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DEVELOPMENT OF A MOBILE WIND POWER PLANT FOR POWER SUPPLY TO TROOPS

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The study examined the feasibility of using wind energy to supply energy to field military shooting ranges of the Armed Forces of the Republic of Kazakhstan. The object of study is a mobile wind turbine with a vertical axis of rotation. Theoretical studies have identified key factors influencing turbine modes and performance, which has led to the selection of optimal placement options. The proposed system took into account the power supply needs of troops in the field, with special attention to the energy-consuming equipment of field military shooting ranges as the main consumers. A comparative analysis has established the superiority of a mobile wind turbine with a vertical axis over traditional wind generators with a horizontal axis. The developed turbine design provides full coverage of the airflow regardless of direction, with an optimal blade angle of 60°. Theoretical studies included studying the airflow around the blade at different angles of attack, which provides insight into drag and lift. The basis for the development was the designed model of a mobile wind turbine, protected by a patent, characterized by mobility, sectionality and the ability to adapt to various environmental conditions. Its simple and compact design, combined with a vertical axis of rotation, ensures an uninterrupted power supply, especially at remote military installations and border areas. This research led to the development of a model for calculating the parameters of a mobile wind turbine suitable for powering troops in the field. The study demonstrates the potential of mobile wind power plants to significantly enhance energy reliability at military shooting ranges. The calculated results confirm the viability of mobile wind turbines in providing power support for shooting activities at these ranges

Keywords: wind turbine, mobile wind turbine, swept area, field power supply

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1. Introduction

Based on the research, a key contradiction exists: While the Republic of Kazakhstan is actively researching, implementing, and establishing legal frameworks for renewable energy sources (RES) at the national level, the Armed Forces have not yet adopted these advanced technologies. Their standard electrical equipment list includes mobile solar modules, hydro, and wind generators, but functional RES-based power plants are unavailable.

The main direction to address this gap is the development and equipping of the Armed Forces with modern power plants utilizing renewable energy sources.

The research is relevant for several reasons. Firstly, RES power plants are a promising, economical, and environmentally friendly solution due to their abundance, renewability, and cleanliness. They can provide electricity to military units, divisions, and training ranges throughout Kazakhstan. Secondly, modern militaries rely heavily on automated control systems for troops and weapons. Operating control points, technical and logistical support units, especially in permanent deployment locations (field conditions), requires significant electricity, making reliance on traditional grids economically burdensome for the state. Thirdly, training centers, training grounds, and units located far from power lines experience frequent disruptions due to outages and accidents, hindering combat training and affecting troop service and daily life. Fourthly, power plants based on renewable energy offer clear advantages for military applications. They are completely autonomous and mobile, have a long service life, require low operating costs and minimal maintenance personnel, and eliminate the need for fuel and lubricants. Finally, the constant high demand for energy resources, the economic and environmental benefits of RES development, and the involvement of the Armed Forces in all aspects of national life make this study highly justified. The development of a pilot model for a RES power plant to equip military units and training grounds is urgently needed.

2. Literature review and problem statement

The world is undergoing a significant shift towards renewable energy sources, with wind power leading the charge. This transition is becoming increasingly critical, and military forces around the globe are actively exploring the use of wind energy to improve their reliability of energy supply.

The papers [1, 2] present the results of research development of wind energy worldwide. As shown, the total global electricity production in 2022 was 25,343 TWh. The installed capacity of wind turbines in the world in 2022 amounted to 934 TW, per 1 MW of installed capacity in the United States there is an average of 2.8 GWh of generated electrical energy. If we take this fact into account, all installed global wind turbine capacities generate an average of 2,625 TWh of electrical energy per year, which is 10.4 % of the total global electrical energy production.

Military operations often rely on portable generators for electricity, requiring constant fuel resupply and creating logistical challenges. Mobile wind power plants offer a potential solution, providing clean, renewable energy in remote locations.

Several studies highlight the advantages of mobile wind turbines for military applications. A report by the U.S. Department of Energy acknowledges the ability of wind turbines to reduce reliance on diesel fuel, lessening the burden of transportation and potential risks associated with fuel convoys. Additionally, wind power offers a quieter and more environmentally friendly alternative to traditional generators [3].

Previous research has identified key design considerations for mobile wind turbines for military applications:

– rapid shipping and installation: military applications require rapid shipping, installation, short-term operation, and quick teardown upon mission completion [4];

– unique design guidance: deployable wind turbines for military operational energy applications necessitate unique design guidance due to the departure from features found in conventional distributed wind turbines [4];

– on-site electricity generation: deployable wind turbines have the potential to produce on-site electricity for defense and disaster relief needs, increasing resiliency and overall energy production diversity [5];

– portable and reconfigurable design: there is a need for portable and reconfigurable wind turbine designs for remote areas, which could be relevant for military applications [6];

– optimal design parameters: various design parameters such as turbine solidity, blade airfoil shape, and turbine moment of inertia have been studied to determine optimal VAWT design configurations for energy harvesting in unsteady winds [7].

The papers [8, 9] present the results of a study of wind generators of various types, showing their effectiveness in stationary conditions as renewable energy sources and intended for generating electricity, but there are still unresolved issues related to the use of wind generators for power supply to troops located far from central power lines. The reason for this may be objective difficulties associated with the remoteness of some military units and subunits, the fundamental impossibility of connecting them to central power lines, and the lack of necessary mobility and the possibility of deployment in the field. There are also unresolved issues with the possibility of deploying compact wind turbines in areas with low wind speeds. By overcoming these difficulties, the use of wind generators for power supply to troops can be proposed. This approach was used in [10, 11], however, during theoretical studies, a wind turbine design with a vertical axis of rotation was chosen. All this suggests that it is advisable to conduct research on the development of the optimal design of a mobile wind turbine with a vertical axis of rotation.

To increase the economic indicators of wind energy and use the energy of gusty wind, which has a multi-vector «wind rose», wind turbines with a vertical axis of rotation are being intensively developed around the world. Currently, increasing attention is being paid to the development of wind turbines with a vertical arrangement of wind-receiving elements and low placement of the generator. This is due to the significant simplification of the design scheme, ease of installation and maintenance. One of the main advantages of such wind turbines is the ability to simultaneously accept wind currents of different directions and generally no need to take into account the wind direction during installation and operation.

However, winds throughout Kazakhstan are characterized by high turbulence and frequent changes in direction and speed. In addition, a high gradient of wind speed with height above the earth's surface is observed everywhere. Continuous changes in wind direction and speed are an insurmountable obstacle to achieving high productivity of propeller-driven wind turbines.

Thus, efficient wind energy requires fundamentally different wind turbines that eliminate the dependence of their energy productivity on changes in wind direction. This requirement is met by wind turbines with a vertical axis of rotation, processing wind with equal efficiency regardless of its direction. Therefore, the use of wind turbines with a vertical axis of rotation, according to international estimates, is defined as a fundamentally new ideology for the implementation of wind energy, the best aerodynamic and design solution. The results of research on a comprehensive review, systematic research of development trends and analysis of scientific achievements in the field of wind energy are devoted to the development and implementation of a mobile wind turbine with a vertical axis of rotation for power supply to units, divisions and ranges of the Armed Forces of the Republic of Kazakhstan.

Despite the high practical value of mobile wind turbines for powering troops in the field, challenges persist. These include ensuring durability in harsh environments, achieving fast and easy setup, balancing power output with transportable size and weight, and generating reliable energy even in low wind conditions.

All this suggests that it is advisable to conduct research with a focus on finding solutions to the previously mentioned challenges.

3. The aim and objectives of the study

The aim of the study is to develop a mobile wind power plant designed to supply power to troops in the field.

To achieve this aim, the following objectives were accomplished:

– to conduct theoretical research to determine the optimal design of wind power plants;

– to give a theoretical justification for the parameters of a mobile wind power plant with a vertical axis;

– to create a model for calculating the parameters of a mobile wind power plant with a vertical axis specifically for power supply to a military shooting range;

– to develop the design of a mobile wind power plant with a vertical axis.

4. Materials and methods

The object of the study is a mobile wind power plant for power supply to troops in the field.

The proposed mobile wind power plant aims to provide expanded functionality for generating electrical energy in field applications. This includes both autonomous and backup power supplies for units, subdivisions, training grounds, remote facilities of the Armed Forces, and other troops and military formations within the Republic of Kazakhstan. The system achieves this by allowing for adjustments in the height of modules placement and redirecting a portion of the airflow to the lower blades of the modules.

To carry out calculations, determine the peak power of a mobile wind turbine with a vertical axis of rotation and the daily energy consumption of a military shooting range, a model has been developed for calculating the parameters of a mobile wind turbine, which includes determining the following parameters:

– swept area;

– position of the blades;

– peak power;

– energy consumption;

– rated power;

– wind turbine rotor parameters.

To develop the design of a mobile wind turbine with a vertical axis, preliminary calculations of the parameters of the installation being developed were performed and design documentation was made using the AutoCAD program.

5. Results of research on designing a mobile vertical axis wind turbine for the power supply of a military shooting range

5. 1. Theoretical study to determine the optimal design of wind turbines

Table 1, provided by the author [12] showed the widely recognized classification of wind turbines, categorized based on their application scale, considering factors such as power range, diameters, and rotation speeds of the wind wheel. This classification is currently prevalent in the wind energy industry and serves as a standard for calculations.

Based on the location of the rotor rotation, wind turbines are divided into two groups. The structural elements of a wind turbine with a horizontal and vertical axis of rotation are shown in Fig. 1 [12].

