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Efficiency coefficient of wind installations

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Abstract:

This study examines the main trends in the modern development of wind energy, addressing the critical tasks and proposing solutions for advancing wind energy technology. It includes theoretical calculations of the efficiency factor of wind turbines, particularly focusing on the Betz limit, which traditionally sets an upper bound on their efficiency. The research highlights the fallibility of Betz's limit calculations in both physics and mathematics, challenging its long-held assumptions. A novel formula for the true dependence of wind turbine efficiency on the utilized energy of the wind flow is derived, providing a more accurate representation of their performance. This new formula is supported by a graph illustrating the relationship between wind energy input and turbine efficiency. Additionally, the study explores various strategies and innovative approaches to enhance the efficiency of wind turbines, aiming to maximize their potential in harnessing wind energy. These findings contribute to the ongoing efforts to improve renewable energy technologies and increase the viability of wind power as a sustainable energy source.

Keywords: vertical-axial wind turbine; horizontal-axial wind turbine; wind flow; coefficient of wind flow energy utilization; blades

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1. Introduction

The use of wind energy has undergone a significant and lengthy evolutionary process, transitioning from simple mechanical windmills used for basic agricultural tasks to sophisticated, large-scale industrial wind turbines. These modern turbines are designed to harness the power of wind more efficiently and are now capable of generating substantial amounts of energy [1]. Over the years, technological advancements have led to the development of wind turbines with impressive capacities ranging from 6 to 8 megawatts (MW) per unit. These turbines are massive structures, with mast heights typically reaching between 120 and 140 meters, and the lengths of their blades extending up to 60 to 80 meters [2]. Such dimensions allow the turbines to capture greater wind energy over a larger swept area, significantly improving their energy output [3].

However, these advancements come with substantial material and structural demands. The total weight of modern wind turbines can reach up to 6,000 tons, including the heavy components of the tower, rotor blades, nacelle, and various other mechanical and electrical systems [4]. This immense weight and size are necessary to withstand varying wind speeds and environmental conditions while maintaining operational stability and efficiency [5]. The scale of these installations also reflects the level of investment in research and development to optimize the design and performance of wind turbines, making them not only more powerful but also more resilient to wear and tear over time [1, 6].

Despite these impressive achievements, the main challenge facing the wind energy sector today is not merely about maximizing energy output from each turbine [7]. A critical focus is on producing renewable energy at a cost that can compete with traditional energy sources, such as those derived from burning hydrocarbon fuels [8]. This involves enhancing the efficiency of wind turbines, improving energy conversion technologies, and reducing the costs associated with manufacturing, installation, and maintenance [9]. The ultimate goal is to make wind energy an economically viable alternative that can contribute substantially to global energy needs while helping to reduce carbon emissions and combat climate change [10].

The purpose of this article is to demonstrate methods to increase the efficiency of wind energy and to reduce the costs associated with the creation and operation of wind turbines [11, 12]. At present, large-capacity horizontal-axis wind turbines, which produce up to 70% of all wind energy, have become the most widespread [11, 13, 14]. However, these turbines come with several significant disadvantages:

- Their large size and weight result in high material consumption and extended manufacturing times. This, in turn, increases the cost of the wind turbines themselves and the energy they produce [15].
- The logistics of delivery, installation, and operation of these large structures are complex and costly, further driving up the cost of the electricity generated [16].
- These turbines have a relatively low coefficient of wind flow energy utilization (EU) on the swept area of the windmill [17]. Typically equipped with three blades, they can only harness a small portion of the available wind flow.

To address these issues, it is essential to explore innovative designs and technologies that can enhance the efficiency of wind turbines [18]. This includes investigating new materials that are lighter and stronger, improving aerodynamic designs to capture more wind energy, and developing more efficient manufacturing processes to reduce costs [19]. Additionally, optimizing the placement and maintenance of wind turbines can help maximize their energy output and operational lifespan [20]. By addressing these challenges, the goal is to make wind energy a more viable and cost-effective alternative to traditional fossil fuels, contributing to a more sustainable and renewable energy future.

