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Methods to select structural solutions for wind power generators in low-rise development

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Abstract. The article is devoted to the prospects for the development of renewable energy sources, in particular wind energy, in rural areas of the Rostov region (Russia). The analysis of the state program of the Russian Federation "Integrated Development of Rural Territories" was carried out. The primary measures that contribute to the implementation of directions for the development and improvement of the reliability of power supply through the use of wind energy are considered. The aim and objectives of the study are to create a classification and develop a methodology for selecting design solutions of wind turbines in low-rise residential construction, to develop criteria for evaluating the choice of renewable energy source (RES) technologies, to conduct a multi-criteria analysis of different types of wind turbine designs and to select the most optimal type of wind turbine design by applying multi-criteria analysis methods for selecting optimal wind turbine designs. The possibility of applying the method of multi-criteria analysis for the choice of design solutions for WPPs is substantiated. The assessment of the Rostov region territory and its priority for the placement of wind farms was demonstrated. The classification of wind turbines has been carried out. Design solutions for wing generator are presented. A technique for choosing optimality criteria is formulated. The results of studies by different scientists are summarized and compared with the proposed methods To select the optimal design of the wind turbine, a multi-criteria decision analysis was applied. Methodology for selecting wind energy generation technology elaborated in the course of research by applying multi-criteria analysis, allows us determining with the highest accuracy the most efficient and economically viable design of the wind power plant.

Keywords: wind energy, wind parks, fitness score, wind generators, multi-criteria analysis; criterion for choosing optimality; choice of optimal technology

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1. INTRODUCTION

Scientific novelty lies in the development of evaluation methods of using multi-criteria analysis to select effective design solutions for wind power generators.

The increase in the global population and the modern development of advanced technology lead to an increase in energy consumption around the world. Every year the problem of energy consumption becomes more and more crucial. In addition to the use of nuclear, alternative and water power, fuel and energy raw materials account for a considerable portion of the energy consumed. The depletion of natural resources has led to fierce competition in the economic, political and geopolitical spheres. Unstable financial situation in the global gas, coal and oil markets seriously aggravates humanity's energy problem. As an approach to solving this problem, the World Energy Council proposed the concept of global energy security, which may be reduced to finding a balance between the desire for power security, affordability of power supply, and environmental sustainability. If the causes of humanity's power problems are removed, and if practical measures are taken to continue to provide the world economy with both traditional fuels and power from alternative sources, a strategy for global power security may be implemented. Moreover, special attention should be paid to the development of alternative power sources.

At present, a significant number of Russian and foreign scientific works devoted to the problem of energy consumption has been published.

"Foreign energy policy" is the scope of the state's activities in international relations to protect and uphold national interests due to the production, transportation and consumption of energy resources. Goals, objectives, priorities and directions of the foreign energy policy of world powers, state policy in the field of power saving management were considered by such authors as [1] and [2]. On the policy of using the renewable power sources, the following researchers have written in their scientific works by authors from [3, 4].

In his work Chacrit Sitdhiwej paid attention to increasing the share of renewable power sources (RPS) in the power balance of a country [5]. The authors of scientific publications [6] described a model for countries with a prevailing water power system and analyzed the impact of integrated RPS variables in long-term future scenarios. The publications of [7] provide an overview of the legal regulation of renewable energy.

Analytical studies of the prospects for the use and development of alternative power sources have been conducted by different authors from [8, 9]. Summing up the results of the research, we can say that the trend towards the development and implementation of renewable energy in world practice seems to be an urgent and promising project, and the use of alternative energy sources is expedient.

Based on the information on alternative power from the Swedish Royal Academy of Sciences Energy Committee, Georgia Destouni and Harry Frank evaluated the contribution of renewable energy sources in the global energy system in their works [10].

Analysis of the theoretical basis of modern studies of energy security in the context of the study of international relations and foreign policy is presented in the scientific works of [11] and [12].

The studies by different authors from [13] deal with the problems in the field of power saving and energy efficiency [14]. In particular, the main problems of energy resource shortages were identified; geopolitical and social dangers. A special role in scientific works is assigned to renewable energy sources and their impact on the environment. Solving the problems of meeting the growing needs in the energy sector with minimal environmental damage lies in the implementation of the concept of energy saving in combination with increasing the production of traditional fuel and the involvement of alternative fuel resources.

Mihaela Păceşilă explored new possibilities for generating electricity and heat [15]. In this context the present work provides accurate information on the research characterizing the solar resource and examines the potential of solar energy in European countries. Other studies on the potential of solar power have been conducted by the authors from [16, 17].

Nidhi Tandon addressed the issues of cost-efficiency of power production from biogas in his works [18].

K. Wang at all presented the results of comparison of four energy conversion technologies within the power system [19].

Wind energy is considered one of the promising alternative energy industries. The development of the industry is connected with the development of new and improvement of old wind turbines models. Innovative ways of wind power development have been reflected in the works by the authors from [20, 21]. The work of W. E. Leithead characterized the condition of wind power industry, discussed the dynamics and prospects of its development [21]. The presented review of modern technologies in the field of wind power industry contains information about Western technologies, including equipment and consumables, in particular, modern developments of universal windmills, various ways of generating and storing energy.

G.B Osadchy applied [22] multi-criteria assessment of the components of economic efficiency of renewable power systems and installations in his research.

In the studies of Russian scientists, the features of the use of GIS in making managerial decisions on the energy development of territories are actively studied. In the works of V.L. Badenko analyzes the issues of effective search for sites for the placement of renewable energy sources, comparison of sites in the GIS environment in order to make the most effective management decision and meet the requirements of the investor [23].

The importance of a comprehensive assessment of the territory to ensure its sustainable development and use of the results when choosing a specific type of alternative energy source was described in their works by S.G. Sheina, A.A. Fedorovskaya, A.A. Pirozhnikova, E.A. Priss and others [24]. Based on the results of the research work carried out in the field of alternative energy, the authors present an overview of the current situation in the development of alternative energy by the countries of the world and Russia, according to "Comprehensive development of rural areas" and on amending some acts of the Government of the Russian Federation [24].

Each considered scientific source is aimed at solving a specific problem and does not have an integrated approach.

The Russian Federation is characterized by a high level of energy intensity of GDP; the current situation requires reducing specific consumption of fuel, heat and electricity by enhancing rational use thereof instead. The use of alternative power sources could significantly alleviate both resource and environmental tensions.

In connection therewith, the Russian Federation Ministry of Economic Development is striving to fulfill the task set by the President of the Russian Federation to reduce the energy intensity of GDP, also as part of the implementation of a comprehensive set of measures to improve the energy efficiency of the Russian economy, approved by Order No. 703-r of the Government of the Russian Federation dd. April 19, 2018. In accordance with the Order№ 707 of the Ministry of Economic Development dd. October 28, 2019, in 2021, in order to save energy and improve energy efficiency, all public authorities, local governments, state and municipal institutions shall submit energy declarations on the consumption of energy resources for the reporting year 2020. These declarations will be used by the Ministry of Economic Development to analyze and forecast the volume of energy resources consumption by the public sector and to form and update a set of state policy measures aimed at improving energy efficiency.

2. METHODS AND MATERIALS

The purpose of this study is to develop a classification and develop a methodology for choosing design solutions for wind turbines in low-rise residential construction, develop criteria for evaluating the choice of renewable energy technologies, conduct a multi-criteria analysis of various types of wind turbine structures and select the most optimal type of wind turbine design.

The object of this research is the structural solutions for wind power generators which require decisions to be made under the conditions of multicriteriality.

The main purpose of the study is to develop a methodology for ensuring the sustainable development of the territories of the subject of the Russian Federation during the introduction of renewable energy sources. To achieve this goal, the following tasks are solved within the framework of the study:

- the structure of a comprehensive assessment of the territory of the subject of the Russian Federation for the placement of renewable energy sources is determined;
- a methodology for calculating the priority of the territory for RES placement has been developed;
- a system of multi-criteria analysis was chosen to solve the problem of choosing constructive solutions for wind farms;
- a classification of the design solutions of the WPS has been developed;
- the implementation of the proposed tools is demonstrated on the example of the Rostov region and the WPS.

The topic being analyzed herein is the methods of analysis for selection of an optimal technology applied in wind power industry which methods require decision-making under multi-criteria conditions.

Methodologically, this research is based on academic papers by both Russian and foreign scientists, as well as articles covering the standards currently in force in the field of multi-criteria selection methods analysis for the optimal structural solutions for wind power generators. To solve the problems raised, the methods of decision-making under multi-criteria conditions have been applied.

To solve the problem of power supply, while taking into account the requirements of environmental and energy safety, a systematic analysis of the criteria for the selection of power generation sources is required. In order to select and justify such criteria, it is necessary to evaluate the effectiveness of conventional and unconventional generators. In general, sources can be classified according to the following criteria: by weather and climate conditions; by technical characteristics; by economic indicators.

In order to improve the quality of life of the rural population, as a strategic objective stipulated in the Decree of the President of the Russian Federation dd. May 07, 2012 No. 600 "On measures to provide citizens of the Russian Federation with affordable and comfortable housing and improve the quality of housing and communal services", as well as to create comfortable living conditions for the dwellers of rural areas, the President of the Russian Federation charged the Government of the Russian Federation with elaboration and approval of a program for the development of rural areas at the meeting of the State Council of the Russian Federation following a working visit to Stavropol Territory on August 31, 2018. Pursuant to the order of the President of the Russian Federation, the State program of the Russian Federation "Comprehensive development of rural territories" was approved by the Government of the Russian Federation on May 31, 2019 under No. 696 (hereinafter referred to as the State Program).

