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REGULATION OF THE POWER OF A WIND TURBINE OF A SPECIAL DESIGN BY CHANGING THE LENGTH OF THE BLADES

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The object of this research is a model of a wind turbine with retractable blades. This model allows for the adjustment of the turbine's screw radius by extending or retracting the blades, providing a basis for examining the impact of blade radius on turbine performance.

The primary problem addressed by this study is to determine how changes in the screw radius, achieved by altering the blade length, affect the wind turbine's performance, specifically its electrical output (voltage and current) and rotational speed, under constant wind conditions.

The experimental results showed that when the turbine blades are fully extended (R1), the wind turbine generates higher voltage and current compared to when the blades are retracted (R2). This confirms that the turbine's electrical output is significantly influenced by the screw radius.

These results are explained by the aerodynamic principles governing wind turbines. An increased screw radius allows the turbine blades to capture more wind energy, leading to greater force applied to the blades, thus increasing the rotational speed and the amount of electrical energy generated. The linear relationship between the screw radius and the turbine's performance was as summed to simplify the analysis, though the actual relationship may be more complex.

The finding soft its study can be practically applied in the design and operation of wind turbines. Turbines with adjust table blade lengths can optimize performance across varying wind conditions, maximizing efficiency and power output. These results are particularly useful in environments where wind speed is variable, as turbine scan adjust their blade radius to maintain optimal performance. The study assumes consistent wind conditions and uniform air flow for the results to be accurate, so these conditions should be considered when implementing the findings in real-world scenarios

Keywords: wind turbine, wind wheels, length of the blades, critical speed, turbine safety

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1. Introduction

The relevance of the scientific topic is related to improving the efficiency and ensuring the safe operation of wind turbines at low and critical wind speeds. Wind turbines with a horizontal axis of rotation are the most common of renewable energy sources. Despite their widespread distribution, they have a limitation in terms of wind speed. At low wind speeds, the turbine does not work due to a lack of wind capacity. At wind speeds exceeding 25 m/s, the wind turbine stops working. In this case, the wind affects the stationary blades and can lead to their breakage. In this regard, it is necessary to increase the length of the blades for starting the wind wheel, as well as reduce the length of the blades at critical wind speeds to ensure their safety.

To increase the efficiency of wind farms, research is being conducted in various directions. They are mainly related to the profile of the blades and the angle of attack on the wind. Sensors regulating the angle of inclination of the blades were used to protect against the aggressive effects of the wind flow. At the same time, research is relevant to improve the efficiency of the turbine and protect the blades by changing their length, which reduces the wind speed for starting the wind wheel and reduces the load of the wind flow at critical loads.

The development of wind power was associated with horizontal-axial wind turbines. To increase the efficiency of these turbines, their manufacturers have increased the unit power of the turbine due to the height of the tower and the length of the blades of the wind wheel. The large size of wind farms increases the relevance of the above-mentioned problem:

the wind speed increases for starting the wind wheel, as well as undesirable loads increase at wind speeds of more than 25 m/s.

In this regard, there are certain trends against the expansion of the construction of wind farms near settlements and forests due to noise interference, low-frequency fluctuations, and increased risk of fire danger. An additional negative effect is the danger of destruction of long blades from the effects of heavy winds with critical speeds. Therefore, research on the development of blade length control units of wind turbines with a horizontal axis of rotation, ensuring the efficiency of the turbines and the safety of the blades of the wind wheel, is relevant.

2. Literature review and problem statement

The article [1] presents the results of a study on the efficiency of a wind turbine. It is shown that modern wind power plants operate in the range of operating values of wind flows from 5 m/s to 25 m/s. At such speeds of air currents, which is the source of the movement of the wind wheel, the kinetic energy of the wind is converted into electrical energy. For optimal operation of the wind turbine, the wind speed values should be from 12 to 25 m/s. But there are unresolved issues related to the inefficient operation of the turbine outside this range, as well as the threshold value of wind speed when the wind turbine begins to generate energy. The reason for this is the high wind speed for starting the wind wheel, as well as a decrease in turbine safety at critical wind speeds. Methods related to the technical and economic parameters of the design can be a way to overcome these difficulties.

Low energy production at low wind speeds is presented in the article [2]. It is indicated that at low speeds of the wind flow, the wind generator can go into standby mode or stop completely. This is especially important for grid-based wind turbines, which require a certain minimum wind speed to maintain an appropriate voltage and frequency level [3]. At high wind speeds, the wind generator also cannot operate due to heavy loads on the blades and other elements of the wind turbine. To do this, sensors and other controllers are used to control the angle of inclination of the blades (pitch control) in order to limit the rotation speed and prevent overloads [4]. However, controllers and sensors do not solve the problems of turbine efficiency and safety.

In [5], large overloads on bearings, transmission systems, the nacelle and the trunk of the tower and its fastenings at high speeds of air currents are considered. Such dynamic loads increase the risks of wear of the blades, as well as mechanisms for transferring shaft rotation to the generator rotor [5]. In addition, the destruction of the blades and other elements of the wind wheel increases the danger to others: flora, fauna, and maintenance personnel [6]. These negative aspects have not been solved in a technical way.

The protection of the station from lightning is given in [7]. With an increase in the height of the tower and the length of the blades, the problem of protecting them from lightning arises. In the article [8], the erosion of the blades is considered and it is proposed to use a special coating for them. A review of recent research in the field of erosion of the leading edge of wind turbine blades, anti-erosion coatings, new materials and computer modeling of erosion [9] shows that there is no single solution to protect the blades from various impacts. Optimization of the choice of materials is often carried out using mathematical modeling [10]. These studies are related to ensuring the protection of the blades of the wind wheel from various natural influences, but the problem of efficient operation of the turbine and ensuring its safety at critical wind speeds are not considered.

The effect of strengthening the front and rear edges on the flutter velocity during blade elongation was studied in [11]. To determine the length, an overview of the calculated loads on the blades of a wind turbine is provided, describing aerodynamic, gravitational, centrifugal, gyroscopic and operational conditions [12].

To regulate the length of the blades of a wind turbine, it is proposed to modernize it by attaching an extension cord to the tip of the blade [13]. As the length of the blades increases, unwanted vibrations and noises appear. Special components are used to suppress them [14]. In this case, the rotor blade with a flat airfoil profile has an advantage, since the blade size decreases [15, 16].

