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Application of vertical-axis wind turbines for environmet-riendly high-rise buildings power supply

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Abstract. The climate changes and depletion of natural resources within the recent decades have given a rise to an interest in sustainable power supply development, wind and solar energy in particular. According to IEA forecasts, the share of the wind power in global power production will have risen from 7% in 2022 to 15% in 2030. Despite the preveilance of the fossil fuels, the use of the wind power in architecture is important for the carbon emission reduction.
Integration of the wind power plants requires an analysis of wind conditions, design, and compliance with the norms. The vertical-axis wind turbines applicable for use in the urban environment are efficient at the low wind speed, they require minimum maintenance and are capable of supplying power to the residential houses. The researches demonstrate that the vertical-axis turbines are more appropriate for installation at the top storeys of the buildings where they are resistant to changes of wind directions and are safe to operate.
Contemporary wind power technologies are of big importance in creating environment-friendly and energy-efficient buildings by promoting the saving of resources and reduction of greenhouse gases emission. this article dwells upon the integration of low-power wind plants into the architecture of the high-rise buildings.
Keywords: renewable energy sources, environment, wind power, horizontal wind turbines, vertical wind turbines, wind turbine, high-rise buildings, power conservation, power-efficient technologies

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1. INTRODUCTION

Within the recent decades the global community has faced the ever-increasing issues of climatic changes and depletion of natural resources which incites the countries to search for sustainable and environmentally clean solutions in energy production. In this context, the renewable energy sources such as solar power, water power and wind power are gaining more and more demand. In particular,

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the wind power is undergoing significant changes due to modern technologies and innovations aimed at the improvement of its efficiency and at the reduction of adverse impact on the environment.

According to the information supplied by the International Energy Agency (IEA), the share of the wind power in global power production will have increased from 7% in 2022 to 15% in 2030. These changes are driven by not only environmental factors by also by economy: the cost of wind turbines installation has decreased significantly within the two past decades. The European Commission report for 2023 stated that, in order to achieve the goals in carbon emission reduction by 2030, the renewable power sources including wind power shall have to have been integrated into both existing buildings and the buildings under construction. The integration is possible as a result of use of the modern low-power wind plants which will enable the creation of power-efficient and environmentally clean cities and towns.

Although in 2022 more than 80% of the global power consumption was still produced from fossil fuels, the Renewables 2023 report by IEA stated that the share of the renewable power sources in 2022 rose by ca. 30%-32% which was the evidence of the growing interest in switching to the clean energy sources form the states and businesses. In researching this issue in the context of current trends in the transition to sustainable energy sources, the IEA concluded that in order to achieve the goals of limiting global warming to 1.5°C by 2030, it is necessary to reduce harmful emissions into the atmosphere by half.

Wind energy is considered to be one of the promising alternative energy sectors. Currently, a significant number of Russian and foreign scientific papers have been published on the transition to clean energy sources, in particular wind generators. Thus, based on the results of the study by H. Pozo, W. L. P. Soares, G.K. Akabane, innovative technologies in wind energy help reduce the level of emissions of carbon dioxide and other greenhouse gases, which is extremely important in the context of global warming [1].

The development of wind power generation is associated with the development of new and improvement of old models of wind turbines. Innovative ways of developing wind energy are reflected in the works of such figures as M.J.M. Stevens and P.T. Smulders [2]; William P. Kuvlesky, Jr., Leonard A. Brennan, Michael L. Morrison, Kathy K. Boydston, Bart M. Ballard and Fred C. Bryant [3]; Giuseppe Failla and Felice Arena [4]; Fred Udo, Cornelis le Pair, Kees de Groot, Ad H.M. Verkooijen and Kees van den Berg [5]; F. Larry Leistritz and Randal C. Coon [6]; Wesley D. Sine and Brandon H. Lee [7]. W. E. Leithead provides a description of the state of wind energy and examines its dynamics and development prospects [8]. The modern Western projects include innovative wind turbines of increased efficiency and reliability, modern materials and equipment are used to optimize capacity. Universal wind turbines allow operation under different conditions, and various methods of power generation and storage ensure sustainable development of wind energy. The work of Sadorsky P., describes the method of logarithmic mean distribution index (LMDI) used to study the factors influencing wind energy consumption [9]. In the article by Russian authors E. A. Cherepanov, O. E. Prusikhin, the potentials and limitations of using wind turbines in different regions of the world are discussed. [10]. A. G. Sadunova focuses on the economic aspects of wind energy [11].