2. Literature and patterns background

The task of this article is to determine the physical processes of converting the energy of the wind flow into mechanical energy and to find mathematical formulas for the dependence of the efficiency coefficient on the mode of operation of wind turbines. The efficiency coefficient, often termed as the "power coefficient", measures the effectiveness of a wind turbine in converting wind energy into usable electrical power. It is defined as the ratio of the turbine's actual power output to the total wind energy passing through the swept area of the turbine blades. It should be noted that even if the entire swept area of the windmill was covered by blades, according to the theory of today's wind energy, the coefficient of wind energy use could not exceed 0.593 according to the Betz limit [11, 21]. However, the authors of this article believe that the analytically obtained maximum theoretical efficiency of all types of wind turbines obtained by Betz does not correspond to reality and prove it based on the reasons given below. There are discrepancies in the equations obtained by Betz and other authors both in the field of physics and in the field of mathematics [11, 12].

Several factors influence the efficiency coefficient of a wind turbine, including blade design, aerodynamic efficiency, wind speed variations, and turbine orientation. Blade shape, material, and length significantly impact the conversion efficiency since they determine how much energy is captured and transferred to the turbine rotor [13, 14]. Additionally, wind speed plays a crucial role in determining efficiency, as power output is proportional to the cube of wind speed. Thus, even small variations in wind speed can cause substantial changes in the turbine's power output. Technologies like pitch control and yaw mechanisms help optimize turbine orientation and blade angle to maintain higher efficiency.

Over the years, advancements in materials and design have led to improvements in the efficiency coefficient of wind turbines [22]. Modern wind installations often use composite materials that offer high strength-to-weight ratios, reducing energy losses due to structural inefficiencies. Additionally, advanced aerodynamic modeling and simulations help optimize blade design, leading to reduced drag and increased lift forces. Control systems, such as smart sensors and real-time feedback loops, help monitor wind speed, direction, and blade position, enabling continuous optimization of turbine performance, thereby improving efficiency.

Despite advancements, challenges remain in achieving higher efficiency coefficients. Wind turbines face issues like turbulence, mechanical losses, and energy conversion inefficiencies. Turbulence near ground level or due to nearby structures can lead to irregular wind flows, affecting the turbine’s efficiency. Additionally, mechanical and electrical losses in components like gearboxes and generators reduce the overall efficiency. Ongoing research focuses on enhancing turbine reliability and durability through better materials, control algorithms, and maintenance strategies to minimize downtime and energy losses. Furthermore, integrating wind installations with smart grids and storage solutions can help in maintaining energy output consistency and better utilization of the harvested wind energy.

The same efficiency limit of wind turbines was independently derived by three distinguished authors from different backgrounds, showcasing the universal nature of their findings. The German physicist Albert Betz first presented this limit in 1919, significantly influencing the field of aerodynamics and wind energy [23]. Prior to Betz, the British scientist Frederick Lanchester explored similar concepts in 1915, contributing to the understanding of fluid dynamics in relation to wind turbines. Meanwhile, the Ukrainian scientist Mykola Zhukovskyi also arrived at this efficiency limit in 1920, further enriching the discourse on wind energy [19, 24]. The concurrence of these three scientists from various nations underscores the fundamental principles governing wind turbine efficiency, highlighting its significance in both historical and contemporary contexts.

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However, the general error of energy selection by the device-wind turbine is uniquely determined by the equation of the flow power at the input and output of the device and, accordingly, the efficiency of the device (wind turbine), fully determines the amount of initial energy given to the device and the energy remaining in the flow [25]. An attempt to add here additional equations of this process during a detailed examination shows the inability of additional equations, their further addition to the equation of state and obtaining an incorrect result.

3. Methods

The Fig. 1 shows the mathematical scheme of the theoretical transformation of part of the energy of the wind flow into mechanical energy with simultaneous transmission of it outside the given wind flow by any device and shows: V_0 – the EU speed at the input to the device, S_0 – cross-sectional area of the flow at the input to the device, S – cross-sectional area of the flow at the output of the device, V – the EU speed at the output to the device.

