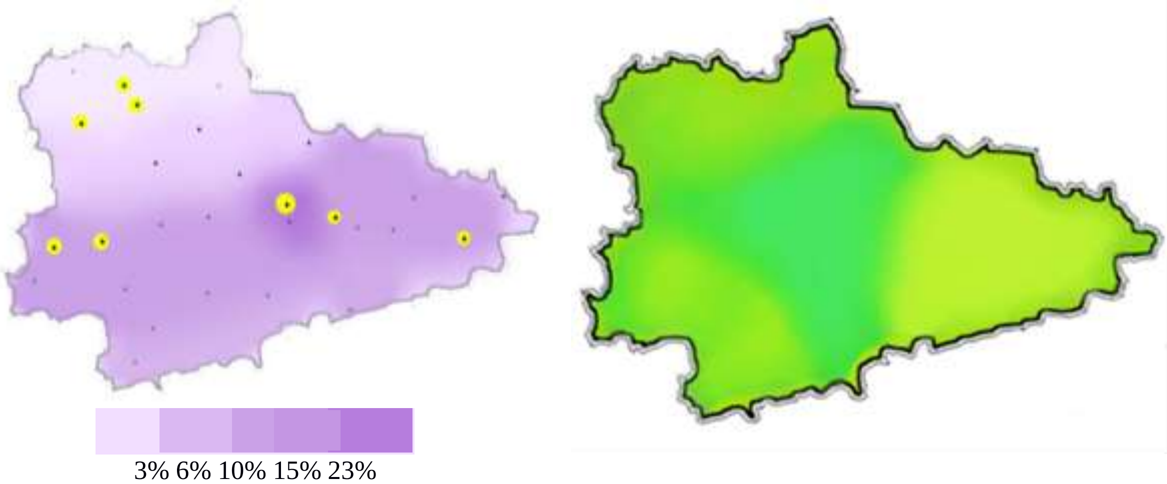

Figure 7. Average efficiency of power use

Figure 8. The map of electric power deficiency and surplus in Kurgan

East area is the most suffering from power shortages with power shortage making about 150 MW [21]. At the same time in the Kurgan energy area power surplus of 382 MW is observed by the data [22] for 2016. Nevertheless, in the Kurgan area there is a significant increase in power consumption due to implementation of the new energy-using equipment. Similar tendencies are observed also in East and Shumikhinsky energy areas.

Comparing maps in figure 2 and figure 3 it might be concluded that there is a possibility of wind power stations use as an alternative connection to the Unified energy system in all the energy areas, except for Shadrinsk as the average output there is insufficient for ensuring steady power supply of consumers.

4. Influence of wind generators operation on electric network

While using the generator as the power supply it is necessary to take into account inconstancy of the generated capacity. It is connected with its dependence on the wind speed [23]. For an assessment of this influence by means of a software package of @Risk Palisade Decision Tools Monte Carlo method [24] and the InorXL program unit [25] were used for calculations of the steady state modes.

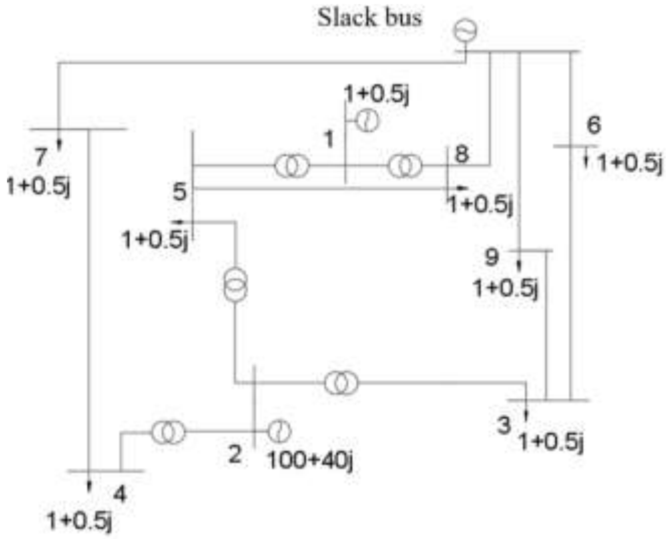

Figure 9. Single-line diagram of the network

One thousand iterations was made for which the capacity of the wind generator P has been presented by the Weibull function received on the basis of data from Table III. Herewith c and k also change in the ranges (0.959; 1.172) and (0.383; 0.469) respectively on formulas (14) and (15).