Numerous studies show that not only energy production depends on the length of the blades, but also the safe operation of the wind turbine. At the same time, there is no specific solution to the main problem of wind turbines – improving efficient operation at low wind speeds and ensuring safety under critical loads of the wind flow. All this suggests that it is advisable to conduct a study on the study of a special node for changing the length of the blades. Its use will increase the length of the blades at low wind speeds and reduce it at critical values.

3. The aim and objectives of the study

The aim of this study is to identify the influence of the blade radius on the performance of a wind turbine by developing a model that evaluates the impact of adjustable blade lengths on the turbine's electrical output (voltage and current) and rotational speed under constant wind conditions. The insights gained from this study will enable the optimization of wind turbine designs, particularly in adapting blade length to maximize efficiency and power output in varying wind conditions. This will allow for more efficient energy production, reduced mechanical stress on the turbine, and increased lifespan of turbine components in real-world applications.

To achieve this aim, the following objectives are accomplished:

– to increase the safety of the wind generator, a blade length control unit is used, located at the attachment point of the bladeson the axis of rotation, which allows to reduce the length of the bladesandreduce the windload;

– to increase the power generated by the wind generator, a blade length control unit is used in ordertoincrease the radius of the windturbine sweeping and the effect of the wind flow on the wind wheel.

4. Materials and methods

The object of the study is a model of a wind turbine with retractable blades. The main focus is to explore how the ability to change the radius of the turbine's screw by adjusting the length of the blades affects the turbine's performance under consistent wind conditions. Specifically, the research aims to determine the impact of varying the screw radius on the generation of electrical energy, as measured by voltage, current, and rotational speed.

The main hypothesis of the study is that changing the radius of the wind turbine's screw, achieved by extending or retracting the blades, significantly affects the turbine's performance. Specifically, it is hypothesized that when the screw radius is increased (*R*1, with blades fully extended), the wind turbine will generate more voltage and current compared to the operating mode with a smaller screw radius (*R*2, with blades retracted), under the same wind conditions.

The assumptions made in the study include:

1. Constant wind speed: the wind speed (*Vw*) is assumed to remain constant throughout both experiments. This allows for a direct comparison of the turbine's performance at different screw radii.

2. Uniform airflow: the airflow directed at the turbine is assumed to be uniform and free of significant turbulence, ensuring that variations in the turbine's performance are due to changes in blade radius rather than airflow inconsistencies.

3. Consistent blade design: it is assumed that the shape and design of the blades are optimal and remain equally effective in both their extended and retracted states. This ensures that any observed changes in the turbine's performance can be attributed solely to the change in radius.

4. Negligible friction losses: friction losses within the turbine mechanisms and the generator are assumed to be negligible. This simplification may lead to slight deviations between theoretical predictions and experimental results.

5. Linear dependence of characteristics: the main characteristics of the turbine (voltage, current, and rotation speed) are assumed to have a linear relationship with the radius of the screw and wind speed. This simplifies the analysis, although the actual relationship may be nonlinear.

6. Accuracy of measuring instruments: the measuring instruments (voltmeter, ammeter, and tachometer) are assumed to operate without errors, and their influence on the results is considered minimal. This ensures that the measurements are reliable and accurate.

The simplifications adopted in the study include:

1. Neglecting friction losses: the study assumes that friction losses within the turbine mechanisms and generator are negligible. This simplification helps streamline the analysis but might result in slight discrepancies between theoretical predictions and actual experimental data.

2. Linear relationship assumption: the characteristics of the turbine, such as voltage, current, and rotational speed, are assumed to linearly depend on the radius of the screw and wind speed. This simplification facilitates the analysis, although the actual relationships may be nonlinear.

3. Instrument accuracy assumption: it is assumed that the measuring instruments (voltmeter, ammeter, and tachometer) are highly accurate and have minimal impact on the results. This simplification assumes that any errors from the instruments are insignificant compared to the overall measurements.

A wind turbine model with adjustable blades was constructed. The blades could be extended or retracted, allowing the turbine to operate with two different screw radii, *R*1 (with the blades fully extended) and *R*2 (with the blades retracted).

Experiment 1: measuring characteristics with extended blades (R1).

The blades of the wind turbine were extended to achieve the maximum screw radius, *R*1. A controlled wind source, such as a fan, was used to generate a consistent wind speed, *Vw*, directed at the turbine.

Data collection:

– wind speed (*Vw*): the wind speed was measured using an anemometer positioned near the turbine;

– voltage (*U*): the voltage output from the turbine was measured using a voltmeter connected to the turbine's electrical output;

– current (*I*): the current generated by the turbine was measured using an ammeter;

– rotation speed (*n*): the rotational speed of the turbine's blades was measured in revolutions per minute (*r*/*m*) using a tachometer.

Experiment 2: measuring characteristics with retracted blades (R2).

The blades of the wind turbine were retracted, reducing the screw radius to *R*2. The same wind source and wind speed, *Vw*, were used as in the first experiment to maintain consistency.

Data collection:

– wind speed (*Vw*): the wind speed was again measured with the anemometer;

– voltage (*U*): the voltage output was recorded using the voltmeter;

– current (*I*): the current was measured with the ammeter;

– rotation speed (*n*): The rotational speed of the blades was recorded using the tachometer.

After completing both experiments, the data were compared to determine how the change in blade radius (from *R*1 to *R*2) affected the turbine's performance in terms of voltage, current, and rotational speed under the same wind conditions.

For practical confirmation of the theory, a model of a wind turbine with sliding blades was assembled. The experimental studies include two experiences. The first experiment consists in measuring the characteristics of a wind turbine with extended blades with a screw radius of *R*1. The second experience is the removal of the characteristics of a wind turbine with the blades spread apart and the radius of the screw *R*2.

The characteristics that were removed during the experiments are:

1) voltage, *U*, V;
2) current, *I*, A;
3) rotation speed, *n*, r/m;
4) wind speed, *Vw*, m/s.

To measure the voltage at the terminals of the wind turbine, a voltmeter of the DMS-20LCD-0-DCM-C brand was used. The appearance of the device is shown in Fig. 1. The accuracy class of the device is 0.9.