The wind turbine includes the following main elements and components:

– a rotor or wind wheel that converts wind energy into shaft rotation energy;

– animator;

– generator, other mechanical and electrical equipment;

– a tower that supports the rotor or wind wheel;

– electrical and electronic equipment;

– control panels, electrical cables, grounding system, equipment for connecting to the network, lightning protection system, etc.;

– the foundation that determines the stability of the wind turbine when exposed to load.

Table 1

Generally accepted classification of wind turbines by scale of application

Wind turbine class	Power range, kW	Range of wind wheel diameters, m	Range of wind wheel rotation speeds, rpm
Very small	0.025÷1	0.5÷2,5	500÷2,000
	1.5÷10	3.0÷9.0	200÷500
Small	20÷60	10÷15	92÷140
	75÷150	18÷24	40÷60
Average	200÷300	26÷30	40
	400÷500	35÷40	30÷35
Large	600÷750	43÷48	30
	900÷1,300	50÷64	20÷32
Very large	1500÷3,000	70÷90	15÷20
	4000÷6,000	105÷124	13÷15

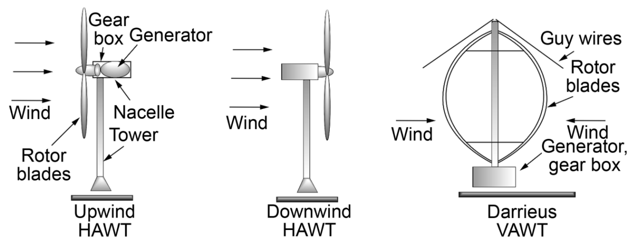

Fig. 1. Wind turbine rotors with horizontal and vertical axis of rotation

Let us look at some of the features of each group. In horizontal-axis wind turbines, the rotating force is the lifting force, and almost all installations are of the propeller type. Relative to the wind speed vector, the wind wheel in the working position can be located in front of the tower or after it [13].

Existing wind turbines convert wind energy into kinetic energy using a wind receiver (wind wheel). The main element of the device is the blades, which transmit torque to the wind wheel when exposed to airflow. Therefore, the efficiency of any wind turbine will greatly depend on the number of blades, as well as their shape; the most appropriate are 3-blade wind wheels, which ensure smooth rotation and minimize the moments acting on the axis of the wind wheel. Multi-bladed wind wheels develop a larger initial moment in low winds, so they are mainly used for lifting water. Another type of wind turbine with a vertical axis of rotation does not require orientation to the wind, and this is their significant advantage. Secondly, the ability to place all the mechanisms below eliminates the need to install a generator at a height and build a powerful tower.

At the same time, there are fundamental disadvantages:

– susceptibility of large rotors to fatigue failure due to frequently occurring oscillatory processes;

– torque pulsation, leading to changes in power and other parameters of generators;

– as shown by the latest test results of Darrieus and H-rotor wind turbines with a power of 5 MW, the main weakness is the bearing of the main shaft of the wind turbine, therefore attempts to build powerful wind turbines with a vertical axis have been stopped. In this regard, the development of low-power wind turbines continues successfully [14].

According to the design of wind turbines and their position in the wind flow, existing wind engine systems are divided into three classes.

The first class includes wind turbines in which the wind wheel is located in a vertical plane. In this case, the plane of rotation is perpendicular to the direction of the wind, therefore, the axis of the wind wheel is parallel to the flow.

The second class includes wind turbine systems with a vertical axis of rotation of the wind wheel. According to the design scheme, they are divided into the following groups:

– carousel, where non-working blades are either covered with a screen or positioned edgewise against the wind;

– rotary wind engines of the Savonius system.

The third class includes wind engines operating on the principle of a water mill wheel and the so-called drum ones. These wind turbines have a horizontal axis of rotation and perpendicular to the direction of the wind.

One of the parameters characterizing the efficiency of a wind turbine is speed, which is the ratio of the peripheral speed of the blade tip to the wind speed [15]:

$$Z=\omega\cdot R/\nu, \quad (1)$$

where ω – angular velocity, rad/s; R – radius of the wind wheel, m; ν – wind speed, m/s.

Vane wind turbines, depending on the type of wind wheel and speed, are divided into three groups:

– multi-bladed, low-speed, with speed $Zn \leq 2$;

– small-blade, low-speed, including windmills, with speed $Zn > 2$;

– small-blade, high-speed, $Zn \geq 3$.

Let us consider the most common types of wind turbines with vertical axes of rotor rotation.

Cup rotor. A wind wheel of this type is rotated by a resistance force; the shape of the cup blade ensures an almost linear dependence of the speed of rotation of the wind wheel on the wind speed in a larger speed range: from 0 to 80 m/s, this circumstance explains the use of this wind wheel in measuring instruments, as a wind speed sensor.

The Savonius rotor rotates by resistance. Its blades are simple and inexpensive. The first wind wheel, invented by the Finnish engineer Savonius, was a barrel cut into two parts and mounted on an axle. The rotating moment is created due to the difference in the moments of resistance provided to the air flow by the concave and convex wind blades relative to it. The wind wheel has a large geometric filling, and therefore a larger initial moment, which is necessary for water-lifting mechanisms.

Darrieus rotor. In the design of French aeronautical engineer Darrieus, the rotating moment is created by lift. The rotor consists of two or three thin curved blades with an aerodynamic profile. The lift force is maximum when the blade crosses the oncoming air flow and is minimum when the blade moves parallel to the flow. Thus, during one revolution, the blade is subjected to the maximum and minimum moment twice, which is the cause of most fatigue failures. The Darrieus rotor cannot rotate independently, so either a generator in engine mode or a special motor is used to start it.

Musgrove rotor. The rotating moment is also created by the lifting force. Two rotor blades having an aerodynamic profile are located vertically at the initial starting moment. As the wind speed increases, the blades begin to fold, reducing the lift force by reducing the swept area; at the maximum design wind speed, the blades fold completely and the wind wheel stops. Like the Darrieus rotor, this rotor must be given an initial rotation.

Evans rotor or H-rotor. The torque is also created by the lifting force of two vertically located blades with an aerodynamic profile. To start it, spinning is also required, and to stop it, the blades are rotated 90 degrees around the vertical axis. As mentioned above, attempts to construct a 5 MW wind turbine with an H-rotor ended in failure, but research continues.

It is known that wind energy is based on the use of wind generators. A wind generator is a device for converting the kinetic energy of wind flow into mechanical energy of rotor rotation with its subsequent conversion into electrical energy [16].

Vertical Axis Wind Turbines (VAWTs) represent a unique form of power-generating technology. Historically, they have been relegated to fulfilling a small niche market in commercially available wind turbines due to their «yaw-less» design. Current VAWT designs lag behind their Horizontal Axis Wind Turbine (HAWT) counterparts in terms of efficiency, as measured by their power coefficient [17].

Vertical axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. The key advantage of this arrangement is that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable. VAWTs can utilize winds from varying directions. With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. The drawback is that some designs produce pulsating torque. Drag may be created when the blade rotates into the wind [18].

This type of wind turbine has been the subject of much research. It has the advantage of not requiring a system for orienting the blades and possessing a mechanical part (multiplier and generator) at the ground, therefore facilitating the operations of maintenance. On the other hand, some of these wind turbines must be trained at start-up, which represents a drawback for the mat, because it receives strong mechanical constraints, making these types of wind turbines abandoned by manufacturers (except for the low power) in favor of horizontal-axis wind turbines [19].

The VAWT is designed to proliferate swept areas and enhance power generation capacity as well as to maintain the intrinsic beauty of the original design. It is designed with the incorporation of a main motor shaft that is set to transverse with the wind speed. The advancement in the design of the VAWT permits the main components of the turbine to be located at its base. With this arrangement, it is very easy to carry out maintenance on the turbine since the main components such as the generator and gearbox are located very close to the ground. This will reduce the maintenance cost. In addition to this, the VAWT is designed in such a way that it does not need to be pointed in the direction of the wind; as a result of this, it does not require the wind-sensing and orientation mechanisms. The wind turbines that have vertical axes are starting to become more popular as a way of generating localized electricity, particularly for new constructions. The benefit of vertical axis turbines is that they can be placed much closer to the ground and are ideal for rooftop arrays [20].

The schematic diagram of the wind power plant is shown in Fig. 2, which consists of:

– a wind turbine (wind engine, rotor), mounted on a mast with guy wires and spun by a rotor or blades;

– electric generator;

– a battery charging controller connected to the batteries (usually maintenance-free 24 V);

– inverter (converts direct current voltage 24 V to ~220 V, 50 Hz), connected to the consumer or to the mains.

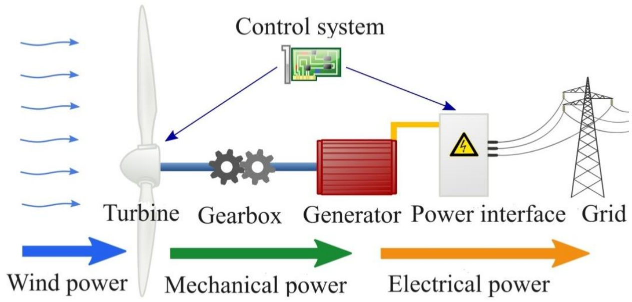

Fig. 2. Schematic diagram of a wind power plant

An important factor influencing the amount of energy produced by a wind generator is wind speed. The calculations carried out using formula (2) show the values of wind energy under standard conditions (dry air, density – 1.225 kg/m^3, atmospheric pressure – 760 mm Hg). The formula for calculating the amount of energy (defined in W/m^2) is as follows:

$$P=0.5\cdot 1.225\cdot \nu^3, \qquad (2)$$

where P is wind energy, W/m^2; ν – wind speed, m/s.

