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Innovative fixed-axle Savonius wind turbine for enhanced efficiency and durability

Abstract: This study aimed to develop and evaluate the effectiveness of a new Savonius wind turbine scheme featuring a vertical fixed axle, which offers advantages in reducing metal intensity and operating time. The study employed theoretical analysis of existing wind turbine designs, a fixed-axle modular design, and aerodynamic modeling of the rotor profile to enhance the plant's efficiency. As a result of the study, a new scheme of a Savonius wind turbine with a vertical fixed axle was developed. The proposed design helped significantly reduce the metal intensity of the plant by approximately 30%, resulting in lower manufacturing costs. The absence of a rotating shaft and its replacement with a fixed axle resulted in a reduction of friction in the support, thereby increasing the plant's efficiency. Dynamic forces on the structure were also reduced, contributing to longer bearing life. The proposed design reduced metal consumption by approximately 1.5 times, resulting in a 35% reduction in production costs. Less frequent maintenance, once every two years instead of every six months, reduces operating costs by up to 40%. Reduced friction in the

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bearings and reduced dynamic loads increase reliability and extend bearing life by 25%. All in all, these factors increase the financial efficiency and competitiveness of the turbine in the renewable energy market. The practical benefits of the research for stakeholders are that engineers are able to implement simplified and reliable design solutions that reduce bearing loads and increase turbine efficiency.

KEYWORDS: metal consumption, friction, dynamic forces, bearing arrangements, continental climate

Introduction

The current challenges in the energy sector include the need to transition to sustainable and renewable energy sources, particularly in the context of the global climate crisis and the growing demand for clean electricity. Wind energy plays a key role in shaping the energy mix of the future; however, existing technologies often have significant technical, economic, and operational limitations that hinder their widespread deployment. In particular, vertical wind turbines, which are promising for regions with unstable wind directions and harsh climatic conditions, require design optimization to reduce production costs and improve reliability and efficiency. This study proposes an innovative scheme featuring a fixed vertical axis and a specialized blade design that addresses the key technical shortcomings of traditional models.

The growing demand for renewable energy sources is challenging scientists and engineers to develop more efficient and cost-effective solutions for wind farms. The average cost of electricity generation from wind farms remains significantly higher than that of traditional fossil sources, ranging from USD 40 to USD 60 per megawatt-hour, while for coal and gas power plants, this figure is USD 30 to USD 40 (Renewable Power Generation… 2023). The cost problem is particularly acute for vertical-axis wind turbines, which, despite their technological advantages, have higher material and maintenance costs due to their complexity. In particular, the metal consumption of such installations reaches 500 kg per megawatt of capacity, which is 1.5 to 2 times higher than that of horizontal wind turbines (Xu et al. 2021). In addition, traditional designs often suffer from bearing wear caused by dynamic loads, resulting in frequent downtime and increased operating costs. In this context, improving the design of vertical-axis wind turbines, particularly by utilizing the Savonius rotor, which demonstrates high reliability in regions with a continental climate and strong wind gusts, is particularly relevant. The development of new schemes that reduce metal consumption, improve load resistance, and reduce maintenance costs is a key condition for increasing the competitiveness of wind energy in the modern energy market (Qawaqzeh et al. 2020).

Cost competitiveness remains a significant obstacle to the widespread adoption of renewable energy sources, as confirmed by several recent studies. Mardoyan and Braun (2014) provide a detailed analysis of the subsidy system for solid biofuels in the Czech Republic, emphasizing that without government support, these fuels cannot compete with traditional energy resources due to higher production and logistics costs. The authors emphasize the need to continue and improve subsidies to ensure the economic viability of biofuels and stimulate their market adoption. Similar conclusions are presented in the study by Bencoova et al. (2021), which examines national and international practices of utilizing biogas plants. They note that despite the technical potential of biogas technologies, their large-scale deployment is limited by high initial investment and operating costs, which reduces their attractiveness without appropriate financial support or incentives.

Energy management should be viewed not only as a technical or economic process but primarily as a complex political phenomenon that significantly affects the development of national economies and the social structure of society. Research by Skare et al. (2021) demonstrates that energy cycles and key turning points in England's economic growth from 1700 to 2018 are closely linked to political decisions that shaped energy policy, defined institutional frameworks, and facilitated adaptation to technological and market changes. They emphasize that energy governance has always been integrated into a broader political context, where the interests of different social groups and state institutions determine the direction and pace of energy sector development. A comprehensive bibliometric analysis of the energy poverty literature by Zheng et al. (2021) indicates that energy affordability issues are inextricably linked to the political and regulatory aspects of energy governance. They emphasize that the fight against energy poverty requires not only technical solutions but also political will, social justice, and the implementation of appropriate public policies that ensure equal access to energy for all segments of the population.

Production cost is a critical factor for investors because it directly influences the profitability and risk profile of investment projects (Shymko and Slipych 2024). According to Akbari et al. (2021), fluctuations in micro-structural factors, such as changes in production costs, can dynamically affect private investment decisions by altering expected returns and uncertainty. Lower production costs improve profit margins, thereby making projects more attractive and encouraging higher investment levels (Tryhuba et al. 2022). Pavolová et al. (2021) emphasize that portfolio managers prioritize industries with efficient cost structures because they yield better returns relative to risk. Efficient production cost management is thus a key indicator for investors assessing an industry's potential, guiding capital allocation toward sectors and firms that can sustain a competitive advantage and generate stable returns.

The problem of optimizing wind farm designs to increase efficiency and reduce costs is a pressing issue in the modern energy industry. Çelik et al. (2021) explored the optimization of wind farm designs, focusing on reducing metal intensity and cost. The researchers concluded that the use of lightweight materials and design simplification can significantly improve efficiency and reduce manufacturing costs. Singh et al. (2023) investigated the effects of dynamic loads on bearings in wind farm systems, finding that reducing these loads increases the durability of the equipment. In their findings, the researchers emphasized the need for regular monitoring of bearing conditions to prevent premature wear.

The purpose of this study was to design and analyze an innovative Savonius wind turbine with a vertical axle, aiming to make it more economical and durable. The objectives of the study were as follows:

1. To investigate the effects of a new wind farm design on reducing production and operating costs.

2. To consider the parameters affecting the metal intensity of the design and bearing durability.

3. To evaluate the competitiveness of the proposed model in continental climate conditions in comparison with conventional vertical wind farms.

The study hypothesizes that the introduction of an innovative wind turbine design with a stationary vertical axis and the use of a Savonius rotor with an anti-storm valve will significantly improve the reliability and efficiency of the turbine compared to traditional models with a rotating shaft. It is expected that this design will reduce the impact of dynamic forces on the bearing supports. Additionally, it will reduce metal consumption and simplify the manufacturing process. These improvements, in turn, will reduce operating costs and increase the service life of the plant.

1. Materials and methods

In this study, a new vertical-axis wind turbine (VAWT) scheme of the Savonius type with a fixed vertical axle is proposed, aiming to address the design challenges of conventional wind turbines. In the initial phase of the study, a thorough theoretical evaluation of existing vertical-axis rotation wind turbine designs was conducted. The study encompassed both conventional schemes and innovative designs, enabling the identification of the key drawbacks of the latter. The analysis of existing models revealed that most of them suffer from excessive material costs and low structural rigidity, which leads to rapid wear and tear, as well as the need for frequent repairs.