In 2020 the implementation of the State Program began. Within the framework of the program for social development of rural areas and sustainable development of rural territories the implementation of measures for utility infrastructure of rural settlements is going on. The implementation of new measures allowing to comprehensively solve the issues of rural development has been started. The State Program is aimed at improving the living standards of rural residents, improving the infrastructure in rural areas, and developing human resources in rural areas.

The task of paramount importance is the power supply of Siberia and the Far East regions which have underdeveloped transport infrastructure, since these regions are located in vast territories with low population density and are isolated from centralized power supply. The reliability of such a power supply, in all likelihood, can be embodied by a centralized power supply, or by creating decentralized zones. Due to the loss of voltage in the supply line, the ability to connect an electrical receiver to the power grid is limited by its remoteness. An alternative to the standard methods of generating energy can be the use of renewable power sources, such as the use of wind power [25, 26, 27].

According to the Russian Association of Wind Power Industry (RAWPI), the year 2020 was the most productive, both in terms of the number of commissioned wind generation facilities and the total capacity of these facilities. In 2020, 282 wind turbines were commissioned at 8 sites, with a total capacity of 908 MW [28].

According to experts' estimates, Rostov Region led the top five regions among the most involved in wind power energy in Russia. According to the results of the last year, high positions were taken by the Republic of Kalmykia, Stavropol Territory, Ulyanovsk Region, and the Republic of Adygea [29].

The construction of wind power plants is a large-scale project in the field of wind energy. For its implementation, technologies are used that have proven their effectiveness. Rostov Region is in the leading position by installed wind power capacity among the regions of the Russian Federation with the result of 346 MW commissioned in 2020. The second place in this respect belongs to Stavropol Territory with 210 MW produced by one of the most powerful wind power plants, Kochubeyevskaya, also commissioned in 2020. The third place is occupied by the Republic of Kalmykia with 204 MW. Along with wind power plants, wind generators are widely used as alternative sources of electric power for low-rise suburban construction of temporary or permanent residence. Often such devices are installed in areas remote from the main power grid and areas with frequent power outages, according to SP 131.13330.2020 Construction climatology.

In the process of research the analysis of natural conditions and economic activity of the territory of Rostov region, determining regional differences of RPS potential, was carried out. Indicators characterizing the possibility of implementing innovative projects in the field of energy efficiency of low-rise residential development (LRD) are:

•average annual wind speed at 10 meters (Fig. 1);

• intensity of the development of areas in municipalities (Fig. 2).

These wind speed parameters, adopted to determine the location of wind power plants, are accepted and proposed based on the local climatic conditions in the Rostov region and the principles of a territorial comprehensive assessment for the subject of the Russian Federation, by dividing the region into appraisal areas - municipalities.

For the analysis of wind speed we used archived data on climatic data of Rostov Region for 10 years [30]. To use wind energy as an alternative source, wind generators are used.

The indicators were summarized in a single system abstracted from specific values. The method of analysis allowed to make an objective assessment of the options of choice in terms of selected criteria. As a result of the evaluation of the possibility of implementing projects using wind energy by districts of the Rostov Region the most favorable were identified, see Fig. 1 [31]. After analyzing the average wind speed at a height of 10 meters in the Rostov region, the authors equated the wind speed from 5 m/s or more to 1 point, to 0.75 points from 3 to 4.5 m/s, to 0.5 from 2,5 to 3 m/s and to 0 from 0 to 2.5 m/s.

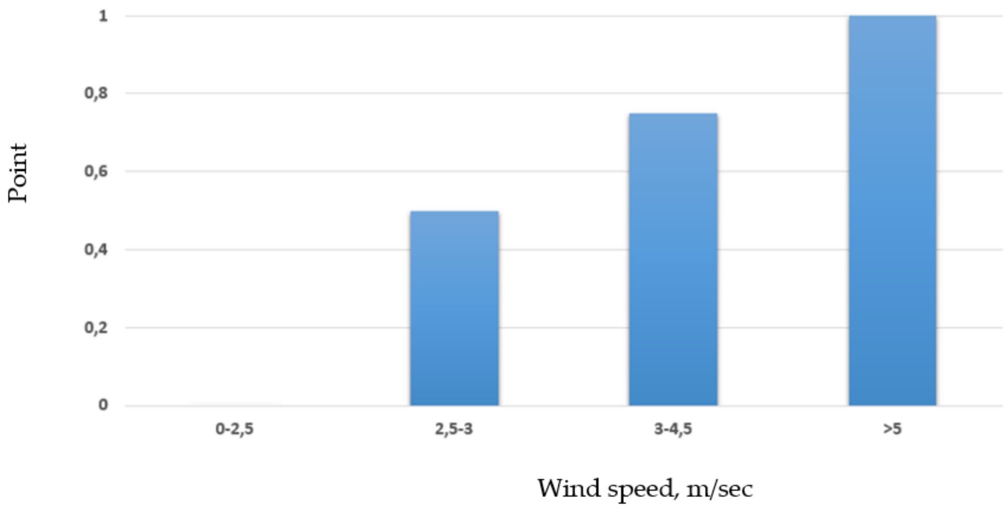

Fig. 1. Area evaluation on the basis of average monthly wind speed in Rostov Region districts. Source [31].

It is economically advantageous to apply wind turbines and wind generators in urban districts, regional districts or municipalities scoring one point or as close to one as possible [32].

According to Figure 1, an electronic map of the region of the Rostov Region clearly showing the degree of suitability of the territories of the Region for the use of wind turbines as an alternative energy source is simulated by means of the geographic information system ArcGIS [33].

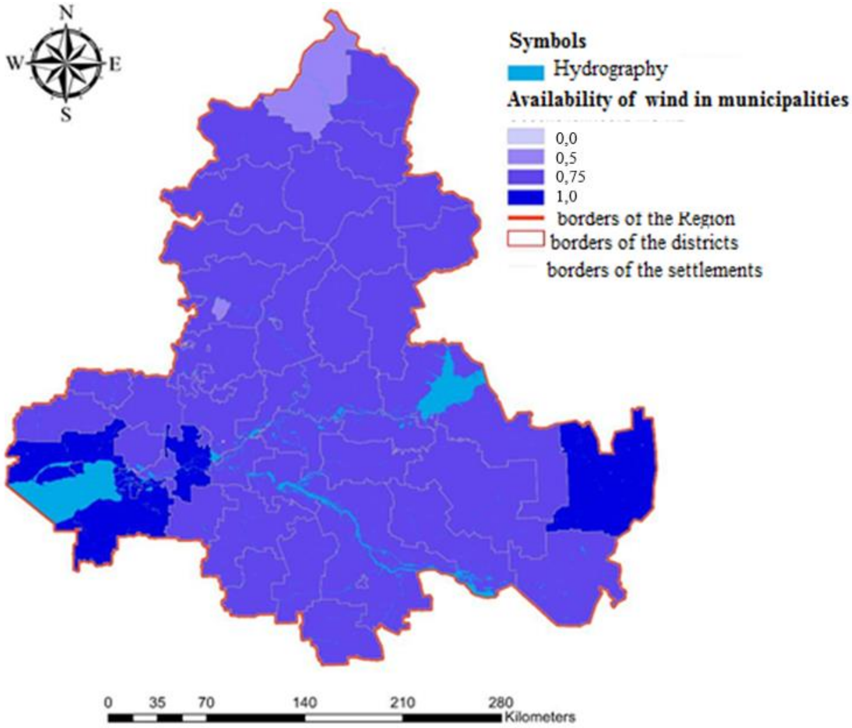

Fig. 2. Average monthly wind speed in municipalities of Rostov Region.

By analyzing Fig. 2 we can conclude that the most promising areas for the use of wind as an alternative power source are Azov District (including Azov), Neklinovsky District (including Taganrog), as well as Zavetinsky District of Rostov Region.

Developed branches of agro-industrial complexes are concentrated in large central municipalities: Rostov-on-Don, Bataysk, Azov, Taganrog, Novocherkassk, Shakhty, Millerovo, Gukovo, Volgodonsk. Volgodonsk.

For the spatial analysis shown on the electronic map, we used the method of comprehensive assessment of the territory. Intensity of development of directions of agroindustrial complexes (AIC), see Fig. 3. After analyzing the intensity of development of areas of agro-industrial complexes (AIC) of the municipal districts of the Rostov region, the authors equated to 1 point from 0 to 35 km, to 0.75 points from 35 to 50 km, to 0.5 from 50 to 70 km and to 0.25 from 70 to 100 km.