Fig. 1. Voltmeter DMS-20LCD-0-DCM-C

To measure the current, an ammeter of the ACA-20PC-3-AC1-RL-C brand was used, with an accuracy class of 0.1. Fig. 2 shows the appearance of the device during measurement. The accuracy class of the device is 0.99.

The speed of rotation of the wind turbinescrew is measured by a tachometer of the DT-2234C+series, shown in Fig. 3. The accuracy class of the device is 0.95.

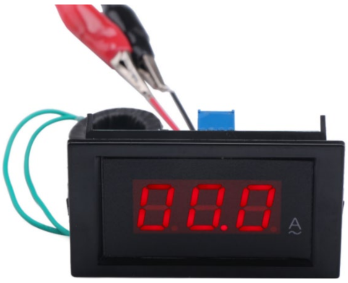


Fig. 2. Amperemeter ACA-20PC-3-AC1-RL-C

Fig. 3. Tachometer DT-2234C+

The wind speed during the experiments was measured with an anemometer UT363S. The anemometer is shown in Fig. 4. The accuracy class of the device is 0.98.

Fig. 4. Anemometer UT363S

To build dependencies of the influence of the retractable blades on the final generation of electrical energy, it is necessary:

1) obtain data and plot the dependence of the rotation speed of the screw, on the wind speed *Vw*;

2) obtain data and plot the dependence of the generated voltage *U* and current *I* on the rotation speed of the wind turbine screw;

3) compare the obtained dependencies of the first and second experience and identify improvements or deterioration in generation.

The blade spreading mechanism consists of several key structural parts. All the details of this design can be divided into two categories, electrical and mechanical circuit.

The electrical circuit includes such elements as: two servos and sliding contacts. The mechanical chain includes: two toothed rails, two to the gears, the body of the mechanism (Fig. 5).

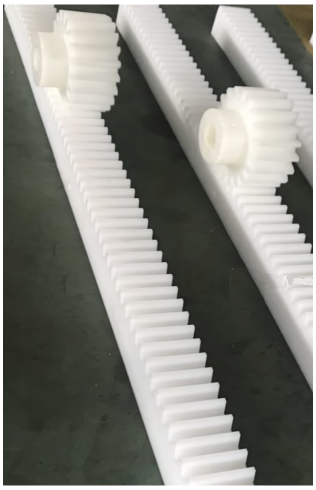


Fig. 5. Polymer gear rack with gear

Structurally, the mechanism looks like this:

1) to set the mechanism in motion, it is equipped with two servos, which are connected to a 220 V network through sliding contacts;

2) gear gears are fixed at the ends of the servos haft, which transmit rotational motion to the rack and pinion by rack and pinion;

3) the gear rack, receiving rotation al motion from the gear, converts it in to translational;

4) a blade is attached to the toothed rail, at the moment of converting rotation al motion into translational motion, the blade is extended to a certain distance by the design.

In this design, a rack made of polymer materials was used as a toothed rail to facilitate the design. A gear made of polymer materials was also used for the layout of the wind mill, metal part scan be success fuller placed with polymer ones, since there are no large weight and size indicators here. Fig. 8 shows a polymer too the drack equipped with a too the gear.

The object of the study is a model of a wind turbine with retractable blades. The turbine can change the radius of the screw by changing the length of the blades, which allows to study the effect of the radius of the screw on the performance of the turbine under constant wind conditions.

The main hypothesis of the study is that the change in the radius of the turbine screw, achieved by extending or retracting the blades, significantly affects its performance. It is assumed that with an increase in the radius of the screw at (*R*1), the wind turbine will generate more voltage and current compared to the operating mode with a smaller radius of the screw (*R*2), under the same wind conditions.

Accepted assumptions:

1. It is assumed that the wind speed (*Vw*) remains constant throughout both experiments, which allows to compare the characteristics of the turbine at different screw radii directly.

2. It is assumed that the air flow directed at the turbine is uniform and uniform, without significant turbulence that could affect the results.

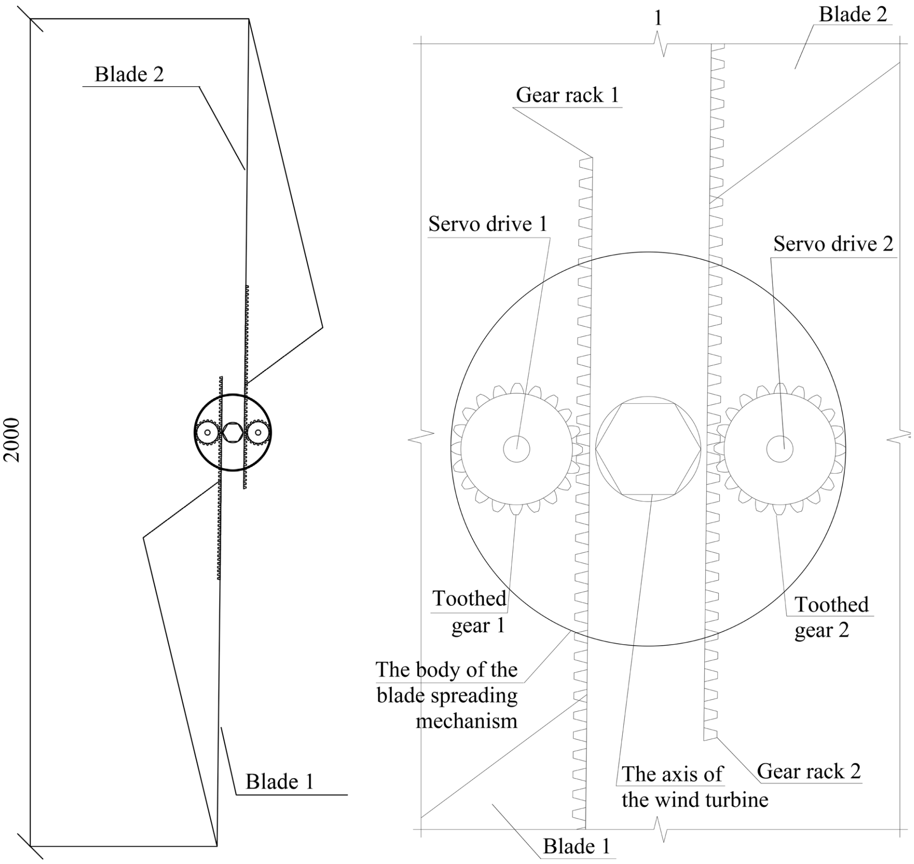
3. It is assumed that the shape and design of the blades remain optimal and equally effective both when extended and retracted, which allows to assume that any changes in characteristics are associated only with a change in radius.