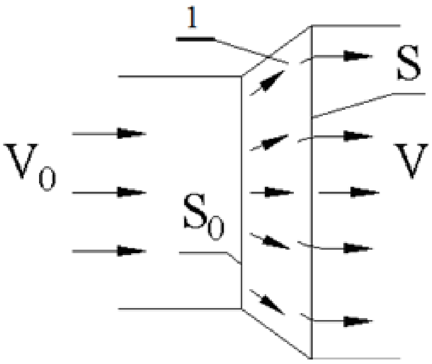

Fig. 1. Scheme of theoretical conversion of part of the wind energy flow: V_0 – the EU speed at the input to the device, S_0 – cross-sectional area of the flow at the input to the device, S – cross-sectional area of the flow at the output of the device, V – the EU speed at the output to the device

For the theoretical determination of the efficiency of using energy units (EU), the design of the EU energy conversion device itself is not of primary importance. The focus is solely on the input and output parameters of the energy unit, disregarding the specific internal mechanisms or structural characteristics of the conversion device. In this context, only the energy entering and exiting the system is considered relevant for calculating efficiency. The internal design elements, such as material composition or mechanical configurations, do not directly impact the theoretical efficiency analysis. This approach allows for a more generalized assessment, independent of variations in device architecture. Therefore, the efficiency can be evaluated by comparing the input energy to the output energy, regardless of how the conversion process is carried out within the device.

According to the law of conservation of mass, the amount of air entering and leaving device 1 (Fig. 1) per unit of time is the same. Based on this, the power of the wind flow used in the device will be the difference in the energies of this wind flow at the entrance and exit of the device per unit of time.

$$P_y = P_0 - P_B \tag{1}$$

where P_0 – EU power at the input to the device 1, P_B – EU power at the output of the device 1, P_y – wind energy power that is converted into mechanical energy and used in the device 1.

Based on this, it is possible to obtain the dependence of the amount of wind energy used by device 1 on its parameters at the input and output of the device.

As you know, the second mass flow of air is equal to:

$$\dot{m} = p \cdot v \cdot s,$$

where $\dot{m}$ – mass second flow of air passing through the transverse wind flow cross section, p - air density, s – cross-sectional area of the wind flow, v – wind flow speed.

For the scheme of Figure 1.

$$\dot{m} = p \cdot v_0 \cdot s_0 = p \cdot v \cdot s \qquad (2)$$

Where $\dot{m}$– the EU mass per second flow through the device, s_0 – cross-sectional area EU at the input to the device, v_0 – the EU speed at the input to the device, p - air density, s - cross-sectional area of the flow at the output to the device, v - the EU speed at the output to the device. Formula (2) shows us that:

$$\frac{v_0}{v} = \frac{S}{S_0} = n \qquad (3)$$

where n a dimensionless quantity.

It is determined that the power is taken from the wind flow in the device, taking the value of the second mass flow from (2), expressing v and S from (3).

Through $\frac{v_0}{n} = v, S = S_0 n$ and also considering that $P = \frac{\dot{m} \cdot v^2}{2}$, and by substituting these values (1) we get:

$$P_y = \frac{\dot{m} \cdot v_0^2}{2} - \frac{\dot{m}}{2}$$

$$P_y = \frac{p \cdot v_0 \cdot S_0 \cdot v_0^2}{2} - \frac{p \cdot \frac{v_0}{n} \cdot S_0 \cdot n \cdot \left(\frac{v_0}{n}\right)^2}{2}$$

Or after transformations we will get:

$$P_y = 0{,}5 \cdot p \cdot v_0^2 \cdot S_0 \cdot \left(1 - \frac{1}{n^2}\right) \qquad (4)$$

the first element of formula (4) $0{,}5 \cdot p \cdot v_0^2 \cdot S_0$ represents the entire power or specific kinetic energy of the wind flow entering the device (1), i.e. it is practically all the energy of the wind flow that can be used in the wind turbine device.

The second element $1-1/n_2$ shows what part of the power of the wind flow is selected in the device (1), i.e.

4. Results of the research

Wind turbines, the same figure is the coefficient of wind flow utilization. Formula (4) presents a graph illustrating the relationship between the power of the wind flow that is harnessed and utilized by the wind turbine (referred to as device 1). This relationship is depicted based on the ratio of the wind flow's energy at the input and output of the turbine.