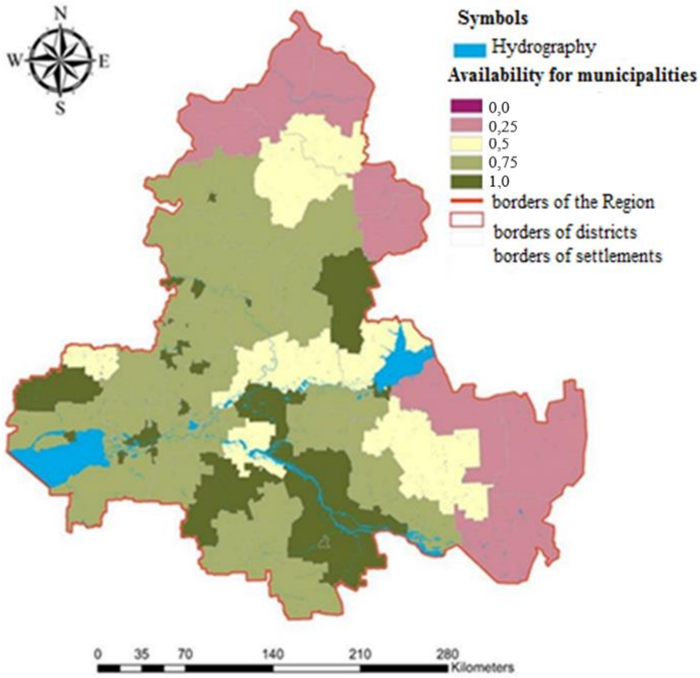

Fig. 3. Intensiveness of development of agro-industrial complexes (AICs) branches in the promising districts of the region.

Spatial analysis o Rostov Region in terms of average monthly wind speed and intensity of the development of branches of agro-industrial complexes showed that the most suitable for the use of wind power plants are the municipalities of Taganrog and Azov, see Fig. 4 [34]. Summing up the scores for the average annual wind speed at a height of 10 m and the intensity of development of various areas of agro-industrial complexes (AIC) of the municipal districts of the Rostov region, we received an overall score for the functional priority of placing a wind power station, Fig. 4.

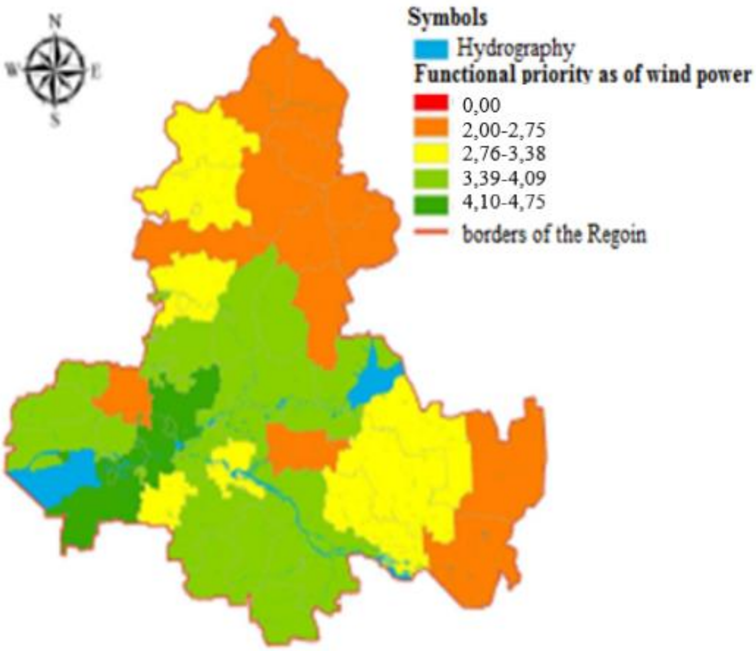

Fig. 4. Functional priorities of the areas of Rostov Region as of wind power generation.

The practical value of the results obtained lies in the implementation of methods of cost-effective use of wind turbines to generate electricity in the municipal areas of the Region with a developed agro-industrial complex. The operation principal of all wind generators is shown in Fig. 5 [35, 36, 37]. A classification of wind power plants has been elaborated Fig. 6 [38, 28].

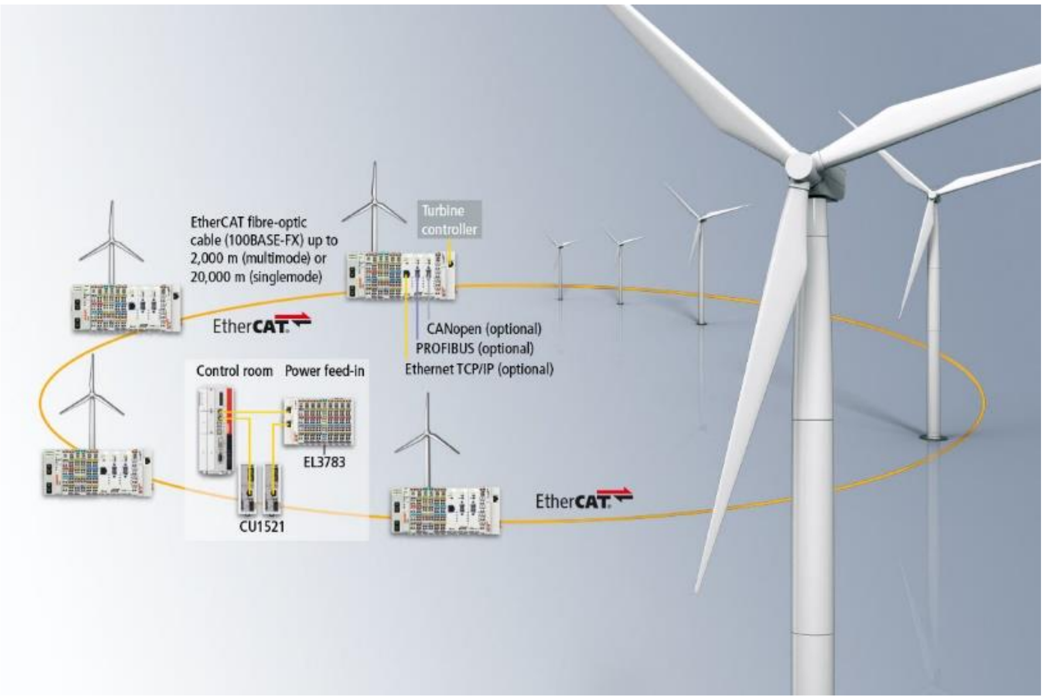

Fig. 5. Operating arrangement of wind generators [37].

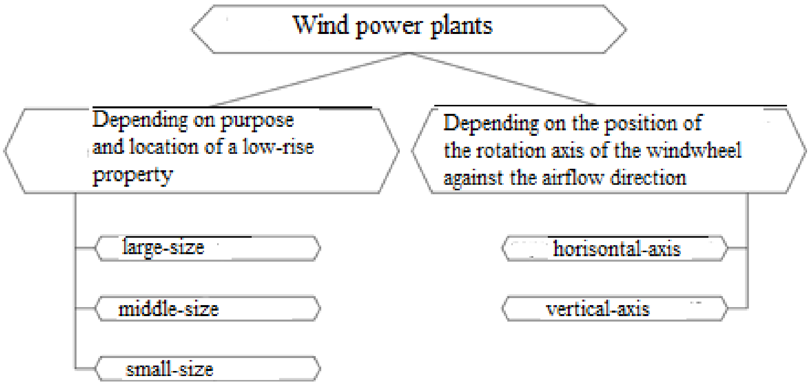

Fig. 6. Classification of wind power plants.

After determining the area for the installation of wind generators, the problem of selecting a rational option for the type of wind generator designs arises. To solve this problem, it is proposed to use multi-criteria decision-making analysis.

Let us consider five types of multi-criteria analysis [39, 40]:

1. The Wald’s maximum model is a pessimistic choice of an alternative from the conceptual point of view. According to it, the best alternative in the worst-case scenario is chosen. In terms of outcomes, the Wald’s maximum model works according to the "minimax" principle, which searches for the minimum among the maximum values of all alternatives. According to the Wald’s maximum model, the assessment of ith alternative is it is least gain (1):

$$W_i = \min(x_{ij}),\ j = 1 \ldots M. \quad (1)$$

The maximum worst-case gain alternative is accepted as the optimal alternative:

$$X=X_k,\ W_k=\max(W_i),\ i=1\ldots N. \quad (2)$$

2. From the conceptual point of view, the maximax criterion is the optimistic choice of alternative. According to it, the best alternative under the best set of circumstances is chosen. The maximax criterion is used to find the maximum among the maximum values of all alternatives. The ith alternative evaluation under this criterion is its highest gain M_i:

$$M_i=\max(x_{ij}),\ j=1\ldots M. \quad (3)$$

The highest gain alternative is accepted as the optimal alternative:

$$X=X_k,\ M_k=\max(M_i),\ i=1\ldots N. \quad (4)$$

3. The Laplace criterion is based on the insufficient reason. Taking into account the fact that when using the Laplace criterion, the choice of the preferred alternative is carried out under conditions of insufficient information, it is considered that all states are equally probable.

The average gain is used under the Laplace criterion as an evaluation of the alternative:

$$L_i=\frac{\sum_{j=1}^{M} x_{ij}}{M}. \quad (5)$$

The maximum average gain alternative is accepted as the optimal alternative:

$$X=X_k,\ M_k=\max(L_i),\ i=1\ldots N. \quad (6)$$

4. The Savage criterion is based on the assessment of alternatives under the so-called risk matrix. A value of outstanding gain (lost profit) equal to a difference between the gain of the alternative and the possible maximum gain of a certain condition is calculated for ach alternative and very certain natural condition.