A key element in developing innovative wind energy technologies for environmentally friendly and energy-efficient buildings is the use of modern procedures aimed at integrating wind energy into architectural solutions. Such solutions include the selection of the optimal design of wind turbines, analysis of local climatic conditions, and the use of advanced materials and technologies. For the successful implementation of wind energy solutions, it is necessary to follow a number of main stages:

1. Review of wind conditions

Initially, it will be necessary to conduct a detailed analysis of wind conditions in the area where the building is planned to be built. The review shall include collecting data on wind speed and direction, as well as the level of turbulence, a precise analysis of wind potential can increase the efficiency of wind turbines by up to 20%. The use of specialized meteorological stations and computer modeling will help to identify the most suitable places for installing wind generators.

2. Engineering research of wind plants

The engineering research stage requires a consideration of the size and type of the wind plants. Innovative vertical wind turbines (VWT) such as Darrieus model, are becoming increasingly more popular due to small size and low noise emission. The VWT are capable of more efficient in the urban development conditions as the ensure lesser load and reduced impact on the environment.

The use of modular systems that can be integrated into the building architecture itself (e.g. wind turbines built into facades) makes it possible to significantly speed up the implementation process and ensure a higher level of energy efficiency. As a rule, such systems require complex calculations and simulations, which emphasizes the importance of the engineering research stage.

3. Energy modeling

Modeling the energy flows in a building with installed wind turbines allows to estimate the energy generation potential. Using software such as EnergyPlus and OpenStudio, architects and engineers can take into account all aspects including the building dome, orientation and historical weather data, the use of such modeling increases the accuracy of estimates by 30%, which is critical for the economic feasibility of projects.

4. Integration with other systems

Integration of wind energy systems with other renewable energy sources such as solar panels is becoming fundamental to maximizing the overall output potential, for example, combined use of wind and solar technologies can lead to a 50% increase in the total energy generated by a building. It is important to consider different energy application scenarios: for self-consumption, storage in batteries or transmission to the grid.

5. Monitoring and optimization

Once the wind system installation has been completed, it is necessary to organize continuous monitoring of its operation; modern automatic monitoring systems can not only track the performance of wind generators, but also collect data for subsequent analysis. This allows to identify problems at early stages and making adjustments; the use of IoT systems for monitoring wind turbines helps to reduce response times to potential failures by 40%, which is critical in urban construction [12].

6. Legislative and normative aspects

An equally important aspect of wind energy technology implementation is legislative and regulatory procedures. Architects and engineers must take into account regional laws and regulations regarding the installation of wind turbines, such as height restrictions and setbacks from building fronts. In particular, design laws in a number of countries require environmental assessments prior to installation of wind turbines, which highlights the need for cooperation with related agencies and organizations.

7. Examples of successful introductions

Examples of successful implementations of innovative wind energy technologies can be found around the world, for example in the Netherlands a number of buildings with integrated wind turbines have been built, which not only provide energy for consumption, but also serve as elements of architectural aesthetics. The bio-architecture model created by the architectural bureau Studio1to1 successfully combines wind turbines and solar panels, providing a comprehensive solution for energy independence. In addition, in the United States, the Edge project in New York integrated small wind turbines into the design of buildings, which allowed not only to reduce carbon emissions, but also to create a new standard for energy-efficient office spaces.

2. METHODS AND MATERIALS

Innovative wind energy technologies are becoming increasingly important in the context of the desire to create environmentally friendly and energy-efficient buildings. These technologies do not only help to reduce the carbon footprint, but also provide new approaches to the production, storage and use of renewable energy. There are two main types of wind turbines: horizontal-axis and vertical-axis. [13- 15] Horizontal-axis turbines are more efficient when oriented directly into the air flow, which ensures maximum energy production, while vertical-axis models can operate regardless of the wind direction, making them more versatile. Both types play an important role in the development of renewable energy, providing a sustainable alternative to fossil sources. Horizontal-axis wind turbines are classic and popular models of wind turbines. Thanks to long-established technology and a high level of mass production, they are becoming increasingly affordable.