The graph highlights how the power captured by the wind turbine changes as the difference between the input and output energy levels varies. Essentially, it demonstrates the efficiency of energy conversion within the turbine by visualizing how much of the incoming wind energy is successfully

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extracted. The graph thus serves as a crucial tool for understanding the turbine's performance and energy utilization in varying wind conditions.

By dividing P_y by P_0, we get the EU energy utilization factor in device 1, that is, the wind turbine:

$$P_y = 0{,}5 \cdot p \cdot v_0^2 \cdot S_0$$

$$K = \frac{P_y}{P_0} = \frac{0{,}5 \cdot p \cdot v_0^2 \cdot S_0 \cdot (1 - \frac{1}{n^2})}{0{,}5 \cdot p \cdot v_0^2 \cdot S_0} = 1 - \frac{1}{n^2} \tag{5}$$

$$\mathrm{K} = 1 - \frac{1}{n^2}$$

The graph of this dependence obtained by formula (5) is shown in Fig. 2.

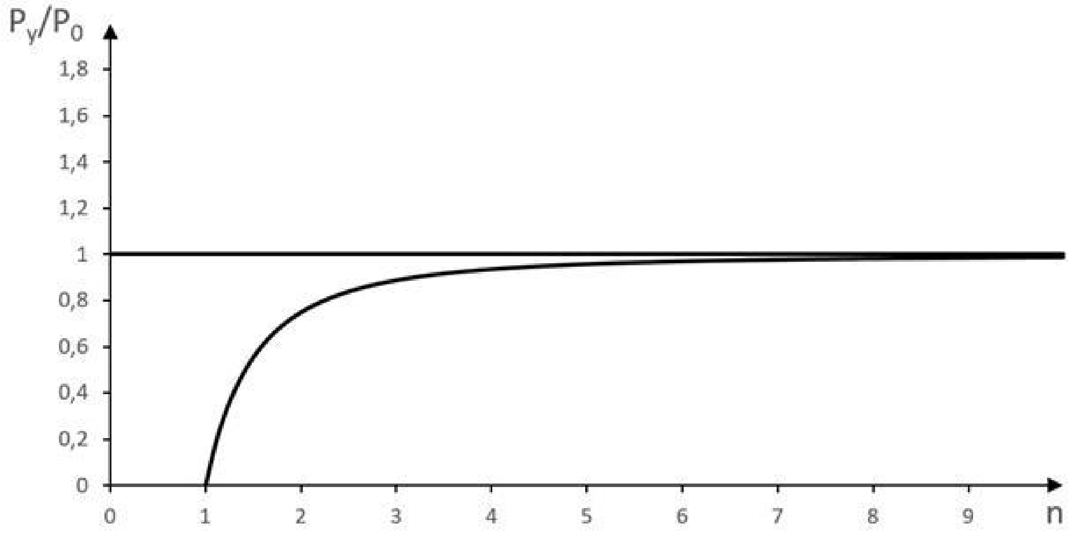

Fig. 2. Wind turbine efficiency dependence graph

For value $n = 1$, $P_y = 0$ means that the speed of the wind flow at the entrance and exit of the device is the same and no energy transfer of the EU of the device 1 has occurred. Further, as the difference in the speed of the EU at the input and output of device 1 decreases, the amount of energy extracted from the EU by the device increases and, accordingly, this is the efficiency of the device.

The efficiency function of wind turbines (5) Fig. 2 does not have an extremum, but smoothly approaches "1", like the efficiency of other machines, particularly in thermodynamics, therefore there are no theoretical restrictions on the efficiency of wind turbines up to "1", since physically it would mean that from a certain position, the moving elements of the wind turbine structure (device 1) perceive the pressure of the wind turbine and convert it into mechanical energy, which is output outside the device 1, cease to perceive the impact of the wind turbine, which is impossible. And if the impact of wind turbines on the moving elements of the wind turbine structure is constant, then it is always possible to use a certain geometry of the moving elements of the wind turbine to remove part of the turbine energy, reducing the velocity of the wind turbine, passing it through a larger section of the wind turbine. When considering the effect of EU on the wind turbine blades, it may seem that the optimal angle of attack of the blades gives the maximum amount of energy received, but this can only apply to the specific design of the wind turbine and has nothing to do with the theoretical efficiency of wind turbines.

