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Construction of the working surfaces of the tillage screw body from the compartments of the developable helicoid

Abstract. Improvement of the screw working bodies for surface tillage is important for increasing the efficiency and quality of agricultural work. The purpose of the work was to calculate the design of the screw a working body for the surface cultivation of the soil from the compartment of the developable helicoid, which would perform the technological process with minimal resistance to plunging in the soil. The surface theory, analytical, and differential geometry were used to design the working body. It is shown in the paper that through a given spiral line, which is the cutting edge of the surface (blade), it is possible to draw developable helicoids with different inclinations of rectilinear generators. Designing the surface for the best plunging into the soil is important. It is established that the proposed working body is an alternative to the existing disc-type tools. It has been proven that for a long time, spherical discs for surface cultivation of the soil were fixed on a common shaft, which was installed on the unit with a certain angle between its axis and the direction of movement

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of the unit, which contributed to the plunging of the discs in the soil. It is confirmed that the disc-type tillage implements were improved, but this complicated the design of the unit since each disc received an individual axis of rotation. Studies have shown that this made it possible to additionally set the roll angle, that is, the deviation of the plane of the disc blade from the vertical direction, which improved the plunging of the disc in the soil and ensured more effective turning and mixing of plant residues. The proposed screw working body combines the simplicity of the design of the common shaft and the presence of the angle of attack and roll, which confirms its effectiveness in comparison with existing analogs. The necessary calculations were made, and the surfaces of the right and left courses were constructed with the designation of the necessary structural parameters. The application of the obtained results can simplify the design of the soil processing unit

Keywords: attack angle; sharpening angle; surface step; screw parameter; ridges; soil profile

INTRODUCTION

Improvement of the tillage screw body can significantly increase the efficiency and quality of surface tillage. Traditional disc tools have their limitations, while screw-type working bodies, in particular developable helicoids, offer an alternative that allows for a more uniform finish with characteristic crests and troughs. The developable helicoid has a shape that contributes to easier plunging in the soil, which reduces resistance and facilitates work. In addition, the precise calculation of the flat workpiece for the manufacture of coils ensures high accuracy and efficiency in the production of these tools. All these factors contribute to increasing the productivity and quality of agricultural work, which is key to ensuring stable and efficient agricultural production.

The influence of operational factors of agricultural machinery on its technical condition was studied in detail by L. Semenenko *et al.* (2021). The authors established that in 90% of cases, increasing the durability and wear resistance of the working bodies of tillage machines is implemented by technological methods. S. Mudarisov *et al.* (2019) noted that there is a global trend toward the formation of a new agricultural strategy, the basis of which is the implementation of modern innovative soil cultivation technologies using the latest combined units. K. Aikins *et al.* (2020) applied the discrete element method to the design and optimization of tillage implements. The dependence of the soil tillage efficiency on the geometric and structural characteristics of the working bodies and their setting was established. The approach proposed by the authors makes it possible to improve existing soil cultivation technologies, including by reducing the energy intensity of the process, which corresponds to modern principles of sustainable agriculture.

Existing methods of processing the surface of the field before sowing, as noted by E. Zykin *et al.* (2022), are implemented by various agricultural machines, which are equipped with working bodies in the form of rotating spherical disks. But the problem of high-quality soil cultivation by such working bodies that meet the quality criteria remains unsolved.

R. Abdrakhmanov *et al.* (2023) give a detailed analysis of the structures of the disk working organs. The authors note that the main disadvantage of all structures is slippage when interacting with the soil, which significantly reduces the quality of soil cultivation. To eliminate this shortcoming, the authors propose a new design of the tillage disc.

V. Zubko *et al.* (2021) claim that field cultivation allows to solve important agrotechnical tasks: destruction of weeds, pests, and pathogens of plant diseases; preservation and increase of moisture reserves in the soil; activation of microorganisms; application of plant residues and mineral fertilizers to the soil; ensuring the necessary conditions for high-quality subsequent tillage of the soil. The analysis of the received data made it possible to determine the parameters of the movement speed of the soil tillage unit of the existing design, the depth of cultivation, and the direction of movement on the field, which allows performing disk tillage in compliance with agrotechnical requirements.

The relative movement of particles on the inner rough surface of the concave tillage disk, which rotates around its axis under the action of the soil reaction force, is considered T. Volina *et al.* (2021). The expediency of equipping such a disk with vertical radially mounted vanes has been investigated. As noted by M. Amantayev *et al.* (2018) and E. Zykin *et al.* (2020), the factors that significantly affect the quality of disk tillage are the shape and size of the disks, their placement on the frame and orientation in the soil, the weight of the machine.

Spherical tillage discs for surface tillage have been used for a long time. If earlier they were mounted on a common shaft in the form of a battery, now each disk has its own rotation node and individual attachment of the axis of rotation to the frame (Rashidov *et al.*, 2022). This allows setting not only the angle of attack but also the angle of inclination concerning the vertical plane. This contributes to a better movement of the soil along the surface of the disc and improves its mixing, but complicates the construction of the unit. The use of a screw surface can combine the fulfillment of the agrotechnical requirements of soil cultivation, the characteristic of units with individual fastening of discs, and the simplicity of design characteristic of battery-type implements (Hevko *et al.*, 2021). Therefore, screw working bodies are an alternative to disc tools.

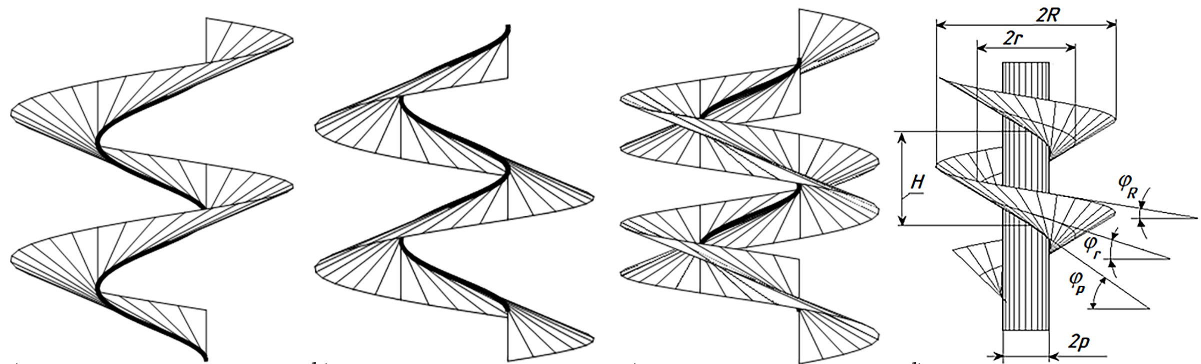
The work of S. Pylypaka *et al.* (2021) is the closest to the conducted research. It considers the design of a screw working body when using which the profile of the treated soil has ridges and depressions, as well as when working with the disk working bodies. In this article, theoretical calculations were performed, the helical surface of the working body was constructed, and on their basis, the profile of the treated soil was obtained concerning structural and technological parameters. It left out of consideration the important issue of plunging the working body into the soil. This issue has been studied for disc working bodies and consists of the fact that when the tillage disc is buried in the soil, it is necessary to eliminate the contact of its rear surface with the soil environment. Otherwise, the disk will try to roll to the surface, that is, its plunging will be unsatisfactory. The same applies to screw working bodies. To prevent such a possibility, there were conducted research in this article. The purpose of the work was to calculate the helical working surface of the working body for surface cultivation of the soil with the available back angle to reduce the resistance of plunging in the soil.

MATERIALS AND METHODS

Research methods were based on the theory of surfaces of differential geometry. According to it, only helical ruled surfaces are classified according to the position of the rectilinear generator in relation to the axis of the surface (intersecting or oblique, what is the angle between them). The paper examined the compartment of the developable helicoid (torso-helicoid) as the surface that is most suitable both in terms of structural parameters and the technology of manufacturing turns. They were obtained by bending and stretching the sweep in the form of a flat ring along the axis of the cylindrical shaft. The developable helicoid is formed by a set of rectilinear generators tangent to the helical line, which for the formed surface is called the turning edge. Based on the method of formation, the parametrization of the surface with a vertical axis has the form:

$$X = p\cos\alpha \mp u\frac{p}{\sqrt{p^2+h^2}}\sin\alpha\,;\; Y = p\sin\alpha \pm u\frac{p}{\sqrt{p^2+h^2}}\cos\alpha\,;$$
$$Z = h\alpha \pm u\frac{p}{\sqrt{p^2+h^2}}, \qquad (1)$$

where α, u are variable parameters of the surface, α is the angle of rotation of the point around the axis of the surface during its movement to the current point on the helical line, which is located on the cylinder of radius p; u is the length of the rectilinear generator from the current point on the helical line to the point on the surface; h is a constant value (screw parameter) through which the step H of the surface is determined: $H = 2\pi h$. The helical parameter h is a constant value and does not depend on the radius r of an arbitrary helical line on the surface. In Figures 1a, 1b, frontal projections of the surface of the developable helicoid were constructed according to equations (1) for the upper and lower sign, respectively.



a) b) c) d)

Figure 1. Developable helicoids formed by a set of rectilinear generators tangent to the helical line

Note: a, b) based on the right helical line with the upper and lower arrangement of rectilinear generators; c) based on the left helical line with the arrangement of straight-line generators extended in opposite directions from the helical line; d) surface with design parameters; R is the radius of the cylinder on which the helical line is located – the edge of the surface; r is the radius of the cylinder on which an arbitrary helical line is located; H is the pitch of the surface; p is the radius of the cylinder, on which the helical line is located – the turning point of the surface; φ_R, φ_r, and φ_p are the elevation angle of the helical line, which is the edge of the surface, an arbitrary helical surface line and the turning edge

Source: developed by the authors based on equations (1), (2)

The left part of the equations (1) of the surface of the helicoid is the parametrization of the helical line (reverse edge) located on the cylinder of radius p. The right parts in front of the variable u are the projections of the unit base vector of the generator. They are obtained by differentiation of the left parts followed by their normalization to a unit vector. The upper sign corresponds to the count of the generator from the point on the spiral line up (Fig. 1a), and the lower one – down (Fig. 1b). As the angle α in equations (1) increases, a helical line is formed as a trajectory of a point in two movements: translational along the OZ axis upwards and rotational around the counterclockwise axis (right-hand helical line). If the direction of rotation is changed to the opposite, then the helical line will be left-handed. The parametrization of the surface based on it had the form:

$$X = p\cos\alpha \mp u\frac{p}{\sqrt{p^2+h^2}}\sin\alpha\,;\; Y = -p\sin\alpha \mp u\frac{p}{\sqrt{p^2+h^2}}\cos\alpha\,;$$
$$Z = h\alpha \pm u\frac{h}{\sqrt{p^2+h^2}}. \qquad (2)$$

The two surfaces corresponding to the upper and lower signs in equations (2) are shown in Figure 1c. Since the rectilinear generators going up and down from the point of contact have a common direction, two surface cavities are formed. Despite the similarity of the surfaces for the right and left helical lines, there is a difference between them: the visible side of one surface is invisible for the other and vice versa.

The helical line (edge of return) is given by two constant values: the radius p of the cylinder on which the edge of return is located, and the step $H=2\pi h$. Through p and h, the angle φ_p of the rise of the turning edge is determined:

$$\operatorname{tg}\phi_p = \frac{h}{p}. \tag{3}$$

A section of the helicoid was cut out by coaxial cylinders at a certain distance from the return edge. The lines of intersection of these cylinders with the helicoid were also helical lines of the same pitch H but with a different angle of elevation. It was determined by the formula (3) when substituting the radius of the corresponding cylinder into the denominator. As the radius of the cylinder increases, the angle of elevation of the helical line decreases (Fig. 1d), but the angle of inclination of the generating helicoid remains constant and equal to the angle of elevation of the return edge.

In equations (1), (2), the guiding curve was a spiral line on a cylinder of radius p, which is a turning edge for the surface. The surface of the helicoid torso passed through other helical lines, including those with the radius of the cylinder R (Fig. 1d). Taking the helical line, which is the outer edge of the compartment, as a base curve, the parametrization of the surface has changed slightly. The index "R" was used to indicate the right spiral line in the equations, and the index "L" was used for the left one:

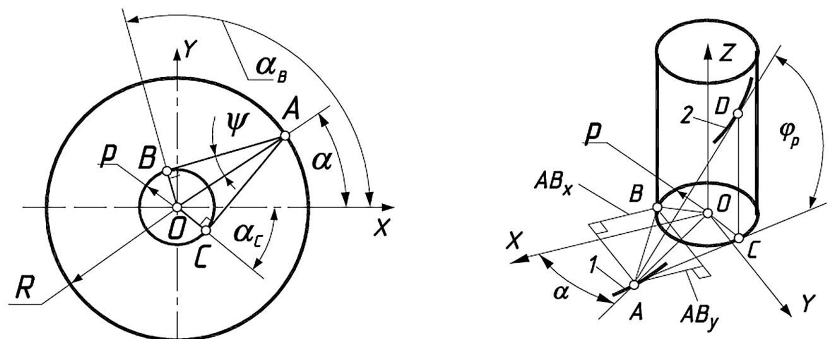
$$\begin{gathered} X_R = R\cos\alpha + ul;\ X_L = R\cos\alpha + ul; \\ Y_R = R\sin\alpha + um;\ Y_L = -R\sin\alpha - um; \\ Z_R = h\alpha + un;\ Z_L = h\alpha + un, \end{gathered} \tag{4}$$

where $l=l(\alpha)$, $m=m(\alpha)$, $n=n(\alpha)$ are direction cosines of the rectilinear generating surface. They had to be such as to ensure the contact of rectilinear generators with the edge of the turn.

The set of rectilinear generators, drawn through a given helical line at an angle φ_p, had to be tangent to the turning edge – a helical line on a cylinder of radius p (Fig. 1d). This means that on the horizontal projection, these generators were tangent to the circle of radius p. This approach of surface formation was applied in the work of S. Pylypaka *et al.* (2021). This research is its continuation.

RESULTS

Figure 2a shows a horizontal projection on which helical lines are depicted by circles of radii R and p. At the current value of the angle α, point A is taken on the given spiral line through which straight lines tangent to the circle of radius p are drawn. There are two such lines (Fig. 2a).



a) b)

Figure 2. Graphical illustrations for determining the direction of rectilinear generators of a helicoid that pass through a given helical line

Note: a) horizontal projection of a given helical line with rectilinear generators of a helicoid; b) axonometric image of fragments of a given helical line and generating helicoid with its reverse edge; R is the radius of the cylinder on which the helical line is located – the edge of the surface; p is the radius of the cylinder, on which the helical line is located – the turning point of the surface; α is the current value of the angle, which is an independent variable; α_B and α_C are values of the angles α for the corresponding points; φ_p – the angle of elevation of the return rib; AB_x and AB_y are projections of segment AB; ψ is the angle between the radial direction and segment AB; *A, B, C, D, O* are points; *1* – a fragment of a helical line – the edge of the surface; *2* – a fragment of the reverse rib

Source: developed by the authors based on conducted research

To find their direction, it was necessary to know the coordinates of points A, B, and C. They were recorded through the current value of the corresponding angle: A $\{R\cos\alpha,\ R\sin\alpha\}$, B $\{p\cos\alpha_B,\ p\sin\alpha_B\}$, C $\{p\cos\alpha_C,\ p\sin\alpha_C\}$. The angle ψ has a constant value: $\psi = \operatorname{Arcsin}(p/R)$. Using the connections between the angles of right triangles, expressions for the required angles could be found: $\alpha B = \alpha - \operatorname{Arcsin}(p/R) + \pi/2$, $\alpha\ C = \alpha + \operatorname{Arcsin}(p/R) - \pi/2$. After that, the coordinates of points B and C could be written as a function of the current value of the angle α: B $\{p\cos(\operatorname{Arccos}(p/R)+\alpha),$

$p\sin(\text{Arccos}(p/R) + \alpha)\}$, C $\{p\sin(\text{Arcsin}(p/R) + \alpha), -p\cos(\text{Arcsin}(p/R) + \alpha)\}$. Having the coordinates of points A, B, and C, the lengths of the segments AB and AC can be found as the distance between the coordinates of their endpoints. The projections of these segments on the axis OX and OY are the projections AB_x, AB_y and AC_x, AC_y (Fig. 2b shows the projections for the segment AB):

$$\begin{aligned}AB_x &= \tfrac{1}{R}\left[(R^2-p^2)\cos\alpha + p\sqrt{R^2-p^2}\sin\alpha\right];\\ AB_y &= \tfrac{1}{R}\left[(R^2-p^2)\sin\alpha - p\sqrt{R^2-p^2}\cos\alpha\right];\\ AC_x &= \tfrac{1}{R}\left[(R^2-p^2)\cos\alpha - p\sqrt{R^2-p^2}\sin\alpha\right];\\ AC_y &= \tfrac{1}{R}\left[(R^2-p^2)\sin\alpha + p\sqrt{R^2-p^2}\cos\alpha\right].\end{aligned} \quad (5)$$

Segments AB and AC are equal, and their length can be found by their projections:

$$AB = AC = \sqrt{AB_x^2 + AB_y^2} = \sqrt{AC_x^2 + AC_y^2} = \sqrt{R^2 - p^2}. \quad (6)$$

In Figure 2b the axonometry shows fragments of the given helical line (marked with the number 1) and the edges of the helicoid return (marked with the number 2), through points A and D of which the generating surface passes. The angle of inclination φ_p of the rectilinear generator (segment AD) can be determined from the right triangle ACD:

$$tg\varphi_p = \frac{CD}{AC} = \frac{CD}{\sqrt{R^2-p^2}}. \quad (7)$$

From expression (7), the length of the segment CD can be found, which is also the projection of the base vector of the rectilinear generating helicoid onto the axis OZ, i.e. $CD{=}CD_z$. According to the known projections of the segment AD $\{AC_x, AC_y, CD_z\}$, one can find the projections l, m, n of the unit base vector of the rectilinear generating helicoid, parallel to the segment AD (Fig. 2b):

$$\begin{aligned}l &= \tfrac{\cos\varphi_p}{R}\left(\mp p\sin\alpha - \sqrt{R^2-p^2}\cos\alpha\right);\\ m &= \tfrac{\cos\varphi_p}{R}\left(\pm p\cos\alpha - \sqrt{R^2-p^2}\sin\alpha\right);\\ n &= \pm\sin\varphi_p.\end{aligned} \quad (8)$$

The two signs in expressions (8) correspond to the two opposite directions of the rectilinear generator, the count of which starts from a point on the given helical line. It should be borne in mind that the radius p and the angle φ_p are connected by the dependence (3), namely: $p = h\text{ctg}\varphi_p$. Taking this into account, the direction cosines (8) will be finally written:

$$\begin{aligned}l &= \tfrac{\cos\varphi_p}{R}\left(\mp h\text{ctg}\varphi_p\sin\alpha - \sqrt{R^2 - h^2\text{ctg}^2\varphi_p}\cos\alpha\right);\\ m &= \tfrac{\cos\varphi_p}{R}\left(\pm h\text{ctg}\varphi_p\cos\alpha - \sqrt{R^2 - h^2\text{ctg}^2\varphi_p}\sin\alpha\right);\\ n &= \pm\sin\varphi_p.\end{aligned} \quad (9)$$

The expressions of the direction cosines (9) include three constant values: R and h, which specify the base spiral line and the angle φ_p of the slope of the rectilinear generators. It can be changed within certain limits, which means that a set of developable helicoids can be drawn through a given helical line. The maximum value of the radius p can be equal to the radius r of the limiting shaft (the case when the internal helical line is the turning edge), and the minimum value can be greater than zero. For the case when $p = r$ from dependence (3): $\varphi_p = \text{Arctg}(h/r)$. Thus, $\text{Arctg}(h/r) \leqslant \varphi_p < 90°$.

Figure 3 shows the frontal projections of the surfaces constructed according to equations (4) taking into account (9). Through the helical line of right-hand movement (Fig. 3a, 3b, 3c), surfaces with different set angles of inclination of the generators pass. Figure 3d is the same, but the helical line is a left-hand line.

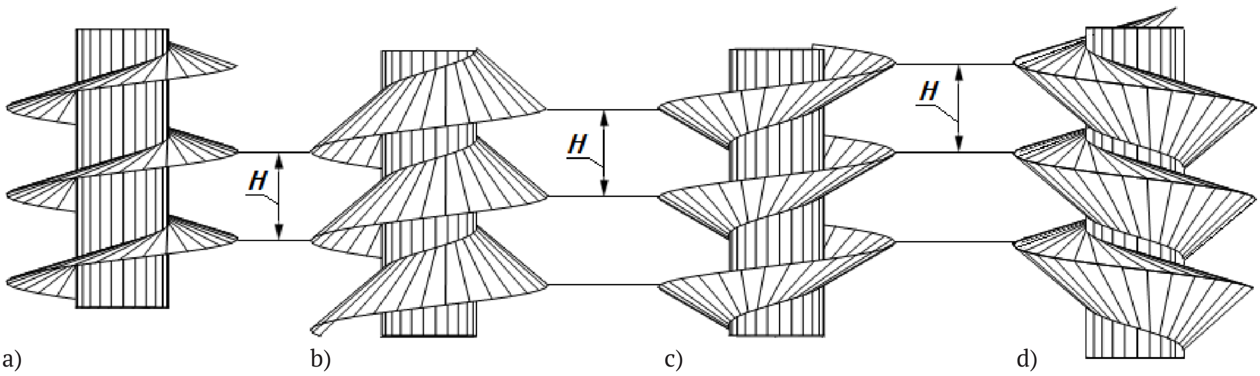


Figure 3. Helicoid torsos passing through a given helical line of the same right-hand and left-hand pitch
Note: a) right-hand course, rectilinear generators are directed downward, $\varphi_p = 17°$; b) right-hand course, rectilinear generators are directed downward, $\varphi_p = 40°$; c) right-hand course, rectilinear generators are directed upwards, $\varphi_p = 30°$; d) left-hand course, rectilinear generators are directed down and up, $\varphi_p = 17°$ and $\varphi_p = 40°$ H – pitch of helical lines, which is the pitch of the surface
Source: developed by the authors based on conducted research

In Figure 3 compartments of helicoid torsos are limited by outer and inner helical lines. The external helical line can be obtained from equations (4) at $u = 0$. At another constant value of the length of the rectilinear generator

$u = const$, an internal helical line will be obtained for the value of the radius r. It is obvious that for all four compartments of surfaces (Fig. 3) the value of parameter u will be the same. On the horizontal projection, all four spiral lines are projected by a circle of radius r, that is, it can be written: $X_R^2 + Y_R^2 = r^2$. By substituting the expressions X_R and Y_R or X_L and Y_L into this equation, a quadratic equation is obtained. Its solution concerning u gives the result:

$$u = \frac{-R(l\cos\alpha + m\sin\alpha) + \sqrt{R^2(l\cos\alpha + m\sin\alpha) - (l^2+m^2)(R^2-m^2)}}{l^2+m^2}. \quad (10)$$

Substitution from (8) of the expressions of the base vectors l and m in (10) and further simplifications make it possible to obtain a simple formula for finding u:

$$u = \frac{\sqrt{R^2-p^2} - \sqrt{r^2-p^2}}{\cos\phi_R}. \quad (11)$$

The substitution in (11) of the dependence $p = h\mathrm{ctg}\varphi_p$ gives the final result:

$$u = \frac{\sqrt{R^2-h^2\mathrm{ctg}^2\phi_p} - \sqrt{r^2-h^2\mathrm{ctg}^2\phi_p}}{\cos\phi_R}. \quad (12)$$

When $r = R$ according to (12), $u = 0$ will be obtained. For other values *of r,* the value u will be obtained from the interval $r = p...R$, at which the spiral line will correspond to the value of the radius r. Disc working bodies are used for surface tillage. For the disk to plunge into the soil, it is placed at an angle of attack to the direction of movement of the unit. If the surface of the helicoid is placed so that its axis is horizontal, then under certain conditions it can also be considered as a tillage body. In Figure 4a, the projections show a developable helicoid with a cylindrical shaft, which lies on the surface of the soil. The points of contact of the external helical line with the soil surface are marked with circles. The shaft is not shown on the horizontal projection so that the angle φ_R at the points of contact can be marked. By analogy with the disk working body, this angle can be considered the angle of attack. If the surface of the helicoid is rolled across the field, its intensive plunging into the soil will obstruct the back side of the surface, which in Figure 4a is painted in light gray. To avoid this, the helicoid should be turned by the angle β, as shown in Figure 4b. If the angle β was equal to the angle φ_p of the slope of the generators, then the angle ε (Fig. 4b) would be equal to zero. However, to prevent the soil from being crushed by the back side of the working surface, this angle (or back angle) for disc working bodies, taking into account the angle of sharpening the blade, should be equal to 3°-5° (Pylypaka *et al.*, 2021). In this study, a surface of zero thickness is considered, therefore it is assumed that $\varepsilon \geqslant 5°$. It can be more accurately determined by taking into account the thickness of the surface of the helicoid and the sharpening angle of the cutting edge. Therefore, the angle of attack will be determined by the sum of two angles: $\beta = \varphi_p + \varepsilon$.

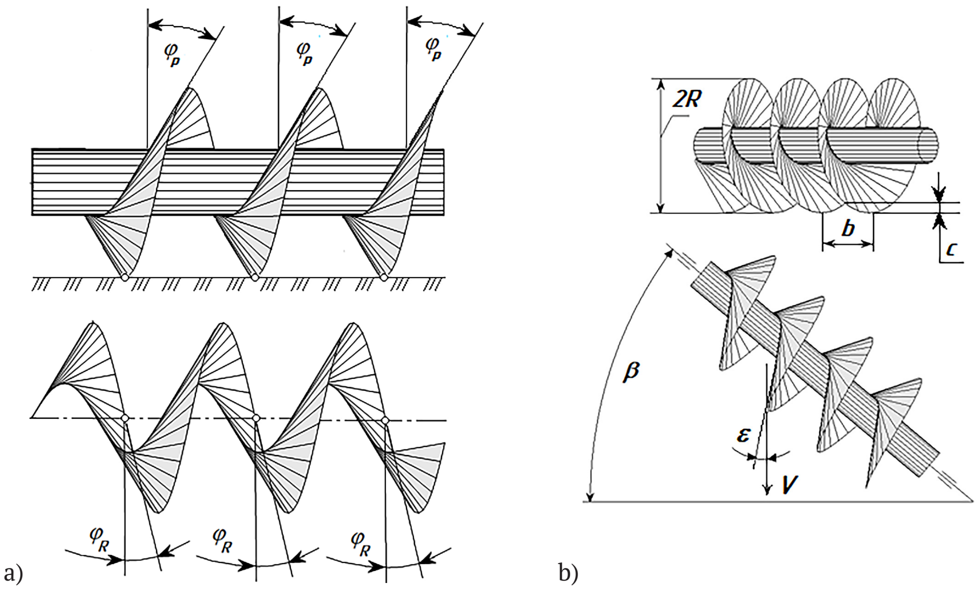


Figure 4. Developable helicoid with a horizontal axis of rotation

Note: a) the horizontal axis of the helicoid is perpendicular to the direction of rolling; b) the horizontal axis of the helicoid forms an angle of 90°– β with the direction V of the aggregate movement; φ_R is the angle of elevation of the helical line, which is the edge of the surface; R is the radius of the cylinder on which the helical line is located – the edge of the surface; β is the angle between the axis of the helicoid and the direction perpendicular to the direction of movement of the unit; V – direction of movement of the unit; ε – rear angle; b is the distance between ridges; c is the height of the ridges

Source: developed by the authors based on research

With this orientation of the helicoid, the back side of the surface is not visible on the frontal projection, unlike the frontal projection in Figure 4a. This means that it will not interfere with the plunging of the surface into the soil. The surface was assumed to plunge into the soil until the cylindrical shaft touched the field surface. The profile at the border of treated and untreated soil (Fig. 4b) will be similar to the profile after passing the disk working bodies. If it is necessary to treat the soil to a depth of 0.1 m at $R = 0.25$ m, the radius of the cylindrical shaft should be $r = 0.15$ m.

If one pulls the screw working body shown in Figure 4b in the direction V of the unit's movement, then it will be plunging into the soil. As a result of the interaction with the soil, a reaction force will arise, which will put pressure on the working surface of the coil. The component of this force will try to move the working body to the side perpendicular to the direction of its movement. To balance this moment of force, it is advisable to make the unit in the form of two working bodies, as shown in Figure 5. The surface of the second working body should have a turning edge with the opposite direction of winding and the direction of rectilinear generators, as shown in Figure 5. The cylindrical shaft for the tool was chosen taking into account the specified depth and tillage of the soil. Also, with this option, the height of the ridges c and the distance b between the ridges could be reduced. (Fig. 5, frontal projection). For the ridges to be of the same height, the position of both helical working bodies must be correctly coordinated.

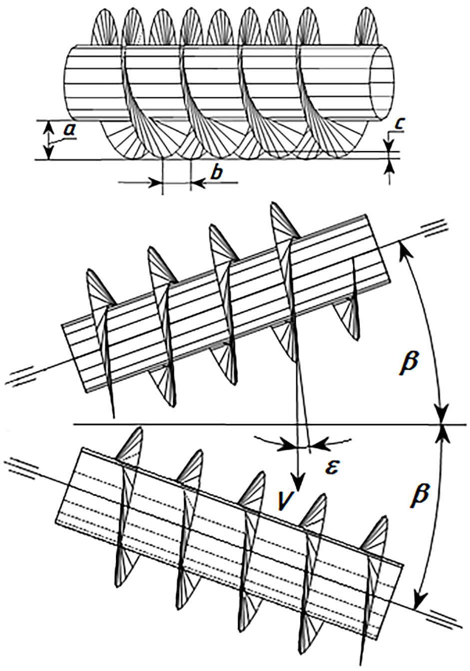


Figure 5. Soil tillage tool in projections, which consists of two screw working bodies
Note: horizontal and frontal projections; β is the angle between the axis of the helicoid and the direction perpendicular to the direction of movement of the unit; V – direction of movement of the unit; ε – rear angle; a – depth of processing; b is the distance between ridges; c is the height of the ridges
Source: developed by the authors based on research

Earlier it was said that the rotation angle β is determined from the expression: $\beta = \varphi_p + \varepsilon$. The angle ε should be as small as possible, but as noted, it cannot be less than 5°. The question arises about the value of the angle φ_p, since the compactness of the tillage tool depends on the value of the angle β. For this, the angle φ_p should also be taken as small as possible, but such that the surface plunges into the soil. It can be seen from formula (3) that the value of the angle φ_p depends on the pitch of the helical line (edge of the turn) and the radius p of the cylinder on which it is located. At a constant step, the angle φ_p can be changed by changing the radius p. The section of the surface located between two coaxial cylinders will have the same pitch as the turning edge, and the angle φ_p of the slope of the generators will depend on the value of the radius p. Therefore, through the given helical line, which was considered the outer edge (blade) of the working helical surface, it is possible to draw a whole set of helicoids with a different angle φ_p of the inclination of the generators, which was considered in the previous subsection.

Based on the obtained results, it is possible to proceed with the construction of the working turns of the screw tillage body with different angle φ_p of the inclination of the rectilinear generating helicoid. For this, the original spiral line – the cutting edge of the working surface – must be specified. Let $R = 0.25$ m. Step H was chosen taking into account the desired distance b between ridges. For one working surface at $\beta = 0$, $H = b$. When the surface is rotated by an angle β, the distance b will be slightly smaller than the step H, namely: $b = H\cos\beta = 2\pi h\cos\beta$ (Fig. 6a). From here, the helical parameter h of the helical line could have been determined, but for this, the angle β needed to be known. Since it is the sum of two angles $\beta = \varphi_p + \varepsilon$, of which φ_p is still unknown, in the first approximation it was assumed that $H = b$. Considering that there will be two surfaces (Fig. 6), the step can be doubled, i.e. $H = 2b$. It was assumed that $b = 0.2$ m, then $h = 0.06$ m. The depth of tillage was assumed to be $a = 0.1$ m. Then the radius r of the internal helical line was determined as $r = Ra = 0.15$ m. The angle of inclination of the generating φ_r was taken as a minimum – $\varphi_p = \mathrm{Arctg}\,(h/r) = 22°$. For this case $\beta = \varphi_p + \varepsilon = 27°$. To construct the surface according to equations (4), it is necessary to know the limits of the change of the u parameter. It can be found from expression (12): $u = 0.21$ m. Therefore, the parameter u varies within $u = 0...0.21$, and the angle α depends on the number of turns (for one turn $\alpha = 0...360°$). In Figure 6a, based on the given data, the working turns of the surface are constructed according to equations (4), in which one output screw line is right-hand, and the other is left-hand. The choice of the sign in expressions (9) – lower or upper – determined the desired reference direction of the rectilinear surface.

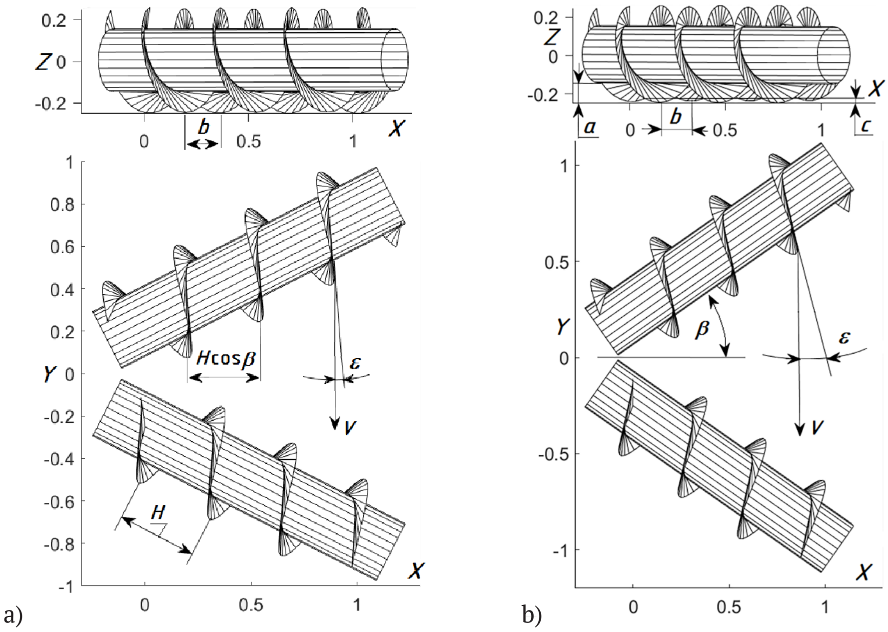


Figure 6. Working surfaces of helicoids passing through right-hand and left-hand helical lines with parameters $R = 0.25$ m and $h = 0.06$ m

Note: a) $\varphi_p = 22°$; $\beta = 27°$; $b = 0.17$ m; b) $\varphi_p = 22°$; $\beta = 35°$; $b = 0.14$ m; a – depth of processing; b is the distance between ridges; c – ridge height; β is the angle between the axis of the helicoid and the direction perpendicular to the direction of movement of the unit; V – direction of movement of the unit; ε – rear angle; H is the pitch of the surface

Source: developed by the authors based on research

Since the angle β is already known ($\beta = 27°$), the refined value of the distance b between the ridges became known: $b = H/2 = 2\pi h\cos\beta/2 = 0.17$ m. The construction of the images took place according to the specified dimensions in scale; therefore, it is possible to estimate the lower profile of the treated soil from the frontal projection in Figure 6a. There are quite a lot of options for the received tillage tool. For example, simply increase the angle of attack β without changing other parameters. Figure 6b shows the diagram of the tillage unit for the angle of attack $\beta = 35°$. At the same time, the distance between the ridges decreased to $b = 0.14$ m, but the height of the ridges did not change. The length of the unit has increased somewhat. The angle ε also increased from 5° to 13°, which is a positive consequence of the increase in the angle of attack. The fact is that the back side of the surface needs to be sharpened, as mentioned earlier. As a result, a narrow strip of the new surface appeared. For a spherical disk, such a surface is a cone, for a helicoid – another helicoid. This is also the rear surface, which should not disturb the soil. To fulfill this condition, an angle margin ε is required. However, it is possible to increase the angle ε by increasing the angle β up to a certain limit. An excessive increase in the angle of attack β can lead to a decrease in the angular speed of rotation due to the drag of the helical surface. The unit can be adjusted. The range of changing the angle of attack β is quite wide – it can reach up to 40° in disc peelers.

If at an angle of inclination of the generators $\varphi_p = 22°$, the plunging of the surface into the soil and its processing occurs normally, then it can be preserved while maintaining the angle of attack $\beta = 40°$, while reducing the step H. Accordingly, the helical parameter h and the minimum value of the angle φ_p will decrease. However, the required value of $\varphi_p = 22°$ was taken, not the minimum. At the same time, the value of the angle ε will not change either. Therefore, the three parameters could be left unchanged, while step H could be reduced (the distance b between the ridges would also decrease). However, the decrease in step H led to a decrease in the space between the turns, which can interfere with the passage of soil lumps between them to the point of jamming the inter-turn space with the soil. In addition, jamming can be facilitated by the solid structure of the shaft, so it is necessary to make it lattice (Fig. 7). In this case, the shaft will perform an additional rolling function.

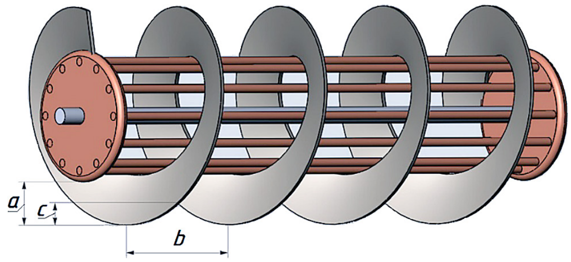


Figure 7. Lattice shape of the shaft
Note: an axonometric image; a – depth of processing; b – the distance between ridges; c is the height of the ridges
Source: developed by the authors based on conducted research

An increase in the angle φ_p leads to a decrease in the angle of elevation of the soil on the surface of the helicoid. According to agrotechnical requirements, it is necessary to ensure the mixing of the soil with harvest residues, which cannot be done without raising the soil to a great height. This requirement can be provided by a decrease in the angle of elevation of the soil, that is an increase in the angle φ_p, which makes it easier for the cut strip of soil to rise along the surface of the helicoid. Of course, the increase in the angle φ_p also has its limit and its rational value can be found during the experiment.