The procedure of the Savage criterion application is as follows: for each natural condition j (matrix column, see formula 13), maximum yield y_j is determined:

$$y_j=\max(x_{ij}). \quad (7)$$

For each initial matrix cell X, the difference between the maximum gain for the given natural condition ω_j and the outcome fr the cell under consideration x_{ij}:

$$\omega_{ij}=y_j-x_{ij}. \quad (8)$$

The values thus obtained are then used to build a new matrix Ω –the matrix of outstanding gains. To assess an alternative under the Savage criterion, we have to calculate the maximum outstanding gain for each alternative in the new matrix Ω.

S_i-is the alternative assessment under the Savage criterion

$$S_i=\max(\omega_{ij}),\ j=1\ldots M. \quad (9)$$

The minimal maximum outstanding gain alternative is accepted as the optimal alternative:

$$X=X_k,\ S_k=\min(Si),\ i=1..N. \quad (10)$$

5. The Bayesian criterion is similar to the Laplace criterion although the difference is that, in case with the Laplace criterion, the natural conditions are equally probable, and in case with the Bayesian criterion, it is assumed that the natural conditions are determined and may vary. By identifying the natural conditions, the problem of choice in a state of uncertainty passes to the problem of finding a preferred alternative in a state of certainty.

Under the Bayesian criterion, the elements in the form below are used for alternative assessment:

$$\mathrm{L_i} = \sum_{\mathrm{j=1}}^{\mathrm{M}} x_{\mathrm{ij}} \cdot q_j \,. \tag{11}$$

The alternative having the maximal L_i value is accepted as the optimal alternative:

$$X=X_k,\ M_k=\max(L_i),\ i=1\ldots N. \tag{12}$$

The application of the scheme for choosing the optimal alternative to justify the decision is presented in Table 1.

Table 1. Application of the optimal alternative selection scheme for the decision rationale.

No. pos.	Criterion	Alternative assessment	Optimal alternative
1	Wald's model	$W_i=\min(x_{ij})$, j=1…M	$X=X_k, W_k=\max(W_i)$, i=1…N
2	Maximax criterion	$M_i=\min(x_{ij})$, j=1…M	$X=X_k, M_k=\max(M_i)$, i=1…N
3	Laplace criterion	$\mathrm{L_i} = \frac{\sum_{\mathrm{j=1}}^{\mathrm{M}} x_{\mathrm{ij}}}{\mathrm{M}}$	$X=X_k, M_k=\max(L_i)$, i=1…N
4	Savage criterion	$y_j=\max(x_{ij})$ $\omega_{ij}=y_j-x_{ij}$ $S_i=\max(\omega_{ij})$, j=1…M	$X=X_k, S_k=\min(S_i)$, i=1…N
5	Bayesian criterion	$\mathrm{L_i} = \sum_{\mathrm{j=1}}^{\mathrm{M}} x_{\mathrm{ij}} \cdot q_j$	$X=X_k, M_k=\max(L_i)$, i=1…N

As a result of the analysis of all factors affecting the decision, an option that meets all criteria best is selected. The optimal alternatives are shown in Fig. 7.

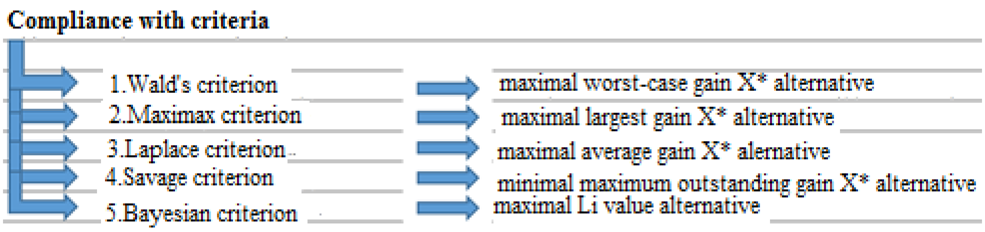

Fig. 7. Optimal criteria of an alternative.

Let us consider the following types of design solutions for wind power generators which are the most common in the global practice (see Fig. 8) [41].

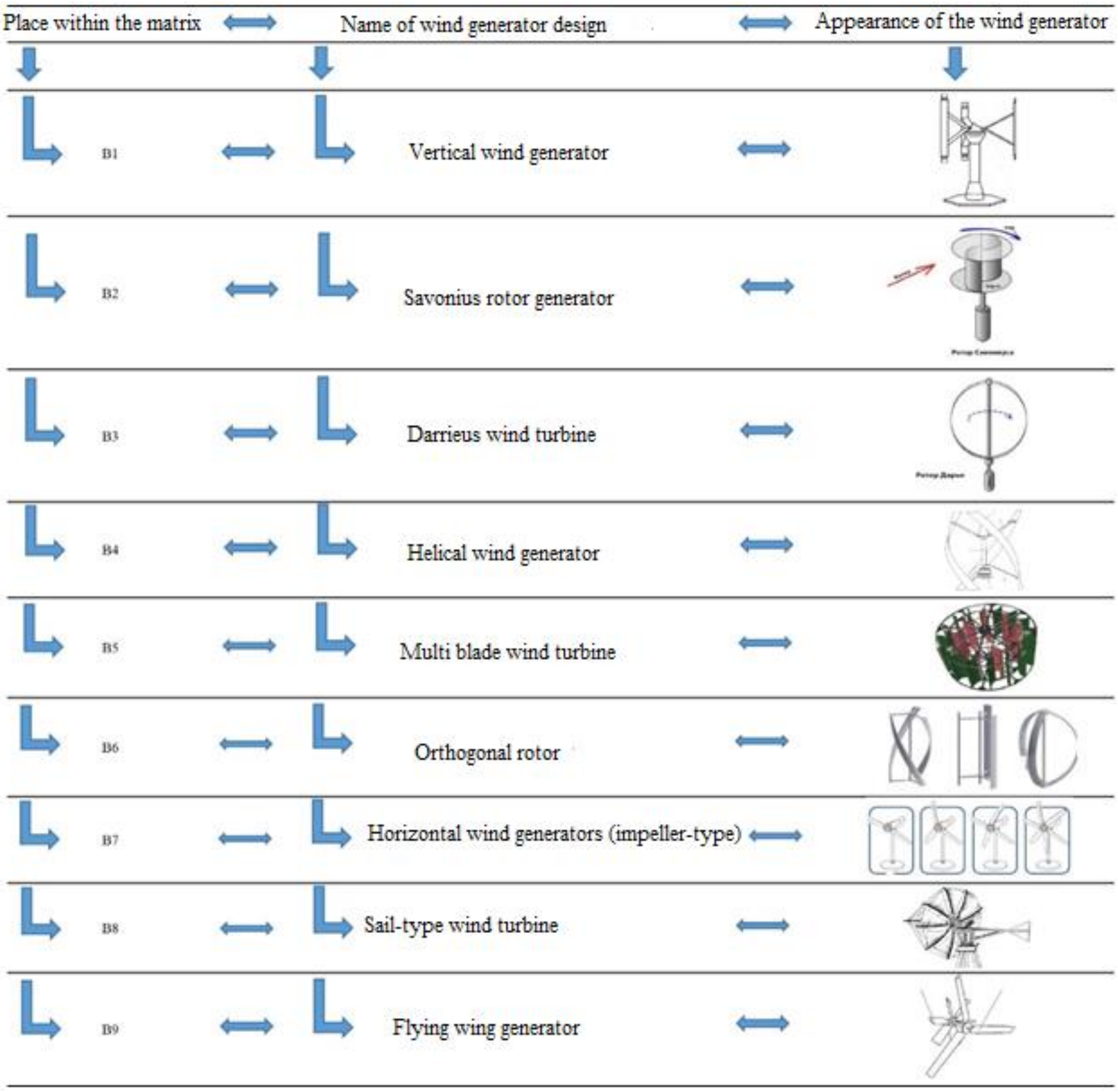

Fig. 8. Design solutions for wing generator.

The resulting indicators of the various options for the design of alternative (wind) power structures can be represented in the form of a matrix as it follows below:

$$
K_p = \begin{array}{ccccc} & A_1 & A_2 & \dots & A_3 \\ B_1 & K_{1,2} & K_{1,2} & \dots & K_{1,M} \\ B_2 & K_{2,1} & K_{2,2} & \dots & K_{2,M} \\ \dots & \dots & \dots & \dots & \dots \\ B_3 & K_{N,1} & K_{N,2} & \dots & K_{N,M} \end{array}, \tag{13}
$$

where, A_1, A_2, …, A_N – matrix columns (considered criterion);

A – evaluation criterion;

B_1, B_2, …, B_N – matrix rows (type of construction);

К1р- Кnр – numerical (score) value of the qualitative criterion;

Кnр – matrix of some criterion, р∈Р;

Р – is the space of all criteria;

w – the calculated cell of the matrix.

The solution of this matrix can be the criteria for choosing the optimal control, among which there are the maximax, Wald's, Savage, Laplace, and Bayesian criteria [39, 42].

In order to conduct a multi-criteria evaluation, it is necessary to set some number of lines and columns, at that, the number of lines depends on the types of structures used in wind turbines, the number of columns is selected on the basis of the generalized criteria of RPS [43, 44]. The basic and additional criteria for RPS selection are presented in Fig. 9, which is confirmed by a number of publications in this field [35]. The classification is based on the requirements STO RusHydro 03.01.102-2013 Wind power plants. Basic requirements, criteria for choosing wind power equipment for wind power plants.