There are discrepancies in the equations obtained by Betz and other authors both in the field of physics and in the field of mathematics [11, 12].

The same efficiency limit of wind turbines was obtained independently by three different authors: the German physicist Albert Betz in 1919, the British scientist Frederick Lanchester in 1915, and the Russian scientist Mykola Zhukovsky in 1920. However, the general error of energy selection by the device-wind turbine is uniquely determined by the equation of the flow power at the input and output of the device and, accordingly, the efficiency of the device (wind turbine), fully determines the amount of initial energy given to the device and the energy remaining in the flow. An attempt to add here additional equations of this process during a detailed examination shows the inability of additional equations, their further addition to the equation of state and obtaining an incorrect result.

Thus, in one of the methods of proving the Betz limit [12], the force created by the wind flow (shaded section in the form of an ellipse) and acting on the sensor in Fig. 3.

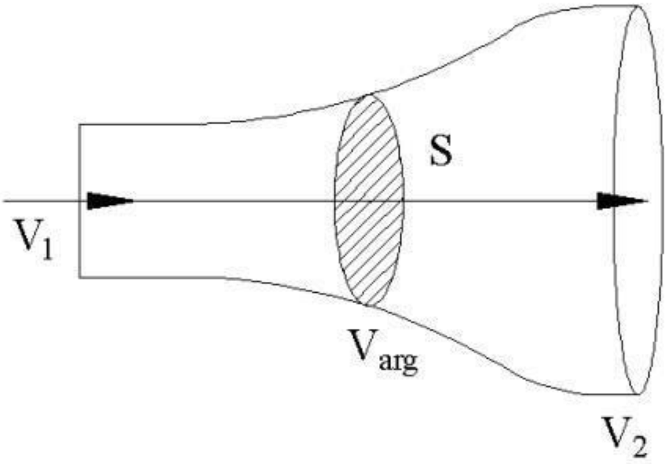

Fig. 3. Scheme of the flow of air through the rotor of the wind generator

A sensor is a device for obtaining wind energy - a wind turbine obtained by applying Bernoulli's theorem twice on one side between a point upstream and a point directly in front of the sensor. On the other hand, a point immediately after the sensor and a point downstream.

$$\frac{P_0}{p}+\frac{v_1^2}{2}=\frac{P_1}{p}+\frac{v^2}{2} \tag{6}$$

$$\frac{P_0}{p}+\frac{v_2^2}{2}=\frac{P_2}{p}+\frac{v^2}{2}. \tag{7}$$

Subtracting (6) from (7) gives:

$$P_1-P_2=(v_1^2-v_2^2)\,. \tag{8}$$

The final equation (3) relates the pressure in the flow on one line at the beginning and at the end of the flow according to this scheme, and the presence of a wind turbine (sensor) is not taken into account here. At the same time, it is assumed that the pressure and flow rate before and after the sensor are the same, and this will mean that the flow did not transfer energy to the sensor. In fact, the parameters of the flow, that is, the pressure and speed before the sensor and immediately after it, differ significantly, since the flow gives the sensor part of its energy and slows down significantly in the sensor, so the difference (6) - (7) does not give (8).

In addition, Bernoulli's equation is derived with the fundamental assumption that the work done to move a specific mass of fluid in the flow is directly proportional to the change in the total energy of that mass. This relationship is crucial for understanding fluid dynamics, as it helps to explain how energy is conserved within a fluid system. However, if, for instance, a device within the flow extracts an unknown portion of energy, the classical application of Bernoulli's equation becomes problematic. In such a scenario, the equation will not hold true at the extreme points of the flow, specifically at the beginning and end of the energy extraction process. This discrepancy highlights a significant limitation in applying Bernoulli's principle when external forces or devices alter the energy distribution in the flow. Therefore, the presence of energy-extracting devices necessitates a more nuanced approach to analyze the fluid's behavior and the energy dynamics involved.