Figure 8a shows the diagram of the tillage unit, which differs from the unit in Figure 6b by the fact that the angle φ_p is increased to 35°. As a result, the angle ε became equal to zero. In principle, such an option is possible if the edge is sharpened not from the outer (back) side of the surface, but from the inner (working) side, but this method of sharpening is not practiced in disc-working bodies. The angle β could be increased from 35° to 40°, then the angle $\varepsilon = 5°$ would appear. Such a scheme of the unit is shown in Figure 8b. In addition, step H has also been increased. At the same time, the angle between the edge of the surface and the direction of entry V_p of the particle on the surface increases (Fig. 8b). This contributes to a better plunging of the surface into the soil. The best plunge would be if this angle were straight, that is, the particle entered the surface perpendicular to the blade (this applies to the lowest point of the blade, as it approaches the surface of the field, this angle will no longer be straight). For this, it is necessary to increase the angle β: $\beta = 90° - \varphi_R = 90° - \mathrm{Arctg}(h/R)$. For example, for the unit, the scheme of which is shown in Figure 8b, the angle β should be 72°. It is obvious that at this value of the angle β, the rotation of the helicoid around its axis will become difficult or impossible.

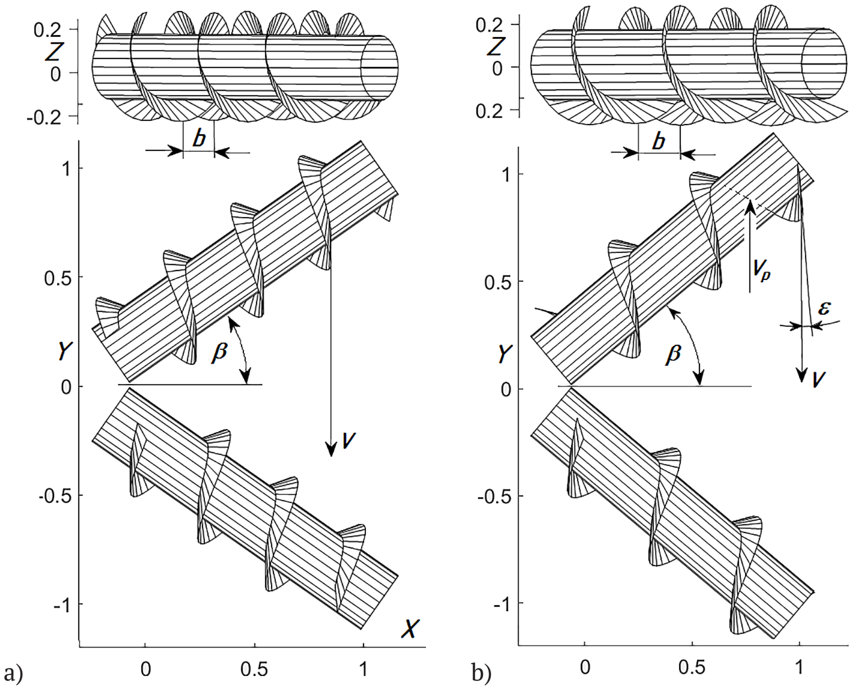


Figure 8. Working surfaces of helicoids of different steps with the same angle $\varphi_p = 35°$ of the inclination of rectilinear generators
Note: a) $h = 0.06$ m; $\beta = 35°$; $\varepsilon = 0$; $b = 0.14$ m; b) $h = 0.08$ m; $\beta = 40°$; $\varepsilon = 5°$; $b = 0.19$ m
Source: developed by the authors based on conducted research

On all diagrams of the tillage unit (Fig. 6, 8), the height c of the ridges is practically the same, only the distance b between the ridges differs. In general, the shape of the profile of the cultivated soil is determined by the parameters h and R of the external helical line (cutting edge) and the angle β of its axis.

DISCUSSION

The experience of industrialized countries over the past century in the issue of weed control has shown that the main criteria for the decisions of manufacturers of tillage machines are simplicity and convenience (Syromyatnikov, 2017). It is important to develop new non-chemical methods of weed control due to the impact of herbicides on human health and increasing the resistance of weeds (Syromyatnikov, 2018). The European Union Commission encourages member states to develop low-pesticide agriculture (Busari *et al.*, 2015). The basis of this process is the improvement of weed control machines. In this sense, research on the improvement of working bodies for surface treatment corresponds to modern trends in the development of agricultural machines. The basis for the design of tillage working bodies is the availability of their simple analytical physical and mathematical models (Ghereş, 2014; Tesliuk *et al.*, 2019), the development of which scientists pay a lot of attention. Experimental studies play an important role in bringing the working bodies to the optimal form so that agrotechnological requirements are met during their work. However, analytical calculations play a big role, which is demonstrated in the proposed article on the provision of a back angle.

Tillage units are used for soil treatment. Working bodies in contact with the ground can be those that are rigidly attached to the frame (loosening paws, spring teeth) and those that rotate around an axis (rolls, disk working bodies). Tillage discs are used to grind and mix plant residues with soil. Previously, they were mounted on a common shaft, the axis of which made a certain angle to the direction of movement of the unit, that is the angle of attack. Under the action of the unit's weight, the discs plunged into the ground and rotated under the action of reaction forces from the side of the ground. Their common axis of rotation remained parallel to the field surface during operation. Recently, for better operation of discs, they are arranged so that the axis of rotation of the disc additionally makes a certain angle with the surface of the field, that is, the roll angle. This requires an individual rotation unit for each disk, which complicates the design. Research on improving the performance of discs and improving their shape is mainly conducted experimentally.

M. Klendii & O. Klendii (2016) developed an analytical model of a concave spherical disk placed in a three-dimensional coordinate system with a given direction of movement of the unit. The model includes the design parameters of the disk and the depth of tillage. In addition, the authors established a relationship between the angle of attack and the roll of the disc for a given value of the rear angle at the level of the field surface. In this work, for the first time, calculations were made on how to combine the angles of attack and roll and at the same time ensure the presence of the rear angle. This is the similarity of the research conducted in this article. The difference is that instead of disc working bodies, a screw working body is offered, which is fundamentally different from the disc working body, but performs the same work. The profile of cultivated soil is also similar: it consists of ridges and depressions. It is also necessary to ensure the presence of a back angle to prevent the working body from rolling out onto the field surface, i.e. for better plunging in the soil. However, the calculations are fundamentally different because the working bodies have different shapes.

Disc coulters are widely used for crushing plant residues on the surface of the field. There are four main types of these discs: smooth, toothed, undulating, and wavy. R. Magalhaes *et al.* (2007) emphasize the problems in the operation of the existing designs of discs and the low efficiency of crushing plant residues. In the case of dry soil, they require a high vertical load to penetrate it. In the case of high soil moisture, the remains are pressed into the soil without crushing them. R. Magalhaes *et al.* (2007) proposed a new geometry of angled disc coulters, which allows crushing plant residues on the field surface in any soil condition, avoiding clogging and reducing traction force.

Analytical calculations also play a big role in this. S. Krivoshapko & M. Rynkovskaya (2017) considered in detail the types of helical ruled surfaces, including developable ones, for their practical application. The article does not talk about working bodies for soil cultivation, although the use of the surface of the developable helicoid as a drill for digging pits is shown. This article is designed to show the possibilities of designing helical surfaces and the features of their shape. It lists five types of helical ruled surfaces. It states that engineers know about straight and oblique helicoids, which are non-developable. One of the helicoids listed in this article is the developable one, which was considered in current study for the design of a screw tillage body.

The application of the developable helicoid as an alternative to tillage discs is considered by S. Pylypaka *et al.* (2021). It shows the use of the developable helicoid surface as the working surface of the tillage tool. At the same time, the profile of the treated soil will consist of ridges and depressions, similar to disk working bodies. The size of the distance between the ridges and the size of the depressions depend on the direction of the spiral line, which is the cutting edge of the working surface, that is, the blade. The profile is also affected by the angle of attack and the depth of plunging of the working surface into the soil. In this paper, it is stated that through a given spiral base line, which is the edge of the surface, it is possible to draw many developable helicoids, which will differ among themselves by the angle of inclination of the rectilinear generators concerning the surface axis. This angle affects the great effort of plunging into the ground of the working surface and the quality of turning over the ground and mixing it with plant residues. Hence, it is assumed that this angle can play the role of roll angle for disc guns. In the work, a comparative analysis of two working organs – disk and screw – was carried out, and it was concluded that the screw organ can be an alternative to the disk. However, at the same time, an important issue was not considered – avoiding contact of the back side of the screw working surface with the soil environment. This issue is discussed in detail in the proposed article, the material of which develops and complements previously conducted research.

CONCLUSIONS

The soil tillage unit, equipped with screw working surfaces in the form of turns of a developable helicoid, is a promising solution for surface soil tillage, which can replace traditional disk tools. This alternative offers not only efficiency but also simplicity of construction, which allows the reduction of costs of production and maintenance of units. The analytical description of the design parameters of turns, developed in this paper, opens up opportunities for optimizing these parameters taking into account various agrotechnical requirements. It is important to note that the design of the unit allowed for variation in the parameters of the working bodies while maintaining key characteristics of soil cultivation, such as continuity of cultivation, the specified depth, the appropriate distance between the ridges, and minimal disturbance of the soil structure on the back side.

One of the key advantages of the screw working body is the ability to adjust the angle of attack and the angle of roll. In particular, changing the angle β to a value of 35° ensures the formation of the rear angle ε, which, even without taking into account the thickness of the helicoid coil, is 13°. This is an important aspect, because the reduction of the angle ε due to the sharpening of the blade can reduce the efficiency of the plunging of the working body into the soil, but a positive angle provides sufficient plunging, which is critical for quality processing. Thus, the unit with screw working bodies provides not only a similar processing profile to disk tools, but also better control over processing parameters.

Prospects for further research are aimed at improving the design of the screw unit. One of the directions is the detailed consideration of the thickness of the helical working surface, which will improve processing efficiency, reduce energy consumption and increase the reliability of the working bodies. Another important direction is the study of the influence of various agrotechnical conditions, such as the type of soil, humidity and the speed of movement of the unit, on the operation of screw organs. This will make it possible to develop universal recommendations for the use of such units in various conditions, which will contribute to their wider implementation in agriculture.

Thus, the development and implementation of screw tillage units has a significant potential for increasing the efficiency and cost-effectiveness of surface tillage. This opens up new opportunities for improving agricultural technologies and reducing the impact on the environment, which are important factors in modern agriculture.

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CONFLICT OF INTEREST

None.

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Конструювання робочих поверхонь ґрунтообробного гвинтового органу із відсіків розгортного гелікоїда

Анотація. Удосконалення гвинтових робочих органів для поверхневого обробітку ґрунту є важливим для підвищення ефективності та якості сільськогосподарських робіт. Метою роботи був розрахунок конструкції гвинтового робочого органу для поверхневого обробітку ґрунту із відсіку розгортного гелікоїда, який би виконував технологічний процес з мінімальним опором занурення у ґрунт. Для конструювання робочого органу застосовано методи теорії поверхонь, аналітичної та диференціальної геометрії. В роботі показано, що через задану гвинтову лінію, яка є ріжучою крайкою поверхні (лезом), можна проводити розгортні гелікоїди із різним нахилом прямолінійних твірних. Це важливо для конструювання поверхні для найкращого занурення у ґрунт. Встановлено, що запропонований робочий орган є альтернативою існуючих знарядь дискового типу. Доведено, що тривалий час сферичні диски для поверхневого обробітку ґрунту закріплювалися на спільному валу, який встановлювався на агрегаті з певним кутом між його віссю і напрямом руху агрегату, що сприяло зануренню дисків у ґрунт. Підтверджено, що ґрунтообробні знаряддя дискового типу були вдосконалені, але це ускладнило конструкцію агрегату, оскільки кожен диск отримав індивідуальну вісь обертання. Дослідження показали, що це дозволило додатково встановлювати кут крену, тобто відхилення площини леза диска від вертикального напряму, що покращувало занурення диска в ґрунт і забезпечувало ефективніше перевертання та перемішування рослинних залишків. Запропонований гвинтовий робочий орган поєднує простоту конструкції спільного валу і наявність кута атаки та крену, що підтверджує його ефективність у порівнянні з існуючими аналогами. Зроблено необхідні розрахунки, побудовано поверхні правого і лівого ходу із позначенням необхідних конструктивних параметрів. Застосування отриманих результатів може спостити конструкцію ґрунтообробного агрегату

Ключові слова: кут атаки; кут заточки; крок поверхні; гвинтовий параметр; гребні; профіль ґрунту

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Renewable energy sources in Kyrgyzstan and energy supply to rural consumers

Abstract. The study assesses the potential of renewable energy sources in Kyrgyzstan and explores their application to provide energy to rural consumers. This study used an approximation of the parabolic function of solar radiation change, statistical processing of data on the average annual water flow of small rivers, as well as calculation of the volume of manure produced and its processing into biogas and bio fertilisers to assess their potential in agriculture and environmental impact. Kyrgyzstan, located between 40 and 68° north latitude, has evenly distributed solar radiation, small rivers and biomass, which have significant renewable resources. The distribution of solar radiation on the territory corresponds to the normal law of the monthly average mathematical expectation of 175.79 kWh/(m^2*month) and a standard deviation of 92.44 kWh/(m^2*month). On average, each square metre of a solar power plant can produce 0.451 kWh of energy. The intervals of average water discharge between the small rivers of Kyrgyzstan follow a power law distribution with a mathematical expectation of 3.112 m^3/s and a standard deviation of 2.46 m^3/s.

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With a natural water flow rate of 0.652 m^3/s, a low-pressure micro-hydroelectric power plant (with a water head of 1 to 2 m) can generate up to 8.95 kW of power. The total consumption of biogas by an average farm in Kyrgyzstan and its consumption for heating raw materials in a bioreactor during the cold season ranges from 16.34 to 18.93 kg/hour. This demand for biogas is met by producing domestic feedstock (animal manure) using compact biogas plants with reactors of up to 20 m^3. These facts indicate that the use of the above-mentioned renewable energy sources in Kyrgyzstan can provide autonomous power supply to remote rural consumers and contribute to solving existing environmental problems, as well as energy-saving

Keywords: solar energy sources; solar collectors; watercourses; micro-hydroelectric power plants; biological resources

INTRODUCTION

The use of renewable energy sources not only meets humanity's energy needs but also serves as a means of combating global greenhouse gas pollution. The continued development of renewable energy sources through the creation of new energy storage technologies will lead to a reduction in the role of traditional centralised energy systems. The practice of autonomous power supply increases its reliability and stimulates the revision of the "base load" concept in favour of the "distribution load" concept. This trend is more efficient in meeting energy supply needs, especially in rural areas, given their remoteness from centralised power transmission networks. The intensive development of agriculture, as well as other sectors of the economy, leads to a significant increase in energy consumption. The demand for electricity, heat and cold for production and domestic needs of rural producers is constantly growing. Solutions should be found for the disposal of large volumes of agricultural waste, especially manure. It is necessary to address the issue of autonomous power supply to rural producers, as it is unprofitable to lay centralised power lines to remote areas with low power consumption.

Kyrgyzstan has significant solar energy resources that can be used to generate electricity using solar panels and collectors. At the same time, the country has an abundance of water resources, including rivers and streams, which can be used to generate energy through small hydroelectric power plants. In addition, Kyrgyzstan has significant biomass reserves, such as animal manure and vegetable waste, which can be used for biogas and biodiesel production. These resources are distributed evenly throughout the country and can be easily developed for energy production (Shakulikova & Akhmetov, 2021). The problem of lack of affordable energy consumption in rural areas of Kyrgyzstan is relevant due to the instability of the centralised energy supply and limited access to energy for agricultural needs. P. Florio *et al.* (2021) investigated the potential of solar energy and proposed a methodology for assessing solar potential using geographic information systems. T.S. Kishore *et al.* (2021) analysed the use of small hydropower plants in rural areas and assessed their impact on energy supply. C. Bumharter *et al.* (2023) considered the potential of biomass and conducted a study on the development of technologies for processing manure into biogas. J. Zhao *et al.* (2022) analysed the economic efficiency of using renewable energy sources in rural areas. M.M. Kamal *et al.* (2022) studied the impact of wind energy on rural energy supply and proposed strategies for its use.

Y. Majeed *et al.* (2023) analysed solar and wind energy as alternative sources for sustainable agricultural development. K.K. Jaiswal *et al.* (2022) explored the environmental and social aspects of renewable energy in rural areas. K. Mehta *et al.* (2021) analysed the energy needs of Kyrgyz agriculture and proposed strategies to optimise the use of renewable energy sources. G. Li *et al.* (2022) studied the possibility of using solar collectors for heat supply. Erdiwansyah *et al.* (2021) proposed a model for the integration of various renewable energy sources to ensure a reliable and sustainable energy supply in rural areas of Kyrgyzstan. Additional research is needed on the social and economic sustainability of renewable energy projects in rural areas, as well as an analysis of technological solutions and infrastructure needs for the successful integration of renewable energy into Kyrgyz agriculture.

The study aims to assess the potential of renewable energy sources in Kyrgyzstan and to investigate their application in providing energy supply to rural consumers. Research goals:

1. Identify the main obstacles to the introduction of renewable energy sources in rural areas of Kyrgyzstan.

2. Employ formulas, reactions and expressions to accurately determine the adsorption and chemical bonding parameters of sulphur-containing gases in the mine atmosphere.

3. Confirm the effectiveness of the proposed methods and improve safety and environmental cleanliness in mines based on the results of measurements and observations in the field, as well as analysis of the use of various technologies.

MATERIALS AND METHODS

Kyrgyzstan, located between 40 and 68° N latitude, has domestic solar energy resources, which were estimated based on data from the Ministry of Energy and Industry of the Kyrgyz Republic (2022). The graphical representation of the dependence of solar radiation (P_c) on geographical latitude (T) over the course of a year forms a parabolic function (Fig. 1).

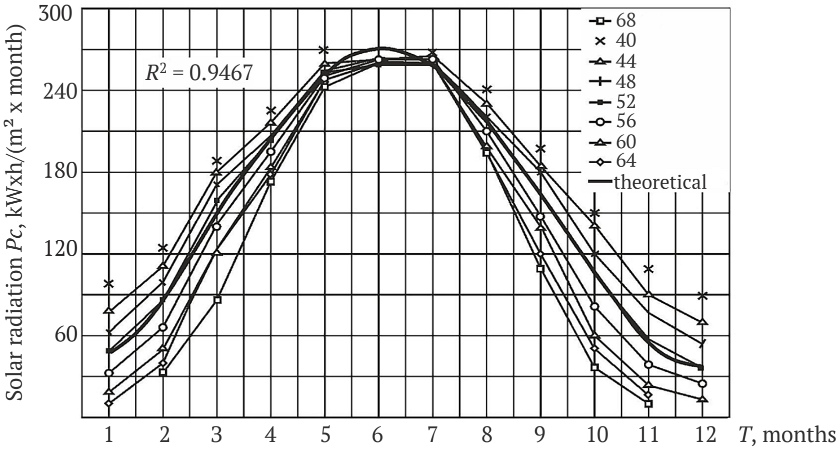

Figure 1. The variation of solar radiation (P_c) with geographical latitude (deg N) during the year(T) is represented by the function P_c=f(T)

Source: compiled by the authors based on the Ministry of Energy and Industry of the Kyrgyz Republic (2022)

This function corresponds to a normal distribution law, which means that the distribution of solar radiation in Kyrgyzstan is described as follows (1):

$$f(P_c) = \frac{1}{92.44\sqrt{2\pi}} \exp\left[\frac{(P_C-175.79)^2}{2(92.44)^2}\right]. \qquad (1)$$

With an average value of 175.79 kW∗h (m²∗month) and standard deviation σ = 92.44 kW∗h/(m²∗month). Using the Lagrange formula (Pasetto *et al*., 2021), the parabolic function P_c = f(T) was approximated, after which an empirical equation was chosen to describe the distribution of solar radiation in Kyrgyzstan during the year (2):

$$P_c = -9.26T^2 + 115.27 * T - 90.68. \qquad (2)$$

Table 1 shows the calculations of solar radiation P_c by month throughout the year.

Table 1. Data on the estimated solar radiation P_c are presented by month of the year

Solar radiation	Months of the year											
	1	2	3	4	5	6	7	8	9	10	11	12
P_c,*kWh/(m²*month)	15.3	109	171.8	222.2	254.1	268.6	262.5	238.8	196.7	136	56.8	39.9
P'_c,*kWh/m²	0.042	0.302	0.417	0.617	0.705	0.743	0.729	0.663	0.546	0.378	0.158	0.11

Source: compiled by the authors based on Erdiwansyah *et al.* (2021)

The highest amount of solar radiation is observed during the months of May, June and July, it varies from 254.1 to 268.6 kW∗h/(m²∗month) or from 0.705 to 0.743 kW∗h/m². From January to April, solar radiation gradually increases (from 0.042 to 0.617 kW∗h/m²), while from August to December it decreases (from 0.663 to 0.11 kW∗h/m²). The average value of solar radiation during the year is 0.451 kW∗h/m², which means that each square metre of solar power plant is capable of generating 0.451 kW∗h of energy. The grazing season in Kyrgyzstan is in May-July, when the highest amount of solar radiation is observed, making the use of solar power plants during this period the most efficient. In addition, autonomous power supply is justified in pastureland conditions due to the remoteness of consumers from centralised power grids, which are inefficient. The main characteristics of water discharge in small rivers of Kyrgyzstan were studied based on the analysis of annual averages and coefficients of variability. It was found that four of these rivers have an average flow of more than 10 m³/s with coefficients of variability ranging from 0.12 to 0.15, while six rivers have an average flow of more than 4 m³/s with coefficients of variability ranging from 0.14 to 0.18 (World Bank, 2024). Sixteen rivers have an average water discharge of more than 2 m³/s with coefficients of variability ranging from 0.11 to 0.14, while the majority, namely 23 rivers, have an average water discharge of less than 2 m³/s with coefficients of variability of up to 0.3. There is a tendency for the coefficient of variability and its range to increase with a decrease in water flow in small rivers.

The analysis of statistical data on the average annual water discharge in 49 small rivers of Kyrgyzstan, ranging from 0.11 to 12.4 m³/s, was used to identify the regularities of this indicator's distribution in these rivers and present them in the form of a typical distribution curve, as shown in Figure 2.

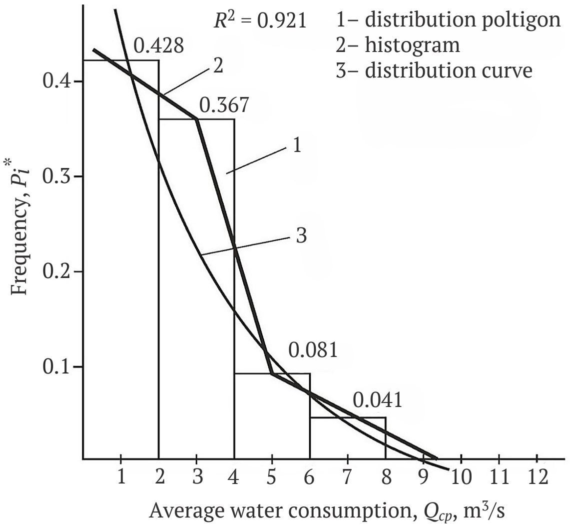

Figure 2. Graph illustrating the distribution of average annual water discharge in small rivers of Kyrgyzstan (49 rivers in total)
Source: compiled by the authors based on the Ministry of Energy and Industry of the Kyrgyz Republic (2022)

The distribution of intervals of average water discharge between small rivers in Kyrgyzstan corresponds to the exponential law (3):

$$f(Q_{av}) = 0.6388 * e^{-0.266*Qav}. \quad (3)$$

The average value is 3.112 m^3/s, and the standard deviation is 2.46 m^3/s. Kyrgyzstan's small rivers with an average water discharge (Q_{av} = 3.112 ± 2.46 m^3/s) are evenly distributed throughout the country, especially on pastures.

The estimated volume of manure produced by all types of farm animals in Kyrgyzstan per year reaches approximately 5.6 million tonnes (Ministry of Water Resources, Agriculture and Processing Industry of the Kyrgyz Republic, 2021). By processing it using biogas technology, it is possible to produce about 110 million m^3 of biogas and 5.5 million tonnes of biological fertiliser. This data was used to provide rural producers with 30% more biogas and fertilise 1300 thousand ha of arable land, which will increase crop yields by 15-20%. In addition, this approach will prevent the emission of about 214 million m^3 of greenhouse gases, including methane and carbon dioxide.

RESULTS

The supply of energy to rural consumers is a significant challenge in many countries, including Kyrgyzstan, due to the remoteness of some rural areas and the lack of infrastructure. In such circumstances, ensuring continuous and stable access to energy can be a challenge. However, renewable energy sources (RES) offer unique opportunities to address this problem. Renewable energy sources such as solar, wind and hydropower have the potential to become a key component of rural energy infrastructure. One of the main reasons for this is the fact that many rural areas have large open spaces and access to natural resources, which are essential for the deployment of renewable energy. For example, solar panels can be installed on rooftops or in open fields, converting sunlight into electrical energy (Asrami *et al.*, 2021). Wind turbines can be located on hills or high ground, harnessing the power of the wind to generate electricity. Hydropower can be generated through the construction of small hydropower plants on streams or small rivers.

One of the main advantages of renewables for rural areas is their potential to provide a decentralised energy supply. This means that rural communities can become more energy-independent, without relying solely on centralised energy transmission systems from remote sources (Streimikiene *et al.*, 2021). Decentralisation ensures access to energy for rural consumers even in the event of problems with the centralised power grid. However, despite all the advantages, the use of renewable energy for rural energy supply can also face some challenges. For example, investments in renewable energy infrastructure and technologies can be expensive and require significant upfront capital. In addition, environmental aspects, such as the impact on the local ecosystem when building hydroelectric power plants or wind turbines, must be considered. Overall, despite the challenges, renewable energy sources represent a promising solution for ensuring sustainable and affordable energy supply in rural areas. Modern technologies and development strategies can help to maximise the use of renewable energy potential, which will lead to improved quality of life and economic development of rural communities in Kyrgyzstan.

Kyrgyzstan, located in the centre of Central Asia, is a unique combination of mountain ranges, valleys and river systems. This landscape creates favourable conditions for the development of hydropower, especially when using the resources of small rivers. With the focus on environmental sustainability and energy security, the construction of small hydropower plants (SHPPs) on these rivers is becoming an important aspect of the country's energy sector development. It is necessary to address the richness of the mountain rivers that permeate the territory of Kyrgyzstan. These rivers offer enormous potential for power generation. Due to their small scale and relative accessibility, small river resources are a reliable source of energy that can supply both urban and rural areas. There are many advantages to building a hydropower plant (Ahmed *et al.*, 2022). They usually have a low cost compared to large hydropower plants, which makes them economically viable and affordable. In addition, SHPPs have a small ecological footprint and low heat losses, making them more environmentally friendly and sustainable than traditional energy sources. An important advantage of SHPPs is their flexibility and scalability. They can be easily integrated into existing infrastructure and used for local service, which is especially important for remote and rural areas. This helps to develop the social and economic potential of these areas and improve the quality of life of their residents. However, there are some limitations to the use of small hydropower plants. For example, there may be issues related to environmental change and the impact on the biodiversity of river ecosystems. These issues require serious analysis and planning to minimise negative consequences. In conclusion, small river resources represent a valuable source of energy for Kyrgyzstan. Harnessing this potential, combined with modern technologies and sustainable practices, can contribute to the country's development, ensuring a stable and environmentally friendly energy future for all its citizens.

Kyrgyzstan, with its vast natural resources, such as mountain ranges and abundant sunshine, has significant opportunities for solar energy development. In the southern regions of the country, where the intensity of solar radiation is higher, solar energy can become an important source of electricity for both urban and rural consumers. It is worth noting the huge potential of solar energy in Kyrgyzstan. The average duration of sunshine in the country is more than 2200 hours per year, making it one of the sunniest countries in the region (Karatayev *et al.*, 2022). This potential can be used to install solar panels on the roofs of buildings, as well as in specially designated areas, which will allow efficient collection and conversion of solar energy into electricity. The development of solar energy has several advantages. One of the key advantages is the ability to diversify energy sources. At a time when many countries are facing energy challenges due to their reliance on traditional sources such as coal or gas, solar energy can be a sustainable source that helps reduce this dependence. It is also worth noting the environmental component of solar energy. Unlike traditional energy sources, such as coal or oil, solar energy production does not result in greenhouse gas emissions or pollution (Kaewpraek *et al.*, 2021). This reduces the negative impact on the climate and preserves natural resources for future generations. The introduction of solar energy can contribute to the social and economic development of a country. The creation of jobs in the design, manufacture and installation of solar systems, as well as the development of local markets and services, will help improve the lives of local people and contribute to the development of rural areas. In conclusion, solar energy represents a promising source of energy for Kyrgyzstan. Maximising this potential will allow the country to reduce its dependence on traditional energy sources, reduce the negative impact on the environment and contribute to the sustainable development of the national energy sector.

In today's world, when the problems of energy security and climate change are becoming increasingly relevant, the development of renewable energy sources is becoming a priority for many countries, including Kyrgyzstan. One of these potential sources is biomass, including manure, which can be effectively used to produce biogas or biodiesel, which are important alternative energy sources (Zhu *et al.*, 2021). Rural areas of Kyrgyzstan have significant manure reserves due to the presence of substantial livestock counts. This opens prospects for the use of biomass for energy purposes. The process of converting manure into biogas or biodiesel not only enables the disposal of livestock waste but also the production of a valuable energy resource that can be used to generate electricity. The use of biomass in the energy sector has significant environmental benefits. Unlike traditional energy sources such as coal or oil, the production of biogas or biodiesel from manure not only does not generate additional greenhouse gas emissions but also helps to reduce the total amount of carbon emissions into the atmosphere. This reduces the negative impact on the environment and mitigates the effects of climate change.

An important advantage of using biomass in the energy sector is its social significance, especially for rural areas. In these areas, access to traditional energy sources is often limited, leading to inequalities in energy access. The use of biomass mitigates this inequality by providing local people with access to clean and affordable energy, which contributes to their social and economic development. In conclusion, the use of biomass, including manure, in Kyrgyzstan's energy sector is an important step towards sustainable development and energy security. This approach not only contributes to reducing greenhouse gas emissions and protecting the environment but also provides social and economic benefits to rural areas by improving their living standards and providing access to energy.

An experiment was carried out with a single-circuit solar water heater equipped with a thermosyphon. The inner diameters of the tube and cover are 47 and 58 mm, respectively, and the length is 1.8 metres. The water tank has a capacity of 140 litres. The angle of the south-facing solar collector is 30° from the horizon. Geographic coordinates of the location: 77°E, 42°N. The study aimed to estimate heat losses from the solar collector to the environment during the heating period (air temperature range +12...-12°C), to determine the efficiency and thermal power of the solar collector. At the beginning of the heating season, at an ambient temperature of 12°C, the heat loss coefficient is estimated at U_L = 7.77W/m²*h, and a temperature of -12°C, this coefficient increases and amounts to U_L=12.67W/m²*h (Fig. 3).

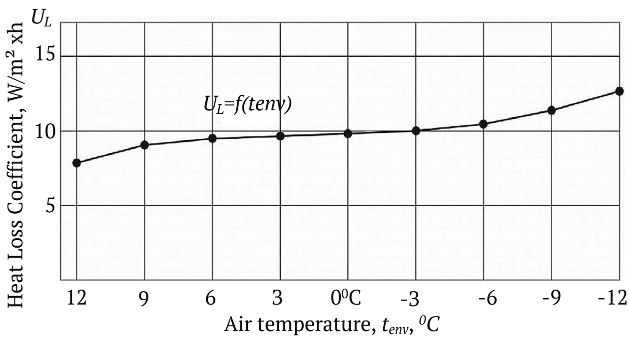

Figure 3. Graph of heat loss coefficient versus ambient temperature

Source: compiled by the authors based on Erdiwansyah *et al.* (2021).

The result of the product of the total heat loss coefficient (U_L) and the absorber panel efficiency (F') of the solar collector (U_L*F') is within the permissible range: from

4.9 to 10.1 W/(m²∗C°), which is in line with standard data (Grob *et al.*, 2021). According to Figure 4, the average daily efficiency of the solar collector is $\eta_{days} = 0.36$, and its thermal output is equal to $P_{ex} = 0.26$ kWh.

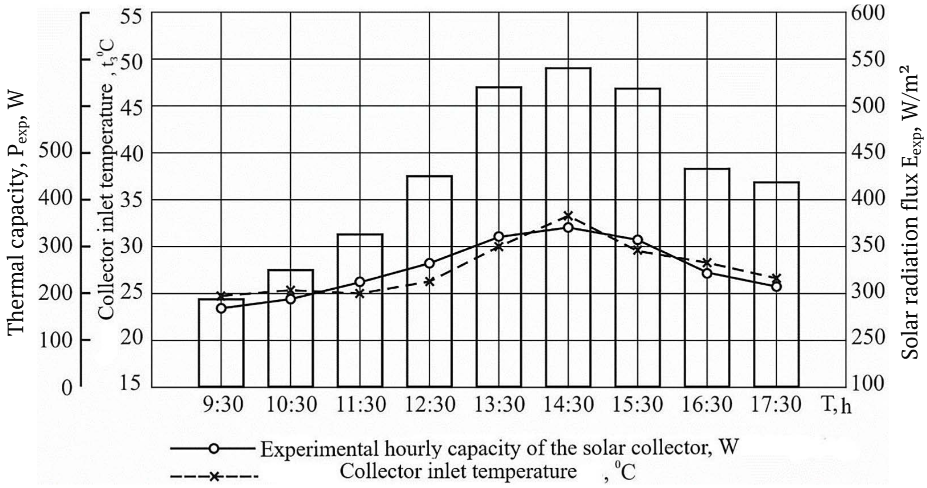

Figure 4. Graphs of the dependence of the water inlet temperature $[t_3 = f(T)]$, solar radiation flux $[E_{exp} = f(T)]$ and heat output $[P_{exp} = f(T)]$ on the heating time of the heat carrier T

Source: compiled by the authors

The following theoretical framework was used in the course of experiments and calculations (4):

$$F' * U_L = \frac{G*C(t_{out}-t_{in})}{A(\bar{t}_{ex}-t_{env})}, \tag{4}$$

where: F' and U_L – the coefficients of absorption panel efficiency and heat loss, respectively; G – the water flow rate through the solar collector, expressed in kilograms per hour; C – the heat capacity of water, measured in watt-hours per kilogram °C; t_{out} and t_{in} – the temperatures of the water at the outlet and inlet of the solar collector, respectively; A – the area of the heat-accepting surface, expressed in square metres; the average liquid temperature is defined as the half-sum of the water temperatures at the inlet and outlet of the solar collector, measured in degrees Celsius; t_{env} – the ambient temperature, expressed in °C (5):

$$Q_s = F_R * S_{sc}[E(\tau\alpha)_e - U_L(t_{in} - t_{env})], \tag{5}$$

where: Q_s – the amount of useful energy per hour measured in kilowatt-hours (kWh); $S_{sc}[E(\tau\alpha)_e]$ – the amount of solar energy falling on the surface of the solar collector per hour, measured in kilowatt-hours (kWh);$S_{sc}[U_L(t_{in} - t_{env})]$ – the amount of energy that is lost to the environment per hour, measured in kilowatt-hours (kWh); F_R – heat transfer coefficient (FR); S_{sc} – solar collector area, measured in square metres (m²); E – solar radiation flux density on the surface of the solar collector, measured in kilowatt-hours per square metre (kWh/m²); $(\tau\alpha)_e$ – optical performance factor (OPF), showing the reduced absorption capacity of the solar collector.

$$F_R = \frac{G*C}{U_L}\left[1 - \exp\left(\frac{U_L*F*}{G*C_p}\right)\right], \tag{6}$$

where: C^P – the specific heat capacity of the pipe material in kilojoules per kilogram of degree Celsius; F^* – the solar collector area utilisation factor, which is defined as the product of 0.98 and the solar collector area (F^*=0.98∗Sgk) (Uçkan & Yousif, 2020).

$$\eta_{days} = \frac{\sum Q_s}{E_{ex}*S_{sc}}, \tag{7}$$

where: η_{days} – average daily efficiency of the solar collector, reflecting the average efficiency of the solar collector during the day; $\sum Q_s$ – total amount of useful energy received in the solar collector per day, measured in kilowatt-hours (kWh); E_{ex} – solar radiation flux density on the surface of the solar collector during its operation, measured in kilowatt-hours per square metre (kWh/m²).

$$P_{ex} = E_{ex} * S_{sc} * \eta_{days}, \tag{8}$$

where: η_{days} – the thermal capacity of the solar collector, measured in kilowatt-hours (kWh). During the tests of the low-pressure micro-hydroelectric power plant, the generated electric power was recorded: for average water consumption (Q_{av} = 3.122 m³/s); P = Q_{av}∗H∗g∗η = = 3112(1...2)∗9.81∗0.7 = 21.4...42.8 kW; for minimum water consumption (Q_{av} = 3.112 - 2.46 = 0.652 m³/s); P = 4.48...8.95 kW. During the tests, the study noted that water pressure fluctuations amounted to 1...2 metres. With minimal water consumption, the low-pressure micro-hydroelectric power plant can produce sufficient electrical power to meet the needs of the farm in pasture conditions for both production and domestic purposes.

The micro-hydroelectric power plant uses a double Blankey turbine (Nasir, 2021). The load is regulated by connecting the generator output to the "Power voltage inverter". The average total consumption of biogas and its consumption for heating raw materials in a bioreactor for the auxiliary needs of an average farm at low air temperature ranges from 16.34 to 18.93 kilograms per hour. The distribution of biogas consumption by consumer category is shown in Table 2.

Table 2. Consumption of biogas by the farm and its use for own needs (in particular, for heating biomass in the reactor)

Consumers of biogas	Biogas demand per day, m^3	Hourly biogas consumption kg/h
1	2	3
Gas cooker three meals a day for a family of 8	5.2...6.24	1.134...1.36
Heating devices at home (total living area of the farmer's house 148 m^2)	22.2...29.6 (t_{env}...-10°C) 31.0...34.04 (t_{env}=-11...-15°C) 36.0...38.48 t_{env}=>-16°C)	11.716...14.081
Heating devices for cow barn heating	23.04	1.92*1.2=2.304
Bioreactor heating device (bioreactor volume 17.93 m^3)	8.08	0.985*1.2=1.182

Source: compiled by the authors

The introduction and development of renewable energy sources in Kyrgyzstan have the potential not only to provide energy to rural areas but also to significantly change the country's energy landscape, leading to a reduction in dependence on traditional energy sources such as coal and oil. This has several advantages and benefits from both an environmental and socio-economic perspective, contributing to sustainable development. The development of renewable energy sources, such as hydropower, solar and wind energy, and biomass, has the potential to significantly reduce Kyrgyzstan's dependence on imported conventional energy sources. This reduction in dependence on volatile coal and oil markets helps to ensure the country's energy security, reducing economic risks and increasing its self-sufficiency. The development of RES contributes to the improvement of the environmental situation in the country (Shahbaz *et al.*, 2021).