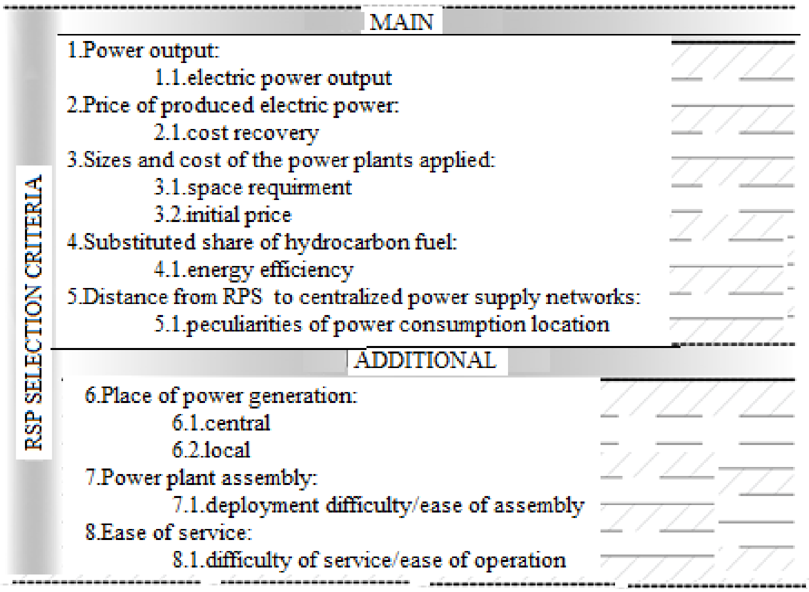

Fig. 9. RPS technology selection assessment criteria.Source [45].

Thus, the criteria for choosing RES of the main and additional ones were considered in the structure of the matrix (13), namely its columns, and the types of design solutions – the structure of the matrix.

3. RESULTS AND DISCUSSION

To select the wind power generator structures, we accept the following criteria [46;45]:
A1 – difficulty of service / ease of operation;
A2 – deployment difficulty / ease of assembly;
A3 – energy efficiency;
A4 – electric power output;
A5 – space requirement;
A6 – central;
A7 – local;
A8 – peculiarities of power consumption location;
A9 – initial price;
A10 – cost recovery
All criteria of wind generator structure and design assessment are based on their technical characteristics and range from 1.0 to 0 [47, 42].
Assessment criterion A1 – difficulty of service / ease of operation for, each wind turbine structure is determined based on peculiarities of wind turbine components.
Assessment criterion A2 – deployment difficulty / ease of assembly, for each wind turbine structure is determined on the bases of peculiarities of components;

Assessment criterion A3 – energy efficiency, for each wind turbine structure is determined based on annual output of power, and ranges from 1.0 to 0;
Assessment criterion A4 – electric power output, for each wind turbine structure is determined based on the power output capacity;
Assessment criterion A5 – space requirement, for each wind turbine structure is determined based on overall dimensions of the plant;
Assessment criterion A6 – central, for each wind turbine structure is determined based on area occupied and the electric power output amount;
Assessment criterion A7 – local, for each wind turbine structure is determined based on area occupied and the electric power output amount;
Assessment criterion A8 peculiarities of power consumption location, for each wind turbine structure is determined based on overall dimensions of the plant, and the area occupied;
Assessment criterion A9 – initial price, for each wind turbine structure is determined based on initial price of the plant;
Assessment criterion A10 – cost recovery, for each wind turbine structure is determined based on electric power tariffs in the plant deployment region (costs of generated power).
After analyzing the criteria for evaluating the varieties of wind turbine designs specified in [42], each indicator was assigned a minimum and maximum score from 0 to 1, respectively.
Further we consider these methods on the example of selecting the type of wind generator design. The input data for the multi-criteria analysis are presented in Table 2 [42].

Table 2. Input data for multi-criteria analysis of various designs of wind power generators.

Design type/Criterion	Difficulty of service / ease of operation	Deployment difficulty / ease of assembly	Energy efficiency	Electrical power output	Space requirements	Central	Local	Peculiarities of power consumption location	Initial price	Payback	min	max
Vertical generators	1.0	1.0	0.8	0.8	0.9	0.8	1.0	0.6	1.0	0.9	0.6	1.0
Savomius rotor generators	1.0	1.0	0.8	0.7	0.8	0.0	1.0	0.3	0.8	0.8	0	1.0
Darrieus rotor generators	1.0	1.0	0.8	0.8	0.9	0.8	1.0	0.5	0.9	0.8	0.5	1.0
Helical rotor generators	1.0	1.0	0.9	0.9	1.0	0.0	1.0	0.8	0.9	0.9	0	1.0
Multi blade rotor turbines	0.9	0.8	0.8	0.7	0.8	0.0	1.0	0.7	0.8	0.8	0	1.0
Orthogonal rotors	0.9	0.9	0.9	0.9	0.9	0.5	1.0	0.8	0.8	0.9	0.5	1.0
Horizontal generators (impeller-type)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0	0.9	1.0
Sail-type generator	0.9	0.7	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	0	1.0
Flying wing generators	0.7	0.6	1.0	1.0	1.0	1.0	1.0	0.9	0.5	0.8	0.5	1.0
max	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		

Let us review the method of optimality criteria selection (matrix):

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
B_1	1.0	1.0	0.8	0.8	0.9	0.8	1.0	0.6	1.0	0.9
B_2	1.0	1.0	0.8	0.7	0.8	0.0	1.0	0.3	0.8	0.8
B_3	1.0	1.0	0.8	0.8	0.9	0.8	1.0	0.5	0.9	0.8
B_4	1.0	1.0	0.9	0.9	1.0	0.0	1.0	0.8	0.9	0.9
B_5	0.9	0.8	0.8	0.7	0.8	0.0	1.0	0.7	0.8	0.8
B_6	0.9	0.9	0.9	0.9	0.9	0.5	1.0	0.8	0.8	0.9
B_7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.9	0.9	1.0
B_8	0.9	0.7	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0
B_9	0.7	0.6	1.0	1.0	1.0	1.0	1.0	0.9	0.5	0.8

According to the Wald's model, the assessment of ith alternative is its least gain under the formula 1.

Maximal worst case gain alternative under the formula 2 is accepted as the optimal alternative.

We obtain thus: $\max\limits_{\min_i} \min\limits_{B_i, i=1..9} \{0.6;0;0.5;0;0;0.5;0.9;0;0.5\} = 0.9$

As a result, the optimal choice under the Wald's model is the horizontal wind generator.

Further we research the optimal value under the maximax criterion.

The entire attention is given to the best outcomes, and thus the assessment of ith alternative under this criterion is its Mi maximum gain under the formula 3.

The alternative with the maximum gain under the formula 4 is accepted as the optimal alternative.

We obtain thus: $\max\limits_{\min_i} \max\limits_{B_i, i=1..9} \{1;1;1;1;1;1;1;1;1\} = 1$

Under otherwise equal conditions, the maximax criterion shows that the best choice under it is the horizontal wind generators.

Further, we carry out the selection of the optimal value under the Savage criterion using the formulas 7, 8, 9 and 10.

We calculate the value ω_{ij} (matrix).