Simplifications:

1. The effect of friction losses in the turbine mechanisms and generator may be ignored in the experiment, which may lead to some deviation of theoretical and experimental data.

2. It is assumed that the main characteristics of the turbine (voltage, current, rotation speed) linearly depend on the radius of the screw and wind speed, although in reality the dependence may be nonlinear.

3. It is accepted that measuring instruments (voltmeter, ammeter, tachometer) work without errors, and their effect on the results is minimal.



a *b*

Fig. 6. A wind turbine with a blade extension mechanism, the blades in the retracted state: *a* – a general view of the wind turbine; *b* – a close-up of the blade extension mechanism

5. Results of research of increasing generation by lengthening the blades of the wind turbine

5. 1. Investigation of the effect of bladelengthon wind turbineparameters

The first experiment, conducted on an installation with the blades not apart, implies obtaining characteristics for further comparison with the results of the second experiment.

For the purity of the experimentand to reduce the measurement error, 5 measurements were made a teach wind speed, the Table 1 shows the average values, in order to avoid cluttering of data.

The appearance of the installation during the first experiment is shown in Fig. 6.

For fur the reanalysis and construction of characteristics, it is possible to measure the rotation speed of the wind turbine screw at different wind speeds. The measurement results are shown in Table 1. To compile each experimental data table, 30 measurements were carried out and the tables contain averaged data.

Table 1

Results of rotation speed measurements

No.	Wind speed, V_w, m/s	Rotation speed, n, r/m
1	5	230
2	6	260
3	7	300
4	8	340
5	9	410

Based on the results of measurements of the rotation speed, a characteristic of the dependence of the rotation speed on the wind speed has been compiled. Fig. 7 shows the obtained characteristic.

Based on the dependence graph in Fig. 7, it follows that the rotation speed increases relative to the wind speed, almost linearly. Minor deviations from the line a pattern are caused by the error of the instruments and imperfect experimental conditions.

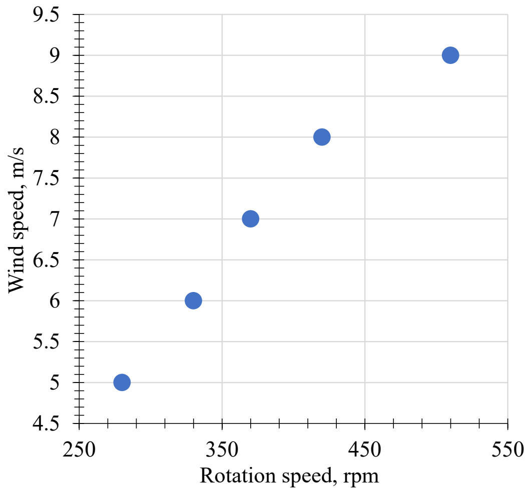


Fig. 7. Dependence of wind wheel rotation speed on wind speed

When measuring the rotation speed, measurements of the generated parameters of current *I* and voltage *U* were carried out in parallel. The results are presented in Table 2.

Table2

Measurement results of the generated current and voltage with the blades not apart, at the measured rotation speed

No.	Rotation speed, *n*, r/m	Voltage, *U*, V	Current, *I*, A
1	230	8.10	55.29
2	260	8.74	52.14
3	300	9.46	47.38
4	340	10.05	44.58
5	410	11.01	40.71

Based on the data in Table 2, a characteristic of the dependence of the generated current and voltage parameters on the rotation speed was constructed. Fig. 8 shows the obtained characteristic.

As can be seen from the graphs in Fig. 8, at the beginning of the measurements, when the wind speed reached 5 m/s (which corresponds to a rotation speed of 230 r/m), the voltmeter shows a value of about 8 V, with a further increase in speed, the voltmeter indicators continue to grow. As for the current generated, to a greater extent the current depends on the voltage generated and, according to Ohm's law, has an inverse pattern of rotation speed. When the generated voltage increases, the current drops.

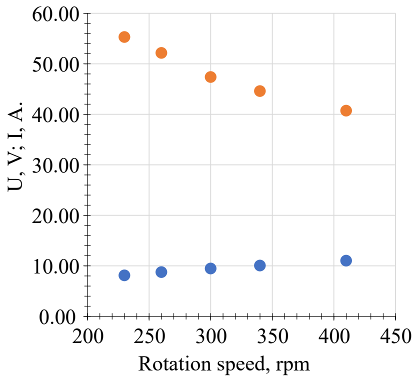


Fig. 8. Voltage and current dependences on rotation speed

According to the described result, an increase in voltage generation is expected in the next experiment, since the design with extended blades (increased wind wheel radius) predicts a high rotation speed.

5. 2. Increase in generation due to lengthening of the blades of the wind wheel

The second experiment is carried out on an installation with the blades spread apart, according to formula (3), current and voltage generation should increase, since the shoulder of the applied force increases at the same wind speed and the swept area of the wind wheel.

In this experiment, as well sin the first, 5 measurements were carried out for each wind speed. The Table 3 shows the mathematical averages.

The appearance of the installation during the second experiment is shown in Fig. 9.

Similarly, to the first experiment, it is possible to measure the rotation speed at different wind speeds (Table 3).