Traditional energy sources, such as coal and oil, are often associated with air and soil pollution, greenhouse gas emissions and ecosystem destruction. In contrast, renewable energy sources are clean sources of energy that do not cause significant environmental damage. This reduces the negative impact on the climate and natural resources, which is a key aspect of sustainable development. An important advantage of renewable energy development is its social benefits. The introduction of renewable energy sources helps to create new jobs in the design, manufacture, installation and maintenance of renewable energy equipment. This helps to develop local economies and support entrepreneurship, especially in rural areas, which often experience high unemployment and economic underdevelopment (Riva *et al.*, 2022).

In conclusion, the development of renewable energy sources in Kyrgyzstan has great potential to improve the energy, environmental and social situation in the country. This contributes to sustainable development, enhancing international competitiveness and improving the quality of life of citizens. The introduction of these technologies should be a priority for the Kyrgyz government and encourage investment in this promising area.

DISCUSSION

Kyrgyzstan has significant natural resources, such as solar energy and hydropower potential, and is uniquely positioned to become an important player in the renewable energy market. The use of renewable energy sources to power rural Kyrgyzstan is a significant strategy with several potential benefits and challenges. This was also investigated by Erdiwansyah *et al.* (2021), where the results confirmed that a comprehensive study of renewable energy sources is key to developing effective energy strategies. This includes not only analysing the technical aspects and potential of different types of renewable energy, such as solar, wind and hydro but also considering the socio-economic and environmental factors that influence their deployment and use. Classification of different RES sources and identification of their main characteristics provide a better understanding of which energy sources can be most efficient in the specific conditions of a country or region. T.Z. Ang *et al.* (2022) also determined that one of the main challenges faced by researchers and practitioners in the field of RES is the need to develop integrated approaches to their implementation. This includes not only the development of new technologies and improvement of existing ones, but also the creation of appropriate infrastructure, development of legislation and regulations, and public education campaigns. In addition, it is important to address the potential social and economic impacts of renewable energy to minimise the negative aspects and maximise the positive. It is worth noting that to overcome these problems and effectively develop the renewable energy sector, it is important to propose a comprehensive approach, including measures to stimulate investment in renewable energy, develop innovative technologies, improve energy education and training, and create a favourable legislative and regulatory environment (Bacherikov *et al.*, 2024). This is the only way to ensure a sustainable and environmentally friendly energy supply for future generations.

It should be noted that Kyrgyzstan has a huge potential for the use of renewable energy. Located in a mountainous area with abundant sunlight and wind, the country has favourable natural conditions for the deployment of solar and wind power plants. In addition, the presence of rivers and streams provides the potential for the construction of small hydropower plants, which complements the energy mix. Many researchers, including J.N. Meier *et al.* (2023), addressed this aspect. The deployment of solar and wind power plants is an important aspect of the transition to sustainable and environmentally friendly energy. Solar power plants use solar panels to convert sunlight into electrical energy. They can be placed on the roofs of buildings, in open fields, and on special plots intended for solar farms. The development of solar energy helps to diversify the energy mix, reduce carbon emissions and create new jobs (Shram & Kachan, 2023). Wind power plants use wind energy to generate electricity. They are usually installed on open plains or on the shores of seas and oceans where winds are strong and stable. The development of wind power can reduce domestic dependence on traditional energy sources such as coal and oil and reduce our negative impact on the environment. A study conducted by M.R. Elkadeem *et al.* (2022) highlights the importance of deploying solar and wind power plants as a key step towards sustainable development and reducing environmental pollution. Accelerated technology development, as well as support from governments and investors, can help accelerate this process and achieve a cleaner and more efficient energy future. These results confirm the above study, as they demonstrate that the deployment of solar and wind power plants has the potential to be a key solution to addressing climate change and reducing dependence on fossil fuel-based energy sources. Efforts to develop such technologies can lead to improved air quality, reduced greenhouse gas emissions and contribute to a more sustainable energy system.

One of the main advantages of using renewable energy in rural areas is the possibility of providing a decentralised energy supply. Instead of relying on centralised transmission networks to transmit energy from distant sources, rural communities can be more independent by being able to produce personal energy on-site (Ismayilov *et al.*, 2019). This is especially important in remote areas where the construction and maintenance of centralised energy systems may be too expensive and impractical. B. Zakeri *et al.* (2021) addressed this phenomenon, noting that rural communities can become more energy-independent without relying solely on centralised transmission systems from distant sources. Decentralised energy supply improves rural area flexibility and adaptability to different conditions, including changes in energy consumption or failures in centralised networks. A study by Y.H. Ha & S.S. Kumar (2021) confirms that the use of decentralised energy supply using renewable energy sources contributes to improving energy security in rural areas. They can avoid the risks associated with interruptions in energy supply due to technical failures or lack of fuel for traditional energy systems. This is especially true in remote rural areas, where restoration of power supply after disasters can take considerable time due to difficult access and limited resources (Yaremova *et al.*, 2024). Thus, decentralised energy supply using renewable energy sources can increase the sustainability and reliability of the energy system in rural areas, which will lead to an improvement in the quality of life and economic development of these areas. Comparing the data obtained during the research, it is possible to note that decentralised energy supply based on renewable energy sources not only increases the sustainability of rural energy systems but also helps to reduce dependence on traditional energy sources such as coal or oil. This ensures a reliable energy supply that is not subject to fluctuations in fuel prices or the risk of interruptions in supply due to technical failures for rural communities.

However, there are also some challenges in using renewable energy to supply rural consumers in Kyrgyzstan. One of them is affordability. Investments in renewable energy infrastructure and technologies can be costly and may not be affordable for some rural communities without support from the state or international organisations (Matiichuk, 2022). L. Li & S. Zhang (2021) concluded that one of the main challenges in the use of renewable energy is instability and uncertainty. Wind and solar resources fluctuate depending on the time of day, weather conditions and seasons, which can lead to uneven energy production. This requires the development of efficient energy storage systems or alternative energy sources to compensate for the volatility. In addition, a study by Q. Yang *et al.* (2021) determined that the cost of renewable energy technologies is decreasing, but there is still a need for significant investment, especially in developing countries. This may be an obstacle to large-scale deployment of renewable energy without additional support and incentives from the government or international organisations. The study results analysis determined that, despite the challenges, the use of renewable energy represents an important step towards a sustainable and environmentally friendly energy future. Addressing these challenges requires a comprehensive approach and cooperation between government agencies, the private sector and the public.

In conclusion, the use of renewable energy sources to supply rural Kyrgyzstan is a promising solution with several potential benefits. However, for the successful implementation of this strategy, financial, socio-cultural and technical aspects need to be addressed, as well as support from the government and international partners. Lastly, the development of renewable energy in rural areas can contribute to sustainable development, reduce inequality and improve the quality of life of the rural population in Kyrgyzstan.

CONCLUSIONS

The analysis of solar energy resources and small rivers in Kyrgyzstan using mathematical statistics methods has provided valuable data. The distribution of solar radiation and water discharge in small rivers in Kyrgyzstan is characterised by significant fluctuations in both space and time. This highlights the need for flexibility and adaptation in the development and use of systems based on these resources.

The study showed that solar power installations have the potential to generate significant amounts of energy, although there is some room for improvement. This confirms the importance of further research and development in this area. The assessment of the potential of small rivers for power generation also demonstrates their significant potential. However, to optimally utilise this potential, efficient and environmentally sustainable small hydropower technologies need to be developed and implemented.

Finally, the results of the study highlight the importance of biogas technologies for agriculture. They can provide not only energy for domestic needs but also serve as an important source of heat for various agricultural processes. However, there are challenges, such as the affordability of technologies and infrastructure, as well as the instability of energy supplies due to fluctuations in renewable resources. In general, the results obtained indicate the wide potential of renewable energy and biogas technologies for the development of sustainable and environmentally friendly energy in Kyrgyzstan. However, to maximise their use, it is necessary to address the specifics and limitations of each resource, as well as to conduct further research and development in this area.

One of the limitations of this study is the limited amount of data on the actual use and efficiency of renewable energy technologies and biogas systems in rural Kyrgyzstan. The economic feasibility and potential social and environmental impacts of introducing renewable energy technologies and biogas systems in rural Kyrgyzstan need to be further studied.

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CONFLICT OF INTEREST

None.

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Відновлювані джерела енергії Киргизстану та енергопостачання сільських споживачів

Анотація. Це дослідження оцінює потенціал відновлюваних джерел енергії в Киргизстані та досліджує їх застосування для забезпечення енергопостачання сільських споживачів. Для цього дослідження використовувалися апроксимація параболічної функції зміни сонячної радіації, статистичне опрацювання даних про середньобагаторічні витрати води малих річок, а також розрахунок обсягу гною, що виділяється, і його переробка на біогаз і біодобрива для оцінки їхнього потенціалу в сільському господарстві та впливу на екологію. У Киргизстані, розташованому між 40 і 68° північної широти, рівномірно розподілені сонячна радіація, малі річки та біомаса, що мають значні поновлювані ресурси. Розподіл сонячної радіації на території відповідає нормальному закону із середньомісячним математичним очікуванням 175,79 кВт*год/(м^2*місяць) і середньоквадратичним відхиленням 92,44 кВт*год/(м^2*місяць). У середньому, кожен квадратний метр геліоенергетичної установки здатний виробляти 0,451 кВт*год енергії. Інтервали середньої витрати води між малими річками Киргизстану відповідають показовому закону розподілу з математичним очікуванням 3,112 м^3/с і середньоквадратичним відхиленням 2,46 м^3/с. Під час природного зниження витрати води до 0,652 м^3/с, низьконапірна мікрогідроелектростанція (з напором води від 1 до 2 м) може генерувати енергію потужністю до 8,95 кВт. Загальне споживання біогазу середньостатистичним фермерським господарством у Киргизстані та його витрата для підігріву сировини в біореакторі в холодні періоди року коливається від 16,34 до 18,93 кг на годину. Цей попит на біогаз задовольняється за рахунок виробництва власної сировини (гною тварин) за допомогою компактних біогазових установок з реакторами об'ємом до 20 м^3. Ці факти свідчать про те, що використання вищезазначених поновлюваних джерел енергії в Киргизстані може забезпечити автономне енергопостачання віддалених сільських споживачів і сприяти розв'язанню наявних екологічних проблем, а також енергозбереженню

Ключові слова: джерела сонячної енергії; сонячні колектори; водотоки; мікрогідроелектростанції; біологічні ресурси

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Research of the regulator of an expander-generator unit

Abstract. The relevance of research is determined by the tasks of increasing the efficiency of alternative and renewable energy power plants. The purpose of the work is to develop a method of coordinating the settings of the automatic excitation regulators and the speed of rotation of the rotor of the generator from the vortex installation of the expander-generator unit, which is part of the autonomous power consumption network. To achieve the goal, the methods of mathematical modelling in the MATLAB environment, physical modelling, processing of experimental data, theory of automatic control, theory of magnetic field, theory of electric machines, programming of microprocessor devices were used. Considering the need to expand the base of alternative energy sources, the task of controlling the energy plant for the utilization of excess pressure of gas transportation networks was considered. The study of the regulator of the expander-generator unit was based on a model reflecting the interaction of mechanical and electrical processes. A set of nonlinear differential equations corresponded to the description of these processes. Accurate consideration of nonlinearities of the considered control object complicates the implementation of the corresponding microprocessor control systems. Modelling is aimed at achieving a compromise between the required accuracy of object control and the possibilities of simplifying the object control structure. The use of experimental and datasheet data of the devices made it possible to evaluate the dynamics of turbine rotation and voltage generation, forming the factors for the untying of the control circuits. The use of MATLAB with the Lookup Table option made it possible to perform a multi-point linearization of the nonlinear description of the process, speeding up the modelling and adjustment of the regulator. This is important to

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coordinate the settings of the frequency control loops and the output voltage, given the trade-off between the speed of the regulator and the minimization of oscillations in the generation frequency. Based on the obtained results, a regulator of the expander-generator unit was developed, which ensures the stabilization of the initial parameters of the unit under the conditions of electrical load disturbances. In practice, the obtained data can be used in the integration of renewable energy sources into the general energy system through the optimization of the operation of generators

Keywords: vortex turbine; rotation frequency; coordination of settings; nonlinear model; synchronous generator; excitation regulator

INTRODUCTION

The perspective of any direction of improvement of power plants is determined by the design features of the main parameters embedded in it, as well as the current characteristics of the used working environments and automation tools. In the conditions of real operation, rapidly changing loads, work at fractions of power from the nominal, can cause a drop in the efficiency of the power plant.

One of such power plants is the expander-generator unit (EGU), which is used for monitoring the modes of technological equipment in gas distribution networks to provide energy. At the same time, there are no strict requirements for electricity generation modes, since electricity is obtained by utilizing excess gas pressure. At the same time, as the power consumption from the EGU increases, problems arise with the stability of the received energy parameters.

The relevance of research is determined by the tasks of assessing the energy efficiency of the operation of the EGU, as well as the prospects of building a system of coordination of local regulators, where deviations of the system parameters are involved in the regulation of the electricity generation process. Therefore, the prediction of the constant correspondence of the volumes of generated and consumed energy during the operation of the EGU determines the possibilities of effective operation of the installation. The need to establish compliance is related to variations in electricity consumption over time in the presence of disturbances in the parameters of the gas flow entering the turbine.

According to J. Bjork *et al.* (2022), the stabilization of the turbine rotation parameters of a power plant can be solved with the help of regulators built based on a turbine model of a certain type. At the same time, power generation specialists S. Rajamand (2020) continued research on improving the means of controlling electric generators. The author noted that the use of a synchronous generator and an adapted voltage drop system is important for maintaining the stable operation of microgrids with inverters. Control of a synchronous generator and modified drop allows for efficient regulation of frequency and voltage in microgrids incorporating inverter technologies. A. Mezerya & S. Pridvorov (2023) analyzed the qualitative indicators of the use of different types of generators at mini-hydroelectric power plants (HPP), focusing on the evaluation of efficiency, reliability and environmental impact indicators. Understanding these indicators helps in choosing the most appropriate type of generator for specific operating conditions and sustainability goals. In addition, this analysis provides insight into maintenance requirements and long-term operating costs, which are important for optimizing the overall efficiency of the mini HPP. The requirements for increasing the efficiency of generation mode control determine the use of more advanced algorithms for regulator settings. Given the value of the moment of inertia of the rotors of the vortex turbine (VT) and the EGU generator, respectively, the small time constant of the plant, adequate methods and algorithms for setting their regulators are necessary.

However, in the absence of correction of the values of gas consumption, which is utilized, according to changes in the electrical load of the network, the stabilization of the rotation of the generator does not ensure an increase in the efficiency of the EGU.

S.M. Baliuta *et al.* (2019) state that it is typical for turbine and generator control loops, "having common input control signals, not only to be designed but also tuned separately". A natural step to overcome such a situation is the development of a unit for coordinating the functioning of the automatic excitation regulator (AER) and the automatic rotational speed regulator (ARSR). In a theoretical aspect, this approach can be classified as subordinate regulation, the parameters of which are synthesized in accordance with the established control quality criteria, in particular, the minimization of output voltage fluctuations during load drops. However, the analysis of the results of the regulator settings, conducted by H. Kulinchenko *et al.* (2023a) in mathematical modelling and experimental studies, shows that in addition to the dynamic parameters of the control circuits, the quality of regulation is affected by disturbances in the mechanical part of the EGU. Therefore, the simulation results are implemented with the help of additional SCADA-system automation tools of the EGU experimental installation.

O. Zenovych *et al.* (2020) concluded that the setting of AER and ARSR during the automation of experiments allows to significantly improve the quality of working out perturbations of the plant, however, the existing methods and algorithms for coordinating the settings of the regulators need improvement. Therefore, increasing the effectiveness of the EGU involves solving the following tasks:

1) development of additional primary parameter converters equipped with microprocessor interface means;

2) visualization of the parameters of the generation process in real time with the required rate of experimental data processing;

3) generalization of experimental data for their further application in the development of utilization units of the model and technical series of VT, and in the future, jet-vortex turbines.

Focusing on the adaptive control of VT, which ensures the stabilization of the generator voltage and the EGU rotational frequency during network load disturbances, the task arises to work out the interaction of the subsystems of the AER of the generator and the ARSR of the VT.

The purpose of the work was to develop a methodology for coordinating the settings of the automatic excitation regulators and the rotational speed of the rotor of the VT generator of the EGU installation, which is part of the power consumption network.

The scientific novelty of the work is evaluated by the prospects of using proven methods of controlling the turbines of utilization plants in alternative energy.

MATERIALS AND METHODS

With the use of MATLAB Simulink options, a mathematical model of the ECU was built, which reflected the results of the interaction of the mechanical and electrical parts of the unit. It contained the previously obtained VT model (Kulinchenko *et al.*, 2023b) and the mathematical model of the synchronous generator (SG) based on Park's equations. The Lookup Table (LUT) toolkit of the MATLAB Simulink environment was used to build the SG model. It made it possible to effectively display the nonlinear properties of the plant in the model by constructing LUT tables based on relevant experimental data.

The experiments were carried out according to the diagram in Figure 1, during which the parametric identification of the synchronous generator (SG) model was performed. As a result, the dependence of the value of the inductance of the excitation winding of the G-273 generator type on the excitation current $L_f = f(I_f)$ was obtained.

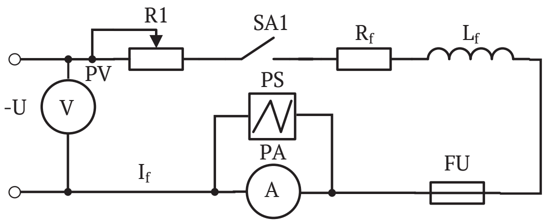

Figure 1. Diagram for estimating the time constants of the excitation winding
Note: R1 – variable resistor; SA1 – switch; R_f and L_f – active resistance and inductance of the SG excitation winding; PV – voltmeter; U – voltage; I_f – excitation current; PA – ammeter; PS – oscilloscope; FU – fuse
Source: created by the authors

The method of measuring the inductance of the excitation winding of the SG was based on the measurement of the time of the transient process of reaching a constant value of the excitation current I_f. The variation of the values of the excitation current of the winding was carried out by changing the values of the resistor *R*1. Registration of the transient process of the increase in current I_f was visualized with the help of a digital oscilloscope PS, which is turned on in parallel with the shunt of the ammeter PA. Thus, transient changes in voltage were matched to changes in the excitation current.

The value of the inductance L_f was determined based on the value of the time constant T_f, which was obtained from the registered transient process for different values of the excitation current I_f. The presence of values of the time constant T_f made it possible to construct the desired dependence $L_f = f(I_f)$ using the relation:

$$L_f = R_f * T_f, \tag{1}$$

where R_f – previously measured active resistance of the SG excitation winding. The experimental dependence $L_f = f(I_f)$ obtained in this way was used in the construction of the *Lookup Table 1-D*, which is included in the diagram for modelling the excitation winding of the SG.

Also, within the parametric identification of the G-273 generator model, the experimental dependence of the electromotive force (EMF) of the generator on the excitation current I_f and the frequency ω_e, that is, the no-load characteristic (NLC) for different rotational frequencies of the source of mechanical energy (M), was obtained. For this purpose, experiments were carried out according to the diagram of Figure 2. It provided regulation of the current in the excitation winding F1-F2 and fixation of the frequency *n* of rotation of the SG using the frequency converter UZ. Discrete stepwise changes in the current in the excitation winding of the SG and the rotational frequency of the shaft of the installation made it possible to obtain a family of dependencies necessary for the creation of the *Lookup Table 2-D*, which is used in the general diagram of the SG model.

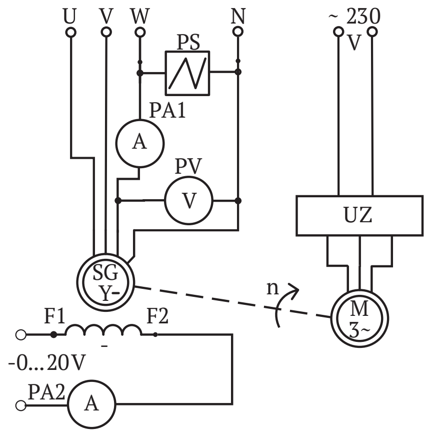

Figure 2. Diagram of the installation for obtaining experimental data on the estimation of SG parameters
Note: U, V, W and N – phases and neutral of a three-phase alternating current source; PS – oscilloscope; PA1, PA2 – ammeters; PV – voltmeter; UZ – frequency converter; SG – synchronous generator; M – asynchronous motor; F1-F2 – excitation winding of the synchronous generator
Source: created by the authors

The same circuit provided measurements of current and voltage values to calculate the resistances *Xd* and *Xq* by the method of small slip. The investigated generator SG, mechanically connected to the asynchronous motor M, was controlled by the frequency converter UZ feeding the motor M. In addition to measuring the voltage, the oscilloscope PS in the diagram of Figure 2 allowed to measure the frequency of the generated voltage. This provided consideration of the ratio of the rotor rotational frequency and the frequency of the generated voltage, which was calculated through the number of SG pole pairs. The measurement of the phase current of the armature winding, the values of which are necessary for the calculation of *Xd* and *Xq*, was carried out with the excitation winding F1-F2 open. The phases of the SG stator were fed from a separate low-voltage three-phase alternating current source. The frequency with which the source of mechanical energy M rotated was slightly different from the speed of rotation of the SG stator field.

The reactive resistance when connecting the stator winding according to the star connection is calculated as:

$$X_d = \frac{U_{Amax}}{I_{Amin}}, X_q = \frac{U_{Amin}}{I_{Amax}}, \tag{2}$$

where I_{Amin}, I_{Amax} – the minimum and maximum value of the phase current measured by the PA1 sensor; U_{Amin} (at I_{Amax}), U_{Amax} (at I_{Amin}) – minimum and maximum value of the phase voltage in the rotation mode measured by the PV sensor. The value of the calculated resistances (2) was used in building of the SG model.

Testing of the EGU regulator adjustment capabilities was carried out in the MATLAB Simulink environment on a mathematical model in the mode of changing the electrical load, which is considered a disturbance of the generation process. Setting the parameters of the EGU regulator was carried out using the MATLAB tool – *SISOTOOL*. This made it possible to carry out step-by-step sequential coordination of EGU circuits and proceed to the practical implementation of the regulator.

The adequacy of the developed model was assessed using an experimental setup (Vaneev *et al.*, 2019), presented in Figure 3. It was manufactured and is located at Sumy State University (Sumy, Ukraine) and includes a compressor as a source of compressed air, a gas regulator armature, turbine, electric generator, electric load, control and measuring devices.

Figure 3. Photo of the EGU experimental installation
Source: created by S.M. Vaneev *at al.* (2019)

Algorithmic software of the EGU controller is implemented on the means of a programmable logic controller (PLC) Simatic S7-300 CPU 314C-2DP (Siemens, Germany). The main software tools needed to build a SCADA-system and implement control algorithms include Step 7 and WinCC (Siemens, Germany).

RESULTS AND DISCUSSION

Development of the EGU model. The result of the interaction of the torque moment of the source of mechanical energy – VT, the aerodynamic torque moment of resistance of VT and the reaction torque moment of the generator to the electrical load is the factor that determines the parameters of rotation of VT/generator. Since this result forms the quality of electricity generation, in order to find out the configuration of the coordinator of the AER and ARSR settings, the structural diagram of the EGU model, shown in Figure 4, was considered.

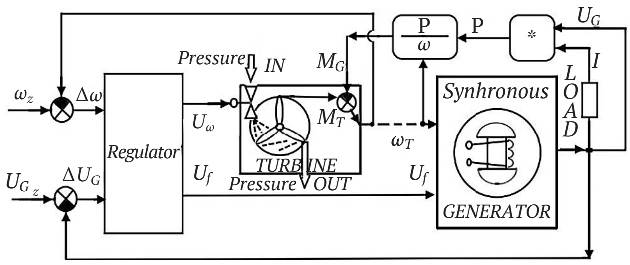

Figure 4. Structural diagram of the EGU model
Note: M_T – turbine torque moment; M_G – torque moment of reaction of the generator; ω_z, $\Delta\omega$ – turbine rotational frequency setpoint, its control error; ω_T – turbine rotational frequency; U_{Gz}, ΔU_G – generator voltage setpoint, its control error; U_f – excitation winding voltage; P – generator power; I – generator current
Source: created by the authors

In this diagram, as in any power plant, the main parameter of the regulated mode is the frequency of the generated alternating current. Since the deviation of this frequency from the nominal value is a parameter of the quality of electrical energy, the task of the EGU control system is to ensure the conditions for the normal functioning of the unit. It is the difficulties of cheap maintenance of the generation frequency that have so far inhibited the introduction of alternative energy installations to existing power grids.

The lack of opportunities to store energy and changes in electrical load cause continuous balancing of generated and consumed power. In the diagram (Fig. 4), this balancing is reflected by the interaction of the VT torque moment – M_T and the reaction torque moment of the synchronous generator M_G. The imbalance of moments (powers) causes changes in the frequency of the generated voltage. In the power plant, maintenance of the balance between generated and consumed power is achieved with the help of an automatic frequency and active power control system (AFAPCS). The AFAPCS system should perform the most economical frequency regulation.

The primary automatic control of the voltage frequency and active power of the SG is carried out in accordance with the tasks of controlling the rotational frequency. As a result of changing the position of the regulating valve, the pressure of the gas flow changes, which corrects changes in the frequency of rotation of the turbine, affecting the parameters of the generated gas power.

Another parameter that determines the modes of operation of the EGU is reliability and economy. Insufficient reliability of generation is manifested in disturbances of network voltage values over time. Voltage sags or surges, distortion of the voltage form are controlled with AER. However, control of the SG voltage is associated with a change in the rotational frequency, since in this case there is a redistribution of power between the mechanical and electrical components of the EGU. These components of the plant are related to each other through a controlled process, since frequency is the only parameter for SG and VT. Neglecting this connection, widespread practice focuses on the independent synthesis of AER and ARSR. However, considering the specifics of the operation of certain types of turbines leads to the need to use interconnected control of the turbine unit (Baliuta & Kuievda, 2017; Baliuta *et al.*, 2019). This approach involves the simultaneous control of the interaction of AER and ARSR, which makes it possible to build a system stabilizer, or coordinator of AER and ARSR settings.

The possibilities of synthesis of the excitation and rotational frequency control system, in accordance with the indicated control tasks, largely depend on the structure and complexity of the plant models used in the synthesis of the regulator.

Previous research by the authors showed that the nonlinear VT model can be represented by a family of transfer functions of the third order (Kulinchenko *et al.*, 2023b). These functions are built on the basis of linearization of the model at the selected operating points of the selected range of operation of the VT. The number of points in this range is determined by the requirements for the quality and stability of ARSR control.

Then, seeing the nonlinearity of the description of the SG functioning, the initial condition for the development of the AER for the EGU is the analysis of the nature of the nonlinearities of the SG model.

Mathematical model of SG. The key point of creating a SG model is a compromise between the necessary detail of its description and the level of reflection errors of this model. It is the excessive detailing of the plant model that complicates its use, hindering the development of simple adequate control criteria.

In addition, the analysis of electromagnetic processes occurring in the SG is associated with serious difficulties that depend on the order of the equations describing the model. In the MATLAB environment, the description of SG is provided by second-, third-, fifth-, or seventh-order models (Spoljaric *et al.*, 2010; Hrytsiuk *et al.*, 2017). Each of these models corresponds to the level of problems solved during modelling.

The system of differential equations, which is formed with respect to the phase currents and voltages of the SG, includes coefficients that change periodically when simulating the rotation of the rotor. These coefficients are formed from the values of inductances and mutual inductances (inductive resistances) of the SG windings. Magnetic asymmetry along the longitudinal (d) and transverse (q) axes is characteristic for the salient-pole design of the SG, since the air gap along these axes is different. This asymmetry is taken into account by the Blondel method, that is, by the method of two reactions of the magnetic field.

The use of two reactions, or components of the inductive resistance of the armature winding of a salient-pole SG in Park's equations (Melkebeek, 2018) makes it possible to simplify the modelling of the generation process. A practical step to significantly simplify the structure of the SG model is to consider the ratio of the time of transient processes in the armature circuits and the time of processes in the circuit of the SG excitation winding. Then, comparing the value of the time for the winding of the armature circuit with the time constant of the excitation winding, it can be assumed that the transient process is absent:

$$\frac{d\psi_d}{dt} = 0; \frac{d\psi_q}{dt} = 0, \tag{3}$$

where ψ_d, ψ_q – flux coupling of the armature according to the d q coordinates.

An additional factor for simplifying the SG model is the absence of a damping winding in the salient-pole SG of the G-273 type, which is used in the experimental EGU installation. Then the simplified system of Park's equations for the armature circuit will look like this (Zenovych *et al.*, 2020):

$$E = \omega * \psi_{fd},\ U_q = E - I_d * x_d,\ U_d = I_q * x_q, \tag{4}$$

where ψ_{fd} – flux coupling of the armature winding with the excitation flux Φ_f, which depends on the excitation current I_f; $x_d = \omega * L_d$; $x_q = \omega * L_q$ – inductive resistances of the SG armature winding along the *d* and *q* axes; I_d, I_q, U_d, U_q, – projections of currents and voltages on the *d* and *q* axis. These projections are related to physical quantities (voltage U_G and generator current I_G) as follows:

$$U_G = \sqrt{{U_d}^2 + {U_q}^2},\ \ I_G = \sqrt{{I_d}^2 + {I_q}^2}. \qquad (5)$$

For the excitation winding, taking into account its resistance R_f and inductance L_f, the equation of the relationship between the voltage U_f and the current I_f of the excitation winding has the form:

$$U_f = I_f * R_f + \frac{d}{dt}(L_f I_f). \qquad (6)$$

Working with the SG model, as with the plant model, involves the need to reflect the impact of disturbances on the output parameter of the SG – the output voltage U_G. The relationship between this voltage and the SG parameters is illustrated by a vector diagram based on the EMF of generator *E* (Fig. 5). This EMF is induced by the excitation winding flux, which, in turn, appears due to the excitation current I_f.

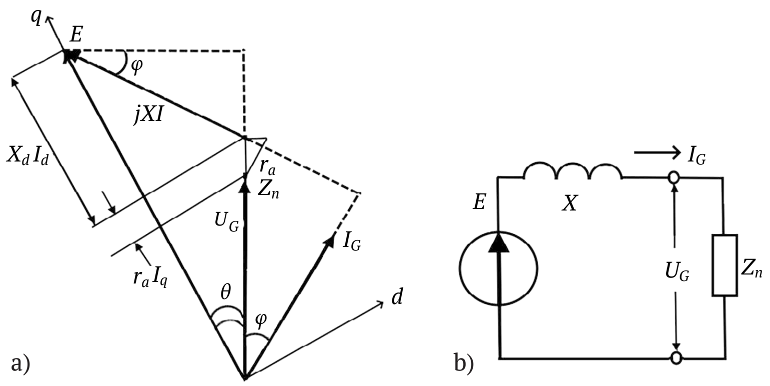

Figure 5. The vector diagram (a) and the substitution diagram of the salient-pole SG (b)
Note: a – vector diagram; b – equivalent substitution diagram; *E* – EMF of the generator, U_G – voltage generated by the SG, I_G– load current, *Zn* – complex resistance of the load, φ – load angle, θ – voltage U_G shift angle relative to the EMF of the generator *E*, X – complex resistance of the armature
Source: created by the authors

The analysis of the vector diagram in Figure 5 gives reason to write down the following equations in relation to the shift angle θ – the voltage U_G relative to the EMF of the generator *E*:

$$Eq = U * \cos\theta + x_d I_d + r_a I_q, \qquad (7)$$

$$\theta = arctg\frac{x_q\cos\varphi - r_a sin\varphi}{z_n + r_a cos\varphi + x_q sin\varphi}. \qquad (8)$$

In addition, we take into account that:

$$I_q = I_G * cos(\theta+\varphi),\ I_d = I_G * sin(\theta+\varphi),$$
$$I_G = U_G/Z_n\ \ cos\varphi = R_n/Z_n\ \ sin\varphi = x_n/Z_n, \qquad (9)$$

where R_n, x_n – active and inductive load resistances; r_a, X – active and inductive resistance of the armature winding.

The angle φ characterizes the ratio of active R_n and reactive x_n components of the complex load resistance Z_n:

$$\varphi = arctg\frac{x_n}{R_n}. \qquad (10)$$

Using the formulas of trigonometric transformations, the dependence of the EMF of the SG on the values of its parameters and load parameters was obtained:

$$E_q = \frac{U_G}{\sqrt{1+tg^2\theta}}\left(1 + \frac{1}{Z_n^2}[x_d(R_n * tg\theta + x_n) + r_a(R_n + x_n * tg\theta)]\right). \qquad (11)$$

Taking expression (8) into account makes it possible to obtain a more compact equation of the output voltage of the SG and its EMF:

$$U_G = \frac{Z_n\sqrt{x_{qn}^2 + r_{an}^2}}{x_{dn} * x_{qn} + r_{an}^2}E_q, \qquad (12)$$

where $x_{dn} = x_d + x_n$; $x_{qn} = x_q + x_n$; $r_{an} = r_a + R_n$. The next step of simplifying the model involves neglecting the value of the active resistance of the SG armature winding r_a, and constructing the equivalent electrical circuit of substitution shown in Figure 5b (Vasko, 2020). In this way, the basic nonlinear function of the $G = U_G/E$ model is obtained:

$$G = \frac{\sqrt{R_n^2 + x_n^2} * \sqrt{(x_q + x_n)^2 + R_n^2}}{(x_d + x_n) * (x_q + x_n) + R_n^2}, \qquad (13)$$

which takes into account changes in the output voltage U_G depending on changes in the reactive resistance values of SG and load parameters.

The specificity of modelling the generation process is related to the need to reflect the influence of the change in the frequency of rotation of the SG on the mentioned changes in the resistance of the SG and perturbations of the load parameters. Using the MATLAB environment, according to equation (13), a diagram of the model of the nonlinear function *G*, shown in Figure 6, is created.

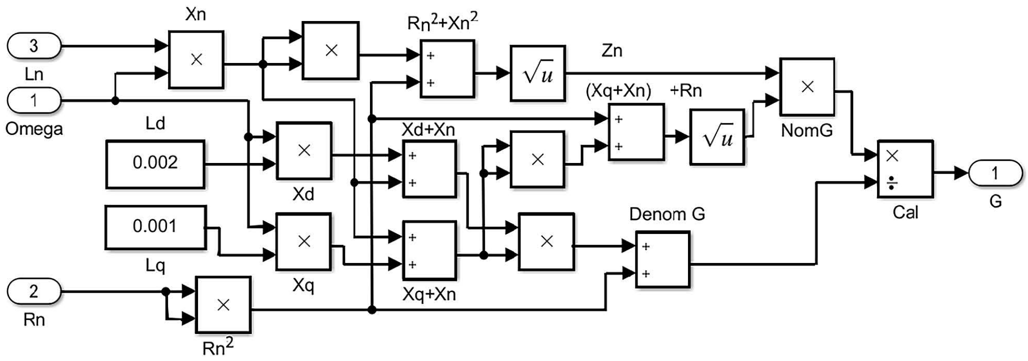

Figure 6. Diagram of modelling the nonlinear function *G*
Note: Xd, Xq and Ld, Lq – inductive resistances and inductances of the SG armature winding along the d and q axes; Rn, Xn and Zn – active, inductive and complex load resistances
Source: created by the authors

The theoretical means of SG modelling are based on the use of its datasheet data *Ld*, *Lq*, which are usually not available, and sometimes do not correspond to reality. A sufficient number of available practical methods, in particular the sliding method, allows us to experimentally determine the necessary data for modelling. At the same time, modern methods of estimating the resistances of the SG reaction, which are based on the complex SG model and its equivalent circuit (IEEE guide..., 2020), appear to be more promising in terms of the practical implementation of the model as a plant.

The general model of SG, in the form of plant, is supplemented by the equation of the excitation winding (6), which reflects the dynamics of the change in the current I_f under the influence of the voltage U_f on the excitation winding with resistance R_f and inductance L_f. As can be seen from equations (4), (6), (13), the nonlinearity of the entire SG model is formed not only by the nature of the relationships of the parameters of the electrical load of the generator, but also by the dependence of the complex resistances of the SG and magnetic fluxes on the characteristics of the magnetization curve.

The nonlinear functions representing the SG model cannot be solved by analytical methods at this stage, which creates problems for the next stages of modelling the EGU and its regulator. Therefore, a successful step, which allows using the Lookup Table (LUT) option of the MATLAB Simulink environment, based on stable modes of operation, to obtain a plant model (Gurskiy *et al.*, 2019).

The LUT tables are built on the basis of experimental data obtained during model adequacy evaluations on an experimental installation. The possibility of adjusting model parameters in accordance with the obtained results increases the advantages of this approach (Quadri *et al.*, 2019). In addition, the use of LUT tables reduces the volume of calculation operations of linearization, since calculation operations are replaced by operations of searching for previously calculated values of the no-load characteristic (NLC) and the short-circuit characteristic (SCC).

Values of EMF or reactive resistance that do not coincide with the marker points of the LUT table are searched for by linear interpolation during modelling. The application of numerical methods for solving nonlinear equations with the help of LUT gives a practical opportunity to build a nonlinear SG model for an autonomous power plant (Michna *et al.*, 2014).

The nature of the formation of controlling influences on the generation of the EMF value of the SG is influenced by the dependence of the inductance of the excitation winding L_f on the current I_f flowing in the winding. Then, in the presence of numerical values of the function $L_f=f(I_f)$, obtained experimentally, a corresponding 1-D Lookup Table is built in the MATLAB Simulink environment. This table is used in the construction of the SG excitation winding modelling unit, the diagram of which, according to (6), is presented in Figure 7.

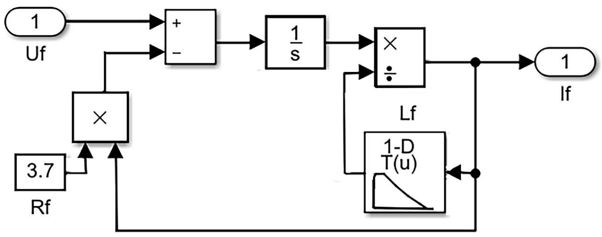

Figure 7. Modelling block of the SG excitation winding
Note: Rf and Lf – active resistance and inductance of the excitation winding; Uf and If – voltage and current of the excitation winding
Source: created by the authors based on O. Zenovych *et al.* (2020)

The data needed to construct the table are obtained using an experimental setup (Kulinchenko *et al.*, 2023a). The experimental values obtained during the generation of voltage by the G-273 generator in the EGU installation form the desired no-load characteristic:

$$E=f(I_f,\omega_e). \qquad (14)$$

Function (14) reflects the dependence of the EMF of the generator on the excitation current I_f and the frequency ω_e, which differs from the speed of rotation of the turbine ω_T by the factor p – the number of pole pairs. The presence of function (14) allows us to build a tabular form of 2-D Lookup Table, which, in interaction with other blocks of the modelling diagram, forms a nonlinear model of the SG. The general diagram of the SG model is shown in Figure 8.