Analysis of formula (2) shows that the amount of electricity generated by a wind power plant increases cubically with increasing wind speed, i.e. if the wind speed doubles, the kinetic energy received by the rotor increases eightfold [21].

The main indicator of the efficiency of a wind turbine is the wind energy utilization coefficient (WEUC). The wind energy utilization coefficient depends on the type of wind turbine, the quality of workmanship and other parameters. The best high-speed wind turbines with streamlined aerodynamic blades achieve a wind energy utilization coefficient of $\xi=0.43\div 0.59$. This means that the wind wheel, when rotating, can usefully use 43÷59 % of the energy of the airflow [22].

It is known that modern bladed wind generators are ineffective in low winds. At the same time, it is possible to obtain energy at low and medium wind speeds from 1 to 5 m/s. For example, to generate electricity in weak winds, the Onipko wind generator was developed, named after the inventor and leader of a group of Ukrainian engineers who created a completely new type of rotor. The Onipko wind generator produces energy at wind speeds from 1 to 20 m/s [23].

In the Russian Federation, in regions with low wind speeds, wind turbines such as FD2.7-500 and FD3.0-1000 are used. The operation of the FD3.0-1000 wind turbine begins already at a wind speed of 2 m/s; accordingly, it produces greater energy production at low wind speeds. This is an ideal solution for mobile consumers for military purposes, in areas with low average wind speeds.

Analysis of wind turbine designs led to the conclusion that wind turbines with a vertical axis of rotation are the most appropriate for use in small wind energy. The main advantage of such a wind turbine is that, at a manufacturing price comparable to traditional installations, the efficiency of wind use is 2 times higher than that of other analogs, as evidenced by the above descriptions of rotor designs. In addition, these wind turbines use a unique rotor-stator system, which boosts the incoming wind. This allows the conversion of kinetic wind energy into mechanical energy at the level of 39÷42 % and the conversion of mechanical energy into electrical energy at the level of 90÷94 %, respectively [24, 25].

Based on the concept of using new technologies in the field of wind energy, as well as in order to increase WEUC, specialists from Kazakhstan and Russia developed a vertical axis Bolotov rotary turbine (VABRT) [8].

The design uses a vertical-axis rotor turbine with two modules rotating in opposite directions. Schematic section of a rotary wind generator with component elements and consisting of axially aligned vertical rotor modules, each of which has a ring guide vane, inside of which a rotor is installed on bearing units. The output shaft is splined and directly connected to the electric generator [9].

Each module is connected to the other using rigid frames. The height of the rotors can have variable parameters; they are fixed to the tower from below at a height of at least 5÷10 m from the ground surface. The tower consists of an upper (machine) compartment, middle and lower (residential or industrial) premises, installed on foundation blocks. A lightning rod spire is fixed on top of the VABRT. The operating principle of VABRT is that the guide vane takes air from the free flow, accelerates it and organizes the flow, then directs it to the working blades of the wind rotor, thereby ensuring the active exit of exhaust air from the volume of the wind rotor. The airflow on the wind rotor blades realizes two parameters – dynamic pressure and speed, which determine the high torque created when starting the engine at low wind speeds and the high speed of load accumulation when the wind speed increases [26].

In order to unify the turbine, an integrated energy system of VABRT has been developed, which contains the following main components: wind rotor turbines, solar converters and elements of photovoltaic systems, batteries, electrical energy converters, controllers and automation devices for power supply systems, energy-efficient electrical receivers. All energy sources operate in parallel on DC buses, power the load through an inverter and charge the battery, have a deep level of modern intelligent automation in the generation and distribution of energy, as well as protection in extreme conditions in accordance with Fig. 3.

One of the advantages of VABRT is also the location of the generator, electrical circuit and battery at ground level. This arrangement ensures timely, easy and cost-effective maintenance of the VABRT. The result is a low cost of kWh of electricity and ease of use [27].

Unlike other wind generators, VABRT has the following distinctive features:

– turbine rotors are located in air flow zones of different speeds and directions, ensuring independent rotation of the generator rotor and stator in opposite directions, which ensures high WEUC;

– original electric generators with the possibility of simultaneous counter-rotation of the rotor and stator provide access to the rated network voltage at low wind speeds;

– the generator, automation system and other equipment are located at ground level, which ensures ease of maintenance;

– independence of operation in winds of any direction;

– increasing structural stability with increasing rotor speed due to the gyroscopic effect;

– noiselessness (30 decibels at a distance of 5 m with a wind of 15 m/s);

– use of the energy of low and high wind speeds, gusts and pulsations of any direction;

– the possibility of autonomous operation or integrated work with other energy sources;

– the possibility of dense placement on the territory in any spatial position, efficient use of space and energy.

Energy production begins at wind speeds of 2 m/s and above without restrictions (Fig. 4).

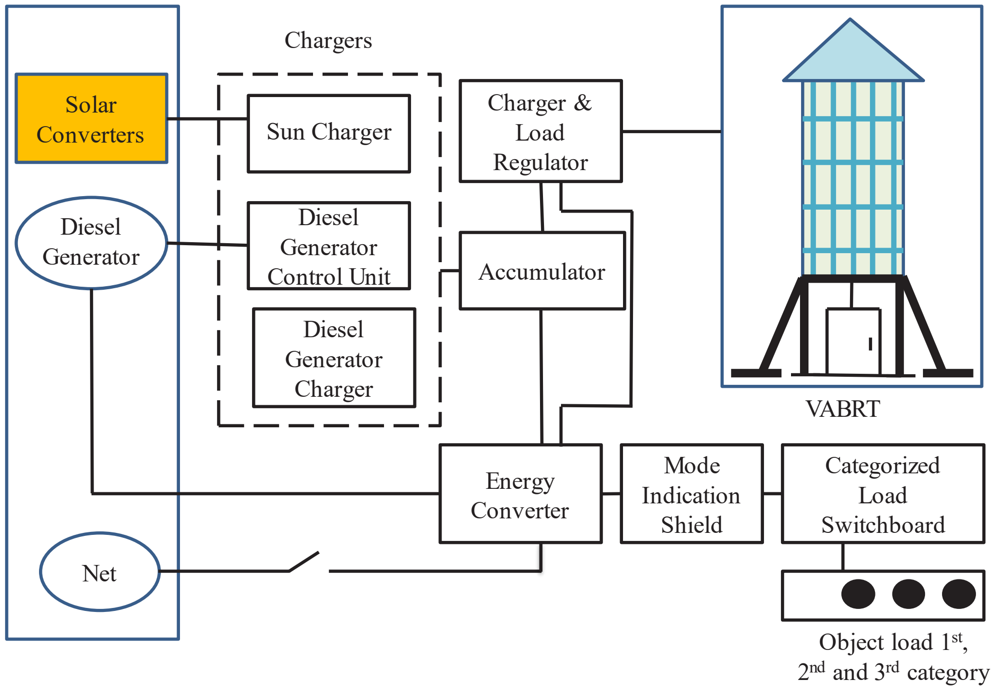

Fig. 3. Diagram of the vertical axis Bolotov rotary turbine integrated energy system

As a result, this study has determined that vertical axis wind turbines (VAWTs) are a promising technology for small wind energy applications, particularly at low wind speeds. VAWTs do not need orientation and house mechanical components at ground level, easing maintenance. The efficiency of wind turbines is influenced by wind speed, with energy production increasing cubically with speed. The wind energy utilization coefficient (WEUC) is a critical efficiency measure, with high-speed turbines achieving up to 59 % WEUC. However, they face issues like fatigue failure and torque pulsation, limiting their power capacity.

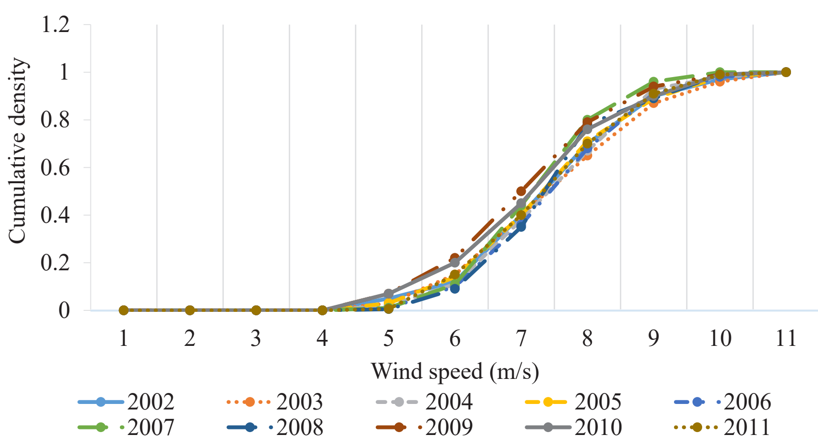

Fig. 4. Dependence of VABRT (vertical axis Bolotov rotary turbine) power on wind speed

5. 2. Theoretical substantiation of the parameters of a mobile wind turbine with a vertical axis

An analysis of the design of a mobile wind turbine allowed us to conclude that the following optimal parameters are the most appropriate for use in small wind energy [28].

Based on the theoretical analysis, VAWTs appear to be a suitable option for the mobile wind turbine solution due to their potential for higher efficiency, ease of maintenance, and ability to operate in variable wind conditions.

Calculation of swept area.

The dependence of the performance of a wind generator on the swept area of the rotor is expressed through WEUC. WEUC is a number that shows what part of the air flow is used by the wind wheel. WEUC without taking into account losses in gears and bearings can be calculated using the formula:

$$\xi = 2 \cdot N / (\rho \cdot v^3 \cdot S), \quad (3)$$

where ξ – WEUC, %; N – power of the wind wheel on the shaft, W; ρ – air mass density (under normal conditions – 0.125 kg/m^3); v – wind speed, m/s; S – the area swept by the wind wheel (for horizontal-axis installations this is the area of projection of the rotor or wind wheel on a plane perpendicular to the axis of rotation, for vertical-axis installations this is the area of projection of the rotor or wind wheel on a plane parallel to the axis of rotation), m^2.