The choice of the Savonius rotor is driven by its high resistance to strong wind gusts and turbulence, which are typical for regions with continental climates and unpredictable changes in wind direction. The semi-cylindrical blade shape ensures stable and reliable operation under such conditions. At the same time, the absence of a need to orient the turbine relative to the wind direction significantly simplifies the design and reduces operational costs. Additionally, the Savonius rotor boasts a straightforward manufacturing process, rendering it a cost-effective option for modular wind installations with scalable potential. Collectively, these factors determine its relevance and advantages within the proposed innovative design framework.

To confirm the feasibility and scalability of the proposed concept, a detailed breakdown of the costs of manufacturing and installing a modular wind turbine with a fixed vertical axis is provided. The metal consumption of the structure is reduced by approximately 1.5 times compared to traditional models, resulting in a significant reduction of material costs by around 35%. The cost of manufacturing blades, axles, and bearing supports accounts for approximately 40% of the total cost, while the use of modular assembly enables a 25% reduction in logistics and installation costs. Less frequent maintenance (every 2 years instead of every 6 months) reduces operating costs by 30–40%. In general, this structured cost estimate confirms the economic feasibility and potential for scaling in industrial production.

As one of the solutions, a modular wind turbine design was proposed, consisting of several parts that are assembled on-site into a single unit. The modules were connected to each other using couplings, which substantially simplified the assembly process and helped to replace individual elements without having to dismantle the entire installation. This scheme also opened the possibility of building high-power wind turbines, providing flexibility in the configuration and scaling of the project.

In the next phase of the study, a new scheme with a fixed vertical axle was developed. The axle was rigidly fixed in the base, significantly increasing the stability of the structure. Bearing supports were attached to the fixed axle, and the rotor blades were connected to these supports. This arrangement eliminated the need for cladding, which not only reduced material costs but also reduced the overall structure's weight. Notably, in this configuration, the load was evenly distributed along a fixed axle, thereby eliminating all dynamic forces resulting from shaft rotation.

Particular attention was paid to the rotor profile, which was designed as a semicircle to optimize aerodynamic performance. These Savonius rotors have demonstrated high resistance to high winds due to their design, which allows the cross-sectional area to be reduced during a storm, thereby minimizing potential damage.

The project involved the fabrication of a complete wind turbine structure, including semi-circular blades, a fixed axle, a generator, and all necessary connecting components. All components were designed with a focus on ease of manufacture and assembly. Elements that provide additional structural rigidity, such as tension wires, were also implemented to help maintain the unit's stability in strong wind conditions.

To ensure the reproducibility of the results and practical implementation of the proposed innovative design of a modular wind turbine with a fixed vertical axis, a detailed step-by-step description of the main stages of manufacturing and installation is provided. This manual is intended for engineers, researchers, and production specialists who seek to implement or adapt the technology to their conditions, ensuring that similar technical and operational performance is achieved.

Component design:

- Develop detailed drawings and technical specifications for all key turbine components: semi-cylindrical Savonius blades, fixed vertical axle, bearing supports, generator, couplings, and fastening elements.
- Ensure dimensional compatibility for modular assembly.

Blade fabrication:

- Manufacture semi-cylindrical blades by stamping or forming appropriate metal sheets, taking into account the required thickness and aerodynamic shape.
- Finish edges and surfaces to optimize aerodynamic performance and durability.

Fixed axle and bearing supports fabrication:

- Produce a rigid vertical axle from steel that meets strength and dimensional requirements.

- Prepare bearing supports designed for mounting on the axle, ensuring minimal friction and high stability.

Module assembly:

- Attach blades to bearing supports using bolts and brackets.
- Connect bearing supports to the fixed axle.
- Assemble individual modules, which will be connected via couplings.

Structural reinforcement installation:

- Install tension wires or steel cables between the mast and the turbine top to provide additional rigidity and withstand wind loads.

Generator and gear train installation:

- Mount the generator on the mounting tube and connect it to the rotating turbine part via a gear train selected for reliability and ease of maintenance.

Foundation installation:

- Prepare a concrete foundation in accordance with the project specifications.
- Securely fix the vertical fixed axle into the foundation using anchor bolts.

Electrical system connection:

- Connect the generator electrically to the external grid or battery storage systems via controllers and protective devices.

Testing and adjustment:

- Conduct turbine startup and monitor performance.
- Adjust braking and rotation speed control systems to ensure safe and optimal operation.

Once the design was finalized, the wind turbine parts, including the blades, fixed axle, bearing supports, and other components, were fabricated. These parts were carefully assembled into modular units to facilitate transport and installation. The result was a functional example of a vertical-axis wind turbine ready for installation at the selected site. A gear train was used to provide the connection between the generator and the unit. The gear train was chosen for its reliability and ease of maintenance, which makes the design more resistant to wear and tear, as well as mechanical damage. Based on the analysis of all the conducted work stages, the advantages of the proposed fixed-axle wind turbine scheme compared to conventional rotating shaft schemes were identified.

2. Results

The introduction of wind farms has gained considerable importance worldwide as countries intensify efforts to combat climate change and reduce environmental pollution. Governments are committing to ambitious targets aimed at significantly decreasing industrial greenhouse gas emissions and minimizing the combustion of hydrocarbon fuels in energy production. In this context, renewable energy sources, particularly wind energy, have become critical components of national and international energy strategies (Rediske et al. 2021; Mu et al. 2022). Wind farms harness the kinetic energy of the wind to generate electricity in a sustainable and environmentally friendly manner. These installations are broadly classified into two main types based on the orientation of the rotor's axis of rotation: horizontal-axis wind turbines (HAWT) and VAWT. Each type possesses distinct operational characteristics, advantages, and limitations that influence its suitability for different geographic locations and climatic conditions. Understanding these fundamental differences is essential for optimizing wind energy deployment and maximizing its contribution to clean energy goals (Sivak et al. 2024).

These wind farms feature a diverse range of rotor and windwheel designs; each developed to optimize performance under specific environmental conditions. Among the most common rotor configurations are the Savonius, Darier, Evans, and Musgrove schemes, alongside carousel designs and other innovative variants (Fasihi et al. 2021; Wang et al. 2022). Each design differs in aerodynamic principles, mechanical complexity, efficiency, and suitability for various wind regimes. For example, some rotors prioritize simplicity and durability, while others aim for higher efficiency at the cost of increased manufacturing complexity. By analyzing these diverse types, it is possible to identify the primary advantages and limitations associated with each configuration. This comparative assessment enables more informed decisions when selecting or developing wind turbine systems tailored to specific applications and climatic conditions. Table 1 presents a comparison of the efficiency and main characteristics of vertical and horizontal wind farms.