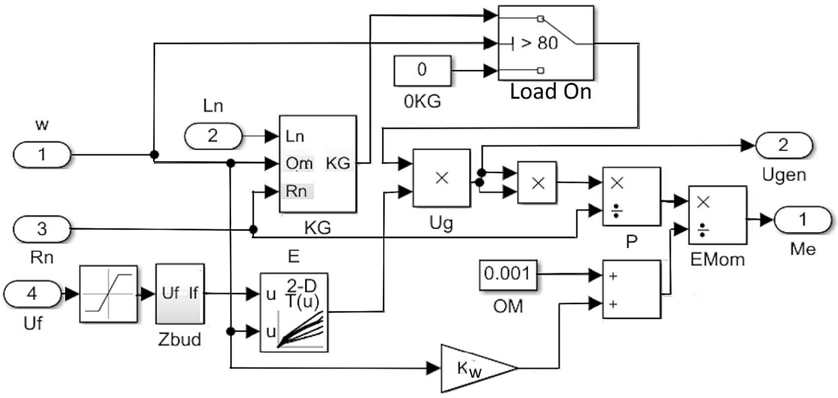

Figure 8. General diagram of the SG model

Note: ω – frequency of the generator magnetic field rotation; Rn and Ln – active resistance and load inductance; Uf – excitation winding voltage; Ugen and Me – voltage and torque moment of the generator

Source: created by the authors

In this scheme, in addition to the equations of the model (6), (13), (14), the function of imposing an electric load after reaching the minimum speed of rotation of the turbine is implemented. To prevent the collision of division by "0", the minimum value of the rotational speed of the turbine shaft is introduced in the diagram, the torque moment of which is not able to overcome the initial torque moment of friction of the SG.

Structural synthesis of the regulator. Returning to the structure of the EGU model, we can state that the output voltage of the SG installation is regulated through two control channels. At the same time, the two output parameters of the EGU model, determined by the modes of its operation, are feedback signals (Fig. 4) for the regulator. In this way, a two-dimensional control system is formed, for the description of which the state space apparatus is used (Baliuta & Kuievda, 2017). In order to practically use the apparatus of the state space during modelling, the plant is linearized at a separately selected operating point of the installation with parametric constraints. However, such an approach is justified only in cases where it is a matter of stable modes of EGU operation. In the current case, with changes in the electrical load, there are abrupt changes in the controlled parameters of the SG, the use of parameters of stable modes for modelling transient modes is not justified.

When considering options for building the structure of multidimensional regulators, attention is drawn to the existence of cross-connections between control channels. Considering the specifics of the studied plant, it can be stated that changes in the excitation field of the SG only indirectly affect the rotational speed of the EGU, while the effect of changes in the rotational speed on the excitation field of the SG can only be estimated theoretically. The study of the interaction of mechanical and electromagnetic processes of power plants involves taking into account the possibility of simultaneous influence of both controllers on changes in output parameters. At the same time, it can be considered that the work of one control channel is a disturbance for another. Then the quality of the control will depend on the ratio between the time constants of the channels, which are determined by the features of the operation of different types of turbines, in particular VT.

Analysis of the results of previous studies by H. Kulinchenko *et al.* (2023b) with VT and parameters of the G-273 generator, which is used in the experimental EGU installation, shows a significant difference in the time constants of the control loops. At the same time, the speed of the control circuit of the excitation of the SG is significantly greater than that of the control circuit of the rotational speed of the installation shaft. This makes it possible to build the structure of the regulator as a set of AER and ARSR subsystems with setting parameters that correspond to the formed criteria of EGU control (Fig. 9).

The diagram includes the Sim Zbur disturbance simulator, which simulates the transient processes of changes in the load of SG. Observing the nature of changes in the controlled parameters of the EGU allows us to adjust the parameters of the involved regulators. The task of ARSR is performed by RReg (relay regulator), and the tasks of control the voltage of the SG are solved with the help of the PID regulator (AER), which controls the value of the excitation current. This representation of the plant control structure greatly simplifies the process of parametric synthesis of the regulator, since it is assumed that these control loops, due to the difference in their time constants, are autonomous. The software-algorithmic connection of these circuits is built in accordance with the tasks of increasing the system's stability margin and obtaining additional effects regarding the quality indicators of the transient processes of the EGU installation.

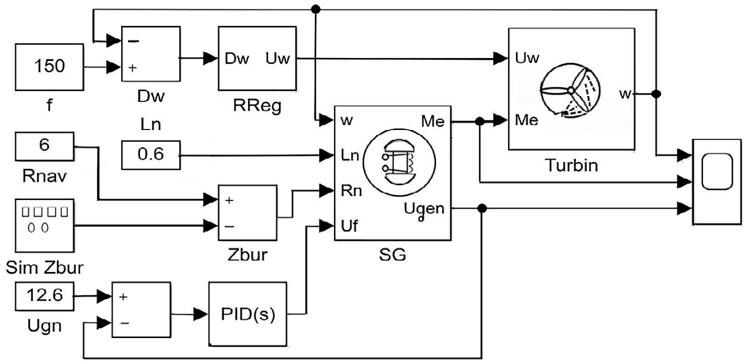

Figure 9. The general control diagram of the EGU
Note: f – generator voltage frequency setpoint; Rnav and Ln – active resistance and load inductance; Ugn – generator voltage setpoint; RReg – rotational frequency relay regulator; SG – synchronous generator; Turbin – turbine
Source: created by the authors

Traditionally, during the construction of regulators of power plants, the main attention is paid to the AER, since it is believed that this circuit directly affects the voltage of the generator. At the same time, considering the limited energy resource of the influence on the excitation field, forcing chains are introduced into the composition of AER or vice versa, when overcoming oscillations and swinging effects – compounding (Rajamand, 2020). To overcome the electromagnetic inertia of the excitation circuit, a control effect is formed, which responds not only to the absolute deviation of the output voltage, but also to the rate of its change. In "strong action" regulators, derivatives of other quantities are used, which determine the modes of operation of the SG, but this is impractical for power plants of small power generation. On the other hand, increasing the complexity of the AER complicates the process of adjusting the regulator parameters from the point of view of ensuring stability. This follows from the dynamics of the interaction of electromagnetic and mechanical processes of EGU.

It can be seen from the equation of the SG model (13) that the change in the frequency of rotation of the EGU, which occurs when the load changes, determines the current reactive resistances of the SG, which also depend on the voltage of the generation U_G. Therefore, the task of stabilizing the rotational frequency of the EGU, which is solved by ARSR, becomes decisive when building the EGU control algorithm, since the stability of the generation frequency also determines the overall quality of object control.

Solving the problems of the parametric synthesis of the regulator is usually based on the results of the estimation of plant parameters. Then the parametric identification of the model involves the determination of its parameters $\prod = (\pi_1, \pi_2, \dots \pi_N)$ in the process of operation of the plant or special experiments with it (Levinskyi & Levinskyi, 2023). It was previously substantiated that due to the non-linearity of the investigated plant, the processing of experimental data obtained directly at the operating object is considered to be the perfect means of parametric identification of the model.

As it follows from the analysis of the tasks of the regulator and its structure, stabilization of the frequency of rotation of the SG shaft is a mandatory condition for the stable operation of the EGU. Previous studies of the autonomous vortex turbine rotational frequency control circuit (VTC) have shown the effectiveness of using a 3-position relay generator (Fig. 9). Having sufficient speed to control the stepper motor of the gas flow valve, this regulator provides the necessary quality of regulation of VTC (Kulinchenko *et al.*, 2023b). However, the prospect of using such a regulator in the EGU is determined by the results of the VT/SG unit. The developed model (Fig. 9), which considers the experimentally obtained parameters of the SG and the known parameters of the VT, allows to simulate the transient characteristics of the EGU parameters in the MATLAB/Simulink environment. Visualization of these characteristics is shown in Figure 10.

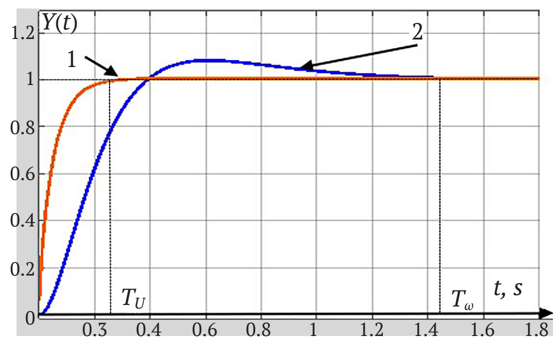

Figure 10. Transient characteristics of EGU parameters
Note: Y – relative units; 1 – transient voltage characteristic; 2 – transient characteristic of rotational frequency; T_U – excitation winding voltage control time; $T\omega$ – rotational frequency control time
Source: created by the authors

From Figure 10, it is possible to estimate the time of transient processes of EGU circuits. The obtained oscillograms confirm the difference in the control time of the EGU control circuits, which is the basis for building the structure of the regulator according to the autonomous structure. The tasks of the parametric synthesis of the EGU regulator stem from the criteria of minimizing the control time and the overregulation value. At the same time, considering the difference in the dynamics of the control channels, there is a need for interaction settings between the circuits, since the control actions of one parameter are disturbances for another. Then, the task of developing control system settings algorithms is added to the tasks of parametric synthesis.

The results of stabilization when turning on the adjusted regulators, obtained on the model of Figure 9, are shown in Figure 11. The demonstrated possibility of setting the parameters of the EGU regulator, which is carried out using the MATLAB tool – *SISOTOOL*, allows us to perform step-by-step sequential coordination of the EGU circuits and proceed to the practical implementation of the regulator.

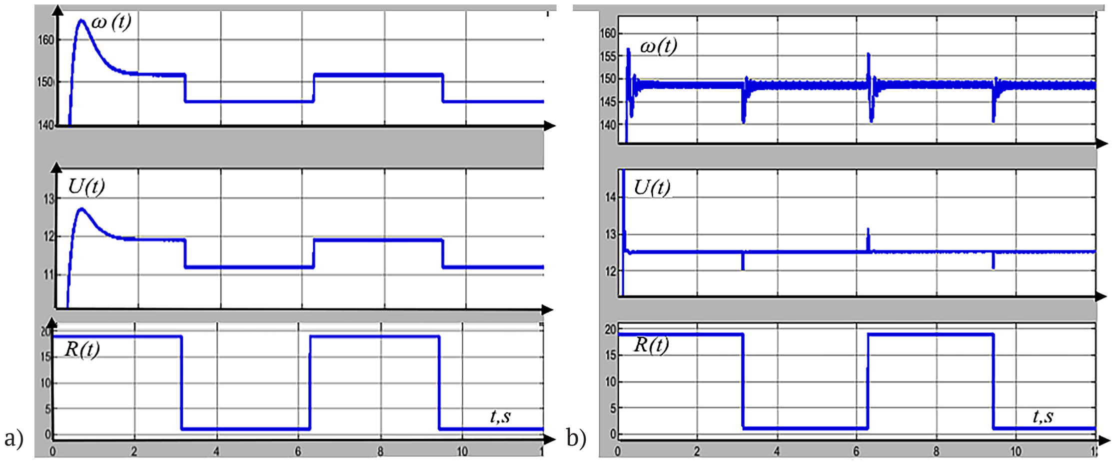

Figure 11. Oscillograms of the EGU output parameterU
Note: a) – oscillograms of generation parameters, regulators are turned off; b) – oscillograms of generation parameters, regulators are turned on; ω(t) – rotational frequency; U(t) – generation voltage; R(t) – load resistance
Source: created by the authors

The effectiveness of the developed regulator can be illustrated by the oscillograms shown in Figure 12. It allows us to stabilize the rotational frequency and voltage of the generator within 5%.

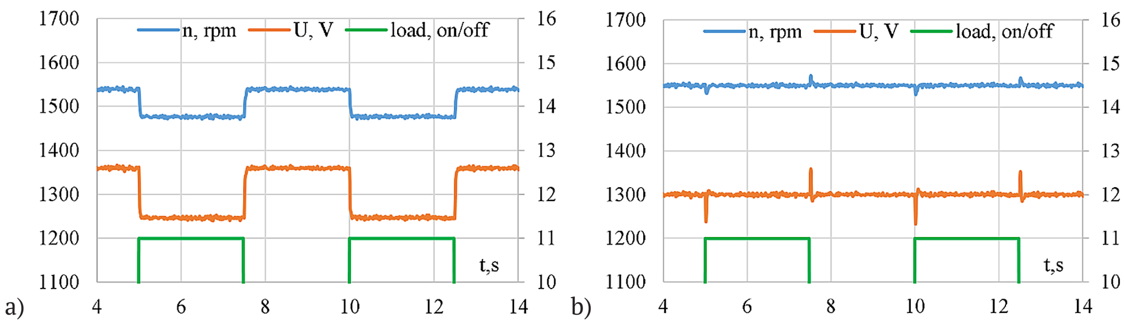

Figure 12. Oscillograms of the EGU experimental installation output parameters
Note: a) – oscillograms of generation parameters, regulators are turned off; b) – oscillograms of generation parameters, regulators are turned on; n – rotational frequency; U – generation voltage; load – load status
Source: created by the authors

Considering the place of EGU in alternative energy, it is advisable to consider the specifics of power plant management, which differ in the source of mechanical energy. Regarding steam turbines, it can be noted that with the development of software and technical control tools, the corresponding classical methods of building control devices are improved to the introduction of digital control platforms. This is due to an effort to make more efficient use of resources spent on operation and maintenance of existing equipment by improving system performance. Factors stimulating the introduction of modern control technologies are the insufficient speed of steam turbine (ST) valve servomotors and the drift of parameters over time. Exploring control systems and ways to improve steam power plant controllers, M. Dulaua & D. Bica (2014), V.N. Severin *et al.* (2016) paid the main attention to the stabilization of the rotation speed of the ST, taking into account a certain inertia and insufficient speed of the controlled equipment due to the large power of the ST. In the sector of hydro-turbine equipment, there is also a prevailing trend towards the introduction of systems for controlling the frequency of rotation of the hydro-turbine rotor. At the same time, the development of control systems is reduced to a plant linearized description. As O. Hasiuk (2023) noted, "improving the dynamic characteristics of speed regulators of hydroturbines requires the development of nonlinear mathematical models followed by the analysis of transient processes in the hydraulic drive of the speed regulator". With a similar purpose, in this study, linearized VT models were used, and SG nonlinearities were taken into account in the development of EGU regulators.

Investigating the construction of control systems of alternative or distributed energy, S. Boiko *et al.* (2021), focused on finding their additional functionality. Accordingly, when developing the structure of power plants, they set the goal of providing consumers with a stable voltage of a constant frequency regardless of changes in system parameters. In this case, the system moves from direct control of the object to a higher level of control – solving optimization problems. In this paper, a similar problem of electricity generation according to the given parameters is also solved in relation to the EGU.

Research by S.M. Vaneev *et al.* (2019) are devoted to increasing the energy efficiency of utilizing turbine generators by optimizing their parameters and characteristics. The perspective of the development of small power utilization turbogenerators is determined by the availability of hardware and software tools that ensure the implementation of turbogenerators in the gas transportation system of Ukraine. The results of this study allow us to move on to the construction of the EGU with the corresponding automated control systems. The successful implementation of alternative energy sources solves the problem of decentralization of energy supply by regulating energy system consumption peaks.

According to S. Denysiuk & I. Boiko (2021), optimization of operating modes of Microgrid with diesel generators can be considered as a decentralization option. Considering the criterion of optimization – the reduction of fuel consumption of diesel generators, the task of direct influence on the amount of generated electricity by technical means of automation has not been solved at the present time. Analysing the development trends of power plant control systems, it can be stated that load frequency control (LFC) has moved from traditional optimization methods to hybrid metaheuristic optimization. This is due to the fact that the introduction of hybrid power systems with solar, wind and diesel power plants leads to a decrease in the overall inertia of the power system. Thermal power plants operating on coal, and which are basic in the energy system, compared to renewable energy sources, have greater inertia. When energy flows during times of load in the power system, frequency fluctuations are observed, which are associated with different inertia of the system blocks. Research by I.A. Khan *et al.* (2023) show that compensation of fluctuations at the current stage of development of power system control systems is carried out with the help of virtual inertial devices, which are implemented on the basis of hybrid and cascade controllers. At the same time, such a phenomenon is not observed during the operation of autonomous power plants. Therefore, an alternative to complex virtual inertial devices is the approach, according to which the control of the installation is based on the coordination of the plant coordinate settings, which is considered in the work of A.A. Gursky *et al.* (2020). In the EGU aspect, these coordinates are the output voltage and the generation frequency. The approach proposed in this paper to solving the tasks of the coordinated functioning of the AER and the ARSR allows to improve the damping characteristics of the system.

Therefore, the development of the EGU model made it possible to determine the rotation parameters of the VT and the generator, which affect the quality of electricity generation. To ensure reliable and effective regulation of the frequency and voltage of the generator, a structural diagram of the EGU model has been developed, which takes into account the interaction of the turbine torque moment, the generator reaction torque moment, and the electrical load. The nonlinear SG model is developed using a family of transfer functions and numerical modelling methods in the MATLAB Simulink environment, which allows considering the specifics of the turbine unit operation and improves the accuracy and stability of regulation.

CONCLUSIONS

A model of the synchronous generator used in the experimental installation of the physical model of the expander-generator unit was developed. The use of the Lookup Table option of the MATLAB environment in the model made it possible to consider the nonlinear characteristics of the control object obtained from datasheet data and experimentally. Using the synchronous generator model and the previously developed turbine model, a EGU model was developed, which is part of the autonomous electricity consumption network. Its use allows us to study control processes and assess possible errors associated with simplifying the description of the control object in the process of building regulators. The evaluation of the dynamic characteristics of the control channels of the studied two-dimensional control object made it possible to virtually untie the channel regulators and consider them autonomous. This made it possible to coordinate the settings of the automatic regulators of excitation and rotor speed of the EGU generator, to investigate the operation of the regulators on the EGU model and to proceed to their practical implementation.

The test of the previously developed microprocessor rotational speed regulator of the vortex turbine and the excitation regulator of the synchronous generator, which are implemented on the basis of the Siemens Simatic PLC S7-300 CPU 314C-2DP, confirmed the feasibility of the approach to the settings of the EGU regulators proposed in the work. Developed EGU regulators provide stabilization of the output parameters of the unit under conditions of electrical load disturbances. The design features of the experimental setup, due to the slight inertia of the processes accompanying the generation process, did not provoke the occurrence of frequency fluctuations of the generated voltage. At the same time, changes in the frequency of rotation of the EGU shaft, which accompany changes in the electrical load, have a fading character.

The perspective of further studies of EGU regulators is presented as the implementation of proven methods of their development in the design of the gas distribution network system. Another direction of using this research is the approbation of various control laws when simulating disturbances at power plants of alternative (renewable) energy. The closest prospect of research is seen in the development of EGU regulators using jet turbines and turbines with a higher generation capacity.

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CONFLICT OF INTEREST

None.

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Дослідження регулятора детандер-генераторного агрегату

Анотація. Актуальність дослідження визначається завданнями підвищення ефективності енергоустановок альтернативної та відновлюваної енергетики. Мета роботи полягає в розробці методики координації налаштувань автоматичних регуляторів збудження і швидкості обертання ротора генератора з вихрової установки детандер-генераторного агрегату, що входить до складу автономної мережі електроспоживання. Для досягнення поставленої мети використовувалися методи математичного моделювання у середовищі MATLAB, фізичного моделювання, обробки експериментальних даних, теорії автоматичного керування, теорії магнітного поля, теорії електричних машин, програмування мікропроцесорних пристроїв. Зважаючи на необхідність розширення бази альтернативних енергоджерел, розглядалася задача керування енергетичною установкою утилізації надлишкового тиску газотранспортних мереж. Дослідження регулятора детандер-генераторного агрегату ґрунтувалося на моделі, що відображає взаємодію процесів механічної та електричної природи. Опису цих процесів відповідала сукупність нелінійних диференційних рівнянь. Точне врахування нелінійностей об'єкта керування, що розглядався, ускладнює реалізацію відповідної мікропроцесорної систем керування. Моделювання спрямоване на досягнення компромісу між необхідною точністю регулювання об'єктом та можливостями спрощення структури керування об'єктом. Використання експериментальних і паспортних даних пристроїв дозволило оцінити динаміку обертання турбіни та генерації напруги, формуючи чинники розв'язки контурів керування. Застосування MATLAB з опцією Lookup Table дозволило здійснити багатоточкову лінеаризацію нелінійного опису процесу, прискоривши моделювання і налаштування регулятора. Це важливо для координації налаштувань контурів керування частотою обертання та вихідною напругою, зважаючи на протиріччя між швидкодією регулятора та мінімізацією коливань частоти генерації. За отриманими результатами розроблено регулятор детандер-генераторного агрегату, який забезпечує стабілізацію вихідних параметрів агрегату в умовах дії збурень електричного навантаження. На практиці отримані дані можна використати в інтеграції відновлюваних джерел енергії до загальної енергосистеми через оптимізацію роботи генераторів

Ключові слова: вихрова турбіна; частота обертання; координація налаштувань; нелінійна модель; синхронний генератор; регулятор збудження

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Development of modern irrigation systems for improving efficiency, reducing water consumption and increasing yields

Abstract. The study was conducted to examine modern irrigation systems aimed at improving water efficiency, reducing water consumption and increasing crop yields. The study analysed the environmental and socio-economic aspects of modern irrigation systems, including their impact on the environment and social sustainability of agriculture. The study determined that the use of modern irrigation systems, such as drip irrigation and IoT-based automatic control systems, can significantly improve the efficiency of water use in agriculture. Data analysis demonstrated that such systems can reduce water consumption by up to 50% while increasing yields by up to 30%. The use of agricultural drones to monitor field conditions and precisely regulate irrigation helps to improve plant health and reduce labour costs. The study also determined that water recycling and reuse systems can significantly reduce the use of freshwater, which is especially important in regions with limited water resources. In general, modern irrigation technologies demonstrate high efficiency

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and economic feasibility, contributing to the sustainable development of agriculture. The study proved that the use of computer modelling and forecasting of plant water requirements provides optimal conditions for their growth, which further contributes to an increase in yields. The results of the study can be used in practice to develop and implement more efficient and environmentally friendly technologies in irrigation and drainage systems, which helps to reduce the negative impact on the environment through more efficient use of water resources and reduction of water runoff

Keywords: agricultural drones; computer modelling; plant needs forecasting; optimal conditions for growth; water use

INTRODUCTION

The development of modern irrigation systems represents a drive to improve the way water is used in agriculture. Key areas of development include the introduction of advanced technologies such as drip irrigation and automated control systems based on the Internet of Things (IoT). These technologies not only help to optimise water consumption but also improve the accuracy and regularity of irrigation, which in turn leads to a significant increase in yields. Another important aspect is the use of agricultural drones to monitor the condition of fields and precisely regulate irrigation, which reduces labour costs and increases the overall efficiency of the process. Additionally, the introduction of water recycling and reuse systems minimises the use of fresh water, which is especially important in conditions of limited water resources. Thus, modern irrigation technologies are aimed at creating sustainable and cost-effective solutions for agriculture.

This study is critically important in the context of the current challenges associated with climate change and sustainable agricultural development. Efficient use of water resources is becoming increasingly important as the population grows and freshwater availability deteriorates. Modern irrigation and watering systems, represented by drip irrigation, automated technologies and data-driven management systems, promise to significantly improve water savings and increase the production results of agricultural enterprises. The research is also needed to confirm the effectiveness and economic feasibility of these technologies, which will contribute to their widespread adoption and sustainable development of agriculture in the future.

The problem existing in the area under study is the need to increase the efficiency of water use in agriculture. Drip irrigation, studied by R. Sidhu *et al.* (2021), has proven to be effective in agriculture due to the precise distribution of moisture to plant roots, which contributes to improved yields and economic efficiency. M. Hamdi *et al*. (2021) confirmed the economic feasibility of IoT-based automatic irrigation systems, pointing to their ability to reduce operating costs and efficiently use water resources. J. Gómez & A. Tascón (2021) demonstrated that the use of agricultural drones to monitor fields increases the efficiency of irrigation and fertiliser management, contributing to improved plant health and yields. F. Parada *et al*. (2021) demonstrated that water recycling systems in agriculture significantly reduce freshwater consumption and improve the sustainability of water use in resource-limited environments. G. Malhi *et al*. (2021) highlighted the need to adapt irrigation systems to a changing climate to maintain sustainable agricultural production. S. Naghdi *et al*. (2021) revealed the significant potential of computer modelling for optimising water resources in agriculture. W. Loiskandl & R. Nolz (2021) emphasised the importance of taking environmental factors into account when developing new technologies in the agricultural sector in a study on the environmental aspects of irrigation systems. G.N. Curry *et al*. (2021) discussed the socio-economic impacts of new technologies in agriculture, emphasising the need to consider social aspects when developing water use policies. W. Zhang *et al*. (2024) identified challenges and proposed solutions for sustainable water use in regions with limited water resources. Lastly, N. Dwijendra *et al*. (2022) highlighted the importance of innovation for sustainable agricultural development in a changing climate. However, there are still gaps in optimising water recycling systems, predicting plant needs using computer modelling, studying the socio-economic impact of new technologies, and understanding the environmental aspects of modern irrigation systems. These gaps need to be further explored to develop more comprehensive and sustainable solutions for agricultural water management.

The study aims to investigate modern irrigation and watering systems aimed at improving water efficiency, reducing water consumption and increasing crop yields. Research goals include:

1. Assessment of the environmental aspects of modern irrigation and watering systems to minimise the negative impact on the environment when using water resources in agriculture.

2. Analysis of the technical characteristics of agricultural drones.

3. Investigation of the potential of water recycling systems to reduce freshwater consumption in conditions of limited water resources.

MATERIALS AND METHODS

A detailed analysis of various technologies in irrigation and watering systems was carried out, including drip irrigation, automatic irrigation systems and spot irrigation. The study included an assessment of the effectiveness of each of these technologies in different climatic and soil conditions, as well as their ability to accurately distribute water directly to plant roots. The advantages, such as minimising water losses and improving yields through optimal use of resources, as well as the disadvantages associated with the technical and operational aspects of implementing these systems, are analysed.

The socio-economic aspects of introducing modern irrigation technologies were also analysed. The economic feasibility of using such systems and their impact on reducing operating costs in agriculture and improving resource management are assessed. The environmental, social and economic aspects of modern irrigation systems were assessed. The environmental impact of such technologies on the environment was analysed, including the potential impact on land resources, aquatic ecosystems and biodiversity. The researchers studied the socio-economic aspects of introducing new technologies in agriculture. The paper analysed the impact of these technologies on employment in the agricultural sector, changes in farm incomes and public support for such innovations. The study examined in detail the possibilities of using the DJI Agras T30 agro-industrial drone (China) to monitor the condition of fields and optimise irrigation. Its technical characteristics and ability to collect data on soil moisture, plant health and the general condition of the fields were analysed. The use of this drone allows agricultural enterprises to conduct more frequent and detailed monitoring, which contributes to accurate and efficient management of irrigation and fertilisation.

The use of computer models to predict plant water requirements and optimise irrigation regimes was evaluated. Mathematical models were developed based on data on climatic conditions, soil types and the needs of different crops. The study of water recycling systems in agriculture included an in-depth analysis of their efficiency and potential to improve the sustainability of the agricultural sector. Technologies were analysed, including the use of treated wastewater and other secondary water sources for crop irrigation. Assessment of the impact of recycling systems on the sustainability of the agricultural sector was prioritised. These technologies help improve the resilience of agriculture to climate change and environmental challenges. A significant reduction in the use of fresh water is not only economically beneficial but also contributes to the preservation of water resources for future generations, which is an important aspect of sustainable agricultural development strategies. The following formulas were used in the study. The formula for calculating the volume of water for drip irrigation (1):

$$W_d = \frac{A \times ET_c \times K_c}{E_a}, \tag{1}$$

where: W_d – volume of water for drip irrigation (l/day); A – field area (m²), ET_c – evaporation and transpiration demand (mm/day); K_c – crop coefficient (dimensionless); E_a – system efficiency (dimensionless, usually 0.9-0.95 for drip irrigation).

The formula for calculating the volume of water for automatic irrigation (2):

$$W_a = W_m \times \left(1 - \frac{R}{P}\right), \tag{2}$$

where: W_a – the volume of water for automatic irrigation (l); W_m – the maximum irrigation volume (l); R is the volume of precipitation (mm); P is the threshold soil moisture level (mm).

The formula for calculating water savings (3):

$$S_j = W_t - W_j, \tag{3}$$

where: S_j – water savings (l); W – traditional watering volume (l); W_j - watering volume using IoT (l). The formula for calculating the efficiency of spot irrigation (4):

$$E_p = \frac{W_p}{W_t}, \tag{4}$$

where: E_p – the efficiency of spot irrigation (dimensionless); W_p – the volume of water for spot irrigation (l); W_t – the traditional volume of irrigation (l).

The formula for calculating freshwater savings (5):

$$S_w = W_t - W_r, \tag{5}$$

where: S_w – water savings (l); W_t – traditional watering volume (l); W_r – recycled water volume (l).

The formula for calculating the drone efficiency (6):

$$E_d = \frac{W_d}{W_m}, \tag{6}$$

where: E_d – drone utilisation efficiency (non-dimensional); W_d – volume of water when using drones (litres); W_m – maximum watering volume (litres).

The formula for calculating optimal fuel volumes (7):

$$W_c = A \times ET_c \times K_c \left(\frac{1}{E_c}\right), \tag{7}$$

where: W_c – optimal irrigation volume (l); A – field area (m²); ET_c – evaporation and transpiration demand (mm/day); K_c – culture coefficient (dimensionless); E_c – model efficiency (dimensionless).

These formulas demonstrated how different irrigation systems can optimise water use and increase yields, which is especially important in the context of global climate change and water scarcity.

RESULTS

Modern irrigation systems are being actively developed to improve efficiency, reduce water consumption and increase yields. Drip irrigation is one of the most efficient and modern irrigation systems that significantly increases agricultural productivity while minimising the use of water resources. This technology is based on the principle of delivering water directly to the roots of plants through a network of tubes, drippers and emitters. This not only improves the quality of irrigation but also reduces water losses, which is especially relevant in the context of global climate change and water scarcity.

Unlike traditional irrigation methods such as sprinkling or surface watering, drip irrigation provides precise water dosing, delivering it directly to the plant root zone. This significantly reduces water losses due to evaporation and surface runoff, which is especially important in arid regions where water resources are limited. This ensures that the plants receive the necessary amount of moisture, which contributes to their better growth and higher yields. In addition, drip irrigation helps improve soil quality. As the water is delivered directly to the roots, the risk of surface crusting and soil erosion is reduced. This, in turn, promotes better oxygen penetration to the roots of plants and improves their overall health. It is also worth noting that drip irrigation allows for more efficient use of fertilisers and pesticides that can be added to the irrigation system, which reduces the cost of their use and reduces the negative impact on the environment.

For drip irrigation, the initial costs include the cost of equipment (tubes, drippers, filters, pumps) and installation work, which can range from $1,500 to $3,500 per hectare. The operating costs for this system include maintenance, replacement parts, energy for the pumps and regular cleaning of the system, which amount to about $100-$300 per hectare per year. Drip irrigation is an effective and sustainable solution for modern agriculture (Bansal *et al.*, 2021). It can significantly increase the yield and quality of agricultural products with minimal water consumption. In the context of global climate change and increasing water scarcity, drip irrigation is becoming an important tool for ensuring food security and sustainable development of the agricultural sector. Drip irrigation provides precise water dosing, minimising losses due to evaporation and surface runoff. For instance, for a 1 ha (10,000 m^2) field with a crop coefficient of 0.7, requiring evaporation and transpiration of 6 mm/day, and given a system efficiency of 0.9, the daily water consumption for drip irrigation can be calculated using the formula (1):

$$W_d = \frac{10000 \times 6 \times 0.7}{0.9} = 46.667.$$

Automatic irrigation systems are advanced technologies that have significantly changed the approach to water management in agriculture (Lopez-Jimenez *et al.*, 2022). Equipped with soil moisture sensors, rain sensors and data-driven control systems, these systems not only optimise the irrigation schedule but also significantly improve water use efficiency by avoiding over-watering or over-drying the soil.

Automatic irrigation, or sprinkler systems, have initial costs for sprinklers, pipework, pumps and control systems that can range from $2,000 to $5,000 per hectare. Operational costs include energy, equipment maintenance and regular inspections, at around $150-$400 per hectare per year. Moisture sensors placed in different parts of the field continuously collect data on soil conditions and transmit it to the control system. This allows the system to automatically adjust the watering schedule, providing plants with the right amount of moisture at the right time. This prevents situations where the soil remains too dry or too wet, which has a positive effect on plant health and yields. An additional advantage is the use of rain sensors that prevent watering during or immediately after rain. This not only prevents water overuse but also reduces the risk of waterlogging, which can lead to plant diseases and poor growth. Thanks to these sensors, automatic irrigation systems can significantly reduce water consumption, which is especially important in regions with limited water resources.

Modern data-driven management systems integrate information from a variety of sources, including meteorological data and weather forecasts. This improves watering plan accuracy, thus covering future weather conditions and plant needs. As a result, automatic irrigation systems become not just a tool for water supply, but a full-fledged part of the agricultural process management system, which significantly increases their efficiency. Modern automatic irrigation systems represent an important step forward in the field of water management in agriculture. They can significantly increase water use efficiency, improve plant health and increase yields, making them an integral part of sustainable and efficient agricultural production. In the context of global climate change and increasing water scarcity, such systems are becoming a key tool for ensuring food security and sustainable agricultural development. Automatic irrigation systems can be optimised with humidity and rain sensors. The optimal irrigation formula (2) assumes that with a maximum irrigation volume of 50,000 litres, 5 mm of precipitation and a threshold moisture level of 20 mm, the volume of water to be irrigated will be:

$$W_a = 50000 \times \left(1 - \frac{5}{20}\right) = 37.500.$$

In 2024, smart technologies and IoT have become an integral part of modern agriculture, opening new opportunities for efficient water management (Salam, 2024). The creation of integrated irrigation management systems based on data on weather conditions, soil conditions and plant needs can be used to automate the irrigation process, making it more accurate and efficient. Employing sensors installed in different parts of the field, IoT systems can monitor soil moisture levels, temperature, rainfall and other important parameters in real-time. This data is transferred to a central server where it is processed and analysed using specialised software. This can be used to create accurate models of field conditions and predict plant water requirements. Automation of the watering process based on collected data significantly increases its efficiency. Smart irrigation control systems can automatically adjust the water supply depending on current conditions and weather forecasts, which helps to avoid both overdrying and overwetting the soil. This not only improves plant health and yields but also significantly reduces water consumption, which is especially important in the face of global climate change and water scarcity.

The use of smart technologies and IoT in irrigation management systems can optimise the use of fertilisers and pesticides (Kumar *et al.*, 2022). In combination with precision irrigation, this ensures a more even distribution of nutrients and protective agents across the field, which improves their effectiveness and reduces the negative impact on the environment. Thus, the integration of smart technologies and IoT into agricultural processes contributes to the sustainable development of agriculture. The economic benefits of implementing smart irrigation management systems are also significant. Despite the initial costs of hardware and software, in the long term, such systems can significantly reduce water and labour costs. Automation of irrigation management processes frees farmers from the need for constant monitoring and manual adjustments, which increases overall productivity and reduces labour costs. However, despite the many benefits, the introduction of smart technologies and IoT in agriculture is fraught with challenges. This requires a significant initial investment and qualified personnel to install and maintain the equipment. It is also necessary to consider data security and protection to avoid potential cyber threats and unauthorised access to information.

The use of smart technologies and IoT in irrigation management systems represents an important step forward in the field of efficient water use and sustainable agriculture. These innovative solutions significantly increase the accuracy and efficiency of irrigation, improve plant health and yields, and reduce water and labour costs. In the context of global climate change and increasing water scarcity, smart irrigation management systems are becoming a key tool for ensuring food security and sustainable development of the agricultural sector. IoT can be used to control irrigation based on data about weather, soil conditions and plant needs. Formula (3) for determining water savings using IoT addresses the difference between the traditional watering volume of 50,000 litres and the IoT watering volume of 35,000 litres:

$$S_i = 50000 - 35000 = 15000.$$

The drip irrigation system is one of the most innovative and efficient irrigation technologies developed to optimise water use in agriculture (Wang & Guo, 2024). The main advantage of this system is the use of special devices that direct water directly to the root zone of plants. This minimises evaporation and surface run-off losses, providing plants with the right amount of moisture with maximum precision and efficiency. The main idea of the "spot irrigation" system is to deliver water precisely where it is most needed – to the roots of plants. Unlike traditional irrigation methods, such as surface or sprinkler irrigation, this system avoids excessive soil moisture and surface runoff, which often leads to soil erosion and loss of nutrients. Instead, the water is delivered through a network of tubes and emitters directly to the root zone, which ensures even moisture distribution and promotes healthy plant growth.

The effectiveness of the "spot irrigation" system has been confirmed by practical application in various climatic and soil conditions (Rocha *et al.*, 2023). It significantly reduces water consumption compared to traditional irrigation methods. This is especially important in regions with limited water resources or in drought conditions when water conservation becomes critical. In addition, drip irrigation helps to reduce plant disease, as it prevents water from reaching the leaves and stems, which reduces the risk of fungal infections and other diseases. In addition, the drip irrigation system improves product quality. Plants that receive the right amount of water in the root zone develop more evenly and healthily, which has a positive effect on the quality of fruits and vegetables. This is especially important for manufacturers focused on the fresh food market, where product quality and appearance play a key role.