The most common type is the horizontal-axis lift wind turbine, which is characterized by high efficiency and quick response to changing wind conditions (Fig. 1). Drag wind turbines have a number of advantages and characteristics that make them popular in wind energy (Fig. 2). They effectively use the resistance on the blades to convert the kinetic energy of the wind into electricity, which ensures stable operation in different wind conditions. These turbines are suitable for large and medium-sized installations due to their reliability and low operating costs. In addition, they are environmentally friendly, as they have a minimal impact on the environment. Their development contributes to the sustainable and efficient development of renewable energy sources. These vertical turbines are characterized by a high speed coefficient at the blade tip, exceeding 4, which ensures efficient use of the wind flow. The maximum power factor reaches 50%, which is a good indicator. However, in modern poer generation such models are less common, as horizontal turbines with higher efficiency are more popular. Mainly, vertical plants are used as drag elements and have a vertical axis, which makes installation and maintenance more simple. Despite some advantages, they are inferior to horizontal models in terms of wind efficiency [16].

Fig. 1. Lift turbine.

Fig. 2. Drag turbine.

Let us consider the advantages and disadvantages of lift and drag turbines (Table 1).

Table 1. Advantages and disadvantages of lift and drag turbines.

Turbine type	Advantages	Disadvantages
Lift turbine	- high efficiency at high wind speeds; - less dependence on wind characteristics due to the appropriate shape of the blades	- complex design and need for precise adjustment; - sensitivity to changing wind conditions and need for stable fastening
Drag turbine	- simple design, which makes them more affordable to manufacture; - better resistance to strong gusts of wind due to their tolerance to overloads	- less efficient at low wind speeds; - usually require more space to achieve the required output

In recent years, vertical-axis wind turbines have become increasingly popular in urban settings. Unlike traditional horizontal turbines, which require specific wind speeds to operate efficiently, vertical models are able to generate power even in weak wind conditions. This makes them ideal for use in densely populated areas where weather conditions can be highly variable.

One of the key advantages of vertical wind turbines is their low noise level. In urban environments where sound pollution is a serious problem, such turbines operate quietly, which helps create a more comfortable atmosphere for residents. Moreover, vertical structures are less susceptible to strong gusts, which reduces the risk of damage.

The structure of vertical wind turbines is usually more compact, which allows them to be installed on the roofs of buildings or in confined spaces. This opens up new opportunities for integrating renewable energy sources into architectural designs, contributing to the creation of energy-efficient buildings and a reduced carbon footprint. As a result, vertical wind turbines are becoming an important element in transforming cities into more sustainable and environmentally friendly spaces.

One of the most important sphere of energy conservation is the use of vertical wind turbines (VWT) for urban buildings. These installations have a number of advantages: they are less noisy, they have smaller dimensions and they can function effectively even at low wind speeds. As the studies conducted by professionals in the field of architecture and energy show, for example, a study titled *Energy and Sustainable Development: How to Find the Golden Mean*, conducted by a team from Promsvyazbank (PSB) and the Research and Expertise Institute of Vedushcheye Expertnoe Byuro (VEB) LLC, such systems can generate enough power to cover the basic needs of residential and business buildings [17].

A small direct drive vertical-axis wind turbine is an efficient solution for converting wind kinetic energy into electrical power. Its main mechanical design elements include a rotor with blades, a vertical axis, a generator, a gearbox (if necessary, although direct drive implies its absence), a base and a control system (Fig. 3).

Fig. 3. Small vertical-axis turbine scheme; 1 – generator; 2 – speed incrementor; 3 – tower; 4 – lower support; 5 – blade brakes; 6 – vertical shaft; 7 – blade; 8 – upper support. Source: [18].

The vertical-axis wind turbines (VAWTs) exist in two main configurations: Savonius and Darrieus. The Savonius configuration employs two or more demilunes that capture the wind to create a lifting force due to varying blade geometry. By contrast, the Darrieus configuration uses thin blades that operate by drag (Fig. 4, 5).

Fig. 4. Savonius vertical-axis wind turbine.

Fig. 5. Darrieus vertical-axis wind turbines.