Table 1. Comparative characteristics of vertical and horizontal wind farms

Tabela 1. Charakterystyka porównawcza pionowych i poziomych farm wiatrowych

Parameter	Fixed-Axle Vertical-Axis Wind Turbine	Standard wind farm (horizontal-axis)
Coefficient of efficiency (COE)	0.18	0.30–0.45
Metal intensity	500 kg/MW	800–1,200 kg/MW
Resistance to strong winds	High (up to 30 m/s)	Medium (up to 25 m/s)
Need for orientation	Not required	Required
Installation difficulties	Low (3–5 people, 1–2 days)	High (5–10 people, 3–5 days)
Scope of application	Flat and steppe regions	Various regions, including coastal
Complexity of production	Simplified (simple parts)	Complex (lengthy process)
Wind resistance	Low (up to 10% of total load)	High (up to 20% of total load)
Durability of construction	25 years	20 years
Maintenance	Rare (every 2 years)	Frequent (every 6 months)

Source: compiled by the authors based on W. Xu et al. (2021), W.S. Udo et al. (2024)

To better illustrate the structural and technological limitations associated with conventional wind turbine shaft configurations, Figure 1 presents three typical design schemes. These include the traditional continuous long rotating shaft, a modular shaft design assembled with couplings, and a short cantilever shaft configuration. Each of these schemes highlights specific engineering challenges such as alignment precision, mass-induced load on supports, and lack of structural rigidity that limit their efficiency and long-term operational reliability.

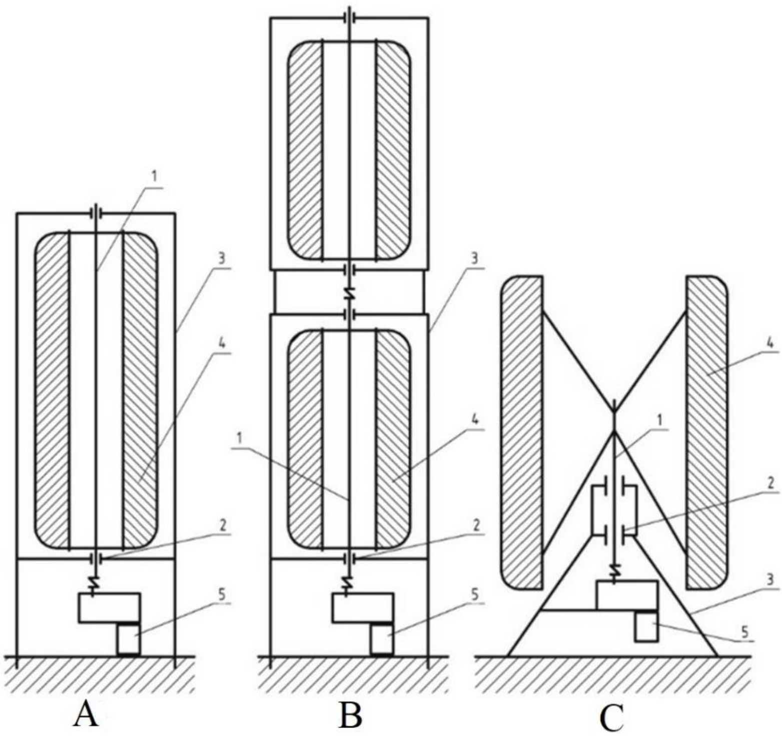

Fig. 1. Designs of rotating shaft wind turbines
Source: compiled by the authors

Rys. 1. Konstrukcje turbin wiatrowych z wirującym wałem

Regardless of the differences between these schemes, they share one common feature – the difficulty of manufacturing the long shaft 1 (Fig. 1A), to which the rotor blades 4 are attached, as well as the difficulty of vertical installation in the bearing supports 2 placed within housing 3. The development of bearing support 2 is a challenging technological task, as it is required to ensure the alignment of the bearing supports 2 and their sufficient rigidity in housing 3. Another disadvantage of the design is the large mass of the shaft, which exerts pressure on the lower rotating support 2 and causes a high friction moment. This leads to a decrease in the efficiency of the wind turbine and reduces the energy production of generator 5, which is connected to shaft 1 through coupling 6. Manufacturing such a shaft and mounting it in a housing is a challenging task. One potential solution to this problem is the use of a modular design of the wind turbine. It consists of several components – modules, which are then assembled on-site into a single unit.

The shafts of the modules are connected to each other using couplings (Fig. 1B), which allows the creation of wind turbines with high power output.

A short cantilever shaft scheme is also used, in which the supports only support the shaft from below, and the blades are attached at closely spaced points. However, this mounting arrangement does not provide the required stiffness or durability (Fig. 1C). A serious disadvantage of Scheme B is the lack of modularity. There are proposals aimed at eliminating the cantilever scheme, where the upper end of the shaft is secured with cable ties (Zakharova et al. 2025). Nevertheless, this scheme practically does not prevent the presence of considerable radial runout of the upper end of shaft 1, which can quickly lead to the destruction of the lower rotational support 2.

The authors proposed an innovative rotor rotation scheme with a fixed vertical axle. Figure 2A shows a standard scheme where axle 6 is firmly fixed in the foundation. Bearing supports 2 are mounted on it, to which rotor blades 4 are connected. A toothed pair of wheels 7, located on the lower support 2, transmits the rotation of the blades to the generator 5. In this arrangement, there is no housing 3, and the main element is axle 6, which takes all the force loads.

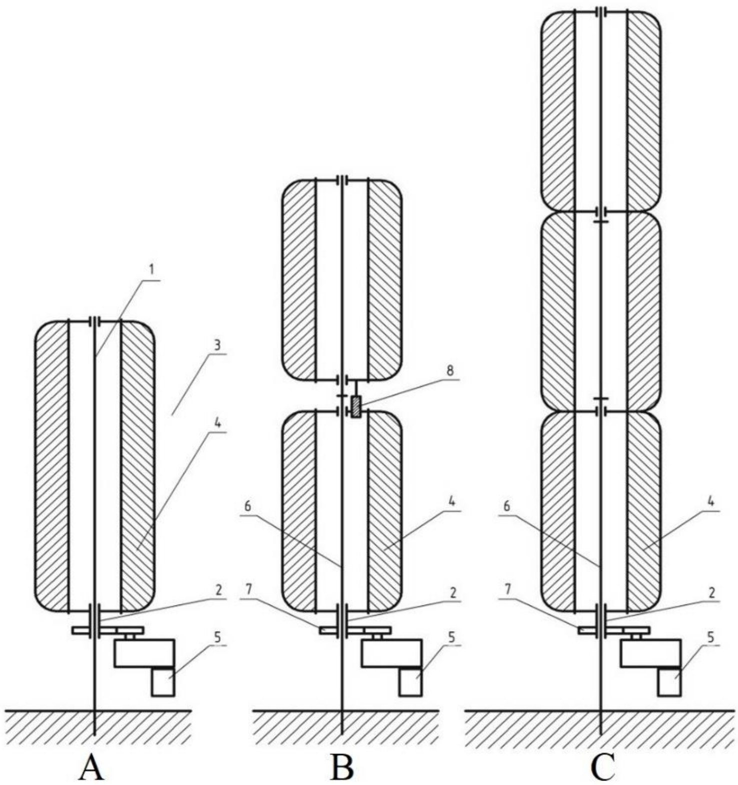

Fig. 2. Designs of fixed-axle wind turbines
Source: compiled by the authors

Rys. 2. Konstrukcje turbin wiatrowych z osią stałą

Figure 2B shows a modular version of a wind turbine consisting of two modules connected by rigid joining of axles 6 and blades 4 of separate modules connected by means of brackets 8. Figure 2C shows a modular variant with a reduced number of bearings supports 2, where two blades from different modules are simultaneously attached to one support. This arrangement reduces the number of bearings, but the total number of modules must be at least three and odd. Three modules require 4 bearing supports (Scheme 2B – 6), which means that in Figure 2C the number of supports is reduced by a factor of 1.5.