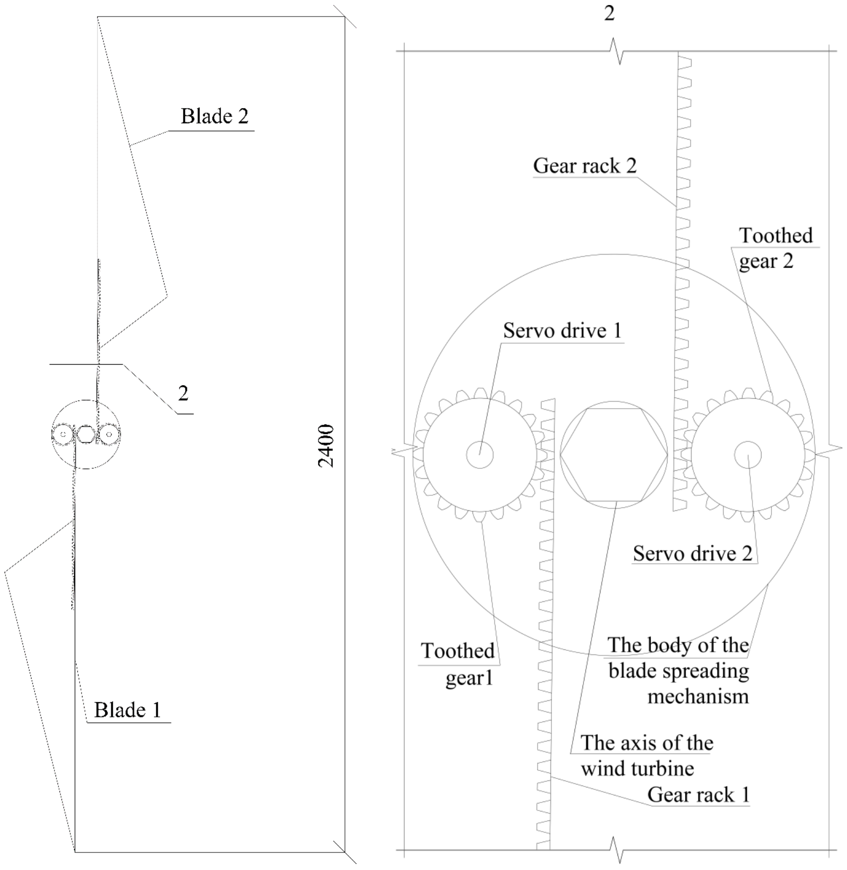
Table 3

Results of rotation speed measurements

No.	Wind speed, *Vw*, m/s	Rotation speed, *n*, r/m
1	5	280
2	6	330
3	7	370
4	8	420
5	9	510

Based on the results of measurements of the rotation speed, a characteristic of the dependence of the rotation speed on the wind speed has been compiled. Fig. 10 shows the obtained characteristic.

According to the results of measurements of the rotation speed, it can be seenthatat the samewindspeed, the rotation speed increased by an average of 20 %, which is an indicator that a wind turbine with extended blades has a high rotation speed of the wind wheel under the same wind conditions.



a *b*

Fig. 9. A wind turbine with a blade extension mechanism, the blades in the extended state: *a* – a general view of the wind turbine; *b* – a close-up of the blade extension mechanism

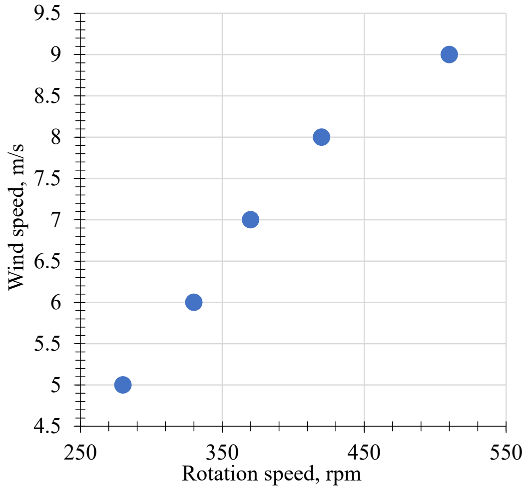


Fig. 10. Dependence of wind wheel revolutions on wind speed

The results of voltage and current measurements are shown in Table 4.

Table 4

Measurement results of the generated current and voltage with the blades apart, at the measured rotation speed

No.	Rotation speed, *n*, r/m	Voltage, *U*, V	Current, *I*, A
1	280	10.12	69.11
2	330	10.93	65.17
3	370	11.82	59.22
4	420	12.56	55.73
5	510	13.76	50.89

Using the data recorded in Table 4, it is possible to construct the characteristics of the dependence of current and voltage on the rotation speed.

Fig. 11 shows the constructed characteristic.

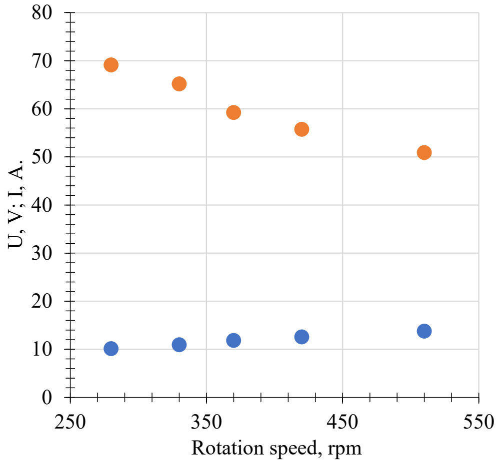


Fig. 11. Characteristic of the dependence of voltage and current on the rotation speed

As can be seen from the graphs in Fig. 14, the trend of linear dependence of voltage and current has remained since the first experiment, but the generated indicators have increased.

A detailed comparison of the results of the experiments is shown below.

To compare the characteristics obtained in the first and second experiments, it is possible to build a summary table of the results (Table 5).

Table 5 is a summary table of the experimental results.

Table 5

Summary table of experimental results

Wind speed, *Vw*, m/s	The first experiment			The second experiment		
	Rotation speed, *n*, r/m	Voltage, *U*, V	Current, *I*, A	Rotation speed, *n*, r/m	Voltage, *U*, V	Current, *I*, A
5	230	8.10	55.29	280	10.12	69.11
6	260	8.74	52.14	330	10.93	65.17
7	300	9.46	47.38	370	11.82	59.22
8	340	10.05	44.58	420	12.56	55.73
9	410	11.01	40.71	510	13.76	50.89

To graphically display the data obtained in the summary table, it is possible to build graphs comparing the characteristics of the first and second experiments. Fig. 12 shows rotation speed comparison graphs, Fig. 13 shows voltage comparison graphs, and Fig. 14 shows current comparison graphs.