$\omega_{1.1}$=maxA_1 – $K_{1.1}$	$\omega_{1.2}$=maxA_2 – $K_{1.2}$	$\omega_{1.3}$=maxA_3 – $K_{1.3}$	$\omega_{1.4}$=maxA_4 – $K_{1.4}$	$\omega_{1.5}$=maxA_5 – $K_{1.5}$	$\omega_{1.6}$=maxA_6 – $K_{1.6}$	$\omega_{1.7}$=maxA_7 – $K_{1.7}$	$\omega_{1.8}$=maxA_8 – $K_{1.8}$	$\omega_{1.9}$=maxA_9 – $K_{1.9}$	$\omega_{1.10}$=maxA_{10} – $K_{1.10}$
$\omega_{2.1}$=maxA_1 – $K_{2.1}$	$\omega_{2.2}$=maxA_2 – $K_{2.2}$	$\omega_{2.3}$=maxA_3 – $K_{2.3}$	$\omega_{2.4}$=maxA_4 – $K_{2.4}$	$\omega_{2.5}$=maxA_5 – $K_{2.5}$	$\omega_{2.6}$=maxA_6 – $K_{2.6}$	$\omega_{2.7}$=maxA_7 – $K_{2.7}$	$\omega_{2.8}$=maxA_8 – $K_{2.8}$	$\omega_{2.9}$=maxA_9 – $K_{2.9}$	$\omega_{2.10}$=maxA_{10} – $K_{2.10}$
$\omega_{3.1}$=maxA_1 – $K_{3.1}$	$\omega_{3.2}$=maxA_2 – $K_{3.2}$	$\omega_{3.3}$=maxA_3 – $K_{3.3}$	$\omega_{3.4}$=maxA_4 – $K_{3.4}$	$\omega_{3.5}$=maxA_5 – $K_{3.5}$	$\omega_{3.6}$=maxA_6 – $K_{3.6}$	$\omega_{3.7}$=maxA_7 – $K_{3.7}$	$\omega_{3.8}$=maxA_8 – $K_{3.8}$	$\omega_{3.9}$=maxA_9 – $K_{3.9}$	$\omega_{3.10}$=maxA_{10} – $K_{3.10}$
$\omega_{4.1}$=maxA_1 – $K_{4.1}$	$\omega_{4.2}$=maxA_2 – $K_{4.2}$	$\omega_{4.3}$=maxA_3 – $K_{4.3}$	$\omega_{4.4}$=maxA_4 – $K_{4.4}$	$\omega_{4.5}$=maxA_5 – $K_{4.5}$	$\omega_{4.6}$=maxA_6 – $K_{4.6}$	$\omega_{4.7}$=maxA_7 – $K_{4.7}$	$\omega_{4.8}$=maxA_8 – $K_{4.8}$	$\omega_{4.9}$=maxA_9 – $K_{4.9}$	$\omega_{4.10}$=maxA_{10} – $K_{4.10}$
$\omega_{5.1}$=maxA_1 – $K_{5.1}$	$\omega_{5.2}$=maxA_2 – $K_{5.2}$	$\omega_{5.3}$=maxA_3 – $K_{5.3}$	$\omega_{5.4}$=maxA_4 – $K_{5.4}$	$\omega_{5.5}$=maxA_5 – $K_{5.5}$	$\omega_{5.6}$=maxA_6 – $K_{5.6}$	$\omega_{5.7}$=maxA_7 – $K_{5.7}$	$\omega_{5.8}$=maxA_8 – $K_{5.8}$	$\omega_{5.9}$=maxA_9 – $K_{5.9}$	$\omega_{5.10}$=maxA_{10} – $K_{5.10}$
$\omega_{6.1}$=maxA_1 – $K_{6.1}$	$\omega_{6.2}$=maxA_2 – $K_{6.2}$	$\omega_{6.3}$=maxA_3 – $K_{6.3}$	$\omega_{6.4}$=maxA_4 – $K_{6.4}$	$\omega_{6.5}$=maxA_5 – $K_{6.5}$	$\omega_{6.6}$=maxA_6 – $K_{6.6}$	$\omega_{6.7}$=maxA_7 – $K_{6.7}$	$\omega_{6.8}$=maxA_8 – $K_{6.8}$	$\omega_{6.9}$=maxA_9 – $K_{6.9}$	$\omega_{6.10}$=maxA_{10} – $K_{6.10}$
$\omega_{1.7}$=maxA_1 – $K_{7.1}$	$\omega_{7.2}$=maxA_2 – $K_{7.2}$	$\omega_{7.3}$=maxA_3 – $K_{7.3}$	$\omega_{7.4}$=maxA_4 – $K_{7.4}$	$\omega_{7.5}$=maxA_5 – $K_{7.5}$	$\omega_{7.6}$=maxA_6 – $K_{7.6}$	$\omega_{7.7}$=maxA_7 – $K_{7.7}$	$\omega_{7.8}$=maxA_8 – $K_{7.8}$	$\omega_{7.9}$=maxA_9 – $K_{7.9}$	$\omega_{7.10}$=maxA_{10} – $K_{7.10}$
$\omega_{8.1}$=maxA_1 – $K_{8.1}$	$\omega_{8.2}$=maxA_2 – $K_{8.2}$	$\omega_{8.3}$=maxA_3 – $K_{8.3}$	$\omega_{8.4}$=maxA_4 – $K_{8.4}$	$\omega_{8.5}$=maxA_5 – $K_{8.5}$	$\omega_{8.6}$=maxA_6 – $K_{1.6}$	$\omega_{1.7}$=maxA_7 – $K_{1.7}$	$\omega_{1.8}$=maxA_8 – $K_{1.8}$	$\omega_{1.9}$=maxA_9 – $K_{1.9}$	$\omega_{1.10}$=maxA_{10} – $K_{1.10}$
$\omega_{9.1}$=maxA_1 – $K_{9.1}$	$\omega_{9.2}$=maxA_2 – $K_{9.2}$	$\omega_{9.3}$=maxA_3 – $K_{9.3}$	$\omega_{9.4}$=maxA_4 – $K_{9.4}$	$\omega_{9.5}$=maxA_5 – $K_{9.5}$	$\omega_{9.6}$=maxA_6 – $K_{9.6}$	$\omega_{9.7}$=maxA_7 – $K_{9.7}$	$\omega_{9.8}$=maxA_8 – $K_{9.8}$	$\omega_{9.9}$=maxA_9 – $K_{9.9}$	$\omega_{9.10}$=maxA_{10} – $K_{9.10}$

Then we conduct a detailed calculation for horizontal wind generators which corresponds to line 7 of the matrix:

$\omega_{7.1}$=maxA_1 – $К_{7.1}$=1–1=0; $\omega_{7.2}$=maxA_2 – $К_{7.2}$=1–1=0;
$\omega_{7.3}$=maxA_3 – $К_{7.3}$=1–1=0; $\omega_{7.4}$=maxA_4 – $К_{7.4}$=1–1=0;
$\omega_{7.5}$=maxA_5 – $К_{7.5}$=1–1=0; $\omega_{7.6}$=maxA_6 – $К_{7.6}$=1–1=0;
$\omega_{7.7}$=maxA_7 – $К_{7.7}$=1–1=0; $\omega_{7.8}$=maxA_8 – $К_{7.8}$=1–0.9=0.1;
$\omega_{7.9}$=maxA_9 – $К_{7.9}$=1–0.9=0.1; $\omega_{7.10}$=maxA_{10} – $К_{7.10}$=1–1=0.

Using the formulas from the ω_{ij} calculation table, we then calculate the risk matrix, under the same method we used for the line 7 (matrix):

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}
B_1	0.0	0.0	0.2	0.2	0.1	0.2	0.0	0.4	0.0	0.1
B_2	0.0	0.0	0.2	0.3	0.2	1.0	0.0	0.7	0.2	0.2
B_3	0.0	0.0	0.2	0.2	0.1	0.2	0.0	0.5	0.1	0.2
B_4	0.0	0.0	0.1	0.1	0.0	1.0	0.0	0.2	0.1	0.1
B_5	0.1	0.2	0.2	0.3	0.2	1.0	0.0	0.3	0.2	0.2
B_6	0.1	0.1	0.1	0.1	0.1	0.5	0.0	0.2	0.2	0.1
B_7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0
B_8	0.1	0.3	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0
B_9	0.3	0.4	0.0	0.0	0.0	0.0	0.0	0.1	0.5	0.2

Then we calculate the maximum for each line: $\{0.4;1;0.5;1;1;0.5;0.1;1;0.5\}$

By taking the minimum from the maximums we obtain an optimal value under the Savage criterion which is 0.1, and that corresponds to the selection of horizontal wind generators.

By using the Laplace criterion, we assume the average gain to be an alternative assessment under the formula 5.

The alternative with the maximum average gain under the formula 6 is accepted as the optimal alternative.

Initially, we multiply each element of the matrix by $\frac{1}{M}=\frac{1}{10}=0.1$

Then we conduct a detailed calculation for horizontal generators which correspond to the line 7 of the matrix:

$$\omega_{7.1}=\frac{К_{7.1}}{M}=\frac{1}{10}=0.1;\omega_{7.2}=\frac{К_{7.2}}{M}=\frac{1}{10}=0.1;$$
$$\omega_{7.3}=\frac{К_{7.3}}{M}=\frac{1}{10}=0.1;\omega_{7.4}=\frac{К_{7.4}}{M}=\frac{1}{10}=0.1;$$
$$\omega_{7.5}=\frac{К_{7.5}}{M}=\frac{1}{10}=0.1;\omega_{7.6}=\frac{К_{7.6}}{M}=\frac{1}{10}=0.1;$$
$$\omega_{7.7}=\frac{К_{7.7}}{M}=\frac{1}{10}=0.1;\omega_{7.8}=\frac{К_{7.8}}{M}=\frac{0.9}{10}=0.09;$$
$$\omega_{7.9}=\frac{К_{7.9}}{M}=\frac{0.9}{10}=0.09;\omega_{7.10}=\frac{К_{7.10}}{M}=\frac{1}{10}=0.1.$$

Then we calculate $L_7=\sum_{j=1}^{10}\frac{x_{7j}}{10}=0.1+0.1+0.1+0.1+0.1+0.1+0.1+0.09+0.09+0.1=0.98$

Under the same method used for horizontal generators, we obtain the following matrix for all structures and designs in matrix:

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	L_i
B_1	0.10	0.10	0.08	0.08	0.09	0.08	0.10	0.06	0.10	0.09	0.88
B_2	0.10	0.10	0.08	0.07	0.08	0.00	0.10	0.03	0.08	0.08	0.72
B_3	0.10	0.10	0.08	0.08	0.09	0.08	0.10	0.05	0.09	0.08	0.85
B_4	0.10	0.10	0.09	0.09	0.10	0.00	0.10	0.08	0.09	0.09	0.84
B_5	0.09	0.08	0.08	0.07	0.08	0.00	0.10	0.07	0.08	0.08	0.73
B_6	0.09	0.09	0.09	0.09	0.09	0.05	0.10	0.08	0.08	0.09	0.85
B_7	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.09	0.09	0.10	0.98
B_8	0.09	0.07	0.10	0.10	0.10	0.00	0.10	0.10	0.10	0.10	0.86
B_9	0.07	0.06	0.10	0.10	0.10	0.10	0.10	0.09	0.05	0.08	0.85

By selecting the maximum from L_i, we see that the optimal value under the Laplace criterion is 0.98, which corresponds to horizontal wind generators.

The Bayesian criterion uses an assumption that under the unknown conditions of operation execution (natural conditions) $П_1, П_2,\ldots, П_n$, the probabilities thereof shown as $q_2,\ldots q_n$, are known, see formula 11.

The alternative with the maximal L_i value calculated using the formula 12 is accepted as the optimal alternative.

Let the natural condition vector be $=\{0.18;0.18;0.18;0.09;0;0.09;0.09;0.09;0;0.09\}$.

Upon that, we conduct a detailed calculation for e. g. horizontal wind generators which corresponds to the line 7 of the matrix:

First, we calculate each element of the sum, by indicating it as $\omega_{ij}=K_{ij}\cdot q_j$:

$\omega_{7,1}=K_{7,1}\cdot q_1=1\cdot 0.18=0.18;\omega_{7,2}=K_{7,2}\cdot q_2=1\cdot 0.18=0.18;$
$\omega_{7,3}=K_{7,3}\cdot q_3=1\cdot 0.18=0.18;\omega_{7,4}=K_{7,4}\cdot q_4=1\cdot 0.09=0.09;$
$\omega_{7,5}=K_{7,5}\cdot q_5=1\cdot 0=0;\omega_{7,6}=K_{7,6}\cdot q_6=1\cdot 0.09=0.09;$
$\omega_{7,7}=K_{7,7}\cdot q_7=1\cdot 0.09=0.09;\omega_{7,8}=K_{7,8}\cdot q_8=0.9\cdot 0.09=0.08;$
$\omega_{7,9}=K_{7,9}\cdot q_9=0.9\cdot 0=0;\omega_{7,10}=K_{7,10}\cdot q_{10}=1\cdot 0.09=0.09$

The sum in the line is: $L_7=0.18+0.18+0.18+0.09+0+0.09+0.09+0.08+0+0.09=0.98$.

Bu means of similar calculations for each structure, we obtain the matrix given in matrix.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	L_i
B_1	0.18	0.18	0.14	0.07	0.00	0.07	0.09	0.05	0.00	0.08	0.87
B_2	0.18	0.18	0.14	0.06	0.00	0.00	0.09	0.03	0.00	0.07	0.76
B_3	0.18	0.18	0.14	0.07	0.00	0.07	0.09	0.05	0.00	0.07	0.86
B_4	0.18	0.18	0.16	0.08	0.00	0.00	0.09	0.07	0.00	0.08	0.85
B_5	0.16	0.14	0.14	0.06	0.00	0.00	0.09	0.06	0.00	0.07	0.74
B_6	0.16	0.16	0.16	0.08	0.00	0.05	0.09	0.07	0.00	0.08	0.86
B_7	0.18	0.18	0.18	0.09	0.00	0.09	0.09	0.08	0.00	0.09	0.98
B_8	0.16	0.13	0.18	0.09	0.00	0.00	0.09	0.09	0.00	0.09	0.83
B_9	0.13	0.11	0.18	0.09	0.00	0.09	0.09	0.08	0.00	0.07	0.84

By selecting the maximum from L_i, we see that the optimal value under the Bayesian criterion is 0.98, which corresponds to horizontal wind generators.

The results of the analysis of the optimality criteria are shown in Table 3.

Table 3. Results of the optimality criteria analysis.

No. pos.	Criterion	Optimal alternative	Structure
1	Wald's model	$\{X = X_k; W_k = \max_{1\le i\le N} \min_{1\le j\le M} x_{ij}\} = 0.9$	Horizontal impeller-type generators
2	Maximax criterion	$\{X = X_k; M_k = \max_{1\le i\le N} \min_{1\le j\le M} x_{ij}\} = 1$	Horizontal impeller-type generators
3	Laplace criterion	$\{X = X_k; L_i = \sum_{j=1}^{M} \frac{x_{i,j}}{M}; M_k = \max_{1\le i\le N} L_i\} = 0.98$	Horizontal impeller-type generators
4	Savage criterion	$\{X = X_k; y_j = \max_{1\le i\le N} x_{ij}; \omega_{ij} = y_j - x_{ij}; S_k = \min_{1\le i\le N} \max_{1\le j\le M} \omega_{ij}\} = 0.1$	Horizontal impeller-type generators
5	Bayesian criterion	$\{X = X_k; L_i = \sum_{j=1}^{M} x_{ij} \cdot q_j; M_k = \max_{1\le i\le N} L_i\} = 0.99$	Horizontal impeller-type generators

As a result of the research, a matrix of indicators for assessing the choice of design solutions for wind turbines based on the multi-criteria optimality method was developed and implemented using spreadsheets with predefined logic. In the context of choosing constructive solutions, it becomes necessary to obtain the most objective assessment of alternatives, which requires a thorough study of all selection criteria, determining the dependencies between them and setting priorities. Determining and examining a range of indicators from multiple perspectives tends to lead to selection problems that take on a multi-criteria form. To select the optimal design of the wind turbine, a multi-criteria decision analysis was applied. In each of the perspectives, the authors recommend highlighting at least eight key indicators for evaluating the choice of renewable energy technologies. This approach makes it possible to determine with high accuracy the optimal type of wind turbine design used in the given climatic conditions of the location area. To conduct a multi-criteria analysis, methods based on ranking and linear convolution by criteria were applied [33].

Multi-criteria decision-making analysis is a range of decision-making methods used in scientific and practical fields of knowledge, which support multiple criteria that are prioritized according to weighting factors, i.e. are specific to the research topic at hand. Multi-criteria analysis does not define any "correct" decision for the decision maker, but only offers an "optimal" choice from a list of alternatives according to some conceptual view of the problem at hand.

Aggregation and conversion of data of different dimensions and types into numerical values is the main distinctive feature of the multi-criteria analysis, giving the maximum transparency to the decisions made. By converting the criteria under this method, it is possible to compare completely different alternatives by comparing the final values directly. The main functions of multi-criteria analysis are the ranking or assigning alternatives to one group or another.

Due to the fact that the determination of the significance of the factors and identification of the evaluation criteria is informal and depends on specific conditions, the result of the evaluation of design types in the multi-criteria analysis can be subjective and ambiguous. Depending on the selected criteria, the preferred type of design may change [48, 49].

The use of RES in Russia is not developed, since the housing stock must meet certain technical requirements for the implementation of programs for the introduction of RES. However, at present, the housing stock of the Russian Federation is in an unsatisfactory condition. As a rule, the introduction of RES is technically possible in the current situations when it comes to new housing. With even greater confidence, we can say that the best conditions for implementation are objects of low-rise development (LRD).

For the exclusive choice of the wind turbine type construction, it is necessary to use as much use as possible, in order to obtain a repeatable result, which is the pattern of using the structure in a given area.

The trend of power security and energy saving associated with the reorientation of the world and national economies mainly to innovative development, requires further research in this scientific field which is confirmed by a number of foreign and domestic scientific publications in this field. The above-mentioned authors were engaged to a greater extent in selecting the territory for the economic feasibility of using RPS. At the same time, the problem of selecting the optimal type of wind generator design proved to have been lacking any thorough studies.

Based on the multi-criteria analysis, we recommend the wind generator design with horizontal axis of rotation (impeller-type) mounted at ground level or on a small mast of 5-10 m high raising it above the roof of the house and tree crowns for use in low-rise housing development, taking into account climatic conditions of Rostov Region (average wind speed - 4.8 m/s). The latter option is the most economical and energy-efficient solution for residential construction objects located remotely from traditional energy supply sources.

In the course of the study, the need to elaborate a multi-criteria methodology for assessment of efficiency of the optimal wind generator design, focused on reducing energy consumption of traditional energy sources and taking into account environmental safety and environmental management has been rationalized. Types of wind turbines and their design features have been analyzed. With the help of ArcGIS software (ESRI) a comprehensive assessment of the territory of the Rostov Region has been carried out and a spatial analysis has been presented demonstrating the degree of suitability of areas for the use of advanced technologies of alternative power sources.

Methodology for selecting wind energy generation technology elaborated in the course of research by applying multi-criteria analysis, allows us determining with the highest accuracy the most efficient and economically viable design of the wind power plant.

In the future, it is planned to apply the methodology for choosing energy generation technology to other types of renewable energy sources (solar, geothermal, hydropower).

4. CONCLUSIONS

The choice of a rational wind turbine power generation technology is one of the key challenges in the field of renewable energy sources. In the conditions of global warming and depletion of traditional resources, it becomes important to find optimal solutions that will allow efficient use of wind as a source of energy. This paper considers a methodology for selecting wind turbine generator designs suitable for low-rise construction, which emphasises the relevance and practical usefulness of the problem under study.

Firstly, the correct choice of a wind generator directly affects the efficiency and economic feasibility of its operation. Depending on the location, wind flow conditions and architectural features of buildings, many factors need to be considered. Therefore, the availability of a clear methodology for selecting design solutions becomes an indispensable tool for making the right decision to use a wind turbine generator in low-rise residential construction.

Secondly, the paper provides an important resource to enhance the knowledge of the different models and technologies available on the market, which will not only help to identify the most efficient and sustainable solutions for specific conditions, but can also guide the choice of designs that will ensure the long-term and reliable operation of wind turbines.

Thus, emphasising the importance of describing the problem of selecting a sustainable wind turbine power generation technology, it can be argued that research and development of methodologies such as the one discussed in this paper contribute to the development of clean energy and support the pursuit of sustainable and cost-effective construction. Taking into account the increasing environmental concerns, such research is becoming an element of a strategy to improve energy efficiency and reduce negative environmental impacts.

REFERENCES

1. Wiśniewski G., Huterer A., Grüne Evolution: Perspektiven für erneuerbare Energien in Polen J. Osteuropa Energie-Dossier 2009: Blick in die Röhre: Europas Energiepolitik auf dem Prüfstand. 2009. P. 141 – 150.
2. Mangotra A.K., Renewable Energy Scenario in India. J. Renewable Energy Law and Policy Review. 2016. 7. P. 30 – 43.

3. Gallagher K.S. Why & How Governments Support. J. The Alternative Energy Future. 2013. 142. P. 59 – 77.
4. Gilmutdinova E.N. Renewable energy prediction errors J. Scientific interdisciplinary research. 2021. 3. P. 41 – 45.
5. Chacrit S. Renewable Energy Law and Policy in Thailand J. Renewable Energy Law and Policy Review. 2016. 7 (2). P. 184 – 189.
6. Pupo-Roncallo O., Campillo J., Ingham D., Hughes K., Pourkashanian M. Large scale integration of renewable energy sources (RES) in the future Colombian energy system J. Energy. 2019. 186 p.
7. Chitzi C. Ogbumgbada Developing an effective legal framework for renewable energy utilization in Nigeria J. Renewable Energy Law and Policy Review. 2018. 8 (3). P. 45 – 52.
8. Livshits S.A., Renewable energy sources: reality and prospects Actual problems of the humanities and natural sciences. 2017. 3-1. P. 102 – 104.
9. Nekhoroshev D.D. Ermolenko E. A. Renewable energy sources J. The Age of Science. 2021. 25. P. 80 – 82.
10. Destouni G., Frank H., Renewable Energy. J. Ambio. 2010. 39. P. 18 – 21.
11. Rosa L.D., Castro R., Forecasting and assessment of the 2030 australian electricity mix paths towards energy transition J. Energy. 2020. 205 p.
12. Yergin D., Ensuring Energy Security J. Foreign Affairs. 2006. 85 (2). P. 69 – 82.
13. Moore-O'Leary K., Hernandez R., Johnston D., Abella S., Tanner K., Swanson A., Kreitler J., Lovich J. Sustainability of utility-scale solar energy – critical ecological concepts J. Frontiers in Ecology and the Environment. 2017. P. 385 – 394.
14. Gilmutdinova E.N. Modeling errors for prediction of renewable energy sources J.Innovative aspects of the development of science and technology. 2021. 7. P. 16 – 20.
15. Păceşilă M. Solar energy policy developments in Europe Theoretical and Empirical Researches in Urban Management. 2015. 1. P. 13 – 24.
16. Balat H., Solar Energy Potential in Turkey J. Energy Exploration & Exploitation. 2005. 23 (1). P. 61 – 69.
17. Pleune R., The Role of Renewable Energy Sources in a Sustainable World J. Energy & Environment. 1992. 3 (4). P. 430 – 443.
18. Tandon N. The bio-fuel frenzy: what options for rural women? A case of rural development schizophrenia J. Gender and Development. 2009. 17 (1). P. 109 – 124.
19. Wang K., Chen Sh., Liu L., Zhu T., Gan Z., Enhancement of renewable energy penetration through energy storage technologies in a CHP-based energy system for Chongming. J. Energy. 2018. P. 988 – 1002.
20. Kuvlesky W.P., Brennan L.A., Morrison M.L., Kathy K. Boydston, Ballard B.M., Bryant F.C. Wind Energy Development and Wildlife Conservation: Challenges and Opportunities The Journal of Wildlife Management. 2007. 71 (8). P. 2487 – 2498.
21. Leithead W.E. Wind Energy J. Philosophical Transactions: Mathematical Physical and Engineering Sciences. 2007. 365 (1853). P. 957 – 970.
22. Osadchy G.B. Components of economic efficiency of using renewable energy systems and installations. Innovatika bulletin. 2013. P. 237 – 247.
23. Badenko V.L., Epova E.I. The concept of creating a geoinformation system "Renewable energy sources of St. Petersburg and the Leningrad region". Collection of materials of the II international scientific-practical conference "Geodesy, cartography, geoinformatics and cadastres. From idea to implementation", St. Petersburg: Polytechnic, 2017. P. 500 – 504.
24. Sheina S.G., Pirozhnikova A.P., Priss E.A. The concept of sustainable development of renewable energy in the modern world. IOP Conference Series: Materials Science and Engineering. 2019. 698 (5). P. 055010, 5 p.
25. Kurbatova S.M., State program "Comprehensive development of rural areas": general characteristics. Problems of modern agricultural science Materials of Intern. scientific. conf. Krasnoyarsk: Publishing house of the Krasnoyarsk GAU. 2020. P. 437 – 440.
26. Wu X., Wang Z., Lei G.A. Study on evaluation of urban-rural integrated development level – a case study of shandong province J.Economic Geography. 2010. 4 p.

27. Xu X., Wei Z., Ji Q., Wang C., Gao G., Global renewable energy development: Influencing factors, trend predictions and countermeasures J. Resour. Policy. 2019. 63 p.
28. Russian Association of the Wind Industry. In 2020, over 200 GW of new wind and solar energy capacities were commissioned in the world. URL: https://rawi.ru/en/?ysclid=m8jcuopeui74556307
29. Kakhkhorov M.M., Chorieva M.R. Alternative energy sources: wind energy J. Modern instrumental systems, information technologies and innovations. 2015. P. 242 – 244.
30. Zemskov V.I. Renewable energy sources in the agro-industrial complex textbook for university students studying in the direction of "Agroengineering", Lan: St. Petersburg, Russia, 2014. 355 p.
31. Yamaletdinova C.S., Galiakberov V.V., Martynova O.G., Rakhmanova S.T., Akhmetshin R.I., Graphic features of the analysis of the economic efficiency of wind energy J. Bulletin of the Chelyabinsk State University. 2018. 3 (413). P. 149 – 156.
32. Islam, M. R.; Mekhilef, S.; Saidur, R. Progress and recent trends of wind energy technology J.Renewable and Sustainable Energy Reviews. 2013. 21. P. 456 – 468.
33. Sheina S.G., Fedorovskaya A.A., Sheveleva A.A. Comprehensive assessment of the territory as a mechanism for choosing the location and type of alternative energy source J.BST: Building Technology Bulletin. 2017. 10. P. 38 – 41.
34. Uskova T.V., Voroshilov N. V. Integrated development of rural areas – a task of national importance J.Problems of territory development. 2019. 6. 104 p.
35. Blagoz Z.U., Popova A.Yu, Making decisions in the face of risk and uncertainty J. Bulletin of the Adyghe State University. 2006. 4. P. 164 – 168.
36. IEEE Transactions on Energy Conversion. 1996. 11 (3). P. 650 – 657.
37. Oelker J. Ultra-fast wind farm networking with EtherCAT. AREVA Wind 2020, URL: https://www.beckhoff.com/ru-ru/industries/wind-turbines/wind-farm-networking/
38. Dey B. et al. Warehouse location selection by fuzzy multi-criteria decision making methodologies based on subjective and objective criteria J. International Journal of Management Science and Engineering Management. 2016. 11 (4). P. 262 – 278.
39. Choi J., Lee K., Reliability Evaluation for Power System Planning with Wind Generators and Multi-Energy Storage Systems Probabilistic Power System Expansion Planning with Renewable Energy Resources and Energy Storage Systems. 2021. P. 141 – 176.
40. Ha J.M. et al. Classification of operating conditions of wind turbines for a class-wise condition monitoring strategy J. Renewable energy. 2017. 103. P. 594 – 605.
41. Kupershtokh V.L., Mirkin B.G., Trofimov V.A. The sum of internal connections as an indicator of the quality of classification J.Automation and Remote Control. 1976. 3. P. 133 – 141 p.
42. Wang M.J.J., Liang G.S. A fuzzy multi-criteria decision-making method for facility site selection J.The International Journal of Production Research. 1991. 29 (11). P. 2313 – 2330.
43. Chizhma S.N., Molchanov S.V., Zakharov A.I. Criteria for choosing the type of wind turbines for mobile wind-solar power plants J. Vestnik of the Baltic Federal University I. Kant. Series: physical, mathematical and technical sciences. 2018. P. 53 – 62.
44. Rozhkova L.G. Criteria for choosing the type, size and design of a vertical-axial wind turbine J.Actual problems of the humanities and natural sciences. 2016. 5-1. P. 98 – 104.
45. Tailanov N. A. et al. On the efficiency of using wind generators J. Problems of Science and Education. 2019. 7. 53 p.
46. Denholm P., Kulcinski G.L., Holloway T. Emissions and energy efficiency assessment of baseload wind energy systems J. Environmental science & technology. 2005. 39 (6). P. 1903 – 1911.
47. Sharapova T.R., Selection criteria and an algorithm for making an effective decision J. Actual science. 2018. 4. P. 35 – 38.
48. Bhutta M.M.A. et al. Vertical axis wind turbine J. A review of various configurations and design techniques.Renewable and Sustainable Energy Reviews. 2012. 16 (4). P. 1926 – 1939.
49. Paraschivoiu I. Wind turbine design with emphasis on Darrieus concept. 2002. 438 p.

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