Spot irrigation requires initial costs for spot irrigation and its installation, which range from $2,000 to $4,000 per hectare. Operating costs, including maintenance and energy, are around $100-$250 per hectare per year. Due to its economic and environmental efficiency, this system is becoming increasingly popular among farmers and agribusinesses seeking sustainable and highly productive agriculture. In the context of global climate change and growing water scarcity, the "point irrigation" system plays a key role in ensuring food security and sustainable development of the agricultural sector. These systems direct water directly to the roots of plants, minimising losses. Formula (4) for determining the efficiency of spot irrigation addresses the ratio of the volume of water used for spot irrigation (30,000 litres) to the traditional volume of irrigation (50,000 litres):

$$\mathrm{E_p} = \frac{30000}{50000} = 0.6.$$

Water recycling and reuse systems are among the most significant innovations in agricultural water use (Chen *et al.*, 2021). These systems use treated wastewater or water from other secondary sources to irrigate crops. The main goal of such systems is to significantly reduce freshwater consumption, which is especially important in the context of global climate change and limited water resources. The use of recycled water in agriculture solves several key problems. Recycled water reduces freshwater usage, which is often under threat of depletion. In the face of drought and climate change, where freshwater resources are becoming scarce, water recycling is becoming vital to maintaining sustainable agricultural production. Using wastewater that has been properly treated helps to reduce environmental pollution and improve the quality of water resources in general. One of the most important aspects of water recycling systems is their environmental sustainability. The treated wastewater used for irrigation can contain certain nutrients, such as nitrogen and phosphorus, which can be beneficial for plants. This helps to reduce the use of chemical fertilisers, which in turn reduces the negative impact on soil and water bodies. Thus, water recycling systems contribute not only to saving water resources but also to improving the environmental situation in agricultural regions.

The practical application of such systems requires careful planning and management. The quality of the treated wastewater must meet certain standards to avoid harming plants and soil (Litynska *et al.*, 2023). This requires the installation of modern treatment facilities and regular monitoring of water quality. In addition, the specific needs of different crops and local climatic conditions must be addressed for optimal system performance. Examples of successful implementation of water recycling systems can be found globally. In Israel, for example, more than half of the water used in agriculture is recycled wastewater. This has allowed the country to achieve significant success in agriculture despite limited water resources. Israeli experience shows that proper management and investment in recycling technologies can ensure sustainable and efficient use of water resources (Onuh & Bassey, 2021).

Water recycling systems have initial costs for the installation of water recycling and treatment systems, which can range from \$3,000 to \$6,000 per hectare, and operating costs for system maintenance and water treatment are about \$200-\$500 per year per hectare. Water recycling and reuse systems represent an important step forward in sustainable water use in agriculture. These systems significantly reduce freshwater consumption, improve the environment and reduce water and fertiliser costs. In the context of global climate change and population growth, the need for such systems will only increase, making them a key element of sustainable agricultural development and food security. These systems use treated wastewater or water from other sources for irrigation. Formula (5) for determining freshwater savings addresses the difference between the traditional watering volume (50,000 litres) and the recycled water volume (40,000 litres):

$$S_w = 50000 - 40000 = 10000.$$

Agricultural drones are an advanced technology that significantly transforms the way agriculture monitors and manages irrigation (Thilagu & Jayasudha, 2022). These unmanned aerial vehicles can quickly and accurately collect data on the condition of fields, allowing farmers to make informed and timely decisions to optimise irrigation and increase yields. The DJI Agras T30 is an advanced agricultural drone that stands out for its technical characteristics (Fig. 1). Its design includes large rotors with a diameter of 2.5 metres and weighs about 18.1 kg unloaded, allowing the drone to effectively carry up to 30 kg of liquid or fertiliser. The maximum flight speed is up to 15 m/s, which enables fast processing of large areas. The drone is capable of processing up to 40 hectares on a single battery charge, depending on the density of the crop and the type of liquid.

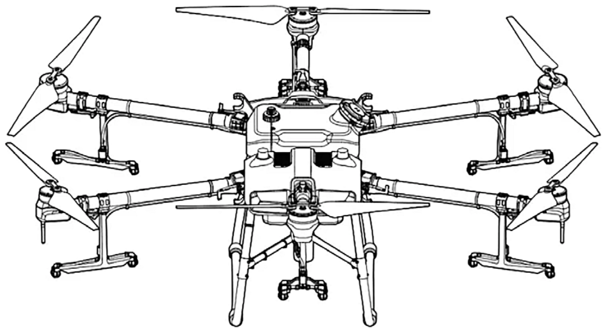

Figure 1. Diagram of the DJI Agras T30 drone
Source: Dji T30 Agras drone user manual (2022)

The T30 spray system is equipped with advanced technology that can adjust the volume and pressure of the spray, which ensures high precision in the application of fertilisers and pesticides. The flight time is up to 20 minutes on a single charge of the lithium-polymer battery, which can vary depending on the load and operating conditions. The drone is controlled by a specialised remote control and an integrated GPS, which allows for route planning and real-time flight monitoring. The DJI Agras T30 is equipped with safety features such as obstacle detection sensors and automatic landing in case of low battery or other malfunctions. In addition, the drone is waterproof and can be used in various weather conditions, including rain and fog (Seidaliyeva *et al.*, 2024). It can also be integrated with various sensors to monitor crop and environmental conditions, making it highly effective for agro-industrial monitoring and irrigation optimisation.

The main advantage of using drones in agriculture is their ability to conduct high-precision aerial photography and collect data on the condition of plants and soil over large areas. Equipped with a variety of sensors and cameras, drones can detect irrigation problems such as lack or excess of moisture, plant diseases and other factors affecting yields. This allows farmers to respond quickly to emerging problems and adjust irrigation regimes, which significantly increases the efficiency of water use. Drones also play a key role in assessing the effectiveness of irrigation methods. They can be used to regularly monitor field conditions and compare the results of different irrigation systems, such as drip irrigation, spot irrigation and automatic systems. This helps farmers identify the most effective methods and optimise their use to maximise yields and save resources. In addition, drones can collect data on soil moisture, plant health and other parameters, which can be used to create accurate field maps and develop individual irrigation strategies for different areas. Drones help reduce labour costs and increase productivity in agriculture. By automating the monitoring and data collection processes, farmers can reduce the amount of manual work and focus on making strategic decisions. This helps to improve labour organisation and increase the overall efficiency of agricultural enterprises. For instance, drones can replace workers who inspect fields, reducing the time and resources spent on these processes.

One of the most significant advantages of using drones is their ability to monitor fields in real-time. This is especially important in the face of unpredictable weather changes and other factors affecting the condition of fields and plants. Operational data obtained with the help of drones allows farmers to respond quickly to any changes and take measures to prevent crop losses. For example, drones can quickly detect drought or waterlogging in certain areas of fields, allowing farmers to adjust watering promptly and avoid plant damage. Agricultural drones are a powerful tool for monitoring and controlling irrigation, helping to improve the efficiency and sustainability of agriculture. Their ability to quickly and accurately collect data on the condition of fields and plants allows farmers to make informed decisions and optimise water use. In the context of global climate change and growing water scarcity, agricultural drones play a key role in ensuring sustainable agricultural development and food security. The use of drones requires significant upfront costs for the purchase of drones and data analysis software, which can range from $5,000 to $15,000 per drone. Operational costs include operator training, drone maintenance and data processing, which amount to around $1,000-$3,000 per year. Drones can monitor the condition of fields and assess the effectiveness of irrigation. Formula (6) for evaluating the efficiency of drone use addresses the ratio of the water volume when they are used (40,000 litres) to the maximum irrigation volume (50,000 litres):

$$E_d = \frac{40000}{50000} = 0.8.$$

Computer modelling and forecasting of plant water requirements are innovative approaches that significantly improve irrigation management in agriculture (Saggi & Jain, 2022). These technologies allow farmers to address many factors, such as soil type, climatic conditions and plant growth stage, to create optimal irrigation regimes. As a result, the use of such models contributes to efficient water use, increased yields and minimised environmental impact. The models can address soil characteristics such as permeability and retention capacity, as well as climatic data including temperature, humidity and precipitation. This allows farmers to plan irrigation activities, avoiding both water shortages and excesses that can negatively affect plant health and productivity. Accurate forecasts can also be used to adapt to weather changes and minimise the risks associated with extreme climatic conditions, such as droughts or heavy rain.

Computer modelling also contributes to the rational use of water resources, which is especially relevant in times of water scarcity. For instance, models can help determine the optimal watering intervals and volumes for different crops, which can reduce overall water consumption. This is especially important in arid regions where water resources are limited, as well as in the context of global climate change, which puts additional pressure on water supplies. Optimising irrigation using computer models helps to save water and increase the resilience of agriculture to changing conditions. Computer modelling also allows data from various sources to be integrated to create more accurate and comprehensive forecasts. For example, data from agricultural drones that collect information about the condition of fields can be used to improve models and increase their accuracy. This allows farmers to make more informed decisions and adapt their irrigation strategies to current field conditions. Modern models can also account for weather forecast data, which provides even more accurate irrigation planning and response to changing climatic conditions.

Computer modelling contributes to the sustainable development of agriculture by reducing the negative impact on the environment. Optimised irrigation minimises water run-off and the pollution of soil and water bodies by chemicals such as fertilisers and pesticides. This helps to improve the environmental situation and preserve biodiversity in agricultural areas. For example, models can help determine the optimal doses of fertilisers and pesticides, which reduces their overuse and pollution.

Computer models predict the water requirements of plants to optimise irrigation. Formula (7) for calculating the optimal watering volume using computer modelling is as follows: for a field of 1 ha (10,000 m²), with a crop coefficient of 0.8, evaporation and transpiration demand of 5 mm/day, and a model efficiency of 0.85:

$$W_c = 10000 \times 5 \times 0.8 \left(\frac{1}{0.85}\right) = 47059.$$

Modern irrigation systems offer many benefits that significantly improve agricultural efficiency and contribute to sustainable development (Table 1). The main ones include water savings, increased yields, reduced labour costs and environmental sustainability. Let us analyse these advantages in more detail.

Table 1. Comparative table of technical characteristics of irrigation systems

Irrigation system	Reduced water consumption	Increase in yields
Drip irrigation	Up to 50%	Up to 30%
Automatic irrigation systems	Up to 40%	Up to 20%
Use of smart technologies and IoT The “spot irrigation” system	Up to 60%	Up to 30%
Use of smart technologies and IoT	Up to 55%	Up to 25%
Water recycling and reuse systems	Up to 70%	Up to 15%
Agricultural drones	Up to 30%	Up to 10%
Computer modelling and forecasting	Up to 45%	Up to 20%

Source: compiled by the authors based on based on H. Veisi *et al.* (2022)

One of the most significant advantages of modern irrigation systems is water saving. Technologies such as drip irrigation and sensor-based automatic irrigation systems allow for precise distribution of water directly to the roots of plants. This reduces water loss through evaporation and surface runoff, which is especially relevant in regions with limited water resources. For instance, drip irrigation delivers water directly to the root zone of plants, minimising losses and ensuring that every litre of water is used more efficiently. Modern irrigation systems create optimum moisture conditions for plants, which contributes to their better growth and development. Precise dosing and even distribution of water ensures that plants receive the right amount of moisture at the right time in their life cycle. This leads to higher yields and improved product quality. For instance, the use of smart technologies and IoT makes it possible to create irrigation management systems that analyse data on weather conditions and soil conditions, ensuring timely and accurate irrigation.

Automation of watering processes significantly reduces the need for manual labour. Automatic irrigation systems can independently regulate the water supply depending on soil moisture, weather conditions and plant needs. This frees farmers from the need to constantly monitor the irrigation process and allows them to focus on other important aspects of farm management. For example, IoT-based automatic irrigation systems not only optimise the irrigation process but also allow agricultural enterprises to more accurately control water costs and reduce operating expenses. Modern irrigation systems contribute to the environmental sustainability of agriculture. Reduced water consumption and the use of treated wastewater for irrigation reduce the pressure on natural water resources. For instance, water recycling and reuse systems allow wastewater to be used for irrigation, which significantly reduces freshwater consumption. This is especially relevant in the context of global climate change when access to water resources is becoming increasingly limited. In addition, the rational use of water reduces the risk of soil and water pollution from chemicals such as fertilisers and pesticides, which helps to maintain the ecological balance.

In conclusion, modern irrigation systems are relevant for increasing the efficiency and sustainability of agriculture. Water savings, increased yields, reduced labour costs and environmental sustainability make these technologies indispensable in the face of global climate change and growing demand for food. Integrating advanced technologies into agricultural practices is a key step towards creating a more sustainable and productive agricultural sector.

DISCUSSION

Modern irrigation and watering systems are crucial in agriculture, providing optimal conditions for plant growth and development. These systems are aimed at solving one of the most pressing problems – the rational use of water resources. In the face of climate change and increasing water scarcity, the development and implementation of innovative irrigation methods are becoming vital. Modern technologies not only reduce water consumption but also significantly improve the efficiency of its use. This was also investigated by M. Attri *et al.* (2022), where the results confirmed that modern irrigation systems play a key role in agriculture aimed at optimal use of water resources. Traditional irrigation methods, such as surface watering or hand-held irrigation, are often characterised by low efficiency due to high water losses due to evaporation and discharge into groundwater. In comparison, modern irrigation technologies, such as drip irrigation and precision irrigation systems, can significantly reduce water consumption by distributing water resources more precisely and on target. This increases agricultural productivity while minimising water consumption and reducing the negative impact on the environment. S. Khriji *et al*. (2021) also showed that one of the main challenges of modern agriculture is water scarcity, exacerbated by climate change and increasing water stress. Innovative irrigation methods, such as aeroponics, hydroponics and precision irrigation systems, offer effective solutions for crop production in areas with limited access to water resources. Aeroponics and hydroponics are particularly important in the context of urbanised areas, where they reduce water consumption and optimise growing conditions. Precision irrigation technologies, such as soil moisture sensors and automated control systems, help to ensure that water is used precisely according to plant needs, which not only saves water but also increases yields and product quality (Atanasov, 2024). It is worth noting that these innovations not only improve the resilience of agriculture to changing climate conditions but also contribute to water conservation, which is critical for sustainable rural development and reducing water shortages.

One of the most promising technologies is drip irrigation, which delivers water directly to the roots of plants through a network of tubes, drippers and emitters. This precise water distribution minimises water losses due to evaporation and surface runoff, which is especially important in arid regions. Drip irrigation not only provides optimal conditions for plant growth but also helps to improve soil structure and prevent soil erosion (Shevchenko & Nikonchuk, 2022). As a result, this technology helps to increase yields and improve the quality of agricultural products. H. Wang *et al*. (2022) concluded that drip irrigation is an advanced irrigation technology that provides precise and targeted distribution of water directly to the roots of plants. This system can significantly improve the efficiency of water use in agriculture, as it minimises losses due to evaporation and runoff into the soil. Drip irrigation is especially effective in areas with uneven terrain or limited water supply, where it helps to save water and increase yields by more precisely controlling soil moisture and delivering the right amount of water and fertiliser directly to the plants. A. Patel *et al*. (2023) determined that in arid regions, drip irrigation plays a particularly important role in enabling agricultural enterprises to cope with limited access to water resources. Drip irrigation systems minimise water loss by directly delivering moisture to the roots of plants, which is especially important in conditions of high temperatures and intense evaporation. This not only saves water but also improves product quality thanks to a more consistent and controlled application of fertiliser and water to the soil. Thus, drip irrigation is an integral part of sustainable agriculture strategies in a changing climate, contributing to increased profitability and reduced environmental footprint of agricultural activities. These results confirm the above study, as they demonstrate a significant increase in yields and a reduction in water consumption due to the use of drip irrigation. Studies show that in regions with limited water resources, the use of drip irrigation can reduce water consumption for irrigation by up to 50% compared to traditional irrigation methods. This significantly reduces the ecological footprint of agriculture, reduces water extraction costs and helps prevent soil degradation by minimising erosion and salt deposits.

Automatic irrigation systems equipped with soil moisture sensors, rain sensors and data-driven control systems represent another important step in the development of modern irrigation methods. Such systems allow precise control of soil moisture levels and automatic adjustment of irrigation depending on current weather conditions and soil conditions. This helps to avoid waterlogging or overdrying, which can have a negative impact on plant growth. The introduction of automatic irrigation systems helps to significantly reduce labour costs and increase the overall efficiency of agricultural production. Notably, M. Pramanik *et al.* (2022) also determined that automatic irrigation systems are advanced technologies that allow precise control and maintenance of soil moisture depending on the needs of plants. These systems are equipped with soil moisture sensors and weather stations that automatically adjust the water supply according to the current environmental conditions and the growth stage of the plants. This approach avoids both moisture shortages and excesses, which contributes to the optimal development of the plant root system and increases yields. In addition, automatic irrigation systems significantly reduce the need for human intervention, which saves time and resources for agricultural enterprises. In turn, A. Jiménez *et al.* (2022) concluded that smart irrigation systems are high-tech solutions that include not only automated irrigation control but also data analytics to optimise agricultural processes. These systems use machine learning and artificial intelligence algorithms to predict plant water and fertiliser requirements based on historical data, weather conditions and current soil parameters. This approach significantly increases the efficiency of resource use, minimises losses and reduces the environmental footprint of agricultural operations. By integrating with modern management systems, smart irrigation systems not only improve product quality but also reduce operating costs and labour, making them an important element of sustainable and innovative agriculture. These data are consistent with the findings in the previous section, confirming that innovative approaches to irrigation management, such as automatic and intelligent irrigation systems, do indeed contribute to a significant increase in agricultural production efficiency. Automatic systems provide precise and timely soil moisture, which contributes to optimal plant growth and minimises inputs. Intelligent systems, in turn, not only automate the irrigation process but also predict the needs of plants, optimising the use of water and other resources based on sophisticated data and algorithms.

IoT and smart technologies are becoming increasingly popular in irrigation management (Nesterov, 2023). They are used to create integrated systems that analyse data on weather conditions, soil conditions and plant needs. These systems automate the watering process, making it more accurate and efficient. The use of IoT not only reduces water consumption but also improves field monitoring, which helps to detect problems promptly and resolve them quickly. As a result, such systems help to increase the resilience of agriculture to climate change. G. Gagliardi *et al*. (2021) also conducted a study that confirmed that the use of IoT in agriculture is a revolutionary approach to irrigation management based on real-time data collection and analysis. IoT systems include a network of sensors that continuously monitor soil parameters, humidity, weather conditions and other factors affecting plant growth. This data is transferred to specialised analysis platforms, enabling agricultural producers to make informed decisions on the optimal use of water resources and irrigation management. This approach not only increases irrigation efficiency by minimising water loss and improving yields but also reduces production costs and the ecological footprint of agriculture. Z. Ahmed *et al*. (2023) also determined that IoT and smart irrigation systems play a key role in making agriculture more resilient to climate change. With their help, agricultural enterprises can adapt to changing weather conditions, and predict and manage the risks associated with droughts or excessive moisture. Dynamic control of irrigation systems based on IoT data can be used to respond quickly to changes and optimise water consumption in real-time. In addition, such systems help to increase overall productivity and improve the quality of agricultural products, ensuring stable and efficient plant growth even in extreme climatic conditions. Based on the research findings, the use of IoT and smart technologies in agriculture not only improves traditional irrigation management methods but is also a key element in achieving long-term sustainability and dramatically reducing the environmental impact of agricultural activities.

The introduction of modern irrigation systems also has important environmental and socio-economic aspects. On the one hand, such technologies help to reduce the negative impact on the environment by reducing freshwater consumption and using resources more efficiently (Askar *et al*., 2023). On the other hand, they can significantly change the economic situation in agricultural regions. For instance, automation of irrigation processes can reduce operating costs and increase revenues for agricultural enterprises, which in turn has a positive impact on employment and income for residents. M. Mallareddy *et al*. (2023) concluded that modern irrigation systems, such as drip irrigation, and automatic and intelligent systems, play a key role in reducing water consumption in agriculture. Unlike traditional irrigation methods, which often lead to significant water losses due to evaporation and runoff into the soil, new technologies allow for more efficient distribution of water resources. Drip irrigation, for example, delivers water directly to the roots of plants, minimising losses and providing optimal conditions for their growth. This not only helps to save water but also reduces the negative impact on the environment by reducing soil degradation and salinity risks. F. Raza *et al*. (2022) determined that the introduction of innovative irrigation technologies has a significant socio-economic impact on agricultural regions. First, improved yields and quality of agricultural products have a favourable impact on farmers' incomes and regional economic development. Efficient use of water resources reduces irrigation costs and increases the competitiveness of agricultural products on the market. Study results analysis determined that innovative irrigation technologies not only contribute to environmental sustainability but also have a significant positive impact on the socio-economic development of agricultural regions, contributing to their sustainable and resilient development.

Despite the advantages, the introduction of modern irrigation systems faces several challenges. This includes the need for significant initial investment, technical difficulties associated with the installation and maintenance of equipment, and the need to train staff to work with new technologies. However, the prospects offered by these innovations for agriculture far outweigh the potential challenges. In the long term, modern irrigation systems can become a key element in the sustainable development of the agricultural sector, ensuring stable and high-quality food production even in the face of a changing climate and limited water resources.

CONCLUSIONS

The development of modern irrigation systems is a significant step in agriculture aimed at achieving several key goals: improving the efficiency of water use, reducing water consumption and increasing crop yields. Research in this area confirms that the introduction of modern technologies, such as drip irrigation, automatic irrigation systems, smart technologies based on IoT, spot irrigation systems and others, helps to optimise the use of water resources.

The analysis of the effectiveness of modern irrigation systems in different climatic and soil conditions is a key aspect of the study, showing that these systems can significantly reduce water losses due to their precise distribution to plant roots. This not only improves the conditions for plant growth and development but also makes efficient use of water resources, especially in conditions where access to water is limited and the climate is variable. Precise dosing of water directed to the roots of plants minimises evaporation and surface runoff, which increases irrigation efficiency and crop yields. The water savings achieved through such technologies play a key role in sustainable agriculture, enabling it to adapt to changing climate conditions and environmental challenges. Socio-economic analysis shows that the introduction of modern irrigation systems has a positive impact on agricultural regions. Automation of irrigation processes reduces operating costs and increases revenues for agricultural enterprises, which helps to improve the economic sustainability of regions and increase employment.

In general, the development and implementation of innovative irrigation and watering methods are essential for agriculture in the modern world. These technologies not only increase the productivity of the agricultural sector but also contribute to the sustainable use of natural resources, which is an important step towards ensuring food security and sustainable development of agricultural regions. The impact of modern irrigation and watering systems on biodiversity and ecological sustainability of agricultural ecosystems needs to be further studied. One of the limitations of this study is the limited availability of data on the long-term environmental and socio-economic impacts of modern irrigation systems.

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CONFLICT OF INTEREST

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Розвиток сучасних систем поливу та зрошення спрямований на підвищення ефективності, зменшення споживання води та збільшення врожайності

Анотація. Дослідження було проведене для вивчення сучасних систем поливу та зрошення, спрямованих на підвищення ефективності використання води, зниження її споживання та збільшення врожайності сільськогосподарських культур. У рамках дослідження було проаналізовано екологічні та соціально-економічні аспекти застосування сучасних систем поливу та зрошення, включно з їхнім впливом на навколишнє середовище та соціальну стійкість сільського господарства. У дослідженні було встановлено, що використання сучасних систем поливу та зрошення, як-от крапельне зрошення та автоматичні системи управління на основі IoT, дає змогу значно підвищити ефективність використання води в сільському господарстві. Аналіз даних показав, що такі системи можуть знизити споживання води до 50 %, при цьому збільшуючи врожайність до 30 %. Використання агропромислових дронів для моніторингу стану полів і точного регулювання поливу сприяє поліпшенню здоров'я рослин і зниженню витрат на працю. Також було виявлено, що системи рециркуляції та повторного використання води можуть суттєво зменшити використання прісної води, що особливо важливо в регіонах з обмеженими водними ресурсами. Загалом, сучасні технології зрошення демонструють високу ефективність та економічну доцільність, сприяючи сталому розвитку сільського господарства. Було доведено, що застосування комп'ютерного моделювання та прогнозування потреб рослин у воді забезпечує оптимальні умови для їхнього росту, що додатково сприяє збільшенню врожайності. Результати дослідження можна використовувати на практиці для розроблення та впровадження більш ефективних та екологічно чистих технологій у системах зрошення та водовідведення, що сприяє зниженню негативного впливу на навколишнє середовище за рахунок більш раціонального використання водних ресурсів та скорочення водних стоків

Ключові слова: агропромислові дрони; комп'ютерне моделювання; прогнозування потреб рослин; оптимальні умови для росту; водокористування

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Research and improvement of the design of a sedimentation tank for hydropower and irrigation

Abstract. The study is devoted to the analysis and optimisation of the design of the sedimentation tank to increase the efficiency of settling solid particles in hydropower and irrigation systems. Both experimental and numerical methods were used to analyse and optimise the design of sedimentation tanks to increase their efficiency in hydropower and irrigation systems. The study examined and analysed various types of sedimentation tanks according to design schemes, flow regime, deposition dynamics and sediment flushing methods, and also considered recommended improvements for hydropower and irrigation of various types of sedimentation tanks. During the study, it was revealed that optimising the geometry of the sedimentation tank significantly increases the efficiency of solid particle deposition. Experimental data have shown that changing the angle of inclination of the walls and increasing the area of the bottom of the sedimentation tank contribute to improving the deposition of silt and sand. It has also been found that the use of special turbulent inserts reduces the particle deposition time and improves the quality of treated water. Hydraulic flow modelling has confirmed that a more uniform velocity distribution in the sedimentation tank reduces turbulence and promotes more efficient particle deposition. The introduction of automated systems for monitoring and controlling the cleaning process has made it possible to increase the reliability and stability of the sedimentation tank. As a result, it was proved that the proposed design and technological changes can significantly increase the efficiency and durability of sedimentation tanks in hydropower and irrigation. The study provides practical recommendations for improving the design of sedimentation tanks, which helps to increase their efficiency and reliability in hydropower and irrigation, thereby improving water management

Keywords: suspended particles; infrastructure elements; pumps and filters; sedimentation; hydraulic flows

INTRODUCTION

Effective water management is a critical aspect for hydropower and irrigation, as both the economic and environmental sustainability of systems depend on it. Sedimentation tanks play a key role in this process, which ensure the removal of solid particles from the water, preventing clogging of equipment and improving water quality for future use. The analysis will identify the most effective approaches to the design and optimisation of sedimentation tanks, which becomes the basis for the development of recommendations to improve their efficiency and increase durability in hydropower and irrigation systems, contributing to more efficient use of water resources and reducing the ecological footprint of industrial processes.

This study was necessary due to the critical importance of improving the efficiency of sedimentation tanks in hydropower and irrigation. Traditional structures often face problems with insufficient deposition of solid particles, which leads to increased wear of equipment, reduced water quality, and increased operating costs. Modern requirements for sustainable management of water resources and improvement of environmental safety emphasise the need to optimise the designs of sedimentation tanks.

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By analysing and improving design schemes, flow regimes, deposition dynamics, and precipitation flushing methods, the efficiency of these systems can be significantly improved, which will better meet the growing needs for clean water and reliable hydraulic structures.

The problem of insufficient efficiency of sedimentation tanks in hydropower and irrigation has long attracted the attention of researchers. K. Hirom & T.T. Devi (2022) investigated the influence of the sedimentation tank shape on the efficiency of solid particle deposition, suggesting optimal geometric parameters for various operating conditions. G.J. Hoffmans (2022) focused on the analysis of hydraulic regimes and found that changing the flow rate can significantly improve the deposition process. Important observations on deposition dynamics and particle behaviour in sedimentation tanks were made by D.A. Yaseen *et al.* (2024), who emphasised the role of turbulence in these processes. H. Feng *et al.* (2023) proposed new methods for washing sediments to reduce cleaning time and improve the overall efficiency of the system. In turn, A.K. Dudhpachare *et al.* (2022) focused on automating the process of managing sedimentation tanks, which significantly increased the reliability of their operation.

The results of the study by R. Singh *et al.* (2021) have shown that the use of composite materials can increase the durability of structures and reduce operating costs. S. Juraev *et al.* (2022) conducted an extensive study of the impact of environmental factors on the operation of sedimentation tanks, suggesting methods to minimise the negative impact on the environment. K. Czernek *et al.* (2021) demonstrated the importance of integrating sedimentation tanks with other elements of drainage systems, ensuring a more coordinated and efficient operation of the entire system. Ultimately, the research conducted by M. Ajith *et al.* (2021) confirmed that the introduction of innovative technologies such as nanomaterials can significantly improve the water purification process and increase the overall performance of sedimentation tanks.

J.C. Iyer & E.J. James (2022) focused on model studies aimed at designing the inlet transition of sedimentation tanks for hydropower projects in regions with high alluvial runoff. Despite extensive research, there are still many gaps that require additional investigation. It is necessary to conduct a more detailed analysis of the influence of various hydraulic modes on settling efficiency, to investigate the long-term effects of using new materials, and to develop more advanced automation and control methods to ensure reliable and stable operation of sedimentation tanks in various operating conditions.

The purpose of the study was to develop and improve the design of a sedimentation tank to significantly improve the efficiency of solid particle deposition in hydropower and irrigation systems. The objectives of the study included:

1. Analysis of existing design schemes of sedimentation tanks to identify their main advantages and disadvantages in the context of the efficiency of precipitation of solid particles.

2. Investigation of hydraulic flows in sedimentation tanks to determine optimal conditions conducive to improving the particle deposition process.

MATERIALS AND METHODS

A study on curved sedimentation tanks at hydroelectric power plants was conducted in Azerbaijan, in 2023, at the National Academy of Sciences of Azerbaijan. During the analysis, a detailed optimisation of both the shape and size of the sedimentation tank was carried out to maximise the process of capturing suspended particles from the water. A study considered various methods of solid particle deposition aimed at improving the efficiency of the process with minimal loss of water and energy. Direct and reverse gradient sedimentation tanks, curved sedimentation tanks, and the use of chemical reagents and innovative technologies in the field of water purification were analysed. The main emphasis was placed on the development of design solutions that contribute to the optimal use of hydraulic flows and the most efficient deposition of particles, which significantly increases the performance of the sedimentation tank in hydropower and irrigation systems.

In the course of the research, modern materials were developed for the construction of sedimentation tanks. This process involved careful research and testing of various materials for strength, corrosion resistance, and durability. The purpose was to determine the best material options, considering the specific operating conditions of the sedimentation tanks, which ensures their efficient operation in various climatic and operational conditions necessary for hydropower and irrigation systems. During the study, a hydraulic analysis was carried out aimed at optimising the flow profile in the sedimentation tank. The main purpose of this analysis was to minimise pressure losses and maximise the efficiency of the particle deposition process. The analysis included an assessment of hydraulic losses, the distribution of flow rates and the influence of geometric parameters of the sedimentation tank on its performance in conditions of hydropower and irrigation.

During the study, the technical parameters of the sedimentation tank design were coordinated with other key elements of the wastewater disposal and water treatment system, such as pumps and filters. The purpose of this process was to ensure trouble-free operation of the sedimentation tank within the framework of an integrated water supply and treatment infrastructure, which contributes to improving the overall efficiency of the system. During the study, environmentally sustainable solutions were developed and implemented aimed at reducing energy and water consumption, minimising emissions and waste into the environment. This is achieved through the use of advanced cleaning technologies and improvement of internal processes in sedimentation tanks, which reduces the environmental footprint of hydropower and irrigation systems.

During the analysis, advanced technologies such as automation of purification processes, the use of nanomaterials, and sensor systems were actively implemented. These measures are aimed at significantly improving the efficiency of sedimentation tanks and improving control over water purification processes in the conditions of hydropower and irrigation. To assess the effectiveness of new designs of sedimentation tanks, comprehensive testing was carried out both in laboratory conditions and in practice using computer modelling. This approach helps to pre-evaluate and verify the operability of the structure by simulating various operating conditions and loads, which reduces risks when introducing new technologies and ensures a high degree of reliability and efficiency of sedimentation tanks in hydropower and irrigation.

The tests were carried out using a large-scale model of the washing gallery with a length of 3.8 m, an initial diameter of 6 cm, and a final diameter of 18 cm. During the experiments, a constant height of the longitudinal slit was maintained to determine the flow coefficient of the slit μ at flow rates from 36 to 41 litres per second at the outlet.

Equations (1-7) were used in the study:

$$u_{avg} = u_k \left(\frac{x}{L}\right)^{1/3}, \tag{1}$$

where: u_{avg} – average flow velocity at point x; u_k – flow velocity on the axis of symmetry; x – distance from the axis of symmetry; L – characteristic size of the flow.

$$Q = \mu \Delta L \sqrt{2gh_{p.avg}}, \tag{2}$$

where: Q – volumetric flow rate of liquid through the pipe; μ – dynamic viscosity of the liquid; Δ – height of the slit; L – length of the slit; $h_{p.avg}$ – average value of the effective pressure.

$$z = (1 + \Sigma\xi)\frac{\upsilon_n^2}{2g}, \tag{3}$$

where: Σξ – sum of the resistance coefficients.

$$\mu = \varepsilon\varphi, \tag{4}$$

where: μ –cavity flow coefficient; ε – compression coefficient; φ – velocity coefficient.

$$\frac{1}{\varphi^2} - \Sigma\xi, \tag{5}$$

where: ε – compression ratio; φ – velocity coefficient.

$$\varphi = \frac{\mu}{\varepsilon}, \Sigma\xi = \frac{1}{\varphi^2}, \tag{6}$$

$$h_{w_m} = \Sigma\xi\frac{\upsilon_n^2}{2g}, \tag{7}$$

where: h_{w_m} – average height of the piezometric pressure in the section with coordinates w; Σξ – sum of the coefficients characterising the velocity distribution over the section; υ_n^2 – flow velocity at the point n of the section; 2g – gravity acceleration.

All these aspects together contributed to the development and improvement of the design of sedimentation tanks, which, in turn, contributed to improving the efficiency and sustainability of hydropower and irrigation systems.

RESULTS

The research and improvement of the design of a sedimentation tank for hydropower and irrigation is a significant task aimed at improving the efficiency of water resources use and reducing the negative impact on the environment. This process is aimed at creating more efficient and environmentally sustainable solutions that can optimise sedimentation tanks to save water, improve the quality of treatment and minimise the environmental footprint during their operation. Sedimentation tanks play a key role in water purification from solid particles such as sand and silt, which significantly affects water quality in hydropower and irrigation systems (Zamanikherad *et al.*, 2022). The research is aimed at optimising the shape and size of sedimentation tanks to achieve maximum particle deposition efficiency and minimise water and energy losses. This includes the development of structures capable of efficiently trapping suspended particles under various hydraulic conditions, which is the main aspect of the study. Laboratory studies and numerical modelling help to determine the optimal operating conditions of the sedimentation tanks necessary to improve water treatment technologies and sustainable use of water resources.

The choice of materials for sedimentation tanks is a difficult task, requiring consideration of chemical resistance to water and chemicals in the treated environment. The strength of the materials is important to ensure the durability of the structure under high hydraulic loads and mechanical influences. The cost and the possibility of recycling materials also play a significant role in the overall economic efficiency of the project. The development of new composite materials with improved resistance characteristics and mechanical properties opens up prospects for improving sedimentation tanks and their application in various climatic conditions. Sedimentation tanks play a key role in the operation of hydroelectric power plants (HPPs) by removing solid particles from the water. This process has several important positive effects. Removing solid particles from the water reduces wear and damage to turbines, extending their service life. Particles such as sand, silt, and other suspended solids can seriously damage the turbines of a hydroelectric power plant if they enter the system. These particles cause abrasive wear of turbine blades and other components, which leads to more frequent repairs and replacement of parts. By removing solid particles, sedimentation tanks reduce the likelihood of damage and reduce the need for maintenance, which ultimately extends the service life of the equipment.

Cleaner water has less resistance to movement through turbines, which increases their efficiency and the overall performance of hydroelectric power plants. The presence of solid particles in the water increases its viscosity and resistance to flow through the turbines. Cleaner water moves more freely through turbines, which contributes to a more efficient conversion of hydraulic energy into mechanical and, eventually, into electrical energy. This leads to an increase in the overall productivity of hydroelectric power plants and more efficient use of water resources. Optimisation of the hydraulic parameters of the sedimentation tank is aimed at improving the efficiency and reliability of hydropower and irrigation systems. Research in this area includes the analysis of pressure losses and the distribution of flow velocities inside the sedimentation tank to minimise hydraulic losses and optimise the deposition of solid particles. This is important to ensure stable operation of systems in conditions of variable water flow and variability of hydrogeological conditions. Important aspects of optimising the hydraulic parameters of sedimentation tanks include pressure loss analysis, uniform distribution of flow rates, minimisation of hydraulic losses, and optimisation of the solid deposition process.

Pressure losses in the sedimentation tanks should be minimal to ensure maximum efficiency of the entire system. This is achieved by designing and optimising the shape of the sedimentation tanks and the path of water movement. It is important to ensure an even distribution of flow rates inside the sedimentation tank so that solid particles can settle efficiently. This contributes to a more complete removal of suspended solids from the water. The optimisation of sedimentation tanks includes measures to reduce hydraulic losses, such as improving the design of sedimentation tanks and using modern technologies to control and manage water flows. The process of precipitation of solid particles should be as efficient as possible, which requires an accurate analysis of hydrogeological conditions and variable water flow. This includes choosing the right size and shape of the sedimentation tanks, and the optimal placement of internal partitions and deflectors. These measures ensure more stable and efficient operation of hydropower and irrigation systems, which is especially important in conditions of variable hydrogeological conditions and changing water volumes.

The integration of the sedimentation tank into the overall drainage and water treatment system is an important aspect in improving water treatment technologies. Interaction with other infrastructure elements, such as pumps and filters, requires an integrated approach to the design and management of the sedimentation tank (Saeed *et al.*, 2021). This includes adapting the design to technological processes and considering environmental aspects to minimise the impact on the environment. The development of environmentally sustainable sedimentation tanks includes reducing energy consumption, minimising emissions, and consideration of the impact on aquatic ecosystems. The use of advanced technologies and materials helps to reduce the environmental impact and ensure the sustainable development of water treatment systems. The introduction of new technologies, such as automation of purification processes and the use of nanomaterials, plays an important role in improving the functionality of sedimentation tanks and improving the quality of treated water (Borysov & Gevod, 2023). This line of research helps to reduce operating costs and ensure the environmental safety of water treatment systems. Water sedimentation is used in hydraulic structures, centralised water supply and sewerage systems (Dev *et al.*, 2021). Sedimentation tanks are water storage tanks or open containers in which mechanical impurities are removed from the water by settling. During settling, the particles of the dispersed phase either rise to the surface of the water or settle to the bottom of the tank, forming a precipitate, depending on their density. In some cases, settling is accompanied by particle enlargement. This method is widely used to remove large mechanical impurities from water in hydraulic structures, centralised water supply and sewerage systems, hydroelectric power plants, irrigation systems, and for urban wastewater treatment and after biological wastewater treatment.