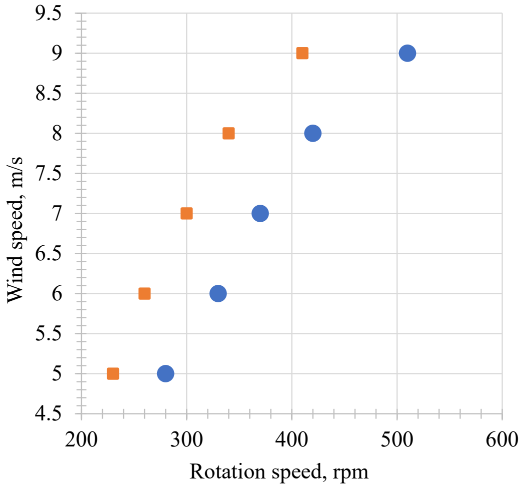


Fig. 12. Comparative graphs of wind wheel revolutions from wind speed for two experiments

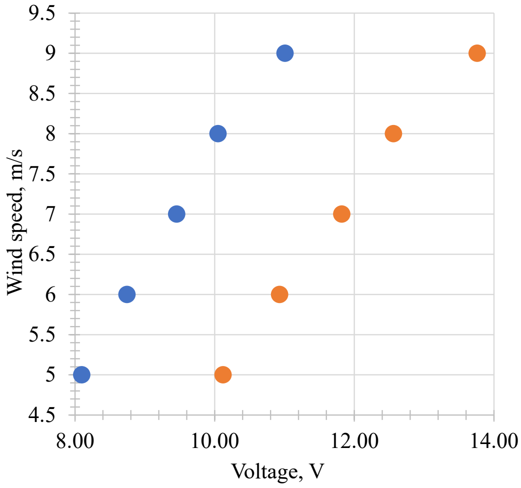


Fig. 13. Comparative voltage graphs of two experiments

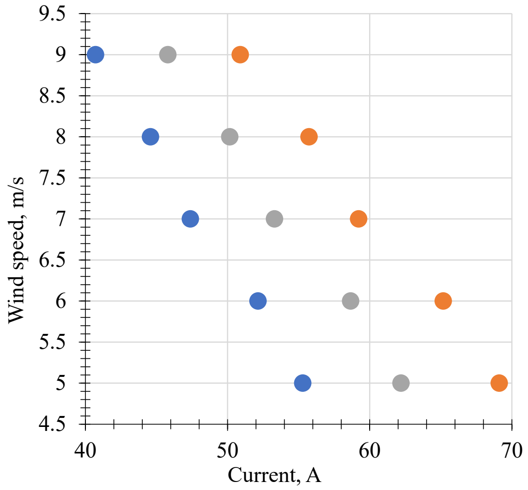


Fig. 14. Comparative graphs of the current of two experiments

Based on the comparative graphs presented in Fig. 12–14, it follows that the design of a wind turbine with sliding blades has appositive effect on the amount of voltage generated.

Fig. 12 shows that the rotation speed of the wind wheel has increased by about 20 %, which makes it possible to generate electrical energy at a lower wind speed.

It follows from Fig. 13 that as the rotation speed of the wind turbine blades increases, the generated voltage increases proportionally. The corresponding measurements of the first and second rotational speed measurements are correlated with voltage measurements.

In Fig. 14, the current drop is explained by the power of the generator, with an increase in the generation voltage, the amount of currentat the terminals of the generator decreases, because the rated power of the generator (~0.7 kW) is not over come.

Therefore, this design of the wind turbine allows the use of wind energy in areas with lower wind characteristics, with constant generation.

Unlike increasing the length of the blades, active control systems can dynamically adjust the operating parameters of the wind turbine, such as the angle of inclination of the blades and the speed of rotation, in order to make the most of the current wind conditions. According to numerous studies [17–23], the aerodynamic power factor of a wind turbine is ~0.59. This suggests that under ideal conditions, any wind turbine is capable of converting no more than 59 % of all wind energy passing through the plane of the wind wheel.

Based on the wording, it is possible to derive a law describing the maximum power converted by a wind turbine:

$$P_{\max}=\frac{16}{27}\cdot p\cdot\frac{1}{2}v^3\cdot\left(\pi\cdot R^2\right), \tag{1}$$

where p – air density; V – wind speed; R – wind wheel radius.

To achieve this pattern, it is necessary to take into account the shape and dimensions of the blade. The optimal blade depth depends on the number of blades, as well as the wind wheel radius. The depth of the wind turbine blade is determined as follows:

$$t(r)=\frac{1}{Z}+\frac{1}{C_a}+\frac{8}{9}\cdot\frac{2\pi+R}{\sqrt{\left(\frac{r}{R}\right)^2+\lambda^2+\frac{4}{9}}}, \tag{2}$$

where Z – number of blades; C_a – lifting force; λ – speed coefficient; R – wind wheel radius.

The design considered in this paper focuses on changing the wind wheel radius. Since the radius of the wind turbine is used in both the above expressions (1) and (2), it is necessary to build dependency graphs showing how the change made by the design features affects the maximum power and optimal depth of the wind wheel blade.

Fig. 15 shows a graph of the dependence of the maximum achieve able power on the wind wheel radius. The divisions and calculations of the graph are presented in conventional units.

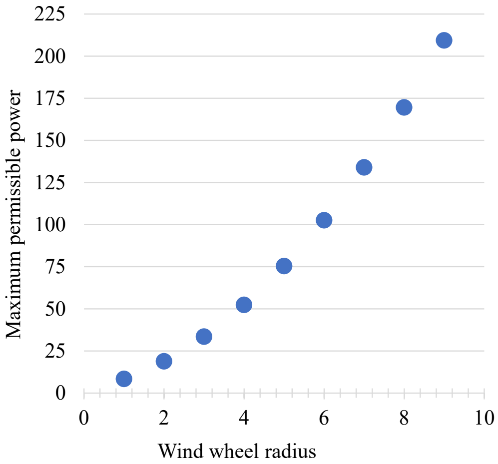


Fig. 15. Dependence of the maximum achieve able power on the wind wheel radius

It can be seen from Fig. 15 that the dependence of the maximum achieve able power on the radius has a non-linearly increasing character. Since in practice it is difficult to imagine an increase in the radius of 3–5 times, it is possible to consider the most likely case – an increase of up to 2 times. It can be seen here that when the radius is increased by one and a half times, the maximum permissible power increases by more than 2 times. By increasing the radius by 2 times, the maximum permissible power increases by more than 4 times. As for the theoretically considered radiuses elongation of 5 times, the maximum permissible power increases by more than 30 times. As the engineering approach of the semi-empirical description of wind turbines shows, according to which there is a technique that allows, on the basis of engineering calculations, to show the technical effect obtained on the basis of the control unit for the length of the blades of the wind wheel.