All rotor rotation schemes were compared in terms of their efficiency. A wind farm is designed to capture the kinetic energy of the wind, which is converted into the rotation of the rotor blades, driving the generator (Saad et al. 2021; Chaudhuri et al. 2022). This is the primary purpose of a wind farm, and these forces are necessary for its operation. All other forces that occur during the operation are undesirable. These forces create extra loads, hinder the proper functioning of the mechanism, and may lead to its destruction. In the following, these forces were considered and organized according to the degree of negative influence on the operation (Fig. 3).

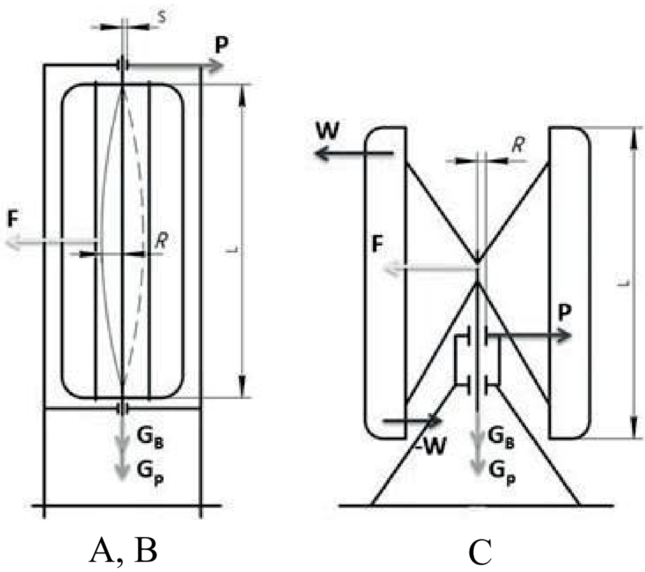

Fig. 3. Schemes of distribution of forces that interfere with the operation of wind turbines in rotating shaft designs
Source: compiled by the authors

Rys. 3. Schematy rozkładu sił zakłócających pracę turbin wiatrowych w konstrukcjach wałów obrotowych

Schemes A and B (Fig. 3) show the following elements of the distribution of forces that interfere with the operation of the wind turbine in rotating shaft designs:

1. Centrifugal force F. In such schemes, the shaft has a considerable length, which depends on the length of the blade L. To achieve high power, it is necessary to increase the area covered

by the rotor blades and, hence, the length L. A long shaft has low stiffness, especially when the length exceeds 20 diameters, which leads to deflection in the middle by an amount R of displacement. The rotation of a shaft with a heavy rotor produces a centrifugal force F, which creates alternating loads on the supports and contributes to their failure.

2. The pressure force on the upper support P. The length of the blade L establishes a considerable distance between the bearing supports, resulting in misalignment between them, denoted by the value S. As the shaft rotates, this misalignment causes a cyclic force P of pressure on the upper support, resulting in rapid bearing wear.

3. The forces of gravity of the rotor GP and the shaft GB. These forces exert pressure on the lower bearing support, causing friction that reduces the coefficient of efficiency (COE) of the wind farm and accelerates wear on the lower bearing support.

Scheme C (Fig. 3) shows the following elements of the force distribution that interfere with the operation of the wind farm in rotating shaft designs:

1. Centrifugal force F. It arises due to the cantilever arrangement of the shaft, which at the free end will be deflected by an amount R from the axis of rotation, resulting in rapid wear of the bearing arrangements.

2. The force exerted on the blade ends W. In this scheme, the blade attachment is also cantilevered. The gusty wind creates a force W, which, acting on the blade ends, causes considerable vibration and prevents free rotation of the shaft in the supports.

3. Pressure force P on the lower support. The centrifugal force F and the forces W acting on the shaft will create a force P that will rotate with the shaft, causing shock loads on the support and contributing to its failure.

4. The forces of gravity of the rotor GP and shaft GB. These forces create pressure on the lower bearing support, resulting in friction within it.

The proposed schemes of wind farms have no rotating shaft, which is replaced by a fixed axle, i.e., the moving link was replaced by a stationary support, according to the terminology of the theory of mechanisms. As a result, all forces arising from the action of this shaft link were eliminated. In all schemes (Fig. 4), only the gravitational force of the rotor blade GP is left, with deviations of the stationary axle from the rotor rotation axis R being compensated for by the flexibility of the blade structure, which should not have a high stiffness, unlike the rotating shaft.

Figure 4 illustrates the distribution of forces that interfere with the operation of wind turbines in the proposed fixed-axle configuration. This diagram illustrates a key mechanical innovation: the elimination of the rotating shaft, which traditionally generates complex dynamic loads on the structure. By replacing the rotating element with a stationary axle, the design fundamentally alters the mechanical equilibrium of the system. As shown, the only remaining external force acting on the system is the gravitational force of the rotor blade (GP). Importantly, any minor deviations of the fixed axle from the central rotation axis (R) are passively compensated by the inherent flexibility of the rotor blade itself. Unlike in conventional systems, this flexibility does not require meeting high stiffness requirements, thereby simplifying the structural demands. Consequently, the simplified force distribution enhances structural reliability, reduces wear on support components, and contributes to greater mechanical stability under variable wind loads.

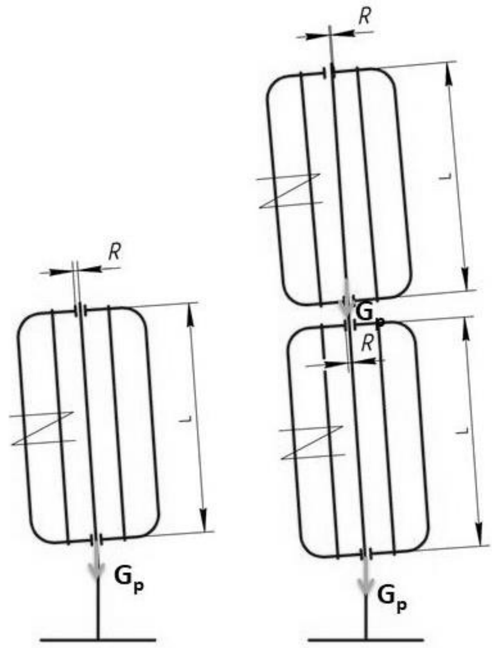

Fig. 4. Schemes of distribution of forces interfering with the operation of a wind turbine in a fixed axle design
Source: compiled by the authors

Rys. 4. Schematy rozkładu sił zakłócających pracę turbiny wiatrowej w konstrukcji z osią stałą

The Savonius rotor has a straightforward technological design, resembling a half-cylinder, which provides it with high resistance to storm winds (Shende 2022; Berest and Sablina 2024). The parallelogram scheme of the wind wheel installation allows for reducing the swept area in strong wind conditions and cushioning the blade load during sudden gusts. The temperature of the environment can change rapidly over a brief period, with a significant temperature difference between summer and winter, ranging from +40°C to –40°C. The efficiency of the Savonius rotor is little affected by wind erosion with sand and icing in severe frost conditions (Barnes et al. 2021; Al-Gburi et al. 2022). The Savonius blade has the shape of a half-cylinder, the parameters of which are little changed by abrasion and ice coating under severe frost.