Vertical wind turbines are particularly valuable due to their ability to be installed at low altitudes, making them ideal for urban environments. They are resilient to changes in wind direction and can generate power efficiently regardless of the wind direction [19-21].

Vertical-axis wind turbines have a number of advantages:

1. Resistance to wind direction changes. They can operate efficiently compared to horizontal turbines, especially in densely populated areas and in the variable wind flows of urban environments. with any wind direction, making them more flexible.

2. Low noise. Such turbines are generally quieter and less visually intrusive.

3. Safety. Due to their design, they are considered safer for birds and animals.

4. Ease of maintenance. The horizontal axis and generator, located close to the ground, simplify access to components for maintenance and repair [22].

Thus, small vertical-axis wind turbines are a promising option for creating sustainable energy sources of low user power in urban environments.

In this computational experiment, the efficiency and safety of vertical-axis wind turbines is tested under strong wind loads on the upper floors of high-rise buildings.

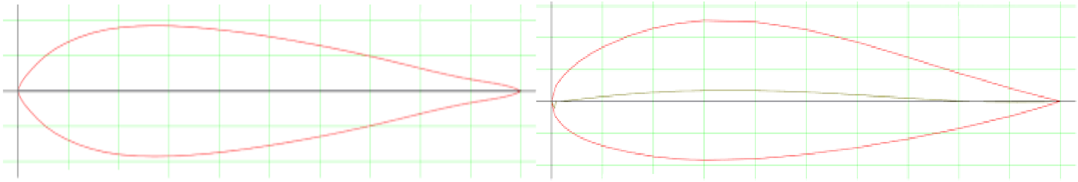
3. RESULTS AND DISCUSSION

Using the methodology for assessing the efficiency, technical aspects, and impact of wind conditions on such installations [23], parameters related to the blades were obtained, with specific values presented in Table 2 below.

Table 2. Wind-turbine related parameters.

Parameter	Value
S	4.8m^2
H	2.4m
D	2m
λ	1
N	4
C	150mm

The aerodynamic profile of the vertical-axis wind turbine blade has a decisive influence on the safety of wind turbine and the utilization of wind energy, the NACA airfoil type was proposed by the NACA committee in the United States and adopted as a standard for the production of blades in many vertical axis wind turbines, Fig. 7 shows two common NACA airfoil types (NACA0018; NACA0024), see Fig. 6.



NACA0018 NACA0024

Fig. 6. Aerodynamic profile (airfoil).

Different aerodynamic profiles affect the performance of vertical-axis wind turbines [24-27]. In literature [28], NACA4 and NACA6 series airfoils are used for vertical-axis wind turbines to simulate the flow field. By comparing the wind energy utilization factors of vertical-axis wind turbines with different airfoils, it can be concluded that NACA4 and NACA6 series have the highest wind energy utilization factor with NACA0018 airfoils, reaching 34.43%.

To achieve high aerodynamic performance of the wind turbine, it is important to minimize the cost of manufacturing the blades. At the same time, the blades should have a high slope of the lift coefficient, which increases efficiency, and a low drag coefficient to reduce air resistance [29]. When designing the wind turbine, the actual size of the territory and the requirements for energy production were taken into account by means of multiple iterative calculations, which made it possible to determine the optimal diameter of the windwheel coverage: 2 m, as well as the blade length of 0.15 m. To improve the efficiency and stability of the design, a four-bladed blade of the NACA0018 type with an H-shaped profile was selected, providing good aerodynamics and strength. According to the graph of the relationship between the lift and drag coefficient of the NACA0018 aerodynamic profile and the incidence angle, when the incidence angle of the blade relative to the wind direction is 13°, the turbine achieves maximum kinetic energy, which contributes to the high performance of the installation (Fig. 7). This approach allows to increase the efficiency of the wind turbine, ensure reliable operation and a long service life, which is important for successful operation and obtaining maximum energy from the wind.