Thus, other forms of derivation of equations [11] include the use of the equation of Newton's second law: "The force acting on the air flow from the side of the rotor is equal to the air mass multiplied by its acceleration." The work done by a force can be written in differential form as:

$$dE = F \cdot dx.$$

Errors in the derivation and obtaining of the Betz formula for the coefficient of performance of wind turbines are eliminated. In accordance with the physics of the process of wind flow energy transfer and according to the mathematical model of this process, the formula for determining the coefficient of performance for wind turbines of any type and design is obtained, the dependence of which is shown in Fig. 2.

$$K = 1 - \frac{1}{n^2}$$

In the analyzed physical model, there is no way of moving the object under the action of force, that is, there is no work performed by this force. Indeed, the force acts on the rotor blades and the rotor itself. But the rotor remains in place according to the conditions of the model and in fact, and the air flow goes strictly along the axis of the rotor and perpendicular to its blades, therefore the projection of the force of the wind flow on the plane of rotation of the rotor blades is zero, and accordingly in this scheme and the work of this force is equal to "0". It follows that the replacement of force with power [11] and all subsequent transformations are erroneous and lead to an erroneous result.

5. Discussion the research results

The discussion of results focuses on the theoretical framework and practical implications of the wind energy conversion depicted in Fig. 1. The mathematical scheme illustrates the transformation of part of the wind flow's energy into mechanical energy and the transfer of this energy outside the wind flow by a wind turbine (device 1). The theoretical model indicates that the efficiency of wind energy conversion relies solely on the input and output parameters – specifically, the wind flow’s speed and cross-sectional area at the input (V_0, S_0) and output (V, S). This approach isolates energy conversion efficiency from internal design specifics, which allows a generalized understanding of the energy exchange process.

The results confirm that, according to the law of conservation of mass, the volume of air entering and leaving the wind turbine remains constant. Consequently, the power harnessed is expressed as the difference between the incoming power (P_0) and the residual power (P_y) that exists the device. This power relationship is mathematically modeled to demonstrate the efficiency coefficient K. As shown in the discussion, when the speed of the wind flow at the input and output remains the same ($n = 1$), there is no energy transfer, resulting in zero power extracted. The increase in energy extraction as the difference in wind speed increases highlights the impact of the wind turbine's design and configuration on its overall efficiency.

The comparison with the Betz limit and the derivation of similar equations by Lanchester and Zhukovsky emphasize discrepancies in historical interpretations of wind turbine efficiency. This discussion challenges the theoretical assumptions underlying the Betz limit, particularly the application of Bernoulli’s principle and Newton’s second law, which suggest that additional complexities in energy transfer are not adequately represented in traditional models. The critique implies that prior methods overestimate the efficiency limits due to incorrect assumptions about energy transfer and flow characteristics within the turbine structure.

Finally, the presented physical model challenges the prevailing assumption that wind turbines achieve maximum efficiency solely at specific blade angles. It argues that optimal energy capture is not necessarily linked to design specifications but is instead governed by the theoretical constraints outlined in the derived formula. This perspective raises significant questions about the traditional limitations imposed on wind turbine efficiency, suggesting that these constraints may be more flexible than previously thought. Moreover, the findings indicate that continuous improvements in turbine design and technology could lead to higher energy utilization rates than currently realized. This opens the door to innovative approaches that go beyond the conventional parameters of wind turbine efficiency. Additionally, the implications of this model encourage further investigation into alternative wind turbine designs, particularly those that explore options beyond existing theoretical limits. Ultimately, embracing this broader understanding of efficiency may lead to more effective strategies for harnessing wind energy in the future.

6. Conclusions

Returning to the problems of wind energy, it is necessary to note that the operation of real wind turbines often differs significantly from theoretical models. A considerable portion of the wind flow that meets the rotor blades can be reflected and lost, delivering only a fraction of its energy to the rotor. Thus, the main challenge in improving wind turbine efficiency lies in utilizing the maximum energy of the wind flow passing through the area of the rotating blades. Although large industrial wind turbines utilize some of this energy, there is potential to achieve similar energy yields with smaller turbines through more complete wind flow utilization.