$$c = x^2 - 0.85 \cdot x + 0.179 \tag{14}$$

$$k = x^2 - 2.218 \cdot x + 1.120 \tag{15}$$

Weibull distribution for wind speeds is presented by a formula (16):

$$P = 1 - \exp\left[-\left(\frac{P_i}{c} \right)^k \right] \tag{16}$$

4.1. Analysis results

Analysis results are shown in the table V and in figure 10 where maxima (max), minima (min) and the most expected (m. e.) modules of voltage in nodes of the considered electric network of 10 kV are displayed.

Table V. Voltage parameters

Busbar	U_1	U_2	U_3	U_4	U_5	U_6	U_7	U_8	U_9
Max	116.113	117.312	10.618	10.640	10.607	10.108	10.112	10.521	10.108
Min	115.540	116.745	10.567	10.588	10.555	10.069	10.073	10.470	10.108
M. e.	115.858	117.063	10.596	10.617	10.584	10.095	10.099	10.500	10.095

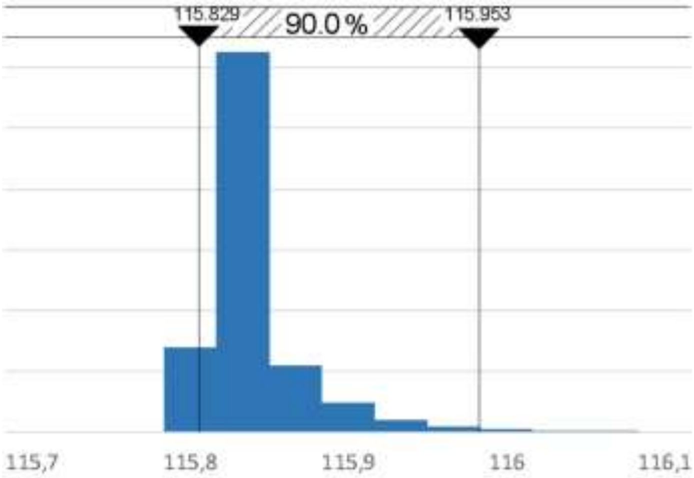

Figure10. Change of voltage on substations busbars

On the basis of each iteration data on the minimum and maximum voltage in each node and also the most probable values of voltage have been obtained. Also nodes voltage and *c*, *k* и *P* parameters relationship have been defined.

Analyzing the obtained data it is possible to conclude that on voltage classes of 110 and 10 kV the difference among the minimum and maximum values of voltage makes about 1 %. Therefore it is possible to conclude that change of the wind generator capacity influences the mode slightly and does not make the voltage in network nodes exceed admissible limits.

5. Conclusion

The research presents practical approbation of a method determining the potential of wind generators use for the choice of the most suitable generator taking into account climate, landscape and influence on external electric network. Criteria for such assessment are the required values of power and voltage and also its acceptable deviations. Besides an algorithm, recommendations for its use simplification and also the map for decisional process visualization are provided in the paper.

Though the preliminary choice might be made on the basis of only values of average wind speeds, such assessment will not provide exact results about expediency degree and a real possibility of use of wind power production in general for concrete electric network. In spite of the fact that installment of wind power generation will require more deep meteorological studies, the simple and evident algorithm accelerates and simplifies process of calculations.

Currently it is impossible to call wind power in Russian Federation widespread. Creation of transparent express methods for definition of expediency of wind power generation use in the long term will allow to improve a situation and to develop domestic market of this type of the generating capacities.

Wind power can become one of real alternatives of power supply from the centralized system and it is possible to make wind energy and renewed power in general more attractive to the end user only by simplifying the process of its use.

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