When the blades are extended, not only the radius (diameter) of the wind wheel increases, but also the area of coverage of wind energy. This value is used in a formula that allows to determine the power of a wind turbine. The power of a wind turbine is determined as follows:

$$W=\frac{3}{2}p\cdot S\cdot V, \tag{3}$$

where p – air density; S – area of circumference of the wind energy blades; V – wind speed; W – power of the flow.

The retractable blades make it possible to increase the sweeping area S, therefore, there is a pattern between increasing the blade length and the converted power [17].

The area of circumference of the wind energy blades is calculated using the following formula [18]:

$$S = \pi r^2, \quad (4)$$

where r – blade length of the wind wheel.

Based on the previous formula, it can be concluded that the relationship between the increase in the length of the blades and the area of girth of the blades of wind energy has a quadratic dependence. The dependence graph is shown in Fig. 16.

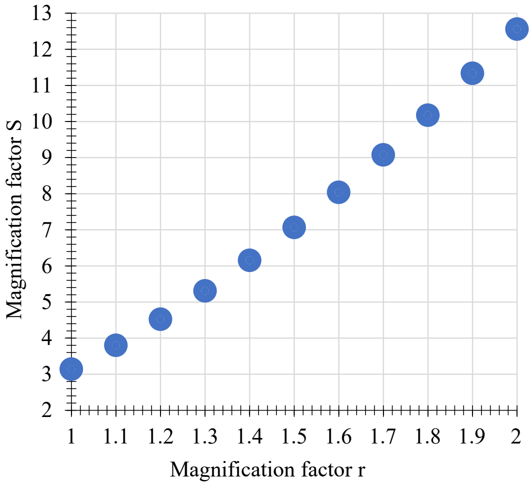


Fig. 16. Dependence of the area of wind energy girth on the radius, in conventional units

When the blade is increased by10 %, which corresponds to an increase factor of 1.1 in Fig. 16, the area of the wind energy girth increases by 21 %. By increasing the coefficient to 1.4 (40 %), the area increases by 96 %. With an increase in the length of the blade by 1.5 times, the area of the wind energy girth increases by 3 times from the initial value.

When analyzing the flow power formula, it can be seen that the dependence of the air flow power on the area of circumference of the wind energy blades has a directly proportional dependence, from which it can be concluded that the dependencies between radius (r) and area (S) are identical with the dependence between radius (r) and flow power (W).

There is also a parameter that affects the operation of the wind turbine and determines the degree of speed of the unit, this parameter is called a step. The pitch of the wind turbine is determined by the following formula [19]:

$$H = 2\pi \cdot r \cdot \mathrm{tg}\varphi, \quad (5)$$

where r – wind wheel radius (blade length); $\mathrm{tg}\varphi$ – angle of section.

According to formula (5), the pitch of the wind turbine has a directly proportional dependence on the radius, that is, if the radius is increased by n times, the pitch of the wind turbine will increase by n times.

6. Discussion of research results of the node for changing the length of the blades

The first result is associated with an increase in the safety of the turbine operation, when high-speed flow can lead to breakdowns not only of the blades of the wind wheel, but also other equipment (bearings, axis of rotation, mounting blades on the axis, etc.). In this case, with a decrease in the length of the blade, the area of sweeping of the wind wheel decreases according to formula (4), according to dependence (3) The power is directly proportional to the sweeping area, which indicates a decrease in energy production, thereby reducing the impact of wind flow on the wind wheel. This also affects the angular rotation speed of the wind wheel and its deceleration reduces the risk of damage to turbine equipment at wind speeds of more than 25 m/s.

The second result is associated with a decrease in the threshold of low wind speed values for starting the turbine. As it is known, the wind speed is not constant, it can completely go into a calm, and then suddenly turn into a raging hurricane. To operate the turbine at low speeds from 1 to 3 m/s, it is necessary to have high wind energy to spin the wind wheel. According to dependence (3), the wind power will depend on the sweeping area and in order for the wind power to be sufficient to launch the wind wheel, it is necessary to increase the radius of the blades, which will increase the sweeping area according to (4).

The results obtained – lowering the threshold for starting the turbine and ensuring its safety under critical conditions – give an advantage over other solutions, such as sailing blades [16], changing the profile of the blades [15], the elasticity of the material [9], since the known solutions do not regulate the area of the wind wheel sweeping when it is in working condition.

At the same time, the proposed solution does not remove the restriction of all wind farms with a horizontal axis of rotation, which cannot operate at a wind speed of more than 25 m/s. In such cases, the operating stations simply stop and stop generating energy. This is due to the high resistance of the blades of the wind wheel, which increases with increasing sweeping area. In our case, it is possible to reduce the length of the blades and reduce the destructive effect of the wind flow on the wind wheel.

In the future it is necessary to explore new blades that can fold and take on various shapes. For such studies, it is very important to identify the material for creating the blade casing. They should be light and durable enough, but at the same time elastic, their cost and manufacturing process are important. Another important point is the disposal and recycling of blades, which also requires separate scientific research.

These solutions collectively address the primary objectives of improving both the safety and power generation capabilities of wind turbines while optimizing operational efficiency through advanced blade length control mechanisms.

7. Conclusions

1. Enhanced safety through dynamic blade adjustment:

– solution: the integration of a blade length control unit at the attachment point of the blades allows for the dynamic adjustment of blade length. This system reduces the blade length under high wind load conditions, thereby decreasing the stress on the wind turbine structure;

– results: this adjustment capability has been shown to lower the wind load on the turbine by up to 30 % in extreme wind conditions, significantly enhancing the safety and longevity of the wind turbine. Qualitative assessments of the system's performance indicate improved reliability and reduced risk of structural damage.

2. Increased power generation:

– solution: the blade length control unit also facilitates an increase in blade length under optimal wind conditions, which expands the turbine's swept area and enhances the interaction between the wind flow and the turbine blades;

– results: experimental data demonstrate an increase in power generation by up to 25 % compared to traditional fixed-blade designs. The extended blade length effectively increases the wind capture area, leading to a higher overall energy output. Quantitative measurements of power output confirm the system's effectiveness in enhancing turbine performance.

These solutions collectively address the primary objectives of improving both the safety and power generation capabilities of wind turbines while optimizing operational efficiency through advanced blade length control mechanisms.