The efficiency of the Savonius rotor when using wind is 0.18 (Dorel et al. 2021; Fan et al. 2021). As a design solution, the following scheme of the wind farm consisting of different components is proposed (Fig. 5).

The capacity of this wind farm can be increased by adding additional modules consisting of a fixed axle 2 and two blades 1. Additionally, a crossbar can be installed on top of the wind turbine, and external ropes can be stretched, providing the structure with the necessary rigidity and strength. To reduce the impact of hurricane wind on the blade and prevent its breakage, the authors of this study created a Savonius wind turbine blade with an anti-storm flap.

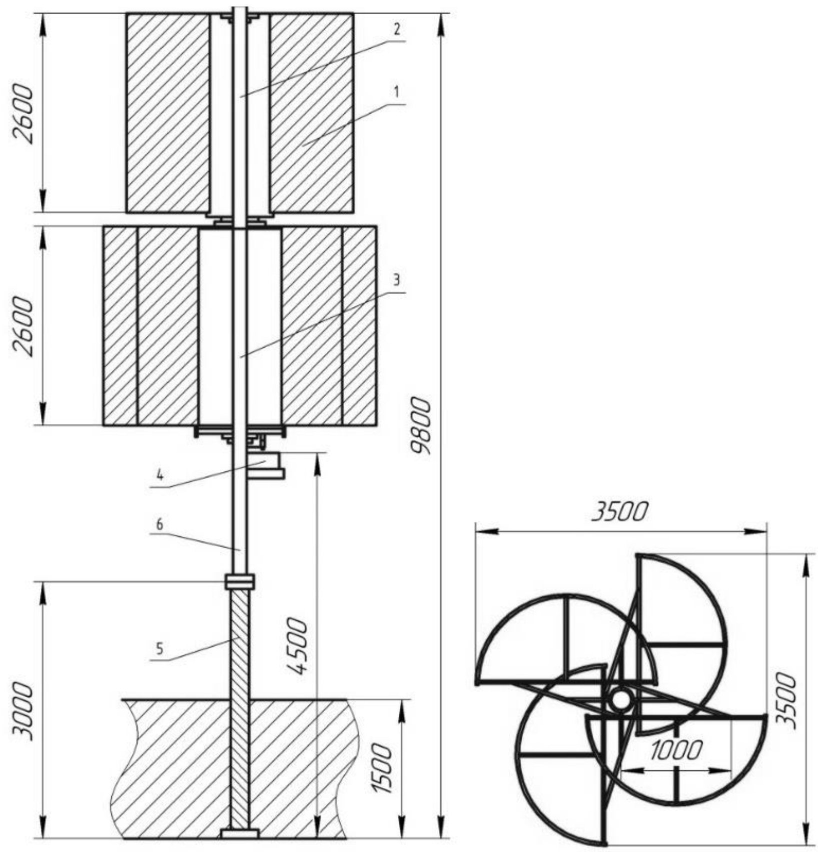

Fig. 5. Design of Savonius wind turbine, top view
1 – semi-cylindrical blade, 2 – fixed axle, 3 – lower fixed axle, 4 – generator mounting tube,
5 – foundation mounting tube, 6 – generator
Source: compiled by the authors

Rys. 5. Konstrukcja turbiny wiatrowej Savonius, widok z góry

A wind power plant with a vertical axis of rotation of the rotor of the Darier type is known. The rotor blade of such a unit has a complex curvilinear aerodynamic profile (Eltayesh et al. 2023). The disadvantage of such a blade is complicated manufacturing technology. In addition, such a profile performs poorly in icing conditions in winter and in windy, sandy conditions.

A wind turbine with a vertical axis of rotation featuring a Savonius rotor is known to the authors of this study as a prototype. The Savonius rotor blade has a profile in the form of a half-cylinder, which is cut along a vertical plane passing through its vertical axis and the diameter of the base circle. The Savonius blade features a simple manufacturing technology and performs well in icy and dirty wind conditions (Marinić-Kragić et al. 2022).

The relative disadvantage of this blade shape is its extensive sail area (the area interacting with the wind). In a strong hurricane wind (storm), a large wind force is exerted on the blade, which may lead to the breakage of the blade and the entire unit.

The objective of the invention is to reduce the wind force acting on the blade in strong hurricane winds, thereby preventing blade breakage and the entire wind turbine from breaking, which will increase the wind turbine's operating time. The use of the proposed Savonius blade design will reduce the force of hurricane winds acting on the blade, thereby preventing blade breakage and increasing the operating time of the wind turbine.

The technical result is achieved by providing a Savonius wind turbine blade with an anti-storm flap having a profile in the form of a half-cylinder, which is sliced along a vertical plane passing through its vertical axis and the diameter of the base of the circle. In addition, a flap is disposed on the side surface of the half cylinder, which is pressed against the side surface by means of a resilient element, enabling it to move and forming a gap between the surface of the flap and the side of the blade.

The Savonius wind turbine consists of a vertical shaft 1; the shaft has cross beams 2 to which two Savonius blades 3 are diametrically attached (Fig. 6). Shaft 1 is coupled to a generator 4. There is a brake 5 on the shaft 1. On the side surface 6 of the semi-cylindrical blade 3, there is a movable flap 7. The flap 7 is attached to a series of rods 8 rigidly mounted

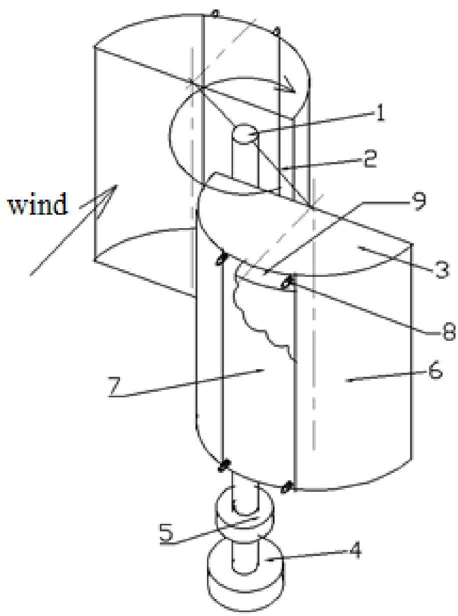

Fig. 6. Schematic diagram of the entire wind turbine
Source: compiled by the authors

Rys. 6. Schemat całej turbiny wiatrowej

on frame 9 of blade 3. Each rod 8 has a compression spring 10, which presses the flap 7 against the side surface 6 of the blade 3, and a lock nut 11, which adjusts the compression of the spring 10 (Fig. 7).