In pumping and hydroelectric power plants, water from open reservoirs is settled to prevent wear of impellers and pump components due to solid particles larger than 0.25 mm. In irrigation systems, the use of sedimentation tanks is justified to prevent clogging of channels with silt. In centralised water supply systems, sedimentation tanks are used at water treatment plants for pretreatment of water with a turbidity of more than 2 g/l. Only contamination particles larger than 10-5 cm are subject to deposition. Particles ranging in size from 10-7 to 10-5 cm form a colloidal microheterogenic system and do not settle due to the balance between gravity and the kinetic energy of Brownian motion, which is typical for low-mass particles. As a rule, flocculants are used to remove colloidal impurities from water, and the resulting flakes are removed in sedimentation tanks or other equipment (Noor *et al.*, 2021). For complete precipitation, the water flow rate should be 0.25...0.5 m/s. The second important factor affecting the completeness of deposition is the settling time, which is usually 1.5...2 hours. Sedimentation tanks can be classified according to various criteria, however, the researcher suggests that the most accurate classification is according to the main flow direction of the treated water. According to this feature, sedimentation tanks are divided into horizontal, vertical, and radial. The most common type is horizontal sedimentation tanks used in water treatment plants with a capacity of 15 to 50,000 m^3/day. They usually remove up to 60% of suspended impurities. Horizontal sedimentation tanks are rectangular reinforced concrete tanks divided into several sections. Their length can reach 48 m, while the width is usually three to five times less than the length. The depth does not exceed 4 m, and the thickness of the water layer is 2-2.5 m. The water enters through a series of holes in the end walls of the horizontal sedimentation tank, is evenly distributed throughout the tank and flows along its entire length. The purified water is discharged through a spillway on the opposite side.

There are several sediment collection pits at the bottom of the sedimentation tank. Sediment that does not enter the pits is removed from the bottom by a special scraper device (Zapico *et al.*, 2021). The scrapers are moved along the sedimentation tank using a gear and chain drive system. The scraper collects sediment as it moves along the bottom and collects suspended impurities as it moves along the surface of the water, directing them into a special chute. Sediment can be discharged through pipes at the bottom, lifted through pipes using water pressure, or removed from the pits using submersible pumps. The disadvantages of horizontal sedimentation tanks are high installation costs, unreliability of the scraper mechanism and the presence of stagnant areas where sediment is not removed. Horizontal sedimentation tanks play a key role in hydropower systems, providing water purification from solid particles before they enter the turbines. They prevent wear and damage to turbines by removing sand, gravel, and other suspended materials, which significantly improves the quality of water supplied to the equipment. This not only increases the efficiency of hydraulic turbines, but also increases their service life, thereby reducing maintenance and repair costs. The protection of sedimentation tanks from clogging and their proper functioning also reduce the risk of accidents at a hydroelectric power plant, which makes operation more reliable and safe. The effective operation of sedimentation tanks is also important from an environmental standpoint, since it prevents pollution of natural reservoirs with solid waste, which contributes to the conservation of biodiversity and ecosystems. Thus, horizontal sedimentation tanks are necessary for the optimal functioning of hydropower systems, ensuring high efficiency of the electricity generation process and minimising the negative impact on the environment.

Vertical sedimentation tanks, which are cylindrical tanks with a conical bottom, are another common type. They are commonly used in wastewater treatment plants for primary water sedimentation and removal of suspended particles after coagulation. In vertical sedimentation tanks, water flows through pipes from above to the lower part of the device, where it is evenly distributed over the entire section. The sediment settles in the lower conical part, and the purified water rises and pours through a circular drain into a collecting tray. A special chamber is located in front of the drain to remove suspended impurities. During settling, sediment accumulates at the bottom of the device and is discharged through a special pit. Scraper mechanisms are installed only in those tanks where a large amount of sediment accumulates. Vertical sedimentation tanks usually remove up to 40% of suspended impurities. Vertical sedimentation tanks have a simpler design and operating conditions compared to horizontal sedimentation tanks (Raeesh *et al.*, 2022). Their main advantage is the presence of an annular spillway in the upper part, which reduces the flow rate and reduces the likelihood of sediment removal. However, the disadvantage of this type of equipment is the lack of a scraper mechanism, which complicates the removal of sediment from the drain lid. Vertical sedimentation tanks are an important device in hydropower systems, which has a significant impact on their operation. The main function of vertical sedimentation tanks is to purify water from solid particles such as sand, gravel and other suspended materials before it enters the hydraulic turbines (Litynska *et al*., 2023). This water purification plays a key role in preventing wear and damage to turbines, which ensures their longer service life and reduces the need for repairs.

The efficient operation of vertical sedimentation tanks also contributes to improving the efficiency of the hydropower plant as a whole. Clean water supplied to hydraulic turbines reduces friction and wear of internal mechanisms, which ultimately increases electricity generation. This also helps to reduce the risk of accidents related to possible blockages and damage to equipment. In addition, vertical sedimentation tanks play an important role in the environmental aspect of energy production. By removing solid particles from the water before its return to natural reservoirs, the negative impact on the environment is minimised and biodiversity in aquatic ecosystems is preserved. In conclusion, vertical sedimentation tanks are an integral part of the infrastructure of hydropower systems, ensuring their efficient and stable operation while maintaining high standards of environmental safety and cost-effectiveness of operation. Radial sedimentation tanks are a type of vertical devices (Ganjare & Patwardhan, 2023). They usually have a height of less than 0.1-0.15 m and a diameter of 16 to 60 m, sometimes reaching 100 m. These tanks are used to treat very turbid water and purify water in industrial water supply systems. Water enters such a device through a central pipe, and purified water exits through a circular spillway at the top of the device. The sediment settling to the bottom is collected using a rotating scraper. Radial sedimentation tanks are used in wastewater treatment plants with a capacity of more than 20,000 m^3/day, ensuring the removal of up to 50% of suspended solids.

Radial sedimentation tanks are key elements in hydropower systems that play a crucial role in ensuring their efficient operation and durability. The main function of radial sedimentation tanks is to purify water from various solid particles such as sand, gravel, debris, and other suspended materials before they enter the hydraulic turbines. This water purification prevents wear and damage to the hydraulic turbines, which can be caused by abrasive particles. The efficient operation of radial sedimentation tanks helps to increase the service life of hydraulic equipment and reduce the need for its repair and replacement. Clean water supplied to hydraulic turbines also helps to increase their efficiency by reducing friction and wear of mechanical elements, which, in turn, increases productivity and electricity generation. In addition, the proper operation of radial sedimentation tanks reduces the likelihood of accidents at a hydroelectric power plant associated with possible blockages and damage to equipment. This ensures a more stable and safe operation of the hydropower complex, which is especially important given the environmental impact.

Thus, radial sedimentation tanks not only protect hydraulic turbines from the negative effects of solid particles, but also contribute to improving the overall efficiency and reliability of hydropower systems, reduce operating costs, and minimise the impact on natural ecosystems. The operation of the sedimentation tanks is considered from the standpoint of using only one type of periodic flushing, also known as energy sedimentation tanks, which are also suitable for irrigation conditions. This type of sedimentation tanks is designed for the deposition of relatively large fractions of suspended particles with a size of 0.2-0.25 mm or more. Since such particles usually do not move in open surface watercourses, the sedimentation tanks are located either within the limits of the hydropower complex or at some distance from it. Regularly flushed sedimentation tanks operate in two cycles (Fig. 1). In the first cycle, which takes most of the time, some of the suspended particles are deposited from the river stream, and the purified water is supplied to consumers. In the second cycle, the sediment is removed from the sedimentation tank, and the water supply from the treatment chamber to the watercourse stops.

Figure 1. Rectangular sedimentation tank with 2 chambers
Source: compiled by the author

Forward and reverse gradient sedimentation tanks play a significant role in the hydropower systems of Azerbaijan, affecting the efficiency of hydroelectric power plants and providing optimal conditions for electricity production (Fig. 2). Direct gradient sedimentation tanks located at various hydroelectric power plants in the country, such as the Mingachevir HPP, play an important role in the process of cleaning water from solid particles before it is supplied to hydraulic turbines. They provide more efficient filtration and removal of suspended sediments, which reduces pollution of turbines and other equipment, extending their service life and increasing the overall performance of hydroelectric power plants. In addition, direct gradient sedimentation tanks help to save water, which is especially important in conditions of limited water resources. Reverse gradient sedimentation tanks provide more efficient removal of fine suspended particles from the water. They minimise the risk of siltation of reservoirs and reduce the environmental impact, improving the quality of the environment in the reservoir areas. Saving reagents used in the water purification process is also an important advantage of reverse gradient sedimentation tanks. The choice between direct and reverse gradient sedimentation tanks depends on the specific conditions of each HPP, such as the size and type of suspended particles, water quality requirements, and economic considerations. The decision should be reasonable and focused on achieving optimal system performance, considering all factors affecting the efficiency and environmental sustainability of electricity production.

Figure 2. Rectangular sedimentation tank with 1 chamber
Source: compiled by the author

Direct slope sedimentation tanks are often used because of their simplicity of design (Xu *et al.*, 2021). Backslope sedimentation tanks are more complex in design, however, they are preferable when the sediment contains a large number of coarse particles (Fig. 3). In such sedimentation tanks, more intensive deposition occurs in the initial part of the tank, and the depth here is greater, which allows retaining more sediment compared to direct sedimentation tanks with a slope.

Figure 3. Rectangular sedimentation tank with 3 chambers
Source: compiled by the author

Curved sedimentation tanks in hydroelectric power plants represent an innovative solution that, although not widespread, demonstrates significant advantages over traditional rectangular sedimentation tanks (Fig. 4). They are usually used in small and medium-sized hydroelectric power plants, where compactness and efficiency are of particular importance. Curved sedimentation tanks significantly increase the efficiency of water purification due to their shape, which ensures a more uniform distribution of water flow (Griborio *et al.*, 2021). This contributes to more efficient deposition of fine suspended particles, which minimises pollution of turbines and other equipment, as well as reduces the risk of siltation of reservoirs. In addition, such sedimentation tanks can reduce the consumption of chemicals used for water purification, which helps to save resources and improve environmental sustainability. The main features of the operation of curved sedimentation tanks include the use of washing pipes with a circular cross-section, which create an upward flow of water that lifts suspended particles to the surface, where they separate from the water. This contributes to more efficient sludge removal, which further increases the efficiency of the system. Among the advantages of curved sedimentation tanks, their high efficiency in water purification, compactness and relative ease of operation should be highlighted. However, it should be borne in mind that such sedimentation tanks can be more complex in design and more expensive to build compared to conventional settling tanks. They also have limited applicability at large hydroelectric power plants with large volumes of water, which makes them less preferable for such facilities. It is important to emphasise that the efficiency of a curved sedimentation tank depends on many factors, including the flow rate of water and the properties of suspended particles. Regular monitoring and maintenance of the sedimentation tank is necessary to ensure its efficient operation and durability.

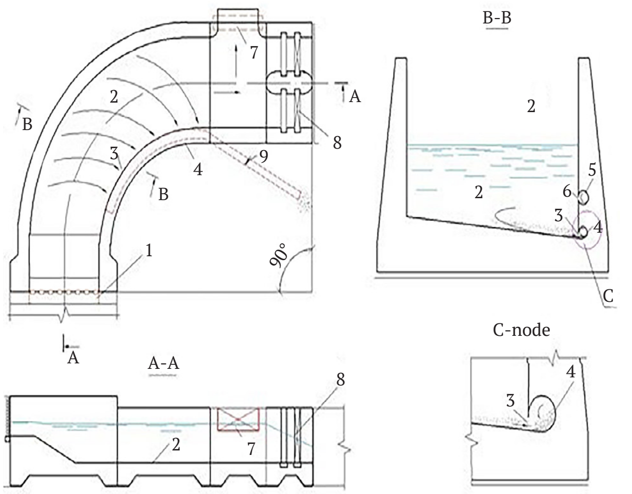

Figure 4. Curved sedimentation tank: plans and sections
Note: 1 – steel grate; 2 – rectangular tray; 3 – flushing slots; 4 – collector; 5 – forming pipe; 6 – gaps of the forming pipe; 7 – valve of the intake device; 8 – flushing valves at the end of the chamber; 9 – valve for regulating the flushing pipe
Source: compiled by the author

The principle of operation of the sedimentation tank is based on the creation of artificially favourable conditions for settling, in which sediments are moved by a circulating stream to the inlet of a round-section washing pipe under a convex wall. It was found that the curved sedimentation tank prevents the deposition of up to 20% of suspended sediments of large fractions with a size of d > 0.25 mm, in addition to sediment at the bottom. The sedimentation tanks are made of rectangular reinforced concrete and equipped with a siphon device for draining the flushing water (Lu *et al.*, 2023). A special feature is the presence of a washing gallery designed to move sediments of sand, gravel, and silt into the lower pool. The prefabricated pipes have a circular cross-section and are located inside the walls of the spillway. At the end of the lower rectangular reinforced concrete drain there is a vertical basin designed to trap sediments of sand, gravel, and silt and vertically connected to a collection pipe. Dampers are installed on the side walls of the drain for periodic cleaning of the sedimentation tank (Fig. 5).

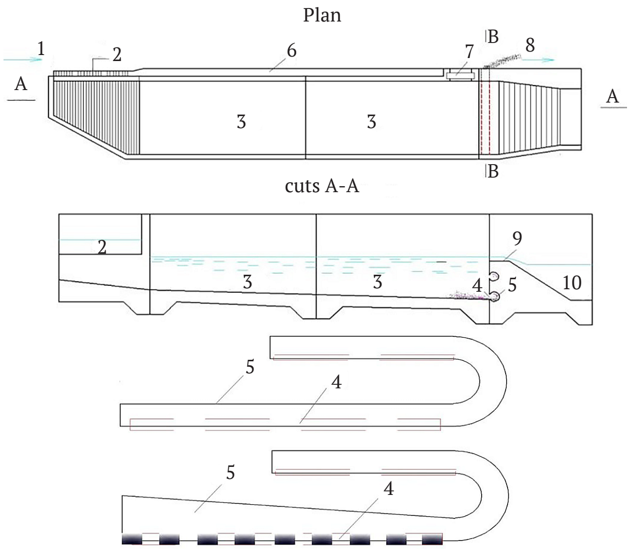

Figure 5. Sedimentation tank: plans and sections
Note: 1 – upper pool; 2 – intake device; 3 – chamber; 4 – gravel catching slots; 5 – collector; 6 – side walls; 7 – gates; 8 – lower pool; 9 – spillway walls; 10 – outlet channel
Source: compiled by the author

The new sedimentation tanks have an advantage over conventional designs by directing the sediments of sand, gravel and silt entering the reservoir into the cracks located at the bottom near the lower wall of the discharge channel. These sediments are mixed with water and transported by a high-speed flow into collecting pipes inside the spillway wall. This efficient transport mechanism easily directs the sediments of sand, gravel, and silt into the lower basin. Closures are installed on the side walls of the tank to facilitate regular cleaning. This configuration turns the sedimentation tank into a barrier that prevents deposits of sand, gravel, and silt from entering the outlet pipes of the hydroelectric power plant. This type of sedimentation tank is designed for the deposition of relatively large suspended sediment particles, usually 0.2-0.25 mm or more. The conditions of its application are similar to those mentioned earlier for sedimentation tanks using periodic flushing. These sedimentation tanks can consist of one or two chambers and be installed either as part of a water intake system or at some distance from it. Screw-flow flushing galleries initially demonstrate a reliable ability to transport sediment and have recently gained popularity for removing bottom sediments at water management facilities. The helical movement inside the gallery is created by the tangential entry of water through its cross-section. To maintain continuous circulation, water must be supplied along the entire length of the gallery, usually through a longitudinal slit inlet. The dimensions of this inlet slot are critically related to the set flow and velocity parameters inside the flushing gallery.

Usually, the height of the longitudinal slit does not facilitate the unobstructed penetration of bottom sediment into the tunnel. Therefore, it is common practice to create intermittent slits and include separate windows of sufficient height to ensure a constant distance between the continuous slit and the window. Laboratory studies of flow hydraulics in treatment rows and practical experience in sedimentation tanks have concluded that for ease of manufacture, the shape of the row should be conical, and the change in the average flow velocity in the row should correspond to the dependence set out in equation (1), which satisfies the initial condition: at $x = 0$, $u_{avg} = 0$, where: u_k – average longitudinal velocity in the final section of the gallery. The results of laboratory studies of the hydrodynamics of flushing galleries and the practical knowledge gained during the design and operation of sedimentation tank galleries show that the adoption of a conical shape for the gallery is beneficial for the rationalisation of production. It is recommended to adjust the change in the average flow velocity in the gallery in accordance with equation (1), which satisfies the initial condition: at $x = 0$, $u_{avg} = 0$, where u_k – average longitudinal velocity in the final section of the gallery. The coefficients μ were calculated using equation (2). In the course of eight experiments, the calculated values of the gap flow coefficient μ ranged from 0.609 to 0.687, with an average value of 0.648.

To ensure adequate consideration of throughput in the design of the flushing gallery, it is recommended to use the cavity flow coefficient $\mu = 0.64$. The pressure difference between the gallery and the level of the free surface is affected by the velocity of the water as it moves through the cavity, overcoming various resistances in its path (3). These resistances include coefficients for entry (ξin), friction (ξfr), exit (ξout) and curvature (ξzak). In hydraulic principles, it is usually assumed that ξin ⩽ 0.5, ξout ≈ 1, and ξfr varies from 0.06 to 0.1. In practice, the combined value of these coefficients at the output often exceeds 1.5. According to equation (5), when the sum of the coefficients Σξ is 1.5, and assuming that the compression ratio ε is 0.8, the ratio can be derived from equation (4):

$$\varepsilon = \frac{\mu}{\varphi} = \frac{0.64}{0.8} = 0.8\,.$$

Thus, the value of ε cannot be less than 0.8. Therefore, the coefficient ε ranges from 0.8 to 1. Taking the average value according to equation 6, ε = 0.9, obtain:

$$\varphi = \frac{\mu}{\varepsilon} = \frac{0.64}{0.9} = 0.71,$$

$$\Sigma\xi = \frac{1}{\varphi^2} = \frac{1}{0.71^2} = 2.$$

The calculated value Σξ=2 is approximate. To achieve greater accuracy, an exact value of ε will be required, which cannot be determined experimentally. However, since the pressure loss due to local resistance is only a small part of the total pressure loss in the gallery, it is sufficient to use an approximate value Σξ for calculations. Therefore, the following equation (7) is used to calculate the pressure loss associated with local resistance:

$$h_{w_м} = \Sigma\xi\frac{\upsilon_n^2}{2g} = 2\frac{\upsilon_n^2}{2g}. \tag{7}$$

A distinctive feature of continuously flushing sedimentation tanks is their ability to simultaneously deposit and remove suspended sediments, supplying purified water to consumers. These tanks maintain a constant water depth, but when the sections are disconnected for flushing, this changes the flow dynamics inside the tank, causing uneven flow conditions. As a rule, the improvement and improvement of the design of sedimentation tanks requires an integrated approach combining engineering, environmental and technical aspects. This holistic approach aims to optimise results in both hydropower and irrigation applications.

DISCUSSION

Research and improvement of the design of sedimentation tanks play an important role in the field of hydropower and irrigation, aimed at ensuring effective management of water resources and reducing negative environmental impacts. This aspect was also considered by S. Dairi *et al.* (2023), and they concluded that one of the key aspects of the research is the optimisation of the hydraulic parameters of the sedimentation tanks. This includes analysis of the water flow profile, calculations of hydraulic losses and the development of design solutions aimed at minimising pressure losses and maximising the efficiency of particle deposition. This approach allows increasing the productivity of hydropower systems and improving the efficiency of irrigation systems, ensuring reliable removal of solid particles from water and preventing clogging of equipment. N. Gemza & M. Kuśnierz (2022) noted that the development of corrosion-resistant materials and composites contributes to increasing the durability of structures and reducing the cost of their operation. In an aggressive environment, for example, with a high concentration of salts or chemically active substances in water, such materials ensure reliable operation of sedimentation tanks and minimise the need for frequent maintenance, which is consistent with the results of this study.

One of the key aspects of the study is the optimisation of the hydraulic parameters of the sedimentation tanks. This includes analysis of the water flow profile, calculations of hydraulic losses, and the development of design solutions aimed at minimising pressure losses and maximising the efficiency of particle deposition. This approach allows increasing the productivity of hydropower systems and improving the efficiency of irrigation systems. This has also been found in the study by A. Ferdowsi *et al.* (2022), where the results confirmed that effective control of the water flow in the sedimentation tanks is crucial to increase their productivity and ensure reliable operation of the entire system. Optimisation begins with an analysis of the water flow profile, which allows identifying areas of uneven distribution of velocity and pressure. With the help of modern modelling methods, accurate calculations of hydraulic losses can be carried out and turbulence zones can be determined where the efficiency of particle deposition decreases. Based on these data, design solutions are being developed to improve flow distribution and minimise pressure losses, which helps maximise particle deposition. As a result of such measures, hydropower and irrigation systems become more reliable and efficient, ensuring stable water quality and preventing clogging of equipment.

S. Yao *et al*. (2022) also found that traditional materials such as concrete and steel, although they have sufficient strength, are often susceptible to corrosion and destruction under the influence of aggressive media. The development and application of new composite materials and corrosion-resistant metals significantly increase the durability of sedimentation tanks and reduce the cost of their maintenance and repair. Modern materials have not only high chemical resistance, but also improved mechanical properties, which makes it possible to create lighter and more durable structures (Ismayilov *et al*., 2021). In conditions of high loads and variable temperatures typical for hydropower and irrigation systems, such materials ensure stable operation of sedimentation tanks. It is worth noting that the introduction of new technologies and methods into the design of sedimentation tanks requires careful testing and modelling to assess their effectiveness and reliability.

An important aspect of improving the design of sedimentation tanks is the choice and use of modern materials. The development of corrosion-resistant materials and composites helps to increase the durability of structures and reduce the cost of their operation (Serikuly *et al*., 2015). This is especially important for sedimentation tanks operated in aggressive climatic conditions and in conditions of high concentrations of salts or chemically active substances in water. This aspect has attracted the attention of many researchers, in particular, M. Amar *et al.* (2021) emphasise that traditional materials such as concrete and steel are often susceptible to corrosion and wear, especially in aggressive climatic conditions or at high concentrations of salts and chemically active substances in water. Modern composite materials and corrosion-resistant metals can significantly increase the durability and reliability of sedimentation tanks. The use of such materials not only reduces the frequency of repairs and replacements, but also reduces the cost of operation and maintenance. The use of innovative materials allows creating lighter and more durable structures that can withstand extreme operating conditions, which is especially important for hydropower and irrigation systems operating in difficult natural conditions.

W. He *et al.* (2021) concluded that the development of new composite materials and corrosion-resistant alloys opens up opportunities for the introduction of advanced technologies in the design of sedimentation tanks. Such materials have high chemical resistance, excellent mechanical properties and durability, which makes them ideal for use in conditions of high load and exposure to aggressive environments. This is especially true for regions with extreme climatic conditions, where traditional materials quickly fail. These results confirm the above study, since the introduction of modern materials into the design of sedimentation tanks is a key factor for increasing their efficiency, durability and economic feasibility, which contributes to the overall improvement of water resources management in hydropower and irrigation.

Environmental aspects also play an important role in the research and improvement of sedimentation tank designs. The development of environmentally sustainable solutions aimed at reducing energy consumption, minimising emissions and waste into the environment, contributes to improving the environmental situation and preserving water resources (Hulevskyi & Postol, 2022). N.N.C. Obiuto *et al.* (2024) investigated this phenomenon, noting that modern technologies such as process automation and the use of renewable energy sources can significantly reduce the carbon footprint of water treatment and water treatment systems. For example, using solar energy to power pumps and other sedimentation tank mechanisms can significantly reduce emissions of carbon dioxide and other greenhouse gases.

A. Ahmad *et al.* (2022) investigated that the use of sediments as fertilisers or raw materials for the production of building materials can significantly reduce the amount of waste to be disposed of. Such solutions contribute not only to reducing the load on landfills for waste disposal, but also to the reuse of resources, which corresponds to the principles of a closed-cycle economy. These data are consistent with the theses given in the previous section, demonstrating the importance of environmentally sustainable solutions in the design and operation of sedimentation tanks. Modern technologies aimed at reducing energy consumption and minimising emissions confirm their effectiveness not only in laboratory conditions, but also in practice. This is confirmed by the findings, where the introduction of such technologies has led to a significant improvement in environmental performance.

Research into new technologies, such as automation of cleaning processes and the use of innovative materials, opens up new opportunities to improve the operation of sedimentation tanks. The introduction of sensor systems and the use of nanomaterials contribute to improving the efficiency of water purification and reducing environmental impact (Kulikova, 2022). The study by L.K. Wang & M.H.S. Wang (2021) revealed that automation of cleaning processes includes the introduction of advanced sensor systems and control algorithms that allow real-time monitoring and adjustment of the parameters of the sedimentation tanks. This leads to a significant increase in the efficiency of the cleaning process, as the system automatically adapts to changing conditions, such as fluctuations in pollution levels or changes in hydraulic flow.

E.F. Latif (2022) also showed that nanomaterials have unique properties such as high adsorption capacity and resistance to aggressive chemical media, which makes them ideal for use in water purification systems. The introduction of such materials allows improving the quality of precipitation of solid particles and significantly reducing water pollution. Moreover, the use of nanomaterials can reduce the environmental impact, as they require fewer reagents for processing and are able to operate in a wider range of conditions. Comparing the data obtained during the research, the use of innovative technologies and materials is a key factor in improving the design and operation of sedimentation tanks, which contributes to more sustainable and efficient management of water resources.

Thus, the research and improvement of the design of sedimentation tanks for hydropower and irrigation are aimed at improving their efficiency, sustainability, and environmental safety. This contributes to improving water resource management and ensuring the sustainable development of agricultural and energy systems.

CONCLUSIONS

As a result of the conducted research, significant progress has been achieved in the development and optimisation of sedimentation tank designs for hydropower and irrigation systems. The main conclusions can be formulated as follows. Optimisation of the shape and size of the sedimentation tanks helped to develop and test various geometric configurations, which ensured maximum water retention time and contributed to the most efficient deposition of solid particles. This significantly increased the performance of the sedimentation tanks and reduced operating costs.

Research and testing of various materials, including modern composite materials and corrosion-resistan alloys, allowed selecting the most suitable options for use in sedimentation tank designs. This provided increased durability and resistance to aggressive operating conditions, which increased the service life and reliability of the sedimentation tanks. Hydraulic analysis helped to optimise the flow profile in the sedimentation tanks, minimise pressure losses, and maximise the efficiency of particle deposition. Solutions have been developed that consider both stationary and dynamic operating conditions of the system, which has improved the overall efficiency of hydropower and irrigation systems.

The introduction of environmentally sustainable technologies has significantly reduced energy and water consumption, and minimised emissions and waste. These measures have reduced the environmental footprint and ensured more sustainable and safe use of water resources. The active introduction of advanced technologies, such as automation of cleaning processes, the use of nanomaterials and sensor systems, has significantly increased the control and efficiency of the sedimentation tanks. These technologies have provided more precise process control and improved the quality of water treatment.

Comprehensive testing and modelling of new designs of sedimentation tanks, carried out both in laboratory conditions and in practice, allowed the authors to pre-evaluate their effectiveness and reliability. The results of these tests confirmed the high degree of readiness of the developed solutions for practical implementation, minimising risks and ensuring reliable operation of the systems. In general, the conducted research has made a significant contribution to the improvement of sedimentation tank designs, which ultimately led to an increase in the efficiency, reliability, and environmental sustainability of hydropower and irrigation systems.

The main limitation of the study is the need for further testing of the developed designs of sedimentation tanks in various climatic and operational conditions to confirm their versatility and adaptability. It is necessary to further investigate the effect of various chemical compositions of precipitating particles on the efficiency of sedimentation tanks and develop methods for their optimal removal.

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CONFLICT OF INTEREST

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Дослідження та вдосконалення конструкції відстійника для гідроенергетики та іригації

Анотація. Роботу присвячено дослідженню та оптимізації конструкції відстійника для підвищення ефективності осадження твердих частинок у гідроенергетичних та іригаційних системах. У даному дослідженні були використані як експериментальні, так і чисельні методи для аналізу та оптимізації конструкції відстійників з метою підвищення їхньої ефективності в системах гідроенергетики та іригації. У дослідженні розглянуто та проаналізовано різні типи відстійників за конструктивними схемами, режимом потоку, динамікою осадження і методами промивання осаду, а також вивчено рекомендовані поліпшення для гідроенергетики та іригації різних типів відстійників. Під час дослідження було виявлено, що оптимізація геометрії відстійника істотно підвищує ефективність осадження твердих частинок. Експериментальні дані засвідчили, що зміна кута нахилу стінок і збільшення площі дна відстійника сприяють поліпшенню осадження мулу і піску. Також було встановлено, що використання спеціальних турбулентних вставок знижує час осадження частинок і покращує якість очищеної води. Моделювання гідравлічних потоків підтвердило, що більш рівномірний розподіл швидкостей у відстійнику зменшує турбулентність і сприяє більш ефективному осадженню частинок. Впровадження автоматизованих систем контролю та управління процесом очищення дало змогу підвищити надійність і стабільність роботи відстійника. У результаті було доведено, що запропоновані конструктивні та технологічні зміни можуть значно підвищити ефективність і довговічність відстійників у гідроенергетиці та іригації. Дослідження надає практичні рекомендації щодо поліпшення конструкції відстійників, що сприяє підвищенню їхньої ефективності та надійності в гідроенергетиці та іригації, тим самим покращуючи управління водними ресурсами

Ключові слова: зважені частинки; елементи інфраструктури; насоси та фільтри; осадження; гідравлічні потоки

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Features of multi-agent evaluation of microgrid systems efficiency in parallel operation with the power system according to the reliability criterion

Abstract. Ensuring reliable electricity supply to consumers in the face of destruction of critical energy infrastructure and shortage of generating capacities in Ukraine requires the development of distribution systems and their management systems. The purpose of the study was to substantiate the development of models for ensuring the optimal structure of electrical distribution networks under the conditions of connecting micro-networks according to the reliability criterion in conditions of limited investments. The paper uses a method for assessing the structural reliability of complex electrical systems with microgrid structures and forms a rational power distribution of such structures according to the criterion of optimising the reliability indicators of the studied electric power system. A mathematical optimisation model based on a computational system was proposed, designed to solve non-convex problems with minimising integral reliability

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indicators, considering financial constraints and the investment efficiency curve. Based on the research, the possibilities of optimisation using the BARON solver available on the NEOS server were examined. The results of the model's performance are demonstrated using examples, considering the parameters of distribution system objects and their limitations on network components. An algorithm and programme for solving the problem of targeting power flows of microgrid structures in multi-node regional power systems are proposed. Algorithms and scenarios for the response of dispatching services are developed, provided that investments are limited, which will ensure the survivability of the power system as a whole. It is established that the development of rational electricity flows of microgrid structures will minimise the under-supply of electric energy by specific load nodes and determine their shares in covering the demand of the energy island in conditions of power shortage. The findings can be used in the operational management of power systems

Keywords: integrated reliability indicators, microgrid structure, power distribution systems, load balancing, microgrid dispatching scenarios

INTRODUCTION

In Ukraine, the structure of electricity generation capacities and power grids is undergoing significant changes, primarily due to the destruction of electricity infrastructure as a result of hostilities, which leads to disruption of existing electricity supply schedules, emergency outages, and significantly increases the integral reliability indicators, which reduces the efficiency of electricity distribution systems. All this determines the need for appropriate restructuring of the network infrastructure based on modern "smart" systems, the introduction of automation systems for controlling electric networks, regulating the operating modes of electric networks and electricity consumption using manoeuvrable capacities, and the introduction of micro-networks. These issues are of considerable scientific and practical interest and are considered by many researchers.

V. Kozyrskyi *et al.* (2020) proved that ensuring the reliability of power grids requires the introduction of partitioning devices and optimised the number and location of these devices. It was pointed out that the proper configuration of partitioning equipment significantly reduces repair costs and increases the reliability of power supply. The mathematical model developed by the authors allows assessing the economic feasibility and stability of the network for end users and is aimed at minimising losses from under-supply of electricity to consumers, but the authors did not consider the presence of microgrid structures in their models.

H. Kruhliak *et al.* (2023) explored dynamic energy component management using state-of-the-art IT technologies. It offers a real-time energy management strategy. The synthesis of a micro-network control system, in particular, its real-time power balance, was investigated. Technical platforms for implementing the principles of energy management and remote control of electric receivers are proposed. From the text of the material, it is not clear how the existing micro-network control systems regulate the reliability of the power supply system.

I. Blinov *et al.* (2022) focused on the problems of regulating the modes of electric distribution networks in Ukraine. Researchers have proposed to implement such regulation through the management of inverters of renewable energy sources, primarily solar power plants connected to this network, according to the "Smart Grid" concept. The researchers did not consider the expediency of complex regulation of modes with a restriction in the form of integral reliability indicators.

The paper by O. Kyrylenko *et al.* (2021) considered options for using electricity storage systems in electric networks. The researchers formalised a general approach to solving the problems of efficient use of electricity storage systems in electric networks as a means of improving the reliability and uninterrupted power supply to consumers. Mathematical models for evaluating the efficiency of their use and determining the optimal configuration are proposed, in particular, for regulating the modes of electrical networks in accordance with the "Smart Grid" concept. The researchers focused on improving consumer reliability, but did not investigate how this affects the reliability of distribution system objects.

H. Bielokha *et al.* (2023) proposed a transition to low-carbon economic development through profound changes in the functioning of energy systems through the use of their hybrid forms, which the researchers consider to be key active agents. However, it is noted that the stochastic nature of renewable energy creates problems that are proposed to be solved based on the mathematical approach of the logic of service dominance. This approach opens up new opportunities, in particular, in interaction with other participants in the energy markets and in preserving the environment. It is indicated that the developed models for optimising the technical and economic indicators of hybrid energy systems helped to reduce costs by 14.7%, but the duration of interruptions in power supply systems was not considered.

E. Bardyk & N.P. Bolotnyi (2023) developed a fuzzy classifier to assess the technical condition of power transformers in case of ambiguity in diagnostic data. The research was based on fuzzy set theory and optimisation methods using the Takagi-Sugeno fuzzy inference system. The results consist in creating a prototype of an expert system for assessing the technical condition of transformers from the standpoint of reliability. This approach formalises expert assessments of the condition of transformers, which allows making objective decisions about their maintenance strategy. It is worth noting that the power transformer is a key element of electrical distribution networks, but the influence of processes occurring in it from the existing microgrid structures that it heals has not been studied.

The optimal composition, location, and coordination of the operation of switching devices and protective equipment in the context of ensuring the reliability of air distribution networks was determined by V. Popov *et al.* (2022). To solve the problem, various reliability indicators were simultaneously optimised and an approach based on a modified greedy optimisation algorithm was proposed, which automatically adjusts the weights of indicators at each iteration to evenly improve all aspects of reliability, but when determining the optimal composition of reliability improvement tools, the presence of microgrid structures in networks was not considered.

H. Bila *et al.* (2022) considered the global optimisation problem using the BARON (n.d.) package – a computing system for solving non-convex optimisation problems to global optimality. It is proposed to use this software to solve purely continuous, integer and mixed-integer nonlinear problems by combining constraints, interval analysis, and duality in the arsenal of reductions with advanced concepts of branches and connections and forming a path through the hills and valleys of complex optimisation problems in search of global solutions, but in this paper a generalised description of the capabilities of the optimisation package was made.

In the study A. Zharkin *et al.* (2022), methods for determining optimal shutdown locations in distribution networks were considered and the use of remote-controlled switching devices was proposed, which is important for cyclic load changes. It is indicated that new technological solutions have made it possible to reduce energy losses and conduct dynamic network management. Strategies and management algorithms based on the economic effect criterion were implemented, but the presence of microgrid structures was not considered.

A method for quickly and accurately determining the best location of a partitioning device in distribution networks with a tree structure has been developed by V. Bezruchko *et al.* (2023). Its application to medium-voltage networks with a vacuum switch was investigated. Systems with automatic load switching and a secondary switch were analysed and the reduction of under-supply of energy to consumers was optimised, but inaccuracy in the development of a mathematical model for determining reliability indicators was made.

The analysis of scientific sources shows that the combination of modern tasks to ensure the reliability and quality of electricity supply to consumers in the conditions of increasing the share of renewable energy sources and the introduction of Smart Grid technologies determines the relevance of creating optimal scenarios for the development of regional micro-networks to improve the reliability indicators of the electric power system to which they are connected, with initially defined means of improving reliability in conditions of limited investment resources. That is why the purpose of the current study was to develop and substantiate approaches aimed at ensuring the managed functioning of regional micro-networks to improve the reliability of electricity supply to consumers. In order to achieve this goal, the task of creating algorithms and scenarios for the development of micro-networks was solved under the condition of limited investment resources and the need to provide electricity to consumers in case of various emergencies in a centralised power supply system.

MATERIALS AND METHODS

To ensure optimal scenarios for the development of electrical distribution networks, including microarrays, the theory and methods of mathematical programming were used. Optimisation problems were formulated as non-linear programming problems. The AMPL modelling language was used to describe them. The problems were solved using the BARON (Branch And Reduce Optimisation Navigator) solver – a computational system for solving non-convex optimisation problems up to global optimality – from the NEOS server (GAMS/BARON, n.d.; NEOS Server..., n.d.). The development of the model and all calculations were carried out with reference to the real economic relationship between the distribution system operator and the supervisory authority – the National Commission for State Regulation of Energy and Public Utilities (NCREPU) (Resolution No. 374, 2018)

The model for improving the reliability of the power supply system, in terms of reducing the resulting SAIDI (System Average Interference Duration Index), is based on the typical scheme shown in Figure 1. It consists of sections of lines between the corresponding nodes of the scheme L_{ij}, loads P_i, and the number of consumers in these loads N_i. Loads, if they are combined by certain conditions, form groups of loads that are indicated by large Latin letters and are accepted by the zones of microgrid formation. The diagram contains heterogeneous means of operational switching: B_1 – input switch, DS_*i* – disconnectors, RR_*i* – reclosers, etc.

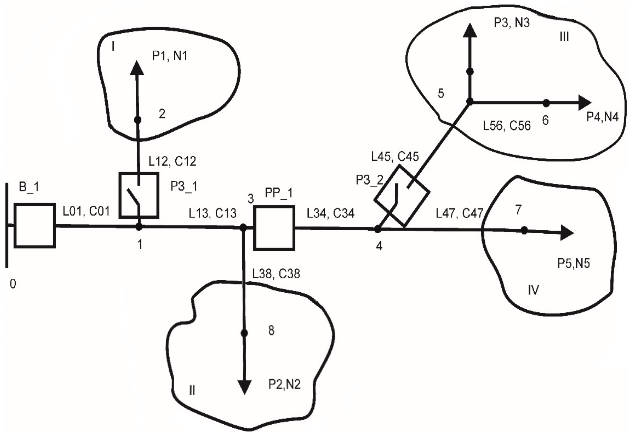

Figure 1. Typical electrical diagram of distribution system facilities.