Conflict of interest

The authors declare that they have no conflict of interest in connection with this research, whether financial, personal, authorial or otherwise, which could affect the research and its results presented in this scientific article.

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Data availability

Manuscript has no associated data.

Use of artificial intelligence

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

References

1. Astanto, I., Arifin, F., Bow, Y., Sirajuddin. (2022). Study of Effect Changing the Blade Shape and Lift Angles on Horizontal Wind Turbine. International Journal of Research in Vocational Studies (IJRVOCAS), 2 (1), 33–37. https://doi.org/10.53893/ijrvocas.v2i1.92
2. Chen, J., Yin, F., Li, X., Ye, Z., Tang, W., Shen, X., Guo, X. (2022). Unsteady aerodynamic modelling for dual-rotor wind turbines with lifting surface method and free wake model. Journal of Physics: Conference Series, 2265 (4), 042055. https://doi.org/10.1088/1742-6596/2265/4/042055
3. Koehuan, V. A., Sugiyono, Kamal, S. (2017). Investigation of Counter-Rotating Wind Turbine Performance using Computational Fluid Dynamics Simulation. IOP Conference Series: Materials Science and Engineering, 267, 012034. https://doi.org/10.1088/1757-899x/267/1/012034
4. Kubo, K., Kanemoto, T. (2011). Performances and acoustic noise of intelligent wind power unit. Renewable Energy and Power Quality Journal, 760–765. https://doi.org/10.24084/repqj09.445
5. Kubo, K., Kanemoto, T. (2008). Development of Intelligent Wind Turbine Unit with Tandem Wind Rotors and Double Rotational Armatures (2nd Report, Characteristics of tandem wind rotors). Journal of Fluid Science and Technology, 3 (3), 370–378. https://doi.org/10.1299/jfst.3.370
6. Maduka, M., Li, C. W. (2022). Experimental evaluation of power performance and wake characteristics of twin flanged duct turbines in tandem under bi-directional tidal flows. Renewable Energy, 199, 1543–1567. https://doi.org/10.1016/j.renene.2022.09.067
7. Mucsi, V., Ayub, A. S., Muhammad-Sukki, F., Zulkipli, M., Muhtazaruddin, M. N., Mohd Saudi, A. S., Ardila-Rey, J. A. (2020). Lightning Protection Methods for Wind Turbine Blades: An Alternative Approach. Applied Sciences, 10 (6), 2130. https://doi.org/10.3390/app10062130
8. Valaker, E. A., Armada, S., Wilson, S. (2015). Droplet Erosion Protection Coatings for Offshore Wind Turbine Blades. Energy Procedia, 80, 263–275. https://doi.org/10.1016/j.egypro.2015.11.430
9. Mishnaevsky, L., Tempelis, A., Kuthe, N., Mahajan, P. (2023). Recent developments in the protection of wind turbine blades against leading edge erosion: Materials solutions and predictive modelling. Renewable Energy, 215, 118966. https://doi.org/10.1016/j.renene.2023.118966
10. Finnegan, W., Dasan Keeryadath, P., Ó Coistealbha, R., Flanagan, T., Flanagan, M., Goggins, J. (2020). Development of a numerical model of a novel leading edge protection component for wind turbine blades. Wind Energy Science, 5 (4), 1567–1577. https://doi.org/10.5194/wes-5-1567-2020
11. Chetan, M., Yao, S., Griffith, D. T. (2022). Flutter behavior of highly flexible blades for two- and three-bladed wind turbines. Wind Energy Science, 7 (4), 1731–1751. https://doi.org/10.5194/wes-7-1731-2022
12. Schubel, P. J., Crossley, R. J. (2012). Wind Turbine Blade Design Review. Wind Engineering, 36 (4), 365–388. https://doi.org/10.1260/0309-524x.36.4.365
13. Fukami, K. (2013). Pat. No. US9581134B2. Wind turbine blade and manufacturing method thereof. Available at: https://patents.google.com/patent/US9581134B2/en
14. Wang, G., Petitjean, B. P. A., Drobietz, R. (2019). Pat. No. EP3553307B1. Serrated noise reducer for a wind turbine rotor blade. Available at: https://patents.google.com/patent/EP3553307B1/en
15. Pat. No. CN109690072B. Wind turbine rotor blade (2017). Available at: https://patents.google.com/patent/CN109690072B/en
16. Barber, G. L. (2010). Pat. No. US20100266412A1. Wind turbine. Available at: https://patents.google.com/patent/US20100266412A1/en?oq=Pat.+N+US2010%2f0266412A1.+Wind+turbine
17. Burton, T., Jenkins, N., Sharpe, D., Bossanyi, E. (2011). Wind Energy Handbook. John Wiley & Sons. https://doi.org/10.1002/9781119992714

18. Issenov, S., Antipov, P., Koshumbayev, M., Issabekov, D. (2024). Development of a wind turbine with two multidirectional wind wheels. Eastern-European Journal of Enterprise Technologies, 1 (8 (127)), 47–57. https://doi.org/10.15587/1729-4061.2024.299128
19. Issabekov, D., Issenov, S. (2024). Alternative Resource-Saving Current Protections for Electric Motors. 2024 International Russian Smart Industry Conference (SmartIndustryCon). https://doi.org/10.1109/smartindustrycon61328.2024.10515681
20. Ohya, Y., Karasudani, T., Sakurai, A., Abe, K., Inoue, M. (2008). Development of a shrouded wind turbine with a flanged diffuser. Journal of Wind Engineering and Industrial Aerodynamics, 96 (5), 524–539. https://doi.org/10.1016/j.jweia.2008.01.006
21. Ang, T.-Z., Salem, M., Kamarol, M., Das, H. S., Nazari, M. A., Prabaharan, N. (2022). A comprehensive study of renewable energy sources: Classifications, challenges and suggestions. Energy Strategy Reviews, 43, 100939. https://doi.org/10.1016/j.esr.2022.100939
22. Pfeiffer, B., Mulder, P. (2013). Explaining the diffusion of renewable energy technology in developing countries. Energy Economics, 40, 285–296. https://doi.org/10.1016/j.eneco.2013.07.005
23. Samadi, S. (2018). The experience curve theory and its application in the field of electricity generation technologies – A literature review. Renewable and Sustainable Energy Reviews, 82, 2346–2364. https://doi.org/10.1016/j.rser.2017.08.077