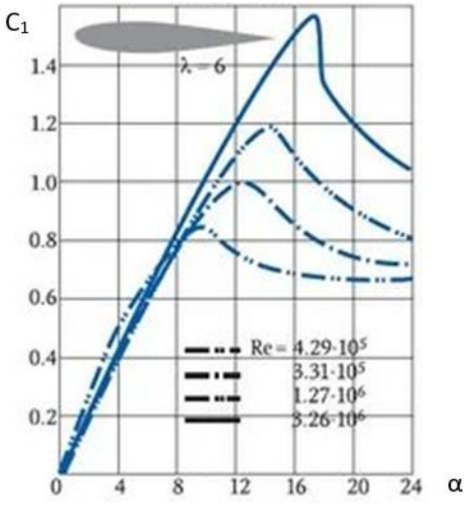


Fig. 7. Relationship between lift and drag coefficient of a NACA0018 airfoil and angle of incidence.

Using the methodology for assessing the efficiency, technical aspects, and the impact of wind conditions on such installations [23], the parameters for the torque of the wind wheel were obtained:

At the wind speed of 2.50 m/s, M=1.40481 N·m.

At the wind speed of 3.00 m/s, M=2.02292 N·m.

At the wind speed of 3.55 m/s, M=2.83265 N·m.

At the wind speed of 4.26 m/s, M=4.07902 N·m.

During the modeling exercise the subject of which was the operation of a wind generator with a vertical axis, the following results were obtained (see Table 3). [30-33]

Table 3. Results of the modeling exercise for simulation of the vertical-axis operation.

Parameter	Value
Power	1000 w
Windwheel diameter	2 m
Rated speed	95.5 r/min
Rated wind speed	10 m/s
Initial wind speed	2 m/s
Operating air speed	3-25 m/s
Safe wind speed	50 m/s
Rated power	1000 w

In 2023, the average wind speed in country at the altitude of 70 m was 5.4 m/s. Judging from the spatial distribution (Fig. 8), the annual average wind speed will exceed 6.0 m/s in most parts of Northeast China, North China, most of Inner Mongolia, Central and Southern Ningxia province, Northern Shaanxi, Western Gansu, part of Eastern and Northern Xinjiang, most of the Qinghai-Tibet Plateau, the mountainous areas of western Sichuan, the Yunnan-Guizhou Plateau, Guangxi and the southeast coast. Among them, the annual average wind speed reaches 7.0 m/s in the western and northeastern parts of Northeast China, central and eastern Inner Mongolia, eastern and northern parts of Xinjiang, western part of Gansu and most of the Qinghai-Tibet Plateau, and can even exceed 8.0 m/s in some areas. The average annual wind speed in Western Shandong and most of the eastern coast of Shandong, most of Jiangsu, Eastern Anhui, etc. is 5.0 m/s to 6.0 m/s. In the rest of the country, the average annual wind speed is below 5.0 m/s, mainly in the central and eastern plains and the Xinjiang basin area.

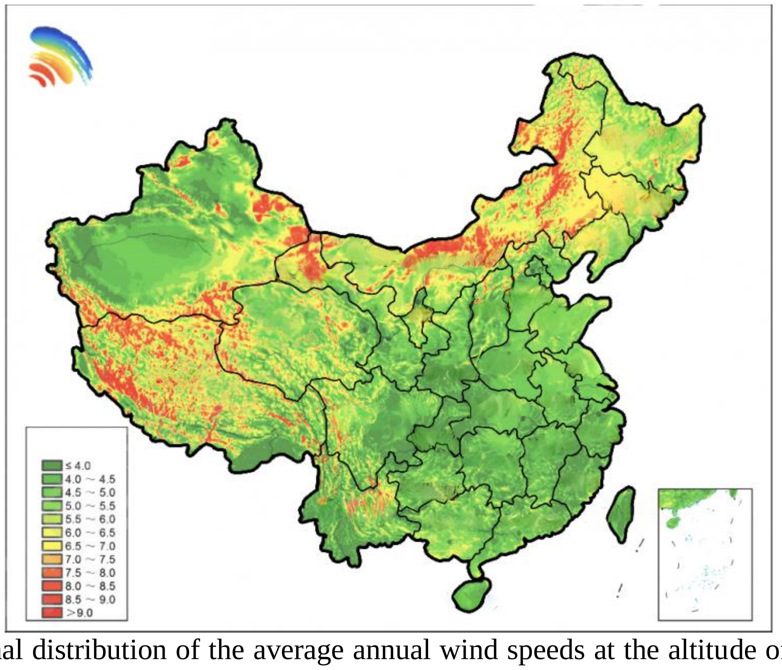


Fig. 8. Dimensional distribution of the average annual wind speeds at the altitude of 70 meters above ground in 2023.