Note: B_1 – input switch; Lij – section length, Cij – price characteristic of energy transfer by section, DS_i – disconnector, RCR_i – recloser, Pi – power consumption of the load node, Ni – number of load node subscribers

Source: compiled by the authors

The network structure was developed in accordance with the technical requirements of IEC TS 62898-4:2023 (2023). The presence of microgrids in the structure of the electrical distribution network, from the standpoint of power supply reliability, significantly depends on the possibility of microgrids operating in island mode. There are several options for the microgrid operation mode in the absence of a centralised power source:

1) offline operation is not possible;

2) "black" start is possible;

3) autonomous operation of the microgrid system with a certain load limit is possible;

4) full autonomous operation of the microgrid system is possible.

These modes of operation of microgrid structures affect the effectiveness of certain means of improving the reliability of both technical and organisational ones. Accordingly, in the developed mathematical models, to assess the optimal specification of measures and the choice of places and the number of installed elements for improving reliability, zones of development of microgrid structures are considered, in which it is impossible to achieve the reliability targets by available means.

When analysing the resulting reliability of the structure, individual reliability indicators of all consumers connected to this structure were calculated. Based on these values, the resulting assessment of the effectiveness of the structure as a whole was compiled according to method of V. Kozyrskyi *et al.* (2020).

To solve this problem, the classical methods of V. Kozyrskyi & O. Gai (2013) and R. Allan (2013) for developing a series of replacement schemes individually for each consumer were used, indicating the typical time of power supply restoration: a transparent rectangle means that the time of power supply restoration is proportional to the time of emergency restoration, and a shaded rectangle is proportional to the time of fault detection and localisation. The following assumptions were made regarding the possible, from the standpoint of reliability, features of the functioning of microgrids of the structure in accordance with the previously developed operating modes in accordance with the technical requirements of IEC TS 62898-4:2023 (2023), namely:

$$\begin{cases} 1)\ N_{\mathrm{i}} = N_{\mathrm{i}}, \\ 2)\ N_{\mathrm{i}} = N_{\mathrm{i}} \cdot f(t), \\ 3)\ N_{\mathrm{i}} = x_i \cdot N_{\mathrm{i}}, \\ 4)\ N_{\mathrm{i}} = 0, \end{cases} \tag{1}$$

where $f(t)$ – function of changing the time and efficiency of the specified "black" start mode, the value of which lies in the range from 0 to 1 and changes in time in accordance with the capabilities of the means of automatic start of microgrids of the structure in island mode of operation; x_i – indicator that reflects the possible degree of providing power to consumers of the microgrid system in offline mode and takes the value $0 \leqslant x_i \leqslant 1$.

RESULTS AND DISCUSSION

As part of the study, the structural reliability for the circuit in Figure 1 was analysed, and a corresponding series of replacement schemes for all P_i consumers was generated, as shown in Figure 2.

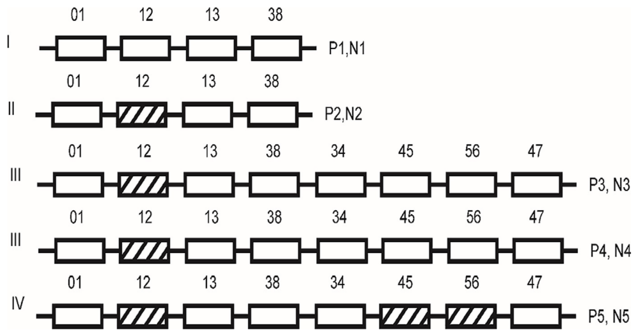

Figure 2. Replacement schemes in terms of reliability for consumers

Notes: Roman numerals I-IV – zones of microgrid structures; 01,..., 56 – equivalent elements of the replacement scheme for the corresponding sections in terms of structural reliability; reliability indicators; P_i – power consumption of the load node, N_i – number of load node subscribers

Source: compiled by the authors

It is worth noting that in the case shown in Figure 2, consumers 3 and 4 are in identical conditions, and therefore, 4 substitution schemes were chosen, which are indicated by Latin numbers, which are possible zones for the development of microgrid structures. It is accepted that consumers are equidistant from the location of the operational field repair team of the distribution system operator, and therefore, the model of finding the recovery time is simplified and taken as a basis:

$$\begin{cases} t_{\text{fast switching}} = 2 \text{ hours}, \\ t_{\text{repair}} = 6 \text{ hours}. \end{cases} \tag{2}$$

Accordingly, the reliability indicators for these structures were calculated using the equation (Kozyrsky & Gai, 2013):

$$\begin{cases} \omega_{\mathrm{Pi}} = \sum_j \omega_j, \\ \tau_{Pi} = \frac{\sum_j \omega_j \cdot \tau_j}{\omega_{\mathrm{Pi}}}, \end{cases} \tag{3}$$

where j – total number of power grids on which the power supply to the i-th consumer depends; w_{pi} – frequency of power supply failures in the Pi-th consumer; τ_{Pi} – time to restore power supply in Pi-th consumer; w_j – failure rate of the j-th section; τ_j – time of restoration of power supply to the j-th section;

Reliability indicators $SAIDI_{practical}$ and $SAIFI_{practical}$ obtained as a result of the operation of a particular distribution system facility are defined by the following expressions:

$$\begin{aligned} SAIDI_{\text{practical}} &= \frac{\sum_i t_{\mathrm{P}i} \cdot N_{Pi}}{\sum_i N_{Pi}}, \\ SAIFI_{\text{practical}} &= \frac{\sum_i^k n_i}{\sum_i N_{Pi}}, \end{aligned} \tag{4}$$

where i – total number of actual emergencies in the electrical network of the distribution system operator under study; $\sum_i^k n_i$ – total number of consumers that are disconnected during long emergency breaks is actually the algebraic sum of the products of the failure rate for each consumer group $w_{\mathrm{P}i}$ by the number of accounting points $N_{\mathrm{P}i}$ in this group; $n = \sum_i N_{Pi}$ – total number of accounting points (in the selected research object, it is assumed that this number is equal to the number of authentic substitution schemes, which are indicated by Roman numerals in Fig. 2, that is $n = 4$).

For theoretical research, the study moves on from the actual data on outages (t_{Pi}, N_{Pi}), which form a certain sample, up to the mathematical expectation of a certain event, which is characterised by the normal distribution law and the time for restoring power supply τ_{Pi} and failure rate $w_{\mathrm{P}i}$ are determined.

$$\begin{aligned} SAIDI_{\text{theoretical}} &= \frac{\sum_j \tau_{\mathrm{P}j} \cdot \omega_{\mathrm{P}j} \cdot N_{Pj}}{\sum_j N_{Pj}}, \\ SAIFI_{\text{theoretical}} &= \frac{\sum_j^n \omega_{\mathrm{P}j} \cdot N_{Pj}}{\sum_j N_{Pj}}, \end{aligned} \tag{5}$$

where j – total number of combined consumer groups (j = I..IV).

Based on a sufficiently large sample of data corresponding to the objects of distribution system operators:

$$\begin{aligned} SAIDI_{\text{practical}} &\cong SAIDI_{\text{theoretical}}, \\ SAIFI_{\text{practical}} &\cong SAIFI_{\text{theoretical}}. \end{aligned} \tag{6}$$

It is assumed that the transition from the state of normal operation of groups of electric consumers, when in an emergency situation in the electrical network, groups of consumers are de-energised according to Figure 2 (which corresponds to the state $x_j = 1$), to the state of operation of the system with microgrid structures according to criterion 4 is carried out in accordance with equation (1) (which corresponds to the state $x_j = 0$). In this case:

$$\begin{aligned} SAIDI_{\text{theoretical}} &= \frac{\sum_j \tau_{\mathrm{P}j} \cdot \omega_{\mathrm{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}}, \\ SAIFI_{\text{theoretical}} &= \frac{\sum_j^n \omega_{\mathrm{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}}. \end{aligned} \tag{7}$$

To describe the effectiveness of investments ($Eff(x)$) in newly developed microgrids, a logistic or sigmoidal function is used:

$$Eff(x) = 1 - \frac{1}{1+e^{-k(x-x0)}}, \tag{8}$$

where k – parameter that determines the steepness of the transition, and $x0$ – point where the function reaches the value 0.5 (Fig. 3).

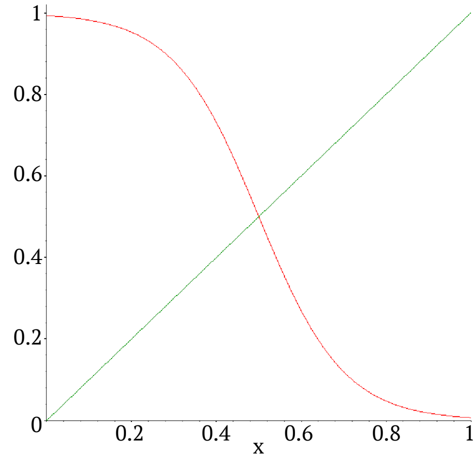

Figure 3. Graph of the dependence of capital investment efficiency in the development of microgrid structures
Source: compiled by the authors

Accordingly, having similar expert assessments for each possible microgrid structure, the investment level was optimised according to the criterion of minimising the SAIDI indicators of the overall structure, provided that the investment fund is limited (C). Thus, two optimisation functions are formed:

$$\begin{cases} SAIDI = \dfrac{\sum_j \tau_{\mathrm{P}j} \cdot \omega_{\mathrm{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}} \to min, \\ \sum_j c_j \cdot Eff(x_j) \le C, \\ 0 \le x_j \le 1. \end{cases} \tag{9}$$

$$\begin{cases} SAIFI = \dfrac{\sum_j^n \omega_{\mathrm{P}j} \cdot N_{Pj} \cdot (x_j)}{\sum_j N_{Pj}} \to min, \\ \sum_j c_j \cdot Eff(x_j) \le C, \\ 0 \le x_j \le 1, \end{cases} \tag{10}$$

where j – total number of combined consumer groups (j = I..IV); c_j – amount of capital investment for the full implementation of the development of microgrids of the structure according to the fourth feature based on expression (1); $Eff(x)$ – sign of the efficiency of capital investments during the transition from the first to the fourth features of the functioning of microgrids of the structure according to the reliability criterion based on expression (1).

Thus, the search for the optimal solution with a limited financial resource C leads to the most efficient distribution of the levels of internal electricity supply to consumers for the existing power supply scheme and possible microgrid structures. The results of the mathematical experiment are interpreted and it is indicated that as a result of optimisation, the smaller is x_j, the more efficient is this microgrid structure to be involved in the reliability management of the object of study. Problem (9) and (10) are described using the AMPL code:

```
# parameters and variables
param n := 4; param C_1 := 7;
param p{i in 1..n}; param c{i in 1..n};
param k{i in 1..n}; param x0{i in 1..n};

var x{i in 1..n} ≥ 0 ≤ 1;

# objective and constraints
minimize obj: sum {i in 1..n} p[i]*x[i];
subject to con1: sum {i in 1..n} c[i]*(1.0-1.0/(1.0 + exp(-k[i]*(x[i]-x0[i])))) ≤ C_1;

option baron_options 'barstats outlev=1 maxtime=120';
problem NLPa: obj,x,con1;

Accordingly, the input data for the AMPL test case and the BARON solver run are formed as follows:

# prepare the Data
data;
# Data SAIDI
let p[1]:=263.8919308; let p[2]:=149.9870317; let p[3]:=819.2723340; let p[4]:=346.4481268;
# Data SAIFI
#let p[1]:=0.7330331412; let p[2]:=0.5015489914; let p[3]:=2.494776657; let p[4]:=1.199243516;
let c[1]:=5; let c[2]:=5; let c[3]:=9; let c[4]:=6;
let k[1]:=10; let k[2]:=10; let k[3]:=10; let k[4]:=10;
let x0[1]:=0.5; let x0[2]:=0.7; let x0[3]:=0.3; let x0[4]:=0.5;
display p,c,k,x0;
display C_1;

solve NLPa; display obj, _solve_time;
display x;
```

A mathematical experiment was performed for the scheme shown in Figure 1, in accordance with the initial information provided by the distribution system operator regarding the number of accounting points (N_{Pi}), which are part of the scheme for certain groups of consumers Pi (Table 1) and parameters of line lengths of the electric power circuit segment (Table 2). Using expression (5), the reliability indicators of the research object for the implementation of the recommended innovations are calculated and obtained:

$$SAIDI_{\text{theoretical}} = \frac{\sum_j \tau_{Pj} \cdot \omega_{Pj} \cdot N_{Pj}}{\sum_j N_{Pj}} = 1{,}579.6 \text{ min};$$

$$SAIFI_{\text{theoretical}} = \frac{\sum_j^n \omega_{Pj} \cdot N_{Pj}}{\sum_j N_{Pj}} = 4.93 \text{ times}.$$

Table 1. Parameters of combined load groups of the electric power scheme segment

Pi	I	II	III	IV
N_i	323	221	570	274

Notes: Pi – power consumption of the load node, N_i – number of load node subscribers
Source: compiled by the authors

Table 2. Parameters of line lengths of the power circuit segment

Land plot number *ij*	01	12	13	38	34	45	56	47
L_{ij}	2.7	3.2	1.5	5.2	3.6	2.2	1.8	4.1

Notes: L_{ij} – plot length
Source: compiled by the authors

As a result of calculations using the BARON solver from the NEOS server, a result was obtained that shows that the optimal value of the indicator SAIDI = 780.4984666 to find this value, 692 iterations were implemented, which helped to distribute a limited investment resource of 7 units between a possible four microgrid structures (Fig. 1) in the ratio 1 – 0.654453; 2 – 0.930648; 3 – 0.300806; 4 – 0.640115, it is worth noting that the closer the result is to zero, the more investment resources should be spent on this particular facility:

```
========================================
Iteration Open nodes Time (s) Lower bound Upper bound
1 1 0.06 592.312 780.498
* 138 6 0.32 741.616 780.498
* 531 9 0.70 780.105 780.498
692 0 0.83 780.498 780.498
Calculating duals
*** Normal completion ***
Wall clock time: 0.84
Total CPU time used: 0.83
Total no. of BaR iterations: 692
Best solution found at node: 531
Max. no. of nodes in memory: 13
All done
========================================
BARON 23.3.11 (2023.03.11): 692 iterations, optimal within tolerances.
Objective 780.4984666
Objective lower bound = 780.497572145, upper bound = 780.498352643
barstatus = 1, modelstatus = 1
max nodes in memory = 13
optimum found at node 531
Baron run time (excluding setup) = 0.83 seconds
obj = 780.498
_solve_time = 0.846831
x [*] :=
1 0.654453
2 0.930648
3 0.300806
4 0.640115
;
sum{i in 1 .. n} c[i]*(1 - 1/(1 + exp(-(k[i]*(x[i] - x0[i]))))) = 7
```

Table 3 summarises the results of calculations and evaluates the effectiveness of capital investments in the development of microgrid structures according to the reliability criterion.

Table 3. Initial information on investment efficiency and modelling results in the NEOS Solver

P_j	I	II	III	IV	$SAIDI_{теор}$	$SAIFI_{теор}$	Δ	Δ, %	Δ, % / C, % C.U.
c_j	5	5	9	6					
x_{0j}	0.5	0.7	0.3	0.5					
$x_{j\ SAIDI}$	0.654	0.931	0.301	0.640	780.498		799.10	50.59	7.23
$x_{j\ SAIFI}$	0.669	0.919	0.309	0.618		2.462	2.468	50.06	7.15

Note: j – total number of combined consumer groups (j = I..IV); c_j – amount of capital investment for the full implementation of the development of microgrid structures according to the 4th feature according to expression (1); $x_{0\,j}$ – point where the function Eff(x_j) reaches a value of 0.5; $x_{j\ SAIDI}$ – solutions of the objective function for certain combined groups of consumers (j = I..IV) when optimising SAIDI; $x_{j\ SAIFI}$ – solutions of the objective function for certain combined groups of consumers (j = I..IV) when optimising SAIFI; Δ, Δ,% – reduction of the reliability indicator in named and conventional units, Δ, % / C – value of capital investment efficiency per conventional unit of resource spent from the investment programme
Source: developed by the authors using NEOS Solver (n.d.)

Table 3 summarises the results of a mathematical experiment that determines the optimal distribution of available limited investment capital, provided that it is directed to increase a certain legally regulated reliability indicator (SAIDI and SAIFI are considered in the model). It is worth noting that the use of limited investment capital in this way partially compensates the owners of microgrid structures for investment in their development and significantly improves the reliability indicators of distribution system operators. For example, in the proposed version, the improvement in reliability indicators will be slightly more than 50%, while % / C – efficiency of capital investments per conventional unit of resource spent from the investment programme is slightly more than 7% per 1 conventional unit of resource spent.

The study by A. Muhtadi *et al.* (2021) focuses on integrating microgrids into electrical distribution systems to improve their reliability. At the same time, the researchers focused more on key aspects of microgrids based on distributed energy resources (DER) and modelled the impact of DER, electric vehicles (EV), and energy storage systems (ESS) on network sustainability. It is worth noting that approaches to ensuring reliability vary: since the current study focuses more on mathematical optimisation and algorithms, while A. Muhtadi *et al.* (2021) analyse the impact of specific technologies and management strategies on the practical aspects of implementing DER, ESS, and EV to improve network reliability and sustainability.

M. Sandelic *et al.* (2021) explores the issue of sustainable electricity supply using microgrids using distributed energy resources, which is consistent with this research. Special attention in the study was paid to improving the methods of reliability assessment through the analysis of wear of power electronics and its impact on the system, this approach is more technical, considering the algorithms and response scenarios of dispatching services under the condition of limited investment, which allows ensuring the survivability of the power system. It is important to note that the study by M. Sandelic et al. (2021) did not analyse the impact of the reliability of microgrids on the development of new procedures for designing and planning future microgrids, which is an important aspect for ensuring the long-term reliability and efficiency of microgrids.

Comparison of the findings of this study with the scientific proposals of V.K. Garg *et al.* (2020), who developed the optimal PV-BESS-based microgrid structure to provide stable electrical energy in the face of load changes and power shortages in rural India, showed that their study did not analyse the possible risks or limitations that may arise when implementing microgrids, in particular, in terms of the reliability of power supply systems.

Comparison of this study with the approaches of C.A. Cortes *et al.* (2017), who proposed an iterative procedure for optimal design of the microgrid topology in active distribution networks, based on graph breakdown, integer programming and performance index for optimal design, however, the researchers did not consider the reliability indicators of microgrids under variable load and equipment failures, which affects the survivability of both microgrids and the distribution system as a whole, and did not form recommendations on the influence of the reliability of microgrid structures on the development of new patterns of design and planning of electrical networks of distribution system operators.

When analysing the results, it is worth referring to the study by S. Peyghami *et al.* (2021), which developed the reliability model of power electronic converters and investigated their impact on the reliability of the power system, but their study does not cover the analysis of the possible impact of reliability on the survivability of the power grid in conditions of failures in the power system itself, and did not conduct mathematical optimisation and did not form algorithms that allow minimising integral reliability indicators, considering financial constraints.

B. Zhang *et al.* (2020) developed a hierarchical structure for evaluating the reliability of an electric power system and considered it from the level of a power electronic converter to the general system. However, it is worth noting that the developed models allow obtaining an estimate of the reliability indicators of microgrid structures considering the system level, but do not form an integral assessment of the reliability of the influence of microgrid structures on the resulting efficiency of distribution systems as a whole.

When comparing the results, it is worth referring to material of X. Guo *et al.* (2024), where the researchers reviewed an integrated index system that takes into account two-level performance and reliability indices, and proposed an agent-based model for modelling physical objects and energy dispatching strategies. The researchers focused on developing indexes, but did not consider exactly how the integrated reliability assessment index system takes into account the interaction between maintenance strategies and limited investment resources.

Comparison of the results obtained with the findings of K. Pang *et al.* (2024), who proposed a new method of long-term planning based on deep learning in the face of various uncertainties, in which the micro-network acts as a backup energy source. They show that in the development of microgrid, it is important to resolve the issue of redistribution and dating of various technical solutions according to the criterion of minimising reliability indicators with a limited investment resource.

In order to compare the conclusions obtained, it is necessary to refer to the study by P.S. Meera *et al.* (2022), which provides an overview of the impact of distributed generation on reliability, considers various methods for evaluating the reliability of the distribution network – analytical, simulation, and hybrid, which affect the optimal placement of switching devices, the use of distributed generation and network reconfiguration, in contrast to this study, where the proposals are evaluated not only from the standpoint of the facility owner, but also consider aspects of improving the efficiency of the distribution system operator as a whole.

It is advisable to compare the findings with the developments of A. Nargeszar *et al.* (2022), which assessed the impact on the reliability of microgrids of changes in the energy characteristics of renewable resources, such as wind speed, tidal flows, and solar radiation, based on the developed equations, but these researchers, unlike the present study, did not interpret the proposed models on the level of centralised power supply and did not assess the possible impact of the reliability of microgrid structures on the efficiency of the system as a whole.

When formulating and approving the investment policy of a distribution system operator in terms of ensuring the planned performance in terms of reliability, it takes a long time to develop adequate responses and scenarios. This introduces significant restrictions on the development of timely management decisions and assessments of effective areas for the development of investment policy to optimise comprehensive indicators of the reliability of the distribution system operator.

As a result of the current study, a mechanism for partial compensation of the cost of forming microgrid structures through the rational allocation of funds from the investment programme of the distribution system operator, the purpose of which is to increase the efficiency of electricity supply to consumers in modern conditions, has been proposed. A method for finding the optimal values of reliability indicators has been developed based on the distribution of the "depth" of microgrid structures at the facilities of distribution system operators, which is formed by the distribution system operator. It is indicated that this approach can be used as an additional tool for the decision-making system in the operational dispatching management of regional energy systems and the assessment of effective areas for the development of investment policy, the purpose of which is to optimise the integral reliability indicators of the distribution system operator.

CONCLUSIONS

As a result of the research, the main goal was achieved – to substantiate the creation of models for ensuring the optimal structure of electrical distribution networks under the conditions of connecting microgrids, considering the criterion of reliability and limited investment. A method for assessing the structural reliability of complex electrical systems with microgrid structures was developed, which helped to develop a rational power distribution of such structures, optimising the reliability indicators of the electric power system under study. The proposed mathematical optimisation model based on a computational system proved to be effective for solving non-convex problems with minimising integral reliability indicators, taking into account financial constraints and the investment efficiency curve. The use of the BARON solver available on the NEOS server confirmed the possibility of optimisation, demonstrating the results using examples, considering the parameters of distribution system objects and their restrictions on network components. Using the basic example, the efficiency of the proposed solutions was demonstrated in the form of slightly more than 50% improved integral reliability indicators and the relative coefficient of investment efficiency per conventional unit of resource spent from the investment programme was determined, which was slightly more than 7% per 1 conventional unit of resource spent. An algorithm and programme for solving the problem of targeting power flows of microgrid structures in multi-node regional power systems was developed, which allows ensuring the survivability of the power system under the condition of limited investments. The results of the study showed that the development of rational electricity flows of microgrid structures minimises the under-supply of electric energy by specific load nodes and determines their recommended shares in covering demand in conditions of power shortage. The results obtained are recommended for use in operational and strategic management of energy systems, which would help to increase their reliability and efficiency of using a limited investment resource.

An important area for further research is to combine methods and models for optimising the number and types of reliability enhancement equipment with the introduction of microgrid structures to increase the investment attractiveness of such technical solutions. It is also advisable to conduct additional research on the efficiency of investments in each specific microgrid structure and to form integral dependencies of the technical and economic efficiency of island modes and the development of a solution based on a multi-criteria Pareto-optimal for a certain group of reliability indicators, since the developed model showed that the optimal solution is slightly different for different reliability indicators.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Особливості мультиагентної оцінки ефективності роботи систем мікрогрід при паралельній роботі з енергосистемою за критерієм надійності

Анотація. Забезпечення надійного електропостачання споживачів за умов руйнування критичної енергетичної інфраструктури та дефіциту генерувальних потужностей в Україні потребує розвитку систем розподілу та систем керування ними. Метою дослідження було обґрунтування створення моделей забезпечення оптимальної структури розподільних електричних мереж за умов приєднання мікромереж за критерієм надійності в умовах обмежених інвестиційних вкладень. В роботі застосовано метод оцінювання структурної надійності складних електричних систем з мікрогрід структурами та сформовано раціональний розподіл потужності таких структур за критерієм оптимізації показників надійності досліджуваної електроенергетичної системи. Було запропоновано математичну модель оптимізації на основі обчислювальної системи, призначену для розв'язання неопуклих задач з мінімізацією інтегральних показників надійності, враховуючи фінансові обмеження та криву ефективності капіталовкладень. На основі досліджень розглянуті можливості оптимізації з використанням солвера BARON, доступного на NEOS сервері. Результати ефективності моделі демонструються на прикладах, враховуючи параметри об'єктів систем розподілу та їх обмеження на компоненти мережі. Запропоновано алгоритм і програму для розв'язування задачі адресності потоків потужності мікрогрід структур у багатовузлових регіональних енергосистемах. Сформовано алгоритми та сценарії реагування диспетчерських служб за умови обмеженості інвестиційних вкладень, що дозволить забезпечити живучість енергосистеми в цілому. Встановлено, що формування раціональних потоків електроенергії мікрогрід структур дозволить мінімізувати недовідпуск електричної енергії конкретними вузлами навантаження і визначати їх частки у покритті попиту енергоострова за умов дефіциту потужності. Результати дослідження можна використати в операційному управлінні енергосистемами

Ключові слова: інтегральні показники надійності; мікрогрід структури; систем розподілу електроенергії; балансування навантаження; сценарії диспетчеризації мікрогрід

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Analytical study on improving the efficiency and environmental friendliness of solid organic fuels

Abstract. The purpose of this study was to analyse methods of increasing the efficiency and environmental friendliness of the use of solid organic fuels (SOF) in electricity generation. This study employed a comprehensive approach to the analysis and optimisation of technological processes, operational systems, and environmental aspects of the use of SOF. The study found that the use of modern technologies, such as gasification and pyrolysis, considerably increases the efficiency of converting SOF into electricity. Optimisation of boiler and turbine designs and automation of fuel supply systems helps to reduce energy losses and improve overall system efficiency. It was found that the use of new materials for boilers increases their resistance to corrosion and erosion, which extends the service life of the equipment. The study also showed that the introduction of gas cleaning and secondary combustion systems significantly reduces emissions of harmful substances, which improves environmental performance. An analysis of ash utilisation opportunities showed that

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its use as a fertiliser or construction material is a promising area. The study proved that an integrated approach to the use of SOF can substantially increase their efficiency and environmental friendliness. The findings of the study suggest that the use of innovative methods of combustion process control allows achieving more stable and efficient power generation. It was proved that the introduction of automated monitoring and control systems reduces operating costs and increases the reliability of equipment. The study also found that the use of advanced analytical tools to predict equipment wear and tear allows for prompt preventive maintenance, which further increases the efficiency and duration of uninterrupted operation of energy systems

Keywords: solid organic fuels; gasification; pyrolysis; electricity; corrosion; erosion; ecology

INTRODUCTION

In the context of global climate change, accompanied by an increase in the average global temperature, melting glaciers, and an increase in the frequency of extreme weather events, the global community is facing serious challenges in reducing the adverse environmental impact. One of the main tasks in this context is to ensure a stable supply of energy necessary to support the vital activity of society, industry, and transport, while minimising greenhouse gas emissions that cause climate change. Considering this, the search for efficient and environmentally friendly energy sources has become particularly important. Solid organic fuels (SOF), including wood, pellets, straw, and other biomass, have gained considerable attention as promising alternative energy sources that can partially replace fossil fuels such as coal, oil, and natural gas (Sivabalan *et al.*, 2021). Biomass, being a renewable resource, can be reproduced in a relatively short time, making it a more environmentally friendly alternative to fossil fuels, which are limited and declining. The use of SOF not only reduces dependence on conventional energy resources, but also helps to reduce greenhouse gas emissions, as the plants that serve as a source of biomass absorb carbon dioxide from the atmosphere as they grow (Palianytsia *et al.*, 2014). The need for this study is driven by current challenges in the energy sector, such as growing global energy demand, limited fossil fuel resources, and the need to reduce greenhouse gas emissions. Due to their renewable characteristics, SOF can play a key role in the transition to more environmentally friendly energy sources. However, the efficient use of SOF requires the improvement of existing processing and combustion technologies, as well as the optimisation of mechanical systems to achieve maximum environmental and economic benefits.

An analysis of the problem of increasing the efficiency and environmental friendliness of the use of SOF points to numerous studies that cover various aspects of this topic. Z. Hameed *et al.* (2021) showed that innovative gasification methods can significantly increase the calorific value of fuel and reduce pollutant emissions. They also investigated how these methods contribute to a more complete utilisation of biomass energy, increasing the overall efficiency of the process. G. Mong *et al.* (2022) reviewed pyrolysis technologies, focusing on reducing waste and improving the quality of end products. Their study also highlighted the significance of temperature control to achieve best results in pyrolysis plants. M. Soleh *et al.* (2023) highlighted the impact of different types of biomass on the efficiency of the combustion process, emphasising the significance of proper fuel preparation. Furthermore, their results showed that biomass preparation influences the reduction of harmful emissions during combustion. L. Martinez-Valencia *et al.* (2021) focuses on the automation of fuel supply systems, which reduces maintenance costs and increases process stability. They also noted that automation contributes to more accurate fuel dispensing, which reduces energy losses. Further research by C. Tang *et al.* (2022) revealed the benefits of using new materials for boiler structures that considerably increase their durability and efficiency. They also pointed to the reduction of corrosion processes due to the use of these materials, which extends the service life of the equipment. A. Islam *et al.* (2023) made a significant contribution to the development of gas purification methods that reduce emissions of harmful particles and improve environmental performance. Their research also focused on the effectiveness of different filter media in cleaning processes. J. Odzijewicz *et al.* (2022) focused on ash utilisation technologies, showing how these by-products can be used as fertilisers or construction materials. They also investigated the economic benefits of such approaches, which help reduce waste. F. Mustafa *et al.* (2023) considered aspects of combustion monitoring and control, focusing on the significance of automated systems to improve efficiency and reduce costs. The researchers also stressed that these systems ensure prompt detection and elimination of deviations in the operation of plants. L. Peiró *et al.* (2022) showed the promise of innovative approaches to integrating biomass into existing energy systems, which can improve their overall efficiency and environmental performance. They also noted that such approaches can contribute to greater flexibility of energy systems in the use of different fuels. Overall, while these studies make a valuable contribution to understanding the efficiency and environmental friendliness of using SOF, there are gaps that need to be further explored, particularly in terms of the impact of various fuels on technological processes, the long-term performance of new materials, and the economic aspects of biomass integration.

The purpose of this study was to analyse methods of increasing the efficiency and environmental friendliness of using SOF in electricity generation. Research objectives:

- to investigate modern technologies for SOF processing, such as gasification and pyrolysis, to assess their impact on the efficiency of electricity production;
- to analyse the mechanical systems used for combustion of SOF and to identify opportunities for their optimisation to improve energy efficiency;
- to evaluate the environmental aspects of the use of SOF, including the reduction of harmful substances and ash disposal, to determine their impact on the environment.

MATERIALS AND METHODS

The present study analysed the aspects of using SOF for electricity generation. Various types of SOF, such as wood, pellets, straw, and other types of biomass, which are widely used in the energy sector, were considered. Significant attention was paid to the examination of each type of biomass in terms of its availability, energy potential, environmental impact, and the possibility of integration into modern energy systems.

Methods for analysing the physical and chemical properties of biomass were also used, including determining moisture content, ash content, calorific value, and composition of volatile substances. The moisture content of the biomass was determined to assess its impact on combustion efficiency and energy costs for grinding and drying the fuel before combustion. The ash content was analysed to determine the amount of residual material after combustion, which can cause problems with equipment maintenance. The calorific value was assessed to determine the amount of energy that can be obtained during combustion, which is a key indicator of fuel efficiency in power plants. The study of the composition of volatile substances helped to assess their impact on the formation of harmful emissions during combustion.

Furthermore, the energy potential of various types of biomass was assessed, considering the possibility of their mass production and market availability. As the efficient use of biomass for energy purposes requires a stable supply of raw materials, the study addressed the regional specifics of biomass cultivation and harvesting. The environmental impact, including emissions of harmful substances during combustion, and the fuel's ability to recover were also considered. The main technologies used for converting SOF into electricity, specifically gasification and pyrolysis, were considered. The study analysed their advantages and disadvantages, process efficiency, and the potential for reducing emissions of harmful substances.

The operational mechanical systems, such as boilers, turbines, and fuel preparation and supply systems used for combustion of the SOF were analysed. Particular attention was paid to the design features of these systems, their reliability, and upgrade capabilities. The possibilities of using new materials and engineering solutions that increase the efficiency of heat transfer, reduce heat loss, and improve the overall performance of energy systems were investigated.

The environmental impacts of the use of SOF, including emissions of harmful substances such as CO_2, NO_x, and slag and ash particles occurring from the combustion process, were also investigated. Methods of reducing these emissions, such as the use of flue gas cleaning systems and secondary combustion technologies, were analysed. Furthermore, the study considered the issue of utilisation of ash, which can be used as fertiliser or construction material.

RESULTS

SOF play an important role in electricity generation, especially in the context of renewable energy sources. The use of SOF, such as wood, agricultural waste, and other biomass, can considerably reduce greenhouse gas emissions if used efficiently. SOF occupy a special place among alternative energy sources due to their availability and potential for sustainable development (Angulo-Mosquera *et al.*, 2021). SOF includes various types of biomass, such as wood, pellets, straw, husks, husks, and other organic waste generated by agricultural and industrial activities. These materials are renewable resources that can be used to produce heat and electricity with minimal environmental impact. Each type of SOF has its unique characteristics that determine their efficiency and environmental friendliness. Wood, as one of the most common SOF, has a high energy potential due to its calorie content. At the same time, its efficiency largely depends on the level of humidity – the lower the humidity, the more energy can be obtained by burning it. Pellets produced by pressing wood waste have a stable calorific value and low moisture content, which makes them one of the most efficient types of SOF.

Straw, peelings, and husks, which are agricultural wastes, are also widely used as a SOF. Although these materials have a lower calorific value than wood, their availability and low cost make them attractive for energy needs, especially in rural areas. However, the use of such fuels is accompanied by certain difficulties, specifically, high ash content and the possibility of harmful emissions during combustion. This requires the implementation of special flue gas cleaning and ash disposal technologies to minimise the negative impact on the environment. Thus, the SOF represent a diverse group of materials, each of which has its characteristics that affect the efficiency of their use in the energy sector. The choice of the suitable type of SOF and its processing technology depends on the concrete conditions and requirements for energy efficiency and environmental friendliness. Therefore, research and development of technologies aimed at optimising the use of SOF is crucial for the transition to cleaner energy sources. Technologies for generating electricity from SOF are key to the development of renewable energy sources (Wang & Wright, 2022).

With the growing demand for environmentally friendly energy solutions, it is important to consider modern methods that enable efficient conversion of biomass into electricity (Table 1). These include combustion, gasification, and pyrolysis, each of which has its unique advantages and challenges.

Table 1. Technologies of electricity generation from the SOF

Technology	Working principle	Advantages	Disadvantages
Combustion	Conversion of fuel into a gaseous coolant for steam production	High enough efficiency, proven technology	CO_2 emissions, reduced efficiency when used in intermediate modes
Gasification	Conversion of solid and liquid fuels into gaseous fuels	Reduced emissions, high efficiency	Complexity of equipment, need for additional gas cleaning systems
Pyrolysis	Heat treatment of fuel in the absence of oxygen	Possibility of obtaining several types of fuel	Complexity of the process, need for special systems to handle the output products

Source: compiled by the authors of this study based on O. Corigliano *et al*. (2022)

Combustion is one of the most conventional and widespread technologies for generating electricity from SOF. The principle of operation of such systems is to use biomass to heat water, which leads to the formation of steam. This steam drives turbine generators that generate electricity. This method is efficient and reliable, but its effectiveness depends on the quality of the fuel used and the design of the equipment. An important aspect is the optimisation of the combustion process to minimise the production of harmful emissions, ash, and slag. Gasification is a more innovative approach, which involves converting SOF into gaseous fuel through partial oxidation at hot temperatures. The resulting synthesis gas consists primarily of hydrogen, carbon monoxide, and methane, and can be used for power generation or as a raw material for the chemical industry. Gasification reduces the amount of ash and harmful emissions, making this method more environmentally friendly than conventional combustion. At the same time, this process requires sophisticated equipment and strict control of parameters, which can increase the cost of implementing the technology.

Pyrolysis is a process of thermal treatment of SOF in the absence of oxygen, which results in the formation of solid, liquid, and gaseous products. These products can be used for further energy production or as raw materials for other industries. The solid residue (biochar) can be used as fuel or as fertiliser, the liquid fractions can be used as biofuels, while the gaseous products can be used to produce electricity or heat. Pyrolysis is a flexible technology that allows to produce various types of energy carriers but requires precise control of temperature conditions and the composition of the feedstock. Thus, technologies for generating electricity from SOF offer a wide range of opportunities for the efficient and environmentally friendly use of renewable resources. The choice of the suitable technology depends on specific conditions, including the type of biomass, availability of process equipment, and requirements for process efficiency and environmental friendliness. The integration of these technologies into the modern energy sector will help reduce dependence on fossil fuels and reduce the negative impact on the environment.

The analysis of mechanical systems used for combustion of SOF is a major step in improving the efficiency and reliability of power plants (Table 2). These systems include diverse types of boilers, turbines, and fuel preparation and feeding systems, each of which plays a critical role in ensuring efficient conversion of biomass to electricity (Chehrmonavari *et al*., 2023).

Table 2. Analysis of mechanical systems for the use of SOF

System	Description	Key features	Challenges and limitations
Solid fuel boilers	Boilers for SOF combustion	Heat output, materials, operating mode	Short service life, need for regular maintenance
Turbines	Turbines for converting thermal energy into electricity	Efficiency, type (steam, gas)	Dependence on steam/gas quality, maintenance costs
Fuel preparation and supply systems	Automatic systems for fuel preparation and delivery	Continuity of operations, automation	Installation costs, problems with fuel recycling

Source: compiled by the authors of this study based on J. Zhuang *et al*. (2022)

The design of boilers is one of the key elements in combustion systems for SOF. The main focus of boiler design is on heat transfer efficiency, which determines how fully and efficiently fuel is converted into heat. The materials used to make the boilers must be resistant to hot temperatures, corrosion and erosion that occur during the biomass combustion process. The choice of materials and optimisation of the boiler design increase their durability and reduce heat loss, which increases the overall efficiency of the energy system. Turbines, which are used to convert thermal energy into mechanical energy and then into electricity, also require careful analysis. The type of turbines and their design features determine the efficiency of energy conversion, which is a key factor in achieving high performance. The optimum operating conditions of the turbines depend on the parameters of the steam generated in the boilers, including pressure and temperature. Furthermore, it is necessary to consider the possibility of using different types of turbines to work with different types of biomass, which may require special adjustments and adaptations.