The sweeping area of the wind wheel can be calculated using the formula:

$$S = \pi \cdot D^2 / 4, \quad (4)$$

where D – rotor diameter, m.

For normal conditions (temperature 15 °C and pressure 760 mm Hg).

The power P_o can be calculated using a simplified formula:

$$P_o = \rho \cdot S \cdot v_o^3 / 2, \quad (5)$$

where v_o – wind speed to the wind wheel, m/s.

The power of the wind turbine P is equal to the power that the wind loses when passing the wind wheel:

$$P = m\cdot\left(\nu_o^2 - \nu_2^2\right)/2, \quad (6)$$

where ν_2 – wind speed after the wind wheel, m/s; m – mass amount of air, kg/s.

The power developed at the selected design speed is called the rated power, which for one section of the wind turbine is 1.5 kW/h. It should be noted that this parameter is needed for calculations since the load is not directly connected to the wind turbine. The actual power is not equal to the rated power, it depends on the current wind speed.

Based on an analysis of the designs of wind turbines with a vertical axis of rotation, the dimensions of the wind wheel are selected with a diameter of D=1.06 m and a height of H=1.92 m:

$$S=D\cdot H=1.06\cdot 1.92=2.035\ \text{m}^2,$$

where H – rotor height, m.

To justify the parameters of the swept area of the wind turbine, its aerodynamic power is calculated using the electrical power of the wind turbine, which is calculated as the product of the aerodynamic power P_A and WEUC:

$$P_e=\xi\cdot P_A, \quad (7)$$

where P_e – electric power of the wind turbine, W; P_A – aerodynamic power of the wind turbine, W.

It has been found that the real WEUC of vertical-axis installations varies within the range of 0.09÷0.48. The theoretical maximum WEUC is ideal and in practice unattainable due to the inevitable presence of losses, the constant value most used in calculations according to Zhukovsky-Betz ξ_{zh}=0.593 and according to Sabinin ξ_C=0.687.

Next, the swept area of the rotor S is determined, at a constant wind speed υ in a laminar flow. Aerodynamic power is the energy of the oncoming wind flow transferred to the rotor (wind wheel) of the wind turbine in 1 second:

$$P_A=m\cdot\nu^2/2=\rho\cdot V\cdot\nu^2/2=\rho\cdot S\cdot V\cdot\nu^2/2=\rho\cdot S\cdot\nu^2/2, \quad (8)$$

where ρ – density of air passing through the rotor (ρ=1.2041 kg/m^3 in dry air at a temperature of 20 °C and a pressure of 101.325 kPa), kg/m^3; m – mass of air passing through the rotor in 1 second, kg; V – volume of air passing through the rotor in 1 second, m_3.

Using the formula (4), the diameter of the wind turbine is determined. It should be noted that the rotor parameters of a vertical-axis wind turbine are determined ambiguously, therefore, to determine the ratio of diameter D and height H, further calculations are necessary:

$$S_{real}=S\cdot 1.33, \quad (9)$$

where S_{real} is the actual swept area, m^2.

From (7) we find the ideal aerodynamic power at the ideal WEUC according to Sabinin ξ_s:

$$P_A=P_e/\xi_s=1{,}500/0.687=$$
$$=2{,}183\ \text{W (ideal variant)}.$$

From (8) the calculated swept (covered) rotor area S_{calc} at nominal wind speed υ=11 m/s is found:

$$S_{calc}=2\ P_A/\rho\upsilon^3=$$
$$=2\cdot 2183/1.2041\cdot 11^3=2.72\ \text{m}^2.$$

In practice, it is necessary to increase the swept area by 33÷35 %, taking into account the correction for the real WEUC, which is 65÷67 % of the ideal:

$$S_{real}=2.035\cdot 1.34=2.72\ \text{m}^2.$$

As a result of the theoretical justification of the swept area of a wind turbine rotor with a vertical axis of rotation, it was found that the real parameters of the swept area S_{real}=2.72 m^2 and the calculated swept area S_{calc}=2.72 m^2 are equal.

Position of the wind turbine blades.

The vertical axis design was chosen for justification, development and optimization due to a number of factors:

1) independence of wind turbine operation from wind direction;

2) high WEUC (up to 0.6);

3) energy generation at wind speeds of 1 m/s and above;

4) the ability to aerodynamically regulate the rotation speed of the structure, the constant swept area of the wind wheel allows you to work with the wind of any power, including storm winds;

5) the generator, automation system and other electrical equipment are located at ground level, which ensures ease of maintenance.

In addition, the vertical-axis wind turbine in its design is energy compatible with energy sources such as the sun or diesel generators, as well as the ability to connect to power grids, i.e. provide connection to any existing high-voltage energy network. Fig. 5 shows the positions of wind turbine blades with horizontal and vertical axis of rotation at different angles of wind direction relative to the rotor axis.

The power developed by a wind wheel depends on the wind speed, the power of the wind flow, the type of wind wheel, as well as aerodynamic parameters. The wind flow is maximally used by wind turbines with a horizontal axis of rotation, only in the direct direction of the wind, i.e. 100 % airflow coverage. The swept area of horizontal rotors depends on the direction of the wind relative to the rotor axis and in some cases may be less than the area of the wind wheel. In accordance with Fig. 5, when the wind direction is at an angle of 45°, the swept area of the wind wheel will be equal to 40 %.

Consequently, the power generated by a wind turbine with a horizontal axis of rotation will not be constant and will depend on the direction of the wind.

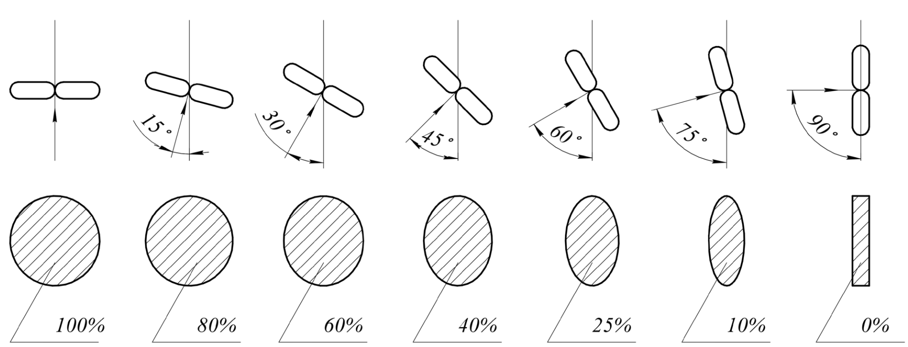

Fig. 5. Positions of wind turbine blades with horizontal and vertical axis of rotation at different angles of wind direction relative to the rotor axis

Angle of installation of the wind turbine blade to the airflow. It is known that the magnitude and direction of the aerodynamic force (R) depend on the shape of the blade and its orientation in the flow. Let us consider the process of airflow around a wind turbine blade and plot the dependence of the coefficients of lift (C_y) and drag (C_x) on the angle of installation of the blade (angle of attack) to the airflow (λ). The relationship between Y and X creates the total R.

Fig. 6 shows diagrams of airflow around a wind turbine blade at different angles of attack:

a) blades along the airflow;
b) the beginning of blade deflection;
c) increasing the angle of attack;
d) maximum value of the angle of attack;
e) flow stall.

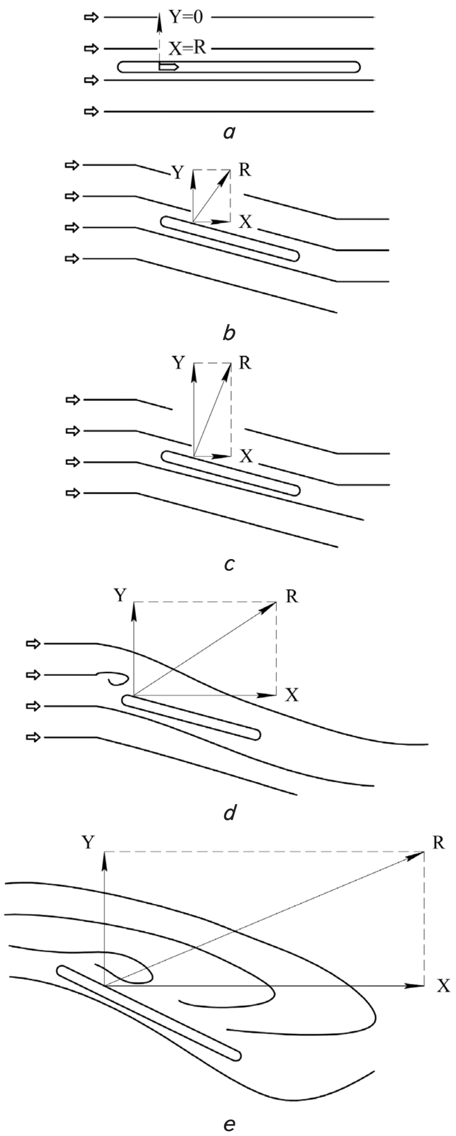

Fig. 6. Schemes of airflow around the wind turbine blade at different angles of attack: *a* — the blades of the wind turbine are located along the airflow; *b* — beginning of blade deflection. X and Y appear; *c* — increasing the angle of attack. Y is growing faster than X; *d* — the most favorable angle of attack value; *e* — flow stall

As shown in Fig. 6, *a*, when the blade is along the airflow, the angle of attack is zero. In this case, the airflow is not deflected by the blade and the lift force Y is zero. Drag X is minimal, and the total aerodynamic force R is minimal and will coincide with the drag force X.