Compared to the past 10 years, the average annual wind speed in Northern Xinjiang, central and western parts of Qinghai, Southern Shaanxi, Northeastern Tibet, Southern Yunnan, most of Hebei and other places is relatively small. Among those areas, the average annual wind speed in north-central Qinghai, southern Jiangsu, Shanghai and other cities. Northern Hainan is much smaller in size. The average annual wind speed in southern Xinjiang, central and western parts of Inner Mongolia, most of Sichuan and other places is too high, including the average annual wind speed in Northeast Liaoning, Northeast Yunnan, Northwest Guangxi and other places is significantly higher. The average annual wind speed in other regions is close to normal (Fig. 9).

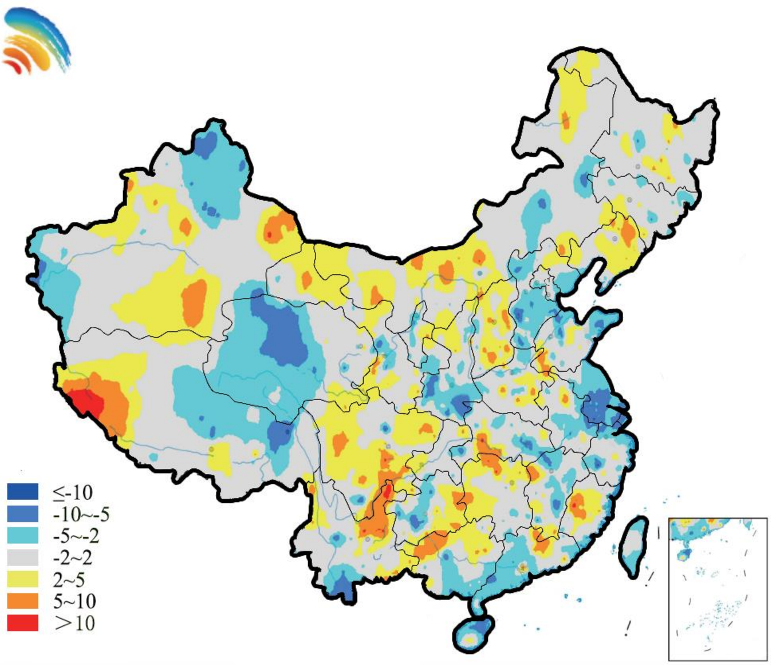


Fig. 9. Percentage distribution of the average annual wind speeds at the altitude of 70 meters above ground in 2023.

Based on the wind power value and distribution in China, and the type of wind turbine selected, we conducted computational experiments. The purpose of the experiment is to investigate the maximum output power of the wind turbine under the load of 0m/s-14m/s, the optimal rotation speed relative to the experimental wind speed, and the maximum output power of the wind turbine relative to the optimal rotation speed. A low-speed DC wind tunnel was used for the experiment (Fig. 10). The test section size was 3×3×8 m, the maximum wind speed was 20 m/s, the boundary layer thickness was less than 15 mm. The magnitude of dynamic pressure pulsations in the wind tunnel is less than 0.5%, the velocity uniformity area is more than 85% of the air flow cross-section, and the standard deviation is less than 0.5%; the direction of the air flow at any point of the model area in the experimental cross-section is at an angle to the wind tunnel axis in the direction of pitch was $|\Delta\alpha| \leq 0.5^{\circ}$ and $|\Delta\beta| \leq 1^{\circ}$ for slew; the average value of the root-mean-square value of pulsations ε is less than 1%; the static pressure gradient along the axis: $\frac{d\bar{p}}{dx} \leq 0.002m^{-1}$, where $\bar{P}$ is the indeterminate pressure coefficient.

Fig. 10. Low-speed direct-current aerodynamic tunnel.

To ensure the accuracy of obtaining the power output curve of this vertical-axis wind turbine, the wind generator was fixed to the pole at the bottom of the wind tunnel so that the windwheel was in the center of the wind tunnel test section. The output of the generator was connected to the voltage and ammeter through a control resistor, and by changing the resistance, the speed of the generator could be changed. Since the wind speed in the wind tunnel was uniform and stable, a stable output voltage and current were usually achieved after 5-10 minutes of waiting after the resistance had been changed. The power Pe at the generator output was obtained by multiplying the current I at the generator input by the measured value of voltage U.