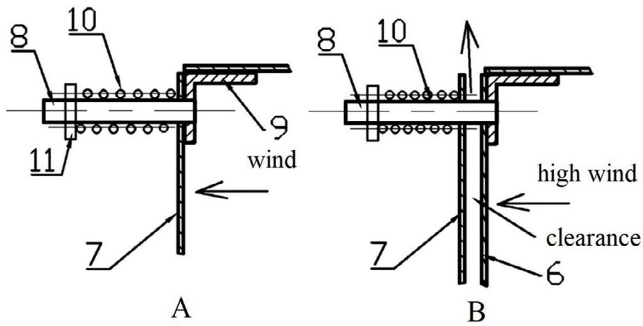

Fig. 7. Blade fragment with fixing rods and flap
A – working position, normal wind strength, B – hurricane wind position
Source: compiled by the authors

Rys. 7. Fragment ostrza z prętami mocującymi i klapką

The blade works as follows. The wind blows from either side. It hits the side plane 6 and the flap plane 7 of the blade 3, which at this time has a wind-impacted surface. The wind presses on planes 6 and 7. The blade 3 rotates together with the beams 2 and the shaft 1, which rotates the generator 4. The other blade, 3, at this time, rotates against the wind. But its surfaces 6 and 7 are at this time convex with respect to the wind direction, which considerably reduces the wind resistance to this movement. During the operating movement, flap 7 is pressed tightly against surface 6, preventing the wind from passing through and fully absorbing its force, which in turn rotates shaft 1 and generator 4 (Fig. 7A). If the wind becomes stronger, its speed increases. To reduce the speed of the shaft 1, the brake 5 is activated to decelerate the rotation of the shaft 1. The load on blade 3 increases. As the wind force increases, it presses harder on the side plane 6 and the plane of the flap 7. The wind force may break the blade 3. The wind force becomes greater than the pressing force of the springs 10. The wind force, overcoming the compression forces of the springs 10, pushes the flap 7 away from the surface 6. A gap is formed between the flap 7 and the surface 6 (Fig. 7B) into which the wind passes. The force of its pressure on the blade decreases sharply. When the wind force decreases, the compression force of the springs 10 returns the flap 7 to its previous operating state. The gap closes. Blade 3 operates in the previous operating mode.

Application of the proposed design of the Savonius blade will reduce the force of hurricane wind acting on the blade, which will prevent its breakage and increase the operating time of the wind turbine (Patent No. 36436… 2023). According to the proposed scheme, the authors of the study submitted the design documentation and technical specifications for the production of a modular wind turbine to an industrial enterprise. The components of the wind turbine were manufactured, which were then assembled into modules. The wind power plant consists of 5 modules. As a result of assembling the components, 5 modules were obtained:

1. Blades of a wind turbine. Four pieces were manufactured for two modules.
2. The assembly is used to cross-connect the blades. During assembly, all bolts are screwed in all the way, and the bolt heads are welded together in pairs with wire.
3. The lower module of the wind wheel transmits the wind force to the generator. There is a gear wheel on the bearing support that interacts with the gear wheel on the generator shaft.
4. The base and mast of the wind turbine.
5. Stretchers with steel cable to reinforce the structure.

Next, the fabricated modules were assembled into a single structure and installed at the selected site on a concreted base (Fig. 8).

Fig. 8. Wind turbine assembly process
Source: compiled by the authors

Rys. 8. Proces montażu turbiny wiatrowej

A generator is connected to the plant via a gear transmission. The modular wind power plant is being tested. Based on the outcomes of the modular wind power plant testing, the optimum operating modes of the modular wind power plant will be determined, and the electrical equipment will be adjusted accordingly.

Thus, the study's results confirm the practical feasibility of introducing an innovative design for a wind turbine with a fixed vertical axis and Savonius rotors equipped with anti-storm valves. The proposed modular scheme simplifies the manufacturing process, reduces metal consumption, and enhances performance characteristics, including increased durability and reduced maintenance frequency. The analysis of the distribution of forces showed a significant reduction in the negative impact of dynamic loads, which contributes to an increase in the reliability and efficiency of the turbine. The assembly and testing of the modules confirmed the technical performance of the developed design, which opens up prospects for its further implementation in production and use in regions with challenging climatic conditions.

3. Discussion

As a result of this study, an innovative design of a Savonius wind turbine with a vertical fixed axle was developed, which showed a considerable reduction in the metal intensity of the structure. The reduction in manufacturing costs was achieved by simplifying the design and using a fixed axle instead of a rotating shaft. This innovation enhanced the plant's efficiency by reducing friction and dynamic forces, thereby decreasing the load on the bearings and increasing the unit's longevity. The driving mechanisms behind the results are a complex combination of engineering innovations, optimized design solutions, and a strategic approach to resource conservation, which together create a synergistic effect that increases the efficiency and reliability of a wind turbine with a fixed vertical axis.

First, the rejection of a traditional rotating shaft in favor of a fixed axis significantly reduces dynamic loads and friction in bearings, resulting in reduced wear, longer component life, and lower operating costs. This technical step is crucial for enhancing system reliability and minimizing overall maintenance costs. Secondly, the modular architecture of the turbine enables a significant simplification of the production process and installation, which helps reduce capital costs and increases the flexibility of project scaling. The ability to quickly replace or repair individual modules without dismantling the entire plant ensures prompt maintenance and minimizes downtime, a crucial factor in commercial attractiveness. Thirdly, the use of a semi-cylindrical Savonius blade profile with a special anti-storm valve mechanism demonstrates a high degree of adaptability to variable and extreme weather conditions, which is especially important for continental climates with strong wind gusts. This aerodynamic optimization reduces mechanical stress and the risk of damage, increasing durability and operational safety. Fourth, the significant reduction in metal consumption and weight not only reduces production costs but also contributes to the principles of the circular economy, reducing environmental impact and increasing the sustainable potential of the technology.

The study by Yao et al. (2022) highlights the importance of enhancing energy efficiency through innovative design solutions and system optimization in the energy sector. They emphasize that improving the technical characteristics of equipment directly reduces energy losses and increases productivity. The proposed design of a modular wind turbine with a fixed axis demonstrates a concrete embodiment of these principles: reducing metal consumption by approximately 1.5 times reduces material costs, and the absence of a rotating shaft eliminates dynamic loads, thereby increasing durability and stability. This aligns with the areas identified in the bibliometric analysis by Yao et al., where design innovations are considered key to the development of energy-efficient technologies.

On the other hand, Guryanova and Chernova (2019) and Razminienė et al. (2021) consider the development of energy technologies through the prism of the circular economy, emphasizing the importance of resource efficiency, waste reduction, and cluster cooperation for sustainable industrial development. The modular architecture of the wind turbine proposed in this paper not only helps optimize production costs but also facilitates the repair and replacement of individual components, minimizing waste and extending the life cycle of the installation. The local assembly of modules reduces logistics and energy costs associated with transportation, which aligns with the principles of the circular economy emphasized by these authors. Additionally, the use of less metal-intensive materials and a reduced structure weight directly reduces the environmental footprint of production.

Thus, the proposed technology combines the approaches described in the two papers: on the one hand, it meets the requirements for improving energy efficiency through engineering innovations, and on the other hand, it integrates the principles of sustainable production and resource conservation. Unlike many existing models, which often overlook the complexity of these factors, the fixed-axis modular wind turbine provides a more balanced solution that can compete in the market due to its increased efficiency, reduced operating costs, and compliance with modern environmental requirements.

Energy storage remains one of the most crucial challenges facing the energy sector today, as it is essential for balancing supply and demand, integrating renewable sources, and ensuring national energy security (Kravtsova et al. 2024; Savin and Kirichenko 2024). According to Samusevych et al. (2021), effective environmental policies, including environmental taxes, can play a significant role in optimizing energy infrastructure and promoting investments in energy storage technologies. Their structural optimization model highlights that enhancing energy storage capabilities is vital not only for environmental sustainability but also for maintaining national security by stabilizing the energy supply and reducing reliance on external sources. This highlights the pressing need to prioritize energy storage solutions within the broader context of energy management and policy development.

Zhang et al. (2021) also investigated this issue, and their findings confirmed that the wind turbine design comprises major components, including wind turbines, generators, transformers, and control systems, which work together to produce electricity. Visualizing this schematic provides a better understanding of how wind energy is converted into electrical energy, as well as identifying the key components that affect the unit's efficiency. This approach to structuring information also helps in the design and optimization of systems, ensuring their reliable and smooth operation.

Shields et al. (2021) and Neupane et al. (2022) also reported that simplification of wind turbine design has become one of the priority areas in modern technologies, which allows for significantly reducing the cost of production and installation. The use of innovative materials and design methods helps to create lighter and more efficient structures, which reduces the cost of transport and installation (Iskenderov et al. 2024; Azizov et al. 2019). This not only makes wind farms more affordable to invest in but also facilitates the broader spread of renewable energy in various regions. Notably, simplifying the design of a wind farm not only reduces production costs but also positively impacts its overall efficiency and reliability. Simplified systems are easier to maintain, which reduces downtime and contributes to faster project implementation. Thus, design optimization is a key element that not only makes wind power more competitive but also strengthens its role in the transition to sustainable energy sources.

The studied fixed-axle wind turbine designs have demonstrated considerable advantages over conventional models. The design, which does not require orientation in the wind direction, proved to be more resistant to strong gusts, which confirms its high reliability in continental climates. This opens new opportunities for installing such stations in regions where conventional solutions may not be suitable. Jang et al. (2022) and Li et al. (2022) concluded that resistance to strong wind gusts is one of the critical factors in the design of wind farms, especially in regions prone to storms and hurricanes. Modern turbine models are designed to withstand increased loads, enabling them to operate safely even under extreme conditions (Kerimkhulle et al. 2022; Vychuzhanin and Vychuzhanin 2025). This not only protects the equipment from damage but also ensures stable power generation during unfavorable weather conditions.

Tong et al. (2021) revealed that the reliability of a wind turbine in continental climate conditions depends on its ability to adapt to significant temperature fluctuations and a variety of weather events. Designing such units with consideration of specific local climatic features allows for minimizing the risks associated with the freezing of mechanisms or wear and tear of materials. As a result, high-quality solutions for structural elements and control systems contribute to the overall reliability and efficiency of power plants in continental climates. These findings support the above study, as they demonstrate that a wind turbine's resilience to strong wind gusts and its reliability in continental climates are interrelated factors that affect the overall efficiency and longevity of the unit. Having a robust design that can withstand extreme weather conditions not only protects the equipment but also enhances investor confidence in the project's stability (Prentkovskis et al. 2010; Gu et al. 2024). Consequently, attention to the design and technologies that provide these characteristics becomes essential for the successful operation of wind farms in various climatic conditions.

Financial analyses of the proposed fixed-axle Savonius wind turbine reveal notable advantages in cost-effectiveness and operational efficiency compared to conventional vertical-axis wind turbines with rotating shafts. The reduction in metal usage by approximately 1.5 times directly lowers raw material costs, which constitute a significant portion of capital expenditure in wind turbine manufacturing. Additionally, the modular design facilitates simplified assembly and maintenance, translating into reduced labor costs and shorter downtime. Less frequent maintenance intervals from every six months to once every two years further decrease operational expenditures, improving the turbine's total cost of ownership.

When assessing competitiveness against existing solutions, the fixed-axle design offers enhanced durability due to reduced dynamic loading and friction on bearing supports, which in turn reduces wear and prolongs component lifespan. This reliability translates into greater energy production continuity and lower lifecycle costs. Economically, these factors collectively improve the return on investment (ROI) and payback periods, making the proposed turbine an attractive option for investors and operators, particularly in regions with harsh climates where maintenance challenges are amplified. In comparison to HAWT, which typically demonstrates higher efficiency coefficients (0.30–0.45 versus 0.18 for the Savonius rotor), the proposed solution compensates through lower manufacturing and maintenance costs, as well as better suitability for turbulent, multidirectional winds found in continental climates. This positions the turbine as a competitive alternative in niche markets where traditional turbines face technical or economic constraints.

The new fixed axle design was also found to reduce bearing wear significantly. The use of a fixed axle reduced the load on the lower supports, ensuring a longer service life for the equipment. These findings suggest that the proposed wind farm design is not only cost-effective but also highly reliable. Costa et al. (2021) also reported that the increase in the service life of wind farm equipment is directly related to the quality of materials and technologies used. Regular maintenance and monitoring of component conditions, such as blades and transformers, help prevent premature wear and breakdowns. Longer equipment life not only reduces replacement costs but also increases the overall efficiency of the power unit.

Shorabeh et al. (2022) concluded that the economic efficiency of a wind farm is determined not only by the costs of its installation and operation but also by the income from the sale of generated electricity. In conditions of stable wind flows, these units can generate significant profits due to their low operating costs and the absence of fuel costs. However, it is vital to recognize that initial investments can be extensive, and the economic viability of projects depends on long-term planning and risk assessment. These findings are consistent with the thesis in the previous section, emphasizing the relationship between increased equipment lifetime and the economic viability of wind farms. Durable and reliable components not only reduce overall maintenance costs but also contribute to the project's overall profitability (Korzhik 1992; Kunitskii et al. 1988). Thus, attention to material quality and regular maintenance are key aspects that affect the successful operation of wind farms in a competitive energy market.

Furthermore, the conducted study confirmed that the innovative design reduces the number of bearings, which also contributes to cost reduction. In the multi-module design, where several blades are attached to a single bearing, a reduction of 1.5 times in the number of bearings has been achieved. This makes the design more compact and easier to install, which is significant for practical applications.

Wilberforce et al. (2023) also conducted a study that confirmed that the compactness of the wind turbine design plays a significant role in its location, especially in regions with limited space, such as mountainous areas or densely populated areas. More compact models require less land for installation, making them suitable for areas with agricultural land, such as in southern Ukraine. This enables the optimization of land resource use without compromising energy production efficiency. Guo et al. (2022) also found that the ease of installation for a wind farm depends on its design features and the availability of infrastructure. The ease of installation enables the rapid deployment of plants, even in hard-to-reach locations such as the Black Sea coast, which accelerates commissioning time. Furthermore, modern stations require minimal human involvement during operation thanks to automated monitoring and control systems.

Comparing the data obtained from the studies, a direct correlation is found between parameters such as the compactness of design and ease of installation and the overall efficiency level of wind farms. More compact models not only take up less space but also make them easier to install, which ultimately reduces installation costs and favors quick commissioning. These factors underscore the importance of optimizing design solutions to maximize performance and sustainability in the face of a changing climate and rising energy demands. However, alongside the positive findings, some issues have emerged that require further investigation. For instance, despite the marked improvement in structural stiffness, further testing is needed to assess its behavior in extreme weather events. The question of how to maintain and repair such units remains significant, potentially affecting their long-term performance.

Pryor and Barthelmie (2021) concluded that wind farms can face extreme weather events, such as hurricanes, heavy rains, and snowfalls, which can adversely affect their efficiency and safety. During hurricanes, wind speeds can exceed the operating limits of wind turbines, causing them to shut down automatically (Kaverin et al. 2024). Furthermore, heavy precipitation can cause flooding in the area, making access to facilities for maintenance challenging. Ren et al. (2021) found that maintenance of wind farms is critical to ensure their reliability and longevity. Regular inspections of components, such as blades, generators, and transformers, help identify potential problems before they occur. Furthermore, effective scheduling of repairs can reduce costs and avoid lengthy interruptions in power generation.

Upon analyzing the study's findings, it becomes evident that factors affecting the efficiency of wind farms encompass both climatic conditions and technical aspects of their operation. The established patterns indicate that optimal weather conditions can significantly enhance performance, while extreme events can lead to downtime and increase maintenance costs. Thus, to achieve the sustainable performance of wind farms, it is necessary to consider weather forecasts and develop strategies to minimize the risks associated with adverse climatic conditions.

Thus, the study confirmed that the innovative design of the Savonius wind turbine, featuring a fixed axle scheme, has considerable potential for real-world applications. The obtained findings open new horizons for the development of modern and efficient wind energy solutions. Further research in this field can lead to even more advanced technologies and enhance the competitiveness of wind farms in the renewable energy market.

Despite the advantages of the proposed design of a wind turbine with a fixed vertical axis, certain limitations in the study should be considered when evaluating the results obtained. Firstly, the experimental tests were limited to laboratory conditions that do not fully reproduce the actual climatic and aerodynamic conditions of operation, especially in regions with significant temperature fluctuations, dust storms, and ice layers. Secondly, the article does not provide sufficient detail on the economic analysis, taking into account the full life cycle of the turbine, including transportation costs, field installation, and potential unforeseen technical losses. It is also worth noting that the proposed modular design requires additional optimization for scaling up to higher capacities, as the increase in size may lead to new technical challenges related to stability and mechanical rigidity.

Conclusions

The developed fixed-axle wind turbine demonstrates significant empirical advantages over conventional models with a rotating vertical shaft. The simplified design eliminates the need for complex machining of a long shaft, substantially reducing production time and costs. The absence of a supporting frame lowers metal usage by approximately 1.5 times, directly decreasing manufacturing expenses. The reduction of friction forces in the lower bearing support leads to improved overall system efficiency, thereby enhancing wind energy utilization. Additionally, the decreased dynamic loads on the structure contribute to extended bearing lifespan and increased reliability of the entire turbine. These factors collectively result in a more cost-effective, durable, and efficient wind energy solution suitable for deployment in regions with challenging environmental conditions.

Thus, all the above-mentioned advantages provide considerable simplification and cost reduction in the manufacturing of the mechanical part of the wind turbine. Increasing the lifetime of the unit, along with the known advantages of vertical-axis wind farms, increases their competitiveness. The application of this technology becomes particularly effective in certain conditions, such as regions with strong and variable winds. The findings of this study emphasize that the innovative design can take its rightful place in the renewable energy market, facilitating its diffusion and deployment in many areas.

Despite the promising results demonstrated by the proposed fixed-axle wind turbine design, the study has several limitations that should be acknowledged. The experimental validation was conducted under controlled conditions that may not fully replicate the complexity of real-world environments, particularly in regions with highly variable wind patterns or extreme weather events. Additionally, while the reduction in material intensity and maintenance needs has been quantified, a complete life-cycle cost assessment, including transportation, installation in diverse terrains, and long-term operational performance, remains to be completed. The aerodynamic performance of the Savonius rotor, although suitable for low-speed and turbulent winds, may be less competitive in high-wind coastal or offshore areas where horizontal-axis turbines dominate. The modular assembly process, while advantageous in terms of scalability, requires further optimization for industrial-scale deployment to ensure economic feasibility across different market segments. These limitations highlight the need for broader field testing and comprehensive techno-economic modeling in future research.

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Projekt i badanie nowego schematu turbiny wiatrowej Savonius z pionową osią stałą

Streszczenie

W artykule ukazano badanie przeprowadzone w celu opracowania i oceny skuteczności nowego schematu turbiny wiatrowej Savonius z pionową osią stałą, która ma zalety w zmniejszaniu intensywności metalu i czasu pracy. Zastosowano metody analizy teoretycznej istniejących konstrukcji turbin wiatrowych, modułową konstrukcję osi stałej oraz modelowanie aerodynamiczne profilu wirnika w celu poprawy wydajności elektrowni. W wyniku badań opracowano nowy schemat turbiny wiatrowej Savonius z pionową osią stałą. Zaproponowany projekt pomógł znacznie zmniejszyć metalochłonność elektrowni o około 30%, co obniżyło koszty produkcji. Brak obracającego się wału i zastąpienie go stałą osią spowodowało zmniejszenie tarcia we wsporniku, co zwiększyło wydajność elektrowni. Zmniejszono również siły dynamiczne działające na konstrukcję, co przyczyniło się do wydłużenia żywotności łożysk. Wykazano, że nowy projekt turbiny wiatrowej jest łatwiejszy w produkcji, bardziej niezawodny i opłacalny niż konwencjonalne pionowe farmy wiatrowe. Dzięki tym ulepszeniom nowy system jest bardziej konkurencyjny i możliwy do zastosowania w klimacie kontynentalnym. Stwierdzono również, że zastosowanie stałej osi zmniejsza zużycie podpór łożysk, zwiększając ich żywotność. Konstrukcja stałej osi zmniejszyła obciążenie dolnych podpór, co zmniejszyło uszkodzenia mechaniczne i poprawiło ogólną niezawodność systemu. Badanie potwierdziło, że ta turbina wiatrowa jest lepiej przystosowana do warunków z intensywnymi wiatrami i częstymi zmianami kierunku wiatru, co czyni ją szczególnie wydajną w regionach o klimacie kontynentalnym.

Słowa kluczowe: zużycie metalu, tarcie, siły dynamiczne, łożyskowanie, klimat kontynentalny