Fuel preparation and supply systems ensure uninterrupted and uniform supply of SOF to the boilers. These systems must be designed to minimise fuel losses during grinding, drying, transport, and storage, and to ensure that the fuel is delivered evenly to the combustion zone. Automation of fuel supply processes helps to optimise system performance, reduce operating costs, and improve equipment reliability. Modern fuel supply systems can include dosing mechanisms, conveyors, augers, and other elements that ensure the accuracy and stability of the process. Thus, the analysis of mechanical systems for the use of SOF is a vital component of improving the efficiency and environmental friendliness of power plants. Optimising the design of boilers, selecting the right turbines and automating fuel supply systems not only increases productivity but also reduces the adverse impact on the environment. These aspects are critical to ensuring the sustainable development of the energy sector and the transition to renewable energy sources. Optimising the design of energy systems to improve efficiency is a key area of development for modern energy systems using SOF (Wang *et al.*, 2021). This process included several key aspects aimed at improving the operation of boilers, turbines, and fuel supply systems, which would increase productivity and reduce energy losses.

The modernisation of boilers has become one of the crucial steps in improving heat exchange efficiency. The use of new materials that were highly resistant to corrosion and erosion considerably increased the boilers' service life and reduced heat losses. The use of advanced designs and the latest heat exchange technologies helped to optimise combustion processes, which increased the overall efficiency of the system. The use of combustion processes for combustion of SOF in oxygen or oxygen-enriched air is important in this area. Improvements to the turbines included the use of more efficient models capable of operating at lower temperatures, which helped reduce energy losses during the conversion of heat into mechanical work. The introduction of new types of turbines increased productivity and reduced energy costs, which had a positive impact on the overall efficiency of power plants. Automation of fuel preparation and supply systems was an essential element in optimising energy processes. The use of sensors and automatic control systems ensured the accuracy and stability of fuel supply, which reduced the cost of its transportation and ensured the smooth operation of the plants. This helped to increase the efficiency of fuel combustion and minimise losses, which had a positive impact on the overall performance of the system. Overall, optimisation of power system designs and technologies enabled a substantial increase in the efficiency of using SOF, which ultimately contributed to reducing energy costs and improving the environmental friendliness of electricity generation. These measures were critical to ensure the stable and efficient operation of modern power plants using renewable energy sources.

The use of SOF for electricity generation has valuable environmental aspects that directly affect the environment and the efficiency of energy systems (Table 3). Improvement of the environmental friendliness of the use of SOF includes reducing pollutant emissions, efficient ash disposal, and rational use of resources.

Table 3. Environmental aspects of using SOF

Environmental aspect	Description	Potential solutions
Reduction of emissions	The use of SOF can lead to emissions of CO_2, NO_x, SO_x, and other pollutants	Use of the latest combustion technologies, modern flue gas cleaning technologies, catalytic converters
Disposal of ash and slag	Ash and slag remaining after combustion of SOF may contain heavy metals and other harmful substances	Use of ash as fertiliser, in building materials or for land reclamation
Rational use of resources	Loss of thermal energy during combustion of SOF can reduce the efficiency of energy systems	Optimisation of the combustion process, introduction of high-efficiency boilers and turbines, utilisation of biomass residues

Source: compiled by the authors of this study based on M.A. Abdelkareem *et al.* (2021)

Reduction of emissions is one of the key tasks when using SOF. For this, gas purification technologies are actively used to reduce the concentration of harmful substances in exhaust gases. Secondary combustion systems provide additional combustion of the remaining particles in the flue gas, thereby reducing emissions of inorganic compounds and soot particles. Catalytic converters are used to convert toxic gases such as nitrogen and carbon oxides into less harmful compounds. The introduction of these technologies substantially reduces the negative impact on the environment, making the use of SOF more environmentally friendly. The disposal of ash and slag is another notable aspect of the environmental benefits of using SOF. The ash and slag produced during biomass combustion can be recycled and used as fertiliser or building material. Biomass ash contains a considerable amount of nutrients such as potassium, calcium, and phosphorus, which are useful for improving soil quality. It can also be used as an ingredient in the manufacture of building materials such as concrete or tiles, which reduces the need for virgin raw materials and reduces the environmental footprint of the construction industry.

Efficient use of resources includes reducing energy losses and using biomass residues. Improvement of the combustion efficiency and conversion of SOF helps to reduce the amount of unused fuel and reduce overall energy costs. Another major aspect is the use of biomass residues, such as husks, stalks, or wood waste, which are often overlooked. Reusing them as fuel or raw materials for new products reduces waste and improves overall system efficiency. Thus, the environmental aspects of using the SOF include reducing pollutant emissions, ash disposal, and efficient use of resources. The introduction of relevant technologies and practices helps to reduce the negative impact on the environment, increasing the environmental friendliness of electricity production from biomass, and ensuring the sustainable development of the energy sector (Al-Ghouti *et al.*, 2021). With the future challenges of the energy sector related to the need to reduce emissions and increase efficiency, the development of innovative technologies in the field of using SOF is becoming critically important. The key areas of this development include new materials for boilers and turbines, innovative methods of processing SOF, as well as automation and digitalisation of processes (Wang & Wright, 2021).

Modern research in the field of materials science focuses on the development of new alloys and coatings that can considerably improve heat resistance and reduce wear and tear on energy system components. New materials, such as ceramic composites and high-strength alloys, can withstand extreme temperatures and aggressive operating conditions. They ensure a longer service life for boilers and turbines, which reduces the frequency of repairs and replacements and increases the overall efficiency of power plants. The introduction of such materials can considerably reduce maintenance costs and improve system reliability. Innovative methods of processing SOF focus on integration with renewable energy sources and the development of innovative processing technologies. For instance, biomass can be combined with solar or wind energy to improve the efficiency of energy systems. Gasification and pyrolysis processes are becoming increasingly sophisticated, enabling the conversion of SOF into high-quality gaseous or liquid fuels with higher energy density. Integrating these technologies into a combined heat and power system can significantly improve overall efficiency and reduce emissions.

Automation and digitalisation of the SOF combustion process is another major area of development. Artificial intelligence (AI) and big data allow optimising management processes, improving the accuracy of system regulation and monitoring. Intelligent control systems can automatically adjust combustion parameters to achieve maximum efficiency and reduce emissions. For instance, AI-powered systems can predict energy needs, optimise fuel supply, and ensure more efficient integration with other energy sources. Digitalisation also facilitates maintenance by monitoring the condition of equipment in real time. The development of new materials, innovative methods of processing SOF, and automation of processes are key to improving the efficiency and environmental friendliness of SOF-based energy systems. These technological advances not only reduce the negative impact on the environment, but also provide economic benefits through reduced maintenance costs and improved overall system reliability. According to current research and innovations, the future use of SOF will be closely linked to the integration of innovative technologies, which opens new opportunities for sustainable energy development (Singh *et al.*, 2021).

Increasing the efficiency and environmental friendliness of using SOF for electricity generation requires a comprehensive approach, including technology improvement, design optimisation, and the use of modern mechanical systems. Efficient use of SOF can considerably reduce greenhouse gas emissions and promote the development of renewable energy sources.

DISCUSSION

The analysis of the results showed a significant potential for increasing the efficiency and environmental friendliness of the use of SOF in electricity generation. Modern technologies such as combustion in pure oxygen, gasification, and pyrolysis were found to considerably reduce emissions compared to conventional methods of use. However, these technologies required complex gas purification systems, which increased production costs. Optimisation of boiler and turbine designs and the introduction of the latest materials have helped to improve heat transfer efficiency and reduce energy losses. This was also investigated by V. Ashokkumar *et al.* (2022), where the findings confirmed that the introduction of technologies such as carbon capture and storage systems significantly reduced carbon dioxide emissions. The use of gasification and pyrolysis of solid fuels has contributed to cleaner combustion, thereby reducing emissions. Z. Xie *et al.* (2021) also showed that modern combustion technologies for combustion of SOF, such as particulate filters and desulphurisation systems, effectively reduce the concentration of harmful substances in emissions. Optimisation of combustion processes ensured more complete combustion of fuel, reducing the amount of residual emissions. Notably, the effectiveness of technologies largely depends on their proper application and integration into existing energy supply systems. Successful emissions reduction also requires constant monitoring and adaptation of technologies to changing operating conditions. Investing in innovative solutions and their adaptation can substantially improve the environmental impact of using SOF, making it more competitive with other energy sources (Chupa & Zhovtulia, 2023).

The study of mechanical systems for the use of SOF has demonstrated the significance of process automation, especially in the context of fuel supply systems. The use of automatic control systems has reduced fuel losses and ensured the stability of power plants (Stoliarov, 2024). On the other hand, the high complexity of such systems required considerable investment and regular maintenance, which raised the question of the feasibility of their implementation in a context of limited funding. A. Marot *et al.* (2022) concluded that automation in energy supply systems with SOF ensures stability and efficiency. Automated control systems help maintain optimised combustion parameters, reducing emissions and increasing efficiency. L. Angulo-Mosquera *et al.* (2021) found that research into mechanical systems for the use of SOF highlighted the significance of automation, especially in fuel delivery systems. Automatic control systems reduce fuel losses and increase the stability of power plants, which has a positive impact on their efficiency. However, the high complexity of such systems requires major investment and regular maintenance, which raises questions regarding their feasibility in a context of limited funding. These findings support the cited study, as they demonstrate that automation truly contributes to the efficiency and sustainability of power plants. At the same time, they emphasise the need for a thorough substantiation of the economic feasibility of such investments, especially for enterprises with limited financial resources. The introduction of automated systems must be balanced with the enterprise's ability to maintain and adapt them to ensure long-term sustainability and economic benefit.

Optimisation of boiler and turbine designs has proven to be effective in increasing the overall efficiency of systems using SOF. The use of new materials, such as high-temperature alloys and nanomaterials, has improved thermal conductivity and corrosion resistance (Orumbayev *et al.*, 2021). This helped to reduce maintenance costs and extend the life of the equipment. It is worth noting the study by M. Nemitallah *et al.* (2023), who also found that optimising boiler and turbine designs is key to improving the efficiency of power plants. Improvements in the geometry of heat exchange surfaces, turbine aerodynamics, and fuel combustion systems can reduce energy losses and increase efficiency. This also helps to reduce emissions, which increases the environmental sustainability of production. Y. Guo *et al.* (2023) concluded that new materials with high thermal conductivity, corrosion and temperature resistance allow for more efficient heat transfer and reduce energy losses. They also increase the equipment's resistance to stress, which extends its service life and reduces replacement costs, contributing to higher efficiency and lower operating costs. These data are in line with the theses presented in the previous section of this study, confirming the significance of both design optimisation and the use of innovative materials to achieve maximum efficiency. Improvements in boiler and turbine designs, together with the use of the latest materials, create a synergistic effect that increases the overall efficiency of power plants (Prypoten *et al.*, 2022). This demonstrates that innovative approaches in engineering and materials science are essential for achieving sustainable development and reducing operating costs in the modern energy sector.

From an environmental standpoint, improving the environmental friendliness of the use of SOF required a comprehensive approach, including both the modernisation of existing technologies and the introduction of innovative methods of reducing emissions. It was found that efficient ash utilisation can considerably reduce the environmental impact of electricity generation if the ash is used as fertiliser or in building materials. However, the issues of safety and economic feasibility of such disposal necessitated additional research. R. Permatasari & A. Sodri (2023) also conducted a study that confirmed that ash utilisation and emission reduction are critical for environmental safety when using SOF. Ash contains toxic substances, and therefore its efficient utilisation, for instance in construction materials, reduces the negative impact on the environment. Modern technologies, such as flue gas filtration, help to reduce emissions of harmful substances in line with environmental standards. N. Rajendran *et al.* (2021) also found that a comprehensive approach includes reducing pollutant emissions, optimising the combustion process to minimise ash, and upgrading equipment and using alternative energy sources. This helps to significantly reduce the environmental impact of using SOF. Comparing the data obtained during the study, it can be stated that an integrated approach to improving the environmental friendliness of the use of SOF has a substantial impact on reducing the environmental burden. The implementation of efficient ash utilisation methods and modern emission reduction technologies is proving to be effective in reducing toxic emissions and improving environmental quality (Mysak *et al.*, 2017). This data confirms that the integration of innovative solutions in the field of recycling and pollution control is the key to achieving sustainable and environmentally friendly use of the SOF.

Innovative developments in the use of SOF, such as integration with other renewable energy sources and the use of AI to optimise processes, have demonstrated the prospects for a considerable increase in the efficiency of energy systems. The use of these technologies would enable the creation of more sustainable and cost-effective SOF-based solutions for electricity generation. A. Shah *et al.* (2022) concluded that innovative technologies such as pyrolysis and gasification considerably increase the efficiency of SOF use, reducing pollutant emissions and lowering operating costs. Automation systems and new materials for flue gas cleaning make the use of the SOF more environmentally friendly and economical. M. Hasan *et al.* (2022) found that integrating SOF with renewable sources such as biomass or solar energy can ensure a stable energy supply, reduce dependence on fossil fuels, and lower greenhouse gas emissions. Combining SOF with renewable sources increases economic efficiency and reduces the environmental footprint of energy systems. When analysing the results of the study, it is clear that the introduction of innovative technologies in the use of SOF substantially increases their efficiency and reduces the negative environmental impact. Specifically, improved combustion processes and new methods of flue gas treatment provide a significant reduction in emissions and lower operating costs. At the same time, the integration of SOF with renewable energy sources opens prospects for more sustainable and economical use of energy resources, improving environmental performance, and reducing dependence on fossil fuels. Thus, a comprehensive approach to technology optimisation and integration with renewable sources is key to achieving sustainable energy.

Thus, the analytical study confirmed the need for further modernisation and optimisation of the systems that use SOF to achieve high efficiency and minimise negative environmental impact. The results also highlighted the significance of investing in innovative technologies and increasing automation to ensure sustainable and environmentally friendly electricity production in the future.

CONCLUSIONS

The analytical study revealed that the use of SOF for electricity generation can be efficient and environmentally friendly, provided that modern technologies and approaches are applied. It was found that the introduction of the latest technologies, such as combustion in pure oxygen, gasification, and pyrolysis, can reduce emissions of harmful substances, which has a positive impact on the environmental situation. However, these technologies require sophisticated gas purification systems, which considerably increases the cost of electricity production.

The optimisation of boiler and turbine designs using high-temperature alloys and nanomaterials has substantially improved heat transfer efficiency. High-temperature alloys increased operating temperature and corrosion resistance, while nanomaterials reduced heat loss and increased wear resistance. This helped to increase the overall efficiency and extend the service life of the equipment. Automation of fuel supply systems ensured the stability of power plants, reducing fuel losses and the risk of interruptions. Despite the high cost, the introduction of such systems has considerably increased the efficiency of electricity generation and reduced maintenance costs. Environmental aspects, such as ash and slag recycling and emissions reduction, have become key to improving environmental safety. The use of ash and slag as fertilisers or building materials reduced waste and provided additional economic benefits, while modern gas cleaning technologies reduced emissions of harmful substances into the atmosphere.

Thus, the study confirmed the significance of modernising and optimising SOF-based systems to achieve high efficiency and environmental safety in electricity generation. The economic feasibility and safety of utilising ash and slag from solid organic fuels as fertiliser or construction material should be further investigated. A limitation of this study was the lack of a detailed analysis of the economic efficiency of implementing modern gas cleaning technologies and automation of fuel preparation and supply systems.

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CONFLICT OF INTEREST

None.

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Аналітичне дослідження з підвищення ефективності та екологічності використання твердих органічних палив

Анотація. Метою дослідження було проаналізувати методи підвищення ефективності та екологічності використання твердих органічних палив (ТОП) у виробництві електроенергії. У цьому дослідженні було застосовано комплексний підхід до аналізу та оптимізації технологічних процесів, експлуатаційних систем та екологічних аспектів використання ТОП. В ході дослідження було встановлено, що використання сучасних технологій, таких як газифікація та піроліз, значно підвищує ефективність перетворення ТОП у електроенергію. Оптимізація конструкцій котлів та турбін, а також автоматизація систем подачі палива, сприяє зниженню втрат енергії та підвищенню загальної ефективності систем. Встановлено, що використання нових матеріалів для котлів підвищує їх стійкість до корозії та ерозії, що продовжує термін служби обладнання. Дослідження також показало, що впровадження систем очистки газів та вторинного спалювання значно зменшує викиди шкідливих речовин, що покращує екологічні показники. Аналіз можливостей утилізації золи показав, що її використання як добрива або будівельного матеріалу є перспективним напрямком. У результаті дослідження доведено, що комплексний підхід до використання ТОП може суттєво підвищити їх ефективність та екологічність. Результати дослідження показали, що застосування інноваційних методів управління процесами горіння дозволяє досягти більш стабільного та ефективного виробництва електроенергії. Доведено, що впровадження автоматизованих систем моніторингу та контролю знижує експлуатаційні витрати і підвищує надійність роботи обладнання. У ході дослідження було також встановлено, що використання передових аналітичних інструментів для прогнозування зношуваності обладнання дозволяє своєчасно проводити профілактичні ремонти, що додатково підвищує ефективність і тривалість безперебійної роботи енергетичних систем

Ключові слова: тверде органічне паливо; газифікація; піроліз; електроенергія; корозія; ерозія; екологія

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Comparative study of PI-controller and neurocontroller performances in optimal by settling time control problems

Abstract. When developing control systems, an important issue arises of choosing an operator, which forms the control function. The standard approach is to use a PI- or PID-controller, a more advanced approach involves ANNs training for this purpose. A comparative analysis of the PI- and neurocontroller performances makes it possible to establish the disadvantages and advantages of each of the compared controllers, which is an important scientific and applied problem. The purpose of the work was to conduct a comparative analysis of the performance of the PI-controller and the neurocontroller based on a set of evaluation indicators for plants of the second and third orders. Such a comparison was carried out by using an approach to the synthesis of both controllers, which involved the minimization of a complex objective function. The latter is obtained as a result of reducing the problem of optimal control with constraints to the problem of unconstrained optimization. The analysis showed that according to the settling time indicator (optimization criterion), the neurocontroller has an advantage of 6.1…96.2% for the modelled plants. At the same time, according to other indicators of the control quality, the PI-controller has an advantage. In addition, the synthesis of a neurocontroller in terms of finding the minimum of the objective function is a more difficult problem. For its solution, a bigger number of iterations of the VCT-PSO optimization algorithm is required. It is rationally to set more than 1000 iterations and swarm population in the range 30…50 particles. A comparative analysis by the settling time of the neurocontroller and PI-controller, which is tuned according to engineering methods, showed significant reserves for improving this indicator. Thus, if the requirements for settling time minimization are quite strict, then it is advisable to use a neurocontroller. The obtained results will make it possible to develop recommendations for the rational choice of the control operator when solving practical problems of the control systems synthesis

Keywords: plant; objective function; comparison; neurocontroller; control estimation indicators

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INTRODUCTION

State of technology development, particularly in the fields of electromechanics, electronics, and automation, involves the use of feedback control (regulation) systems. For their synthesis, engineers may use an extremely diverse range of mathematical methods. Quite often, the same control problem can be solved by using different approaches. PID-controllers are simple and very common (O'Dwyer, 2009). H_2-controllers (Brand & Cole, 2021) are optimal in a sense of quadratic criterion. Fuzzy-controllers (Tong *et al.*, 2020) and neurocontrollers (Ghahramani *et al.*, 2020) implement a soft-computing approach for solution of control problems.

This is far from a complete list of types of controllers, that may be used to solve a specific control problem. At the same time, there is a need to determine which approach will be rational. In order to give an answer to this question, it is necessary to perform a comparative analysis of the qualitative indicators of the work of various controllers.

Certain steps in this direction have already been taken. For example, M. Dhandapani *et al.* (2024) reviewed the use of a PI- and a neuro-controller when charging the batteries of vehicles with electric traction ensures a stable voltage of the direct current link. However, suppression of higher harmonics is somewhat better performed by the neurocontroller.

According to A. Nouri *et al.* (2024), combined schemes of controllers make it possible to obtain a better effect when controlling the accumulation of electrical energy in photovoltaic energy technologies. In their work, it is proved that the ANN in combination with the linear-quadratic-regulator (LQR)-controller provides better performance and stability of the energy storage installation compared to the artificial neural network – proportional-integral (ANN-PI)-controller.

Interesting are the comparative studies of M. Yessef *et al.* (2022) on the use of PI-, fuzzy-, neuro-controllers, sliding controllers, and controllers in which the "backstepping" method is applied to control the parameters of wind turbines. The results of the comparison showed that the neurocontroller has the best values of response duration, static error, and accuracy when changing the set point among the compared controllers. The worst quality indicators correspond to the work of the PI-controller.

In a study by D.E. Beladjine *et al.* (2021), the authors used PI- and neurocontrollers for the problem of control of the brushless motor rotation speed. The PI-controller showed a response time of 0.0523 s, and the neurocontroller – 0.0447 s. Such a difference can be significant in applications where precision and high speed of the actuator are required.

For a similar task in the study of H.S. Sridhar *et al.* (2020) used a slightly different approach. Here, for the control problem of a brushless motor, the performance of a PI-controller and a PI-controller configured by using ANN technology are compared. As these studies have shown, the operation of the last controller is not characterized by overshoot, it has a much higher speed and almost zero static error.

In these works, the authors usually focus on one plant (wind turbine, brushless motor, etc.). However, the involvement of a certain class of plants of different orders in the research will make it possible to obtain more general results. This is the approach implemented in this study.

Thus, the results of a comparative analysis of the work of one or another controller will make it possible to establish the disadvantages and advantages of each of them, which is an important scientific and applied problem to solve.

The aim of the work was to conduct a comparative analysis of the work of the PI-controller and the neurocontroller based on a set of evaluation indicators for plants of the second and third orders, since they are the most common in practice.

MATERIALS AND METHODS

The methodology of the research was as follows:

1) carry out the statement of the control problems of linear the second and third orders plants;

2) find solutions to control problems by using linear (PI-) and nonlinear (based on ANN) control operators;

3) conduct a comparative study of the results of the work of controllers for selected plants;

4) to establish the peculiarities of the application of controllers for the problem of optimal control of linear plants.

To ensure the general applicability of the technique, test plants described by Yu. Romasevych *et al.* (2019) were utilized. Their transfer functions are given in Table 1.

Table 1. Plants and their features

Plant transfer function	Features
$G_1(s)=\frac{1}{(s+1)^2}$	Systems with such transfer functions are very common in practice. These transfer functions have been used for a long time for the problems of testing the developed controllers.
$G_2(s)=\frac{1}{(s+1)^3}$	
$G_3(s)=\frac{1-0.1s}{(s+1)^3}$	These transfer functions have three identical poles and zero, which is in the right half-plane. The quality of control is determined by the parameter 0.1 in the numerator: when this value increases, the controls quality deteriorates.
$G_4(s)=\frac{e^{-s}}{(0.5s+1)^2}$	This transfer function has been used in many studies of PID-controllers. When the value 0.5 increases, the delay of the plant increases.

Source: compiled by the authors

For plants whose transfer functions were given in Table 1, it was necessary to synthesize optimal control operators. In this study, the settling time was taken as the optimality criterion:

$$t_s \to \min, \tag{1}$$

where t_s – settling time, i.e. time moment, when the following condition is meet:

$$\frac{|r-x(t)|}{r} \leq \Delta, t \geq t_s, \tag{2}$$

where r – setpoint; x – process variable; Δ – relative acceptable deviation of process variable from the setpoint (according to the engineering requirements Δ was set Δ = 0.05).

In addition to the requirement to minimize criterion (1), the absence of overshoot was required:

$$\frac{max(x(t))-r}{r} \leq 0, t \in [0, t_s]. \tag{3}$$

The main requirement for the synthesis of any controller operator is to ensure the stability of the closed-loop control system. This requirement was written in the following form:

$$\begin{cases} \lim\limits_{t\to\infty} x(t) = r; \\ \lim\limits_{t\to\infty} \dot{x}(t) = 0; \\ \dots \\ \lim\limits_{t\to\infty} \overset{n}{x}(t) = 0, \end{cases} \tag{4}$$

where n – plant order. Here and further, the number above the symbol means the order of the time derivative.

In order to ensure that all conditions (1)-(4) are met, the objective function was considered:

$$Cr = Ter + Osh + t_s \to \min, \tag{5}$$

where Ter and Osh – the terminal criterion and the criterion responsible for the meeting of the condition of no overshoot (3), respectively.

The components of the objective function (5) Ter and Osh impose penalties when conditions (3) and (4) are not met, respectively. They were written as follows:

$$Ter = \begin{cases} \left(|x(t)-r| + \sum_{i=1}^{n}\left|\overset{i}{x}(t)\right|\right)\delta_{Ter}, if\,|x(t)-r| > \Delta_x \vee |\dot{x}(t)| > \Delta_{\dot{x}} \vee \dots \vee \left|\overset{n}{x}(t)\right| > \Delta_{\overset{n}{x}}; \\ 0, if\,|x(t)-r| \leq \Delta_x \wedge |\dot{x}(t)| \leq \Delta_{\dot{x}} \wedge \dots \wedge \left|\overset{n}{x}(t)\right| \leq \Delta_{\overset{n}{x}}; \end{cases}$$

$$Osh = \begin{cases} \frac{max(x(t))-r}{r}, if\,\frac{max(x(t))-r}{r}\delta_{Osh}; \\ 0, if\,\frac{max(x(t))-r}{r} \leq 0, \end{cases} \tag{6}$$

where δ_{Ter} and δ_{Osh} – weighting coefficients that form the desired topology of the objective function and were set as follows: $\delta_{Ter} = 10^{10}$ $\delta_{Osh} = 10^4$ (these values were set in order to provide a "pit-in-pit" topology of the objective function. When optimizing the objective function (5), a solution that satisfies the condition $Ter = 0$ was first found, and only then a solution for which $Osh = 0$ was found. Consistent fulfillment of the specified conditions facilitates the process of finding the minimum of the function (5), $\Delta_x, \dots, \Delta_x^n$ – respectively, the limit values of the process variable and its higher derivatives by time, including the order of the plant (all these values were set equal to 10^{-3}; this further ensures the achievement of the desired solutions of the problem and allows the conditions (4) to be approximately fulfilled).

Within the framework of the study, a mathematical operator – ANN was chosen to control the test linear plants the second and third orders (Table 2). This choice is due to the nonlinear properties of ANNs, which, as is known (Cybenko, 1989), form powerful approximation properties of ANNs. They, in turn, can be used to design a control operator that would meet the conditions of the control problem (1)-(4) – i.e. perform the required nonlinear mapping of input variables (state variables of the plant) into the output control function. In addition, for the synthesis of the operator that ensures the control conditions (1)-(4), a PI-controller was chosen. It is described by the following expression:

$$u = K_p(r - x(t)) + \int_0^t (r - x(t))dt, \tag{7}$$

where K_p and T_i – proportional and integral gains of the PI-controller, respectively, which are should be found as arguments on which the objective function (5) reaches a minimum. Features of the control operators used in the study (linear – PI-controller and nonlinear – neurocontroller) are shown in Table 2.

Table 2. Features of control operators

Plant transfer function	Neurocontroller						PI-controller	
	Inputs number	Outputs number	Number of neurons in the hidden layer	Neuron activation function	Parameters number (weights and biases)	Search domain	K_p search domain	T_i search domain
$G_1(s)$	2	1	5	arctg	21	-1…1	0…20	
$G_2(s)$	3				26			
$G_3(s)$	3				26			
$G_4(s)$	2				21			

Source: compiled by the authors

Since this research used the settling time criterion (1), the presence of constraints on the control function, which is formed at the output of the control operator, was a significant factor. It had a significant effect on the t_s value. Taking into account the constraints was also related to the possibility of technical implementation of the control strategy with the help of existing executive devices of the control system. In this study, for this the following expression was used:

$$\tilde{u} = \begin{cases} 5u, \text{ if } u_{\min} \le 5u \le u_{\max}; \\ u_{\min}, \text{ if } u_{\min} > 5u; \\ u_{\max}, \text{ if } 5u > u_{\max}, \end{cases} \quad (8)$$

where u_{max} and u_{min} – maximum and minimum control value, respectively ($u_{max}=2$; $u_{min}=0$). In expression (8), the empirical coefficient 5 is used in order to increase the value of control at the output of one or another controller and, thus, to increase the speed of the reaching of the setpoint r. The modified VCT-PSO particle swarm method (Romasevych *et al.*, 2022) was used to minimize the objective function (5). Its characteristics are given in Table 3.

Table 3. Features of VCT-PSO algorithm

Feature	Numerical value
Iterations number	100
Swarm population	30
Coefficients values:	
w	0.72
c_1	1.19
c_2	1.19
RC	5

Source: compiled by the authors

The choose of the VCT-PSO algorithm was grounded by its strong search features. Indeed, it localized a global minimum for quit complex objective functions (Romasevych *et al.*, 2022). Thus, one may hope, that this optimization algorithm will found the needed solutions of the stated problems.

RESULTS AND DISCUSSION

As a result of the application of the VCT-PSO algorithm, the K_p and T_i coefficients of the PI-controller, as well as the values of the weights and biases of the neurocontroller were obtained for all optimization problems. Moreover, for different problems, a different nature of the process of minimization of the objective functions (5) was observed. To evaluate it, the plot the convergence of the objective function (5) (in a logarithmic scale) was built (Fig. 1).

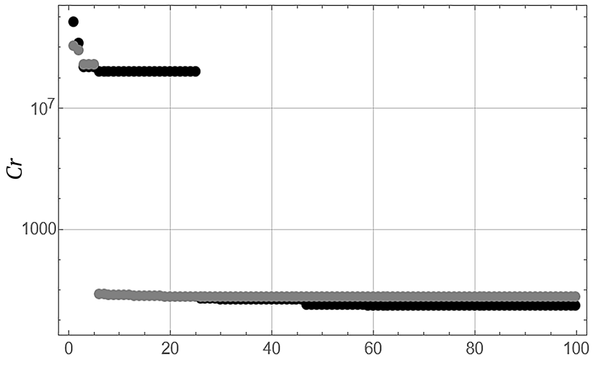

Figure 1. Plots of objective function (5) reducing in the problem of optimal PI-controllers (grey plot) and neurocontroller (black plot) for the plant with transfer function $G_2(s)$

Source: compiled by the authors

From Figure 1, it can be seen that for the case of using a PI-controller, the VCT-PSO algorithm already finds a solution on the sixth iteration that ensures the fulfillment of conditions (6). In the future, only the minimization of criterion (1) is performed. In contrast, finding a similar solution in the case of using a neurocontroller occurred at the twenty-sixth iteration. This is explained by the more complex topology of the objective function. Indeed, the number of arguments that must be determined in the process of neurocontroller training is 26, which is 13 times more than the number of PI-controller coefficients. In addition, since the neurocontroller is a nonlinear operator, the topology of the corresponding objective function (5) will be much more complicated.

The minimization of the objective function for other plants has a similar to that shown in Fig. 1 feature. The only difference lies in the number of iterations at which the components of the function (5) *Ter* and *Osh* are become zero. For cases with a smaller number of arguments of the *Cr* function (the number of parameters of the neurocontroller of second-order plants is equal to 21), there is a faster search of a solution in which the *Ter* and *Osh* components become zero. As a result of the conducted research, the numerical values of the coefficients of the PI-controller K_p and T_i, as well as the weights and biases of the neurocontroller (Table 4) were obtained for each plant (Table 1).

Table 4. Values of the obtained controllers' parameters

Plant transfer function	Neurocontroller				PI-controller	
	Matrix weights of hidden layer	Vector of biases of hidden layer	Vector of weights of output layer	Bias of output layer	K_p	T_i
$G_1(s)$	$\begin{pmatrix} -0.687 & 0.688 \\ 0.570 & -0.367 \\ -0.237 & -0.566 \\ 0.207 & -0.598 \\ -0.960 & -0.984 \end{pmatrix}$	$\begin{pmatrix} 0.733 \\ -0.827 \\ 0.187 \\ 0.402 \\ 0.941 \end{pmatrix}$	$\begin{pmatrix} 0.256 \\ 1.000 \\ 0.866 \\ 0.899 \\ 0.962 \end{pmatrix}$	0.874	0.334	6.568

Continued Table 4.

Plant transfer function	Neurocontroller				PI-controller	
	Matrix weights of hidden layer	Vector of biases of hidden layer	Vector of weights of output layer	Bias of output layer	K_p	T_i
$G_2(s)$	$\begin{pmatrix} -0.400 & -0.146 & -0.581 \\ -0.018 & -0.398 & -0.111 \\ 0.347 & -0.114 & -0.912 \\ -0.590 & -0.659 & -0.068 \\ 0.043 & -0.405 & -0.879 \end{pmatrix}$	$\begin{pmatrix} 0.231 \\ 0.198 \\ -0.814 \\ 0.358 \\ 0.506 \end{pmatrix}$	$\begin{pmatrix} 0.238 \\ -0.01 \\ -0.284 \\ -0.221 \\ -0.259 \end{pmatrix}$	0.646	0.124	15.735
$G_3(s)$	$\begin{pmatrix} -0.766 & -0.239 & 0.471 \\ 0.232 & 0.027 & -0.973 \\ 0.521 & 0.962 & -0.989 \\ 0.863 & 0.675 & 0.319 \\ -0.506 & -0.405 & 0.985 \end{pmatrix}$	$\begin{pmatrix} 0.787 \\ 0.923 \\ -0.849 \\ -0.503 \\ -0.045 \end{pmatrix}$	$\begin{pmatrix} 0.946 \\ 0.201 \\ 0.301 \\ -0.677 \\ -0.790 \end{pmatrix}$	0.311	0.124	15.735
$G_4(s)$	$\begin{pmatrix} 0.447 & -0.166 \\ -0.991 & -0.511 \\ 0.978 & -0.068 \\ -0.212 & 0.112 \\ -0.382 & 0.007 \end{pmatrix}$	$\begin{pmatrix} 0.406 \\ 0.796 \\ -0.872 \\ 0.402 \\ -0.400 \end{pmatrix}$	$\begin{pmatrix} 0.211 \\ -0.212 \\ -0.682 \\ 0.788 \\ -0.833 \end{pmatrix}$	0.770	0.259	8.815

Source: compiled by the authors

The results of modelling the reaching the process variable $x(t)$ the set point $r = 1$ (black curve) and the control function (gray curve) for various plots are shown in Figure 2. Here, the graphical dependences on the left correspond to the control carried out with the help of a PI-controller, and on the right - a neurocontroller.

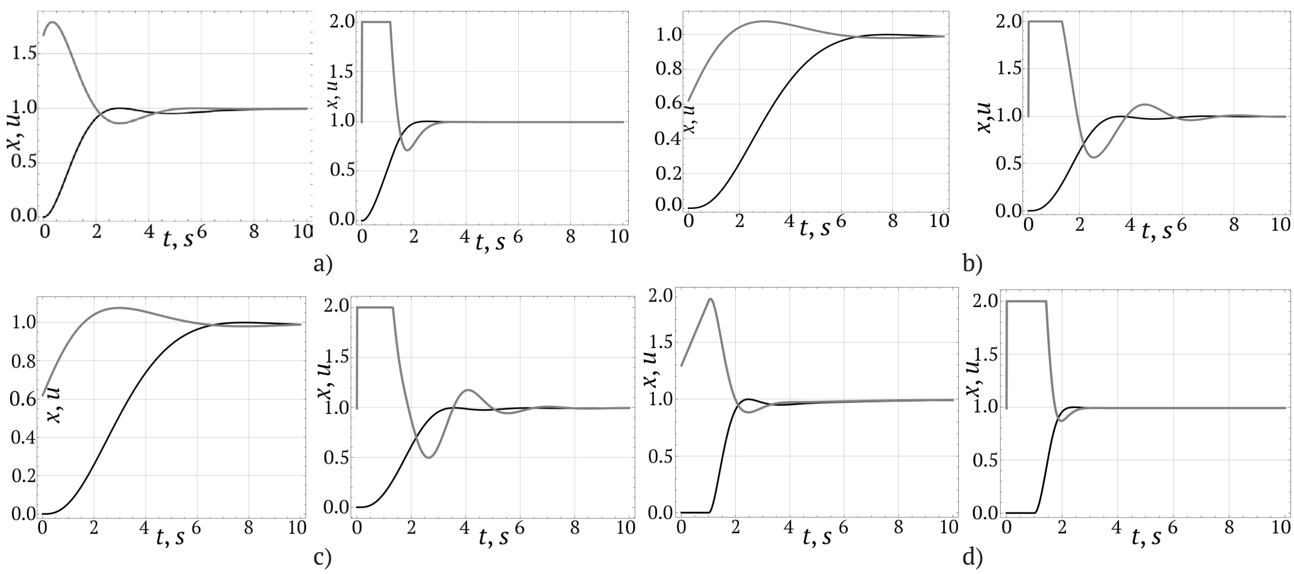

Figure 2. Plots of control function and process variable under PI-controller and neurocontroller application for the plants with transfer function

Note: a) $G_1(s)$; b) $G_2(s)$; c) $G_3(s)$; d) $G_4(s)$

Source: compiled by the authors

For the completeness of the analysis of the obtained results, the numerical values of the estimated indicators of the control quality, corresponding to the application of the PI-controller and the neurocontroller (Table 5) were given.

Table 5. Values of quality control indicators

Plant transfer function	Settling time		Mean error value		Mean control value	
	PI-controller	neurocontroller	PI-controller	neurocontroller	PI-controller	neurocontroller
$G_1(s)$	2.19	1.79	0.511	0.544	1.432	1.636
$G_2(s)$	5.73	2.92	0.533	0.595	0.988	1.430
$G_3(s)$	5.73	2.95	0.533	0.606	0.988	1.393
$G_4(s)$	2.09	1.97	0.743	0.763	1.504	1.775

Source: compiled by the authors

The analysis of graphical dependencies (Fig. 2) shows that for all cases of transfer functions $G_1(s)...G_4(s)$ the use of a neurocontroller is associated with the reaching the u_{max} constraint. This reduces the settling time t_s. In addition, from Figure 2a, 2d, it can be seen that after