1000 W vertical-axis wind turbine under 0 m/s – 14 m/s load to obtain a curve of the maximum output power versus wind speed (Fig. 11). The relation between the optimal speed and the experimental wind speed (Fig. 12), and the relation between the maximum output power of the wind turbine and the optimal speed (Fig. 13).

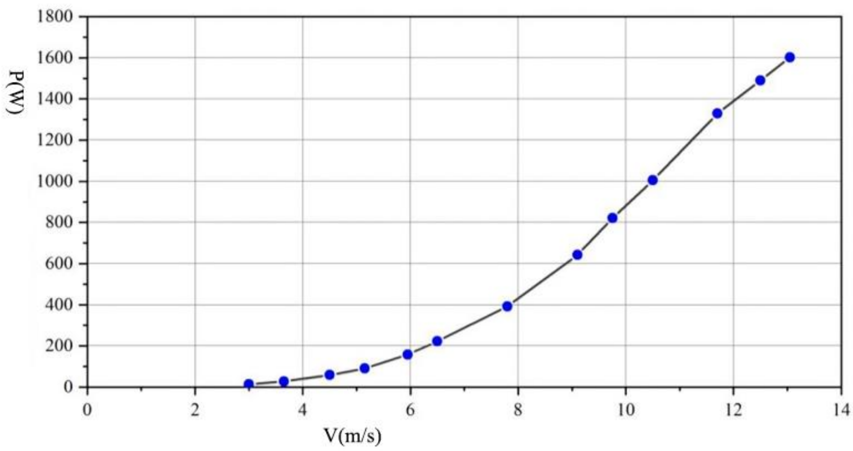


Fig. 11. Dependence between the maximum output power and the simulational wind speed.

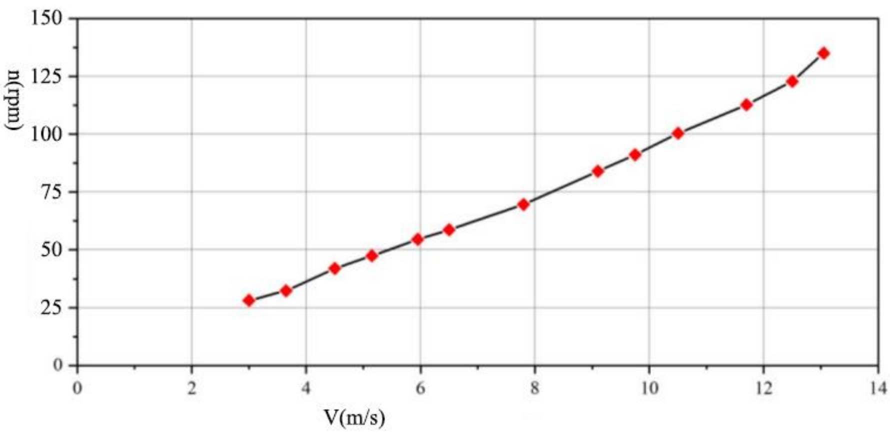


Fig. 12. Relation between the optimal speed and the experimental wind speed.

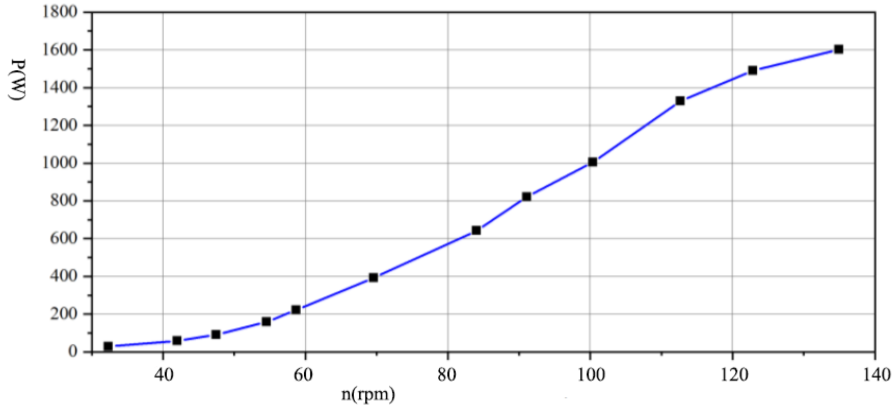


Fig. 13. relation between the maximum output power of the wind turbine and the optimal speed.