Wind turbines that rely on the lifting force of the wing to rotate the rotor face certain structural limitations. The lifting force occurs only when the blade interacts correctly with the wind flow, limiting the amount of energy the air can transfer. This results in relatively low efficiency. However, wind turbines designed to use the pressure of the wind flow show greater potential, especially in modern vertical-axis turbines, where a higher degree of energy extraction is possible.

The evolution of wind energy technology has led to substantial advancements, transforming basic windmills into large industrial turbines with capacities ranging from 6 to 8 MW. The masts of these turbines now reach heights of 120 to 140 meters, and blade lengths extend to 60 to 80 meters. By enlarging the swept area of the blades, modern turbines can capture more energy from wind flows, optimizing overall efficiency and output.

Despite these advancements, the considerable size and weight of modern turbines, which can reach up to 6,000 tons, pose challenges. While the increased weight provides structural stability, especially under changing environmental conditions, it also emphasizes the need to improve efficiency. The limitations in current designs mean that a significant portion of wind energy remains unutilized. This calls for a focus on innovations that can harness more energy from the same wind flow.

One of the primary goals of wind energy development is to make wind-generated power economically competitive with conventional energy sources. The objective is to produce renewable energy at a cost per kilowatt-hour comparable to that of burning hydrocarbon fuels. Achieving this requires improving not just the capacity of wind turbines, but also their efficiency in extracting wind flow energy, potentially through more refined designs.

Future strategies to enhance wind energy production involve improving energy conversion technologies, enhancing component durability, and refining manufacturing processes. Vertical-axis wind turbines, which rely on wind flow pressure rather than lift forces, present a promising opportunity for better energy extraction. This could lead to smaller, more efficient turbines capable of delivering higher energy yields.

In conclusion, while the evolution of wind energy technology continues to drive advancements in turbine size, efficiency, and cost-effectiveness, further development is essential. By addressing current limitations and focusing on maximizing wind flow utilization, the industry can move closer to achieving its sustainability goals. Such efforts, combined with careful consideration of environmental and social impacts, will be crucial for establishing wind energy as a significant and viable component of the global energy mix. It also, be the topicks of our further research investigations.

References

[1] Darvish Falehi A., & Rafiee M.: Maximum efficiency of wind energy using novel Dynamic Voltage Restorer for DFIG based Wind Turbine. Energy Reports, 2018, 4, 308–322. https://doi.org/10.1016/j.egyr.2018.01.006

[2] Pereira S., Ferreira P., & Vaz A. I. F.: Short-term electricity planning with increase wind capacity. Energy, 2014, 69, 12–22. https://doi.org/10.1016/j.energy.2014.01.037

[3] Mahfouz M. Y., & Cheng P.: A passively self-adjusting floating wind farm layout to increase the annual energy production. Wind Energy, 2022,26(3), 251–265. Portico. https://doi.org/10.1002/we.2797

[4] Leahy R.: Proposed circuit design could increase switching efficiency in wind energy grids. Scilight, 2018, 34, 23-41. https://doi.org/10.1063/1.5053101

[5] Khomenko O., Rudakov D., Lkhagva T., Sala D., Buketov V., & Dychkovskyi R.: Managing the horizon-oriented in-situ leaching for the uranium deposits of Mongolia. Rudarsko-Geološko-Naftni Zbornik, 2023, 38(5), 49–60. https://doi.org/10.17794/rgn.2023.5.5

[6] Somoano M., & Huera-Huarte F. J.: Bio-inspired blades with local trailing edge flexibility increase the efficiency of vertical axis wind turbines. Energy Reports, 2022, 8, 3244–3250. https://doi.org/10.1016/j.egyr.2022.02.151

[7] Berg E.: Wind Energy Conversion. Energy Efficiency and Renewable Energy Handbook, 2015, 1371–1416. https://doi.org/10.1201/b18947-52

[8] Kondoh J.: Autonomous frequency regulation by controllable loads to increase acceptable wind power generation. Wind Energy, 2009, 13(6), 529–541. Portico. https://doi.org/10.1002/we.375