When the blade deflects (Fig. 6, *b*), due to the flow bevel, a lift force Y appears. The resistance X increases slightly due to the increase in the cross-section of the blade relative to the flow.

As the angle of attack continues to increase (Fig. 6, *c*), it becomes more difficult for the airflow to flow around the blades. Lift continues to increase, but more slowly. Drag increases faster and outpaces the increase in lift, causing the total aerodynamic force R to be pushed back.

As shown in Fig. 6, *d*, a further increase in the angle of attack leads to a change in the airflow around the blade. Air flows are unable to smoothly move around the top surface of the plate. Further increasing the angle of attack (Fig. 6, *e*), an air vortex is formed on the leeward side of the blade. The lift begins to fall, a phenomenon in aerodynamics called «flow stall»:

$$F_x = C_x \cdot (\rho v)^2 / 2 \cdot S$$

and

$$F_y = C_y \cdot (\rho v)^2 / 2 \cdot S, \quad (10)$$

where F_x – blade resistance force; F_y – blade lifting force; $\rho v^2/2$ – velocity pressure; C_x – resistance coefficient; C_y – lift coefficient.

The dependence of the lift (C_y) and drag coefficients (C_x) on the angle of attack (λ) is shown in Fig. 7.

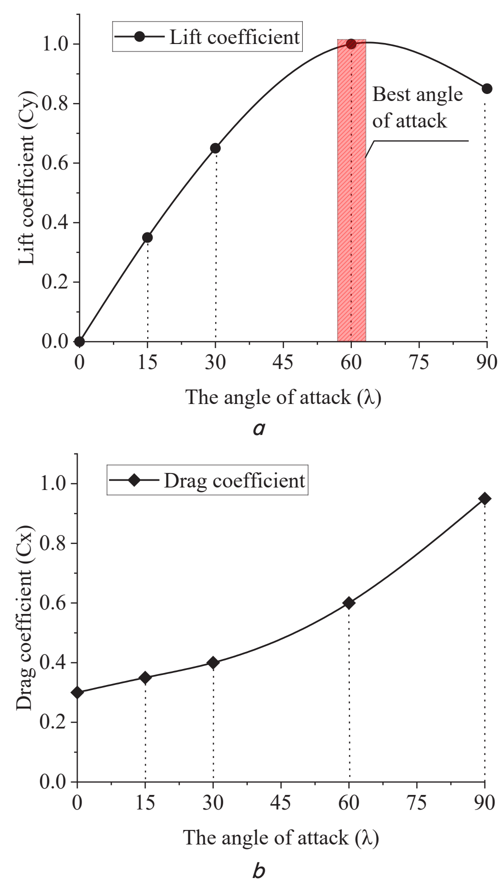

Fig. 7. Dependence of the coefficients C_y and C_x on the angle of attack λ: *a* — dependence of the lift coefficient C_y on the angle of attack; *b* — dependence of the drag coefficient C_x on the angle of attack

It is known that the rotor area for vertical-axis rotors is determined by the formula $S=D\cdot H$, i.e. when the blade angle changes from 0 to 180°, the swept rotor area at different angles of attack – S_λ, changes its value in a sinusoidal dependence, due to D_λ and H_λ, respectively, i.e. $H_\lambda=1920\cdot\sin\lambda$, it follows:

$$S_\lambda=530\cdot H_\lambda=530\cdot 1{,}920\cdot\sin\lambda.$$

Next, according to the formula, the resistance force is determined at $v=3$ m/s:

$$F_x=C_x\cdot\rho v^2/2\cdot S=1\cdot(0.125\cdot 3^2/2)\cdot 0.53\cdot 1.92\cdot\sin\lambda= =0.5724\cdot\sin\lambda.$$

Similarly, using the formula, the lift force is determined at $v=3$ m/s:

$$F_y=C_y\cdot\rho v^2/2\cdot S=1\cdot(0.125\cdot 3^2/2)\cdot 0.53\cdot 1.92\cdot\sin\lambda= =0.5724\cdot\sin\lambda/2.$$

The resulting two graphs are combined into one. As shown in Fig. 8, along the X axis we plot the values of the angle of attack from 0° to 180°, and along the Y axis, we plot the values of the lift force (green bar) and resistance force (yellow bar). The resulting sinusoidal curve is the main graph characterizing the aerodynamic properties of the wind turbine blade. Plotting the lift coefficients C_y and drag coefficients C_x on the coordinate axes, this graph shows the magnitude and direction of the total aerodynamic force R at an angle of attack of 60°, which is the most favorable angle of attack.

As a result of the theoretical justification, it was found that, compared to traditional energy sources, the use of wind turbines with a vertical axis of rotation is more profitable and efficient.

The optimal parameters for the swept area, blade position, and installation angle of the wind turbine blades relative to the wind flow have been determined. Through calculations, the most favorable angle of attack for the mobile wind turbine blade was found to be 60°, at which the rotor reaches its maximum rotational speed.

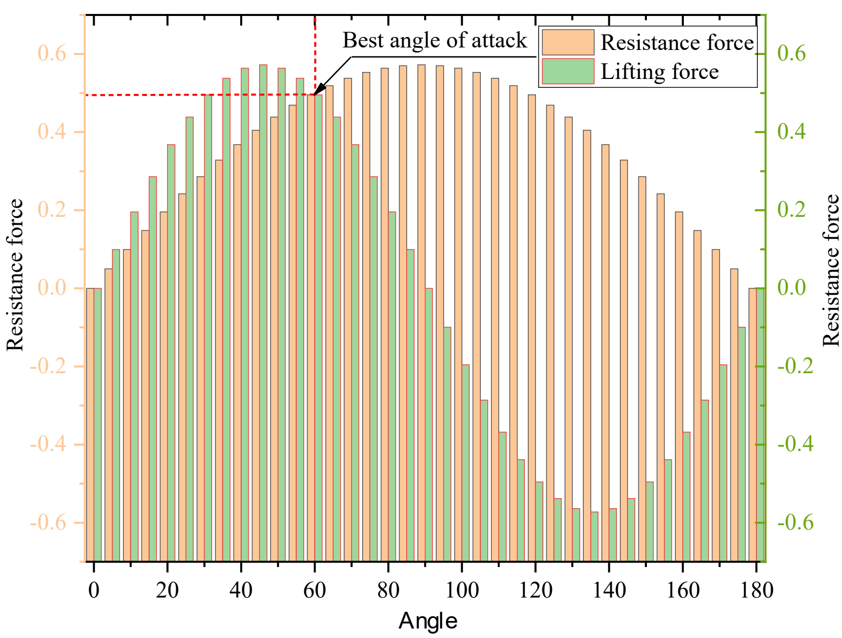

Fig. 8. Dependence of the resistance force and lifting force of the blade of a mobile wind turbine at different angles of airflow

Vertical Axis Wind Turbines (VAWTs), with their optimized parameters and design, offer a more efficient and practical solution compared to traditional horizontal axis wind turbines. The performance of VAWTs is significantly influenced by the swept area, blade position, and angle of attack, making them an ideal option for mobile wind energy applications.

5. 3. Development of a model for calculating the parameters of a mobile wind turbine with a vertical axis for the power supply of a military shooting range

As a similar calculation, we took the example of calculating the parameters of a wind power plant for low-power consumers, presented in the literature [29]. In contrast to the calculation given in this literature, we calculated the peak power and energy consumption, rated power, and aerodynamic parameters of the rotor of a mobile wind turbine for power supply to a military shooting range. This is the first time such a calculation has been performed.

Modeling the calculation of wind turbine parameters consists of three components: determination of energy power, determination of wind turbine power and determination of its aerodynamic parameters. For an autonomous electrical power supply for a military shooting range, we calculate the parameters of the above-mentioned installation [15, 30, 31].

To do this, we determine the initial condition for the calculation:

– research base – military shooting range;

– combat mission – performing small arms shooting exercises;

– type of task – performing 2 test firing exercises (2 TFE) from a gun, conditionally performed 2 times per day (firing during the day, at night);

– time for 1 shooting – 5 hours (300 minutes during the day, 300 minutes at night);

– number of shooters – platoon (30 people).

Determining the peak power of an energy consumer is not difficult, since the power and operating schedule of each piece of equipment are initially known. Constructing a consumption schedule and calculating the peak power of an energy consumer can be carried out with a certain probability or prediction due to the unpredictability of the energy consumption schedule. In this regard, calculations are always performed individually with appropriate assumptions and approximations.

Peak power calculation.

Each electrical consumer currently installed at the facility was measured to find its power rating (in watts). Determine with appropriate assumptions the simple probability of turning on the consumer at different times of the day and note this in the table, indicating the instantaneous power consumption day and night. Add up the data from the columns of instantaneous power P_i and obtain the peak power consumption P_{peak} at a specific time of day: day and night (P_d, P_n). The data is shown in Table 2. These data are subsequently used to calculate the rated power of the inverter P_{inv}:

$$P_{inv}>\max(P_d, P_n). \quad (11)$$

Table 2

Power of electrical consumers and instantaneous power consumption of a military shooting range

Name of electrical consumers	Installed power P_i, W	Instantaneous power consumption P_i, W	
		Day, P_d	Night, P_n
Control panel	100	100	100
Automated target (target No. 8), range 25 m, 4 pcs.	240	240	240
Automated target (target No. 10, 4), 4 pcs.	240	240	240
Automated target (target No. 8 moving targets), 4 pcs.	240	240	240
Automated target (target No. 8 targets appeared), 4 pcs.	240	240	240
Electric motor	300	300	300
Emergency lighting, APU lamp	60	60	60
Lighting lamp, (40÷60W), (10÷15 pcs)	600	–	600
Spotlight	200	–	200
Total at peak P_i	2,220	1,420	2,220

It is known from practice that the real peak power of the vast majority of facilities at a specific time of day is less than the sum of all the capacities located at the energy consumer's facility, since, as a rule, they are not turned on simultaneously. However, there may be exceptions that must be taken into account. When carrying out calculations, a formal increase in peak power at a specific time of day is allowed to create a power reserve and predict an increase in energy consumption in the future.

As a result of the calculations, the power of electrical consumers and the instantaneous power consumption of a military shooting range were determined. The total installed power was P_i=2,220 W, the total instantaneous power consumption: during the day P_d=1,420 W and at night P_n=2,220 W. This indicates the feasibility of using the developed wind turbine with a vertical axis for power supply to military facilities.

Calculation of energy consumption.

Determine, with appropriate assumptions, the operating time of each consumer at a specific time of day and enter the data into the table. Add up the data in the «day-night» columns for each electrical consumer and multiply the resulting value by the power of the device, obtaining the energy consumption of each consumer per day [32, 33]. The sum of the energy consumption of all consumers E_{day} will be the amount of energy consumed by the facility per day:

$$E_{day}=P_i \cdot \Sigma E_i. \quad (12)$$

These data are subsequently used to calculate the rated power of the wind turbine and batteries. Let us consider a problem with the following initial data: power of devices according to the operating manuals.

We determine the peak power and average daily energy consumption of the facility.

Solution:

1. Calculation of the peak power of a military shooting range. Let us determine the operating status of each electrical consumer in the corresponding period of the day (day, night). To do this, we will compile a table of the devices present at the facility similar to Table 2, indicating the power of electrical consumers and the instantaneous power consumption in each period of the day. We find the peak of electricity consumption, day and night, respectively, as the sum of the powers of all used consumers. Let us determine the highest peak power P_{peak} for each period of the day (an example is shown in Table 2):

– day: P_d=1,420 W;

– night: P_n=2,220 W.

The maximum peak power per day is P_{max}=2,220 W, then the inverter power should be P_{inv}>2,220 W.

We accept, P_{inv}=2,230 W=2.3 kW.

2. Let us calculate the energy consumption of all periods of energy consumption during the day, i.e. 24 hours. To do this, we add up the data in the «day-night» columns for each consumer and multiply the resulting value by the power of the device, obtaining the energy consumption of each consumer per day in the right column of Table 3. Find the sum of the obtained values.

An example is shown in Table 3.

Table 3

Electrical consumers of a military shooting range

Name of electricity consumers	Installed power P_i, W	Usage time T, hour		Electricity consumption, Wh
		Day	Night	
Control panel	100	5 (300 min)	5 (300 min)	1,000
Automated target (target No. 8), range 25 m, 4 pcs.	120	0.13 (8 min)	0.13 (8 min)	31
Automated target (target No. 10, 4), 4 pcs.	120	0.25 (15 min)	0.25 (15 min)	60
Automated target (target No. 8 moving targets), 4 pcs.	120	0.16 (10 min)	0.16 (10 min)	38
Automated target (target No. 8 targets appeared), 4 pcs.	120	0.16 (10 min)	0.16 (10 min)	38
Electric motor	300	0.16 (10 min)	0.16 (10 min)	100
Standby lighting	60	–	5 (300 min)	300
Lighting lamp	600	–	5 (300 min)	3,000
Spotlight	200	–	5 (300 min)	1,000
Total	1,740	5.86	20.86	5,567

The amount of energy consumed by an object per day is shown in the lower right cell of the table: E_{Day}=5,567 Wh.

This value must be used as a guide when further calculating the rated (installed) power of the wind turbine and the battery capacity.

Determination of the rated power of wind turbines.

Determination of the rated power of a mobile wind turbine for autonomous power supply of an object is made taking into account the average wind speed in the region and the energy consumption of the object [28]:

1. Determination of the average wind speed in the design region based on data from meteorological services. It must be borne in mind that weather station data are averaged. In this regard, in addition to these data, reference to the local landscape can be guided. The average wind speed V_{av} in the study area can be determined using the developed methodology for calculating wind energy potential. The calculation method of determination provides more detailed information about the wind energy potential of the study area.

2. Determination of the average hourly energy consumption of an object based on the data obtained in task 1.1 (13). Energy consumption per hour is E_{day} divided by 24 hours:

$$E_h=E_{day}/24. \quad (13)$$

3. Determination of the rated power of a wind turbine, which can be used to supply power to a given facility. The power $P_{developed}$ by the wind turbine is hourly divided by the time of consumption, i.e. by 1 hour:

$$P_{developed}=E_h/1. \quad (14)$$

This is the instantaneous power developed by the wind turbine at the calculated average wind speed. Having determined the estimated wind speed and carried out our own calculations, according to Table 3, using the average wind speed, we find the instantaneous power of the wind turbine P_{instWT}, developed at this wind speed of a particular wind turbine. The search is carried out using columns of average wind speed, identifying data that satisfies the condition:

$$P_{instWT} \geq P_{developed}. \quad (15)$$

In some cases, it is possible to install not one, but several wind turbines (wind farm modules). This decision is determined by the fact that the greater the number of sections, the greater the electricity generation. After this, take the rated power of the selected wind turbine as the basis for further calculations.

Knowing the amount of energy consumed by the facility per day, shown in the lower right cell of Table 3, E_{day}=5567 Wh, we determine the rated power of the wind turbine for the autonomous power supply of the military shooting range, Table 4. To do this, it is necessary to determine the average wind speed at the object under study. When assessing the wind energy potential on the territory of a military shooting range, it was determined by calculation that the average V_{av}=3 m/s. A similar calculation can be carried out using other methods.

The average daily energy consumption of the facility from task 1.2 is:

$$E_{day}=5{,}567 \text{ Wh};$$

respectively:

$$E_h=5{,}567/24=232 \text{ Wh};$$

$$P_{developed}=232/1=232 \text{ W}.$$

Select the appropriate number of wind turbine sections from Table 3 in the amount of 4 pcs:

$$4 \cdot P_{instWT} \geq P_{developed} \text{ or } 4 \cdot 60 \geq 232.$$

Let us do a check. The total daily output of each wind turbine will be:

$$E_{day}=1.4 \text{ kWh}.$$

Total output of four wind turbine sections:

$$E_{dayWT}=1.4 \cdot 4=5.6 \text{ kWh}=5{,}600 \text{ Wh}.$$

This satisfies the conditions of expression (15) because:

$$E_{dayWT} \geq E_{day} \text{ or } 5{,}600 \text{ Wh} \geq 5{,}567 \text{ Wh}.$$

Thus, in the calculation process, 4 sections of wind turbines were selected as energy-generating equipment. The rated (installed) power of each installation is 1.5 kW, which corresponds to the proposed wind turbine.

Calculation of wind turbine rotor parameters.

The rotor of each wind turbine section consists of a hub and blades:

1. Let us calculate the aerodynamic power using the electrical power using formula (8).

2. Determine the swept area of the rotor S at a constant wind speed v in a laminar flow using the formula (9).

3. Determine the rotor diameter for vertical-axis rotors from the formula:

$$S=D \cdot H.$$

4. We draw a conclusion about the technical and operational feasibility of manufacturing a mobile wind turbine rotor and its applicability in specific conditions based on overall dimensions.

Initial data: type of wind turbine – mobile vertical-axis.

Table 4

Rated power and power generation of mobile wind turbines

Wind speed v, m/s	3	4	5	6	7	8	9	10	11	12
Instantaneous power P_{instWT}, W	60	200	400	700	900	1,100	1,300	1,400	1,600	1,800
Daily output E_{day}, kWh	1.4	4.8	9.6	16.8	21.6	26.4	31.2	33.6	38.4	43.2

The aerodynamic and geometric parameters of the mobile wind turbine are determined using the previously given formulas:

– rated power of the wind turbine P_{WT}=1.5 kW;

– nominal rotation speed v=11 m/s;

– diameter D=1.06 m;

– height H=1.92 m;

– ideal aerodynamic power P_A=2,183 W;

– sweepable rotor area S=2.72 m^2;

– real swept rotor area S_{real}=3.62 m^2;

– rotor diameter D=2.1 m.

As a result of research, a model has been developed for calculating the parameters of a mobile wind turbine for power supply to military consumers, which makes it possible to determine the peak power and energy consumption, rated power, and aerodynamic parameters of the wind turbine rotor. Based on this calculation model, we can select the power of a wind generator, as well as the number of sections depending on the average wind speed of the region under study. This model provides a practical solution for selecting and sizing wind turbines to support military activities, confirming the feasibility and advisability of manufacturing and deploying such turbines.

5. 4. Development of the design of a mobile wind turbine with a vertical axis

During the research, a mobile wind turbine was developed, which is a technical device that converts wind energy into electrical energy and has no analogs.

The design and main details of a mobile wind turbine were developed based on a study of the obtained design parameters. Fig. 9 illustrates the assembly process of this full-size mobile wind turbine in progress.

The developed design can be used in any region of the Republic of Kazakhstan; it is not tied to the weather characteristics of the area and is capable of operating in low light conditions and low winds.

Several prototypes were taken as analogs. The first prototype was a wind generator design containing a wind wheel, a generator, magnetic blades, an induction coil and solar panels [34]. The disadvantages of this wind generator design are:

– difficulty in regulating the speed of rotating elements during possible and sudden gusts of wind;

– complexity of service maintenance and maintainability of mechanical equipment;

– lack of mobility in case of redeployment of military units.

The second prototype is the design of a wind generator suspended on a helium balloon and including a winch, rope-type cable, generator and blades [35]. The disadvantages of this wind generator design are:

– difficulty in regulating the speed of rotating elements during possible and sudden gusts of wind;

– inability to increase, if necessary, the power of generated electricity.

The third prototype is the design of a wind generator installed at the bottom of the kite including a winch, rope-type cable, generator and blades [36]. The disadvantages of this wind generator design are:

– constant dependence on the power of rising air currents for the ability to glide the kite;

– difficulty in regulating the speed of rotating elements during possible and sudden gusts of wind;

– inability to increase, if necessary, the power of generated electricity.

The general disadvantages of the presented designs are: their inability to supply energy to military units associated with constant relocation and work in the field, the complexity of maintenance and the maintainability of mechanical equipment.

The closest prototype of the mobile wind turbine being developed is a mobile sectional module of wind generators, consisting of a metal container frame in the form of a parallelepiped, a pair of identically vertically located curved blades installed in the bearing supports of the container frame, a generator, metal rotating blinds, an electrical supply system and automatic control [10].

By the authors, a mobile wind turbine has been developed for the Armed Forces of the Republic of Kazakhstan, a utility model patent RK No. 8021 [11]. The characteristics of this model are described below. Fig. 10 shows a general view of the mobile wind turbine in its initial position and top view of the structure of the upper module of the wind generator.

The mobile wind turbine contains: several modules 1 of a wind generator, consisting of a housing 2; in the upper and lower edges of the housing 2, a vertical shaft 4 is installed in bearing supports 3, on which the blades 5 are rigidly fixed. On the lower edge of the housing 2, a generator 6 is mounted, a mounting frame 7, in the form of four articulated rods, installed in the upper part of the module with the ability to move in the guides of 8 housings of 2 lower and upper modules.

In the upper modules 1 of the wind generator, guides 9 are installed, which with their lower end rest on the body of the lower module, and in the upper part there is a bypass block 10, through which a lifting cable 11 is thrown, connected at one end by means of a thimble 12 to the upper part of the body 2 of the upper module, and the other end of the cable 11 is connected to the lifting mechanism 13 located in the lower module 1.

Fig. 9. The assembly process of the full-size mobile wind turbine

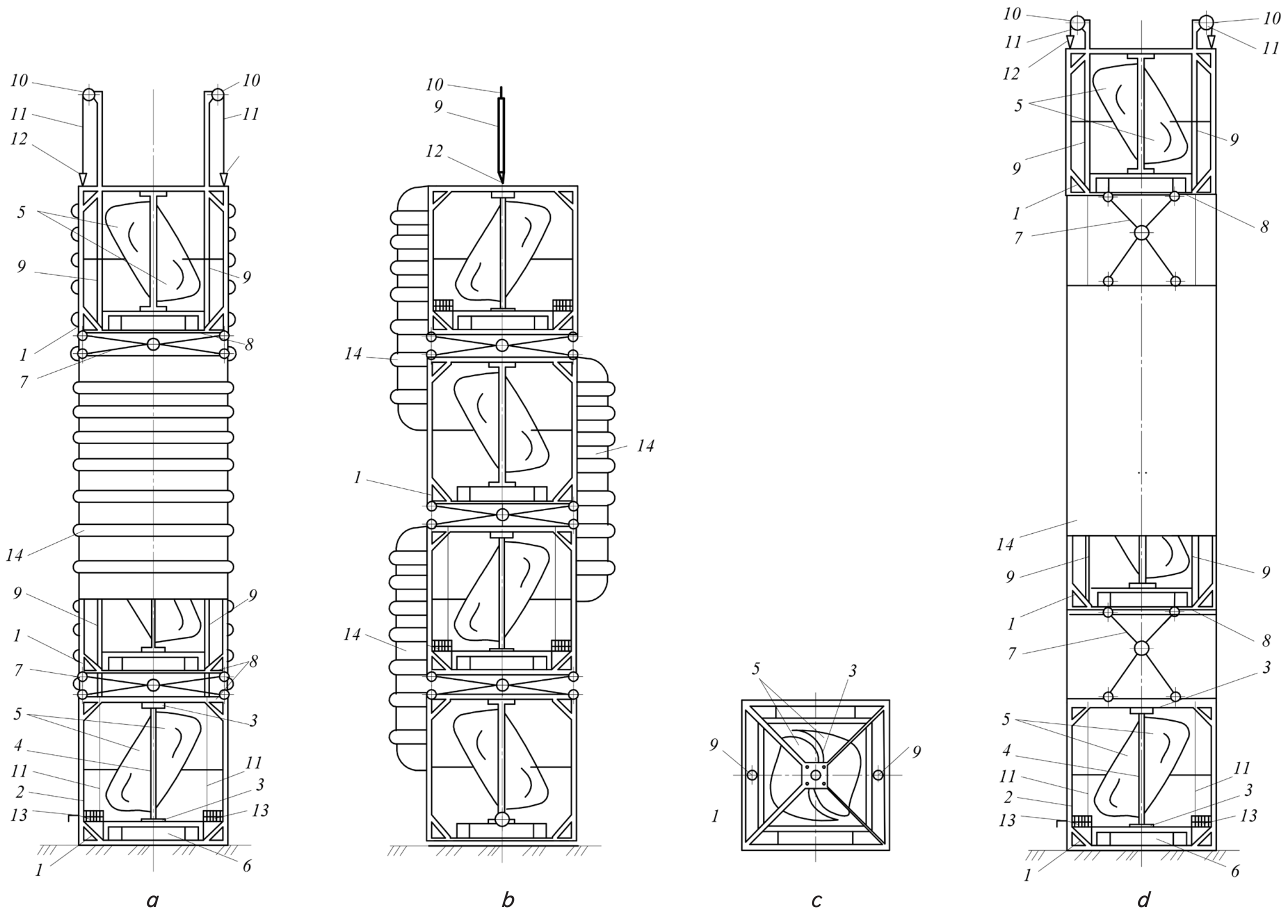

Fig. 10. General view of a mobile wind turbine: *a* — view in initial position; *b* — side view; *c* — view in extended position; *d* — top view of a mobile wind turbine

The upper parts of each wind generator module on one side and 1/2 of the side area of housing 2 are connected to each other by corrugated casings 14.

The operating principle of the wind turbine module system is as follows. Air flows entering the system of modules 1 of the wind turbine set in motion both blades 5, mounted on a rotating shaft 4, which transmits wind energy to the generator 6. With an increase in the height of the module 1 (Fig. 5) of the wind turbine from the surface of the Earth, an increase in wind speed is observed. Air flows passing through the blades 5 of the upper modules 1 of the wind generators, which rotate faster, are directed through the corrugated casings 14 to the blades 5 below the wind turbine modules 1, thereby increasing the rotation speed of their shaft 4.

Vertical change in the positions of the housings 2 of the system of modules 1 of the wind generator is ensured by their extension by the lifting mechanism 13 along the guides 9 using cables 11 located inside the guides 9, thrown over the bypass blocks 10, and connected by thimbles to the upper part of the housing 2 of the upper module 1.

Modules 1, forming a system of wind turbine modules, are kinetically connected to each other using a mounting frame 7, in the form of four articulated rods moving along guides located in the upper and lower parts of the housing 2.

This design of the wind turbine module system ensures that the maximum wind load on the blades 5 of all modules 1 is obtained and their rotation speed is increased.

As a result of the research, a mobile wind turbine with a vertical axis was developed to convert wind energy into electrical energy, with no existing analogs. This wind turbine is suitable for use across various regions of the Republic of Kazakhstan, independent of weather conditions, and can operate in low light and low wind scenarios. The design process involved studying existing prototypes, each with significant limitations such as difficulty in regulating rotating elements, complexity in maintenance, and lack of mobility and scalability in power generation.

The new mobile wind turbine design addresses these issues and is intended for use by the Armed Forces of the Republic of Kazakhstan, as evidenced by the utility model patent RK No. 8021. The design features several interconnected modules with vertical shafts, rigidly fixed blades, and a generator mounted at the lower edge of the housing. A lifting mechanism adjusts the height of the modules, enhancing wind capture and increasing rotation speed.

The operational principle involves air flows entering the modules and rotating the blades, which then transmit energy to the generator. The modular system ensures increased wind load and rotation speed by directing air from the upper to lower blades, utilizing a system of guides, cables, and bypass blocks for vertical extension and efficient energy conversion.

6. Discussion of the research results of a mobile wind power plant with a vertical axis

Military facilities and training grounds of the Armed Forces of the Republic of Kazakhstan, when performing their functional tasks, consume a significant amount of electricity. Currently, this problem is being solved by power plants based on high-cost, short-life diesel engines. Therefore, the use of renewable energy sources is a promising, economically and environmentally feasible direction. In this regard, the study of options for creating a mobile wind power plant requires a systematic study, taking into account the analysis of the climatic conditions of our country, the interconnections and mutual complementation of one device with another, using different types of energy.

Theoretical studies were carried out to determine the optimal design of wind turbines. An analysis of wind turbine designs has led to the conclusion that the most appropriate for use in small wind energy are wind turbines with a vertical axis of rotation, the rotor of which is shown in Fig. 1. The main advantage of such a wind turbine is that, with a manufacturing price comparable to traditional installations, the efficiency of using wind is 2 times higher than in other analogs. In addition, these wind turbines use a unique rotor-stator system, which boosts the incoming wind. This allows the conversion of kinetic wind energy into mechanical energy at a level of 39–42 % and the conversion of mechanical energy into electrical energy at a level of 90–94 %, respectively.

Wind turbines with a horizontal axis at the same time have other fundamental disadvantages:

– susceptibility of large rotors to fatigue failure due to frequently occurring oscillatory processes;

– torque pulsation, leading to changes in power and other parameters of generators;

– as shown by the latest test results of Darrieus and H-rotor wind turbines with a power of 5 MW, the main weakness is the bearing of the main shaft of the wind turbine, therefore attempts to build powerful wind turbines with a vertical axis have been stopped.

In this regard, the development of wind turbines with a low-power vertical axis is an urgent task.

A theoretical substantiation of the parameters of a mobile wind turbine with a vertical axis was carried out. The design of a mobile wind turbine with a vertical axis has been developed in accordance with Fig. 5, 9. It has been found that this design of the system of modules developed by the wind turbine ensures the maximum wind load on the blades 5 of all modules 1 and an increase in their rotation speed.

The design of one wind generator contains a wind wheel, a generator, magnetic blades, an induction coil and solar panels [34]. The disadvantages of this wind generator design are:

– difficulty in regulating the speed of rotating elements during possible and sudden gusts of wind;

– complexity of service maintenance and maintainability of mechanical equipment;

– lack of mobility in the event of redeployment of military units.

The design of another wind generator is suspended on a helium balloon and includes a winch, cable, generator and blades [35]. The disadvantages of this wind generator design are:

– difficulty in regulating the speed of rotating elements during possible and sudden gusts of wind;

– inability to increase, if necessary, the power of generated electricity.

The design of the next wind generator is installed at the bottom of the kite and includes a winch, cable, generator and blades [36]. The disadvantages of this wind generator design are:

– constant dependence on the power of rising air currents for the ability to glide the kite;

– difficulty in regulating the speed of rotating elements during possible and sudden gusts of wind;

– inability to increase, if necessary, the power of generated electricity.

The general disadvantages of the presented designs of utility models are: their inability to supply energy to military units associated with constant redeployment and work in the field, the complexity of servicing and repairing mechanical equipment.

The practical significance of this research lies in developing a mobile wind power plant and utilizing a renewable energy source to support the life needs of troops deployed in the field.

As a result of research, a model has been developed for calculating the parameters of a mobile wind turbine for power supply to military consumers, which makes it possible to determine the peak power and energy consumption, rated power, and aerodynamic parameters of the wind turbine rotor using (4), (7), (8), (11)–(14). Thanks to this model for calculations, you can select the wind generator's power and the number of sections depending on the average wind speed of the region under study. The results of calculating the power of electrical consumers and the instantaneous power consumption of a military shooting range are presented in Table 2. The results of calculating the electrical consumers of a military shooting range, the rated power and energy production of a mobile wind turbine are also given in Tables 3, 4.

Unlike wind generators [14–18, 22], where horizontal-type rotors are used, wind turbines with a vertical axis of rotation are most appropriate for use in small wind energy. This becomes possible due to the fact that these wind turbines use a unique rotor-stator system, which forces the incoming wind.

The developed design of a mobile wind turbine with a vertical axis will be manufactured as a prototype, on which field tests will be carried out in a military training ground. During the field tests the following tasks will be solved:

– determination of wind turbine energy production depending on the time of day, by measuring wind speed with an anemometer;

– measuring the number of revolutions of the wind wheel using a tachometer;

– increasing the energy efficiency of wind turbines with various changes in installation height from the ground level.

The main parameter that determines the efficiency and performance of wind turbines is the wind speed in the study area. Verification experimental studies will be carried out to determine wind speed, the number of revolutions of the wind wheel, as well as experiments to compare electricity generation from placing wind turbines at a height above ground level. In addition, the energy production of wind turbines will be determined depending on the time of day.

The results of field tests may be affected by the meteorological and physical-geographical conditions of the study area. Further research may be limited to this area. To obtain more objective and complete data, it is necessary to conduct research in other parts of the Republic of Kazakhstan, which we consider impossible due to the large time and financial costs.

After manufacturing a prototype of a mobile wind turbine with a vertical axis, taking into account the results of field tests, additional research is necessary to adjust its design. Changing the design of a mobile wind power plant can be achieved by mounting it on a trailed wheeled chassis with the possibility of placing it in a transport position and installing a telescopic mast with wind generator blades in a vertical working position using the design of a roller base assembly, followed by fastening it to the platform of a wheeled trailer.

The results obtained allow us to solve part of the problem under study. To obtain more complete results, experimental studies are required to determine the dependence of aerodynamic forces on geometric and operating parameters, such as the Reynolds number, flow direction, rotation speed, wind turbine diameter, etc. The obtained scientific data can be useful in solving problems of turbulent flow around the profiles of a combined system of various blades, as well as practical use in applied problems of aerodynamics.

Using a manufactured experimental sample of a mobile wind turbine is planned to determine its aerodynamic characteristics to optimize the thrust force on the shaft and aerodynamic drag, which will be carried out in stages according to the following methodology: laboratory studies of the model will be carried out in the T-1-M wind tunnel, determining aerodynamic forces and parameters using precise aerodynamic balances and other measuring instruments.

The main characteristics of the working part of the T-1-M wind tunnel: diameter – 500 mm; length – 800 mm; turbulence level – (3÷4) %; airflow speed – (2÷30) m/s.

An aerodynamic balance installed in a wind tunnel allows one to measure the drag force, lift force, thrust force and torque of the vertical shaft of a combined wind turbine.

Calculation of the technical parameters of the experimental version of the wind turbine and modeling of aerodynamics based on the theory of similarity will be carried out using modern application packages and based on the theory of similarity.

Testing of a prototype mobile wind turbine at a test site in natural wind conditions. To carry out measurements, traditional measuring instruments will be used: an anemometer, aerodynamic balances of varying accuracy, a dynamometer, a micro manometer, a tachometer, Pitot-Prandtl tubes and various instruments for measuring electrical quantities.

The introduction and use of the developed mobile wind turbine in the Armed Forces of the Republic of Kazakhstan for field power supply of troops is the most profitable and expedient from both the economic and environmental sides. When implementing this development, units and formations of the Armed Forces of the Republic of Kazakhstan will be reliably provided with electricity to conduct autonomous operations at the tactical and operational command level.

7. Conclusions

1. Based on the results of theoretical studies, a mobile wind turbine with a vertical axis of rotation is defined as a fundamentally new ideology for the implementation of wind energy, processing wind with equal efficiency, regardless of its direction. Meteorological, physical-geographical, qualitative, and technical conditions affecting the wind regime and the performance of a mobile wind turbine have been identified. It has been found that wind turbine energy production begins at wind speeds of 1 m/s or more; at wind speeds of more than 3 m/s, energy production is 1.5 kWh. The values of the number of revolutions of the wind wheel were obtained, at a wind speed of 3 m/s, its value is within 60 rpm. Studies on wind turbine blade positioning and angle of attack (the angle between the blade and airflow) have shown that the resulting aerodynamic force is dependent on both the blade's shape and its orientation relative to the wind.

2. As a result of the theoretical justification, it was found that the use of a mobile wind turbine with a vertical axis of rotation is more profitable and efficient compared to wind generators with a horizontal axis of rotation. The swept area $S=2.72$ m^2, the coverage of the airflow, regardless of its direction, is equal to 100 %, the angle of installation of the blades to the wind flow (angle of attack) is $\lambda=60°$. Schemes of airflow around a blade at different angles of attack are presented: blades along the airflow, the beginning of blade deflection, an increase in the angle of attack, the maximum value of the angle of attack, and stall. The dependence of the resistance force and lifting force of the blade at various angles of its installation to the oncoming air flow was obtained.3. To calculate the parameters of a mobile wind turbine for power supply to a military shooting range, a model has been developed that includes determining its power, energy, and aerodynamic parameters. The peak power of the wind turbine per day was determined: during the day $P_{day}=1{,}420$ W, at night $P_n=2{,}220$ W, daily energy consumption of the military shooting range $E_{day}=5{,}567$ Wh, respectively, the optimal number of wind turbine sections was 4 pieces. The swept area of the wind turbine blades was determined to be 2.72 m^2. Airflow coverage, regardless of direction, was 100 %. The angle of installation of the blades relative to the wind flow (angle of attack) was $\lambda=60°$. The document presents schematics of airflow around a blade at different angles of attack: blades aligned with the airflow, initial blade deflection, increasing angle of attack, and maximum angle of attack with flow stall. The dependence of the resistance force and lifting force on the blade's angle of installation to the oncoming airflow was obtained. The calculation model allows for determining the power output of a wind generator and the number of blade sections required based on the average wind speed of the region under study. The calculation results confirm the advisability of using a mobile wind turbine to provide power support for shooting at a military shooting range.

4. The design of a mobile wind turbine has been developed, the novelty of the design of which is confirmed by the utility model patent of the Republic of Kazakhstan No. 8021. The advantages of this device lie in its mobility, sectionality and the ability to be placed in any environmental conditions, etc. The module is a simple and compact design with a vertical axis of rotation, ensuring uninterrupted power supply to troops; it can be used in the field, at military facilities located far from populated areas, in units performing tasks in the border zone of the state and experiencing regular problems with electrical power.

Leveraging the research findings and calculated data, a project for developing a mobile wind power plant prototype has been initiated. Currently, the team is assembling a full-scale prototype of the mobile wind turbine.

Following design completion, field tests are planned. These tests will provide real-time data on wind speed, power generation, and system performance under various weather conditions. This data will be valuable in understanding deployment logistics, installation time, and ease of operation in remote locations.

The field test results will be used to refine the calculation model, enhancing its accuracy and informing future design improvements. Finally, an analysis of field data will be conducted to develop final design documentation with practical recommendations for military use.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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