With that, five various sets of wind speed were selected: 3 m/s, 5 m/s, 8 m/s, 10 m/s, 13 m/s; this enabled to retrieve data on noise level, rotation speed, torque (the aggregate tangential power of blades) generated by the blades upon receiving the wind energy, the output power of the wind generator, the linear speed of blades near the wind generator, and the rotation speed factor for the blades tips (Table 4).

Table 4. Influence of the wind speeds on the wind generator performance values.

Air speed, v (m/s)	Rotation speed (rpm)	Torque, M (N·m)	Output power, P (W)	Linear speed, v (m/s)	Noise level, dB (A)	Rotation speed factor of the blades tips (λ)
3 m/s	25	2.02292	21	2.6	27.9	1.006
5 m/s	46	5.61924	108	4.8	38.3	1.003
8 m/s	70	14.38525	421	7.3	49.4	1.003
10 m/s	95	22.47696	893	10	53.6	0.994
13 m/s	132	37.98606	1600	13.2	59.4	1.046

According to the Chinese Technical standard for performance assessment of residential buildings (GB/T50362-2005) [34], when the comprehensive performance of a residential building reaches level 3A, the sound insulation performance of the floors and walls shall meet certain requirements. The specific requirements are that the weighted standardized impact sound pressure level of the floors should not exceed 65 dB, the weighted sound insulation of airborne noise should not be less than 50 dB, and the weighted sound insulation of airborne noise in the walls of partitioned blocks should not be less than 50 dB. Therefore, when the vertical axis wind turbine is operating, it will not affect the normal life of people inside the building [35-40].

Vertical-axis wind turbines installed on the upper floors of high-rise buildings have a number of advantages, their placement at the top of the building allows for the maximum use of the features of vertical turbines, such as independence from wind direction and high operating stability. The turbines are perpendicular to the wind, which ensures efficient use of wind flows and increases energy production; installation on the upper floors promotes efficient use of building space and reduces operating costs due to their simple design and low maintenance costs. This approach allows for the full potential of wind energy to be realized, energy efficiency to be increased, and a contribution to the city’s environmentally friendly energy system to be made. A vertical-axis wind turbine installed on high-rise buildings ensures stable and efficient operation regardless of wind direction and strength; its unique vertical-axis design allows it to catch wind flows at any angle, which is especially important in urban conditions with variable winds. At the same time, such turbine operates successfully even in strong winds – up to 50 m/s, due to its stable design and reliable materials. Installation of these turbines on high-rise buildings enables megacities to independently generate environmentally friendly energy, reducing the need for traditional sources and cutting emissions of harmful substances. This significantly reduces the ecological footprint of urban structures, facilitates the transition to greener energy and creates a more sustainable urban environment.

4. CONCLUSIONS

Modern innovative wind energy technologies play a key role in the creation of environmentally friendly and energy-efficient buildings, help reduce the carbon footprint, and cut energy costs. One of the most significant directions in this area is the integration of low-power wind turbines into the architecture of buildings.

Low-power wind turbines, especially vertical-axis wind turbines, are becoming increasingly popular for installation on roofs and facades of buildings. Research shows that such installations can generate enough energy to meet the electricity needs of one residential building.

The present article discusses the application of vertical-axis wind turbines as a solution for environmentally friendly energy supply for the high-rise buildings.

The importance of the problem statement lies in the absence of the need for buildings to transport energy, reduce the consumption of fossil resources and greenhouse gas emissions, which in turn leads to a stable balance in the ecosystem.

Thus, vertical-axis wind turbines present a promising solution for the clean energy supply of high-rise buildings. Their integration into the architectural solutions of modern cities will allow the creation of a more sustainable and energy-efficient infrastructure, facilitating the transition to a green economy. In addition, innovative wind energy technologies represent an important step towards the creation of environmentally friendly and energy-efficient buildings.

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