[9] Dychkovskyi R., Dyczko A., & Borojević Šoštarić S.: Foreword: Physical and Chemical Geotechnologies – Innovations in Mining and Energy. E3S Web of Conferences, 2024, 567, 00001. https://doi.org/10.1051/e3sconf/202456700001

[10] Dychkovskyi R., Saik P., Sala D., & Cabana E. C.: The current state of the non-ore mineral deposits mining in the concept of the Ukraine reconstruction in the post-war period. Mineral Economics, 2024, 37(3), 589–599. https://doi.org/10.1007/s13563-024-00436-z

Publisher: **KOMAG Institute of Mining Technology, Poland**

[11] Betz A.: Introduction to the Theory of Flow Machines. D. G. Randall, Trans., Oxford. Pergamon Press, 1966, 165 p.

[12] Bulat A.F., Mineev S.P., Antonchyk V.E., Maltseva V.E., Demchenko S.V.: Patent UA 124749 F03D 3/04 publ. 11/10/2021 Bul. No. 45 Vertical-axial wind turbine

[13] Bulat A.F., Mineev S.P., Antonchyk V.E., Chelkan V.V.: Patent UA 153208 F03D 3/04 publ. 06/07/2023 Bul. No. 23 Biaxial wind turbine

[14] Mineev S.P., Antonchyk V.E., Maltseva V.E.: Patent UA 154098 F03D 3/06 publ. 11.10.2023 Bul. No. 41 Vertical-axial wind turbine.

[15] Lam G. C. K.: Wind Energy Conversion Efficiency Limit. Wind Engineering, 2006, 30(5), 431–437. https://doi.org/10.1260/030952406779502687

[16] Kazemzadeh E., Fuinhas J. A., Shirazi M., Koengkan M., & Silva N.: Does economic complexity increase energy intensity? Energy Efficiency, 2023, 16(4). https://doi.org/10.1007/s12053-023-10104-w

[17] Barthelmie R. J., & Jensen L. E.: Evaluation of wind farm efficiency and wind turbine wakes at the Nysted offshore wind farm. Wind Energy, 2010, 13(6), 573–586. Portico. https://doi.org/10.1002/we.408

[18] Max L., & Lundberg S.: System efficiency of a DC/DC converter-based wind farm. Wind Energy, 2007, 11(1), 109–120. Portico. https://doi.org/10.1002/we.25

[19] Xydis G., & Mihet-Popa L.: Wind energy integration via residential appliances. Energy Efficiency, 2016, 10(2), 319–329. https://doi.org/10.1007/s12053-016-9459-2

[20] Wiser R., & Bolinger M.: Wind Technologies Market Report. Office of Scientific and Technical Information (OSTI), 2011. https://doi.org/10.2172/1219205

[21] Smith R. B.: Gravity wave effects on wind farm efficiency. Wind Energy, 2010, 13(5), 449–458. Portico. https://doi.org/10.1002/we.366

[22] Saik P., Dychkovskyi R., Lozynskyi V., Falshtynskyi V., Cabana E. C., & Hrytsenko L.: Chemistry of the Gasification of Carbonaceous Raw Material. Materials Science Forum, 2021, 1045, 67–78. https://doi.org/10.4028/www.scientific.net/msf.1045.67

[23] Riegels F., & Backhaus H.: ALBERT BETZ 65 Jahre/ERNST LÜBCKE 60 Jahre. Physikalische Blätter, 1951, 7(1), 32–33. Portico. https://doi.org/10.1002/phbl.19510070107

[24] Dolgopolov A. V., Kazancev D. A., Markin I. V., Orlova O. A., & Shalaev S. V.: The Modern Method of Creating Dynamically Scaled Models to Study Aircraft Flutter Characteristics. Uchenye Zapiski Kazanskogo Universiteta. Seriya Fiziko-Matematicheskie Nauki, 2020, 162(4), 441–454. https://doi.org/10.26907/2541-7746.2020.4.441-454

[25] Krishna M., Fraser E. J., Wills R. G. A., & Walsh F. C.: Developments in soluble lead flow batteries and remaining challenges: An illustrated review. Journal of Energy Storage, 2018, 15, 69–90. https://doi.org/10.1016/j.est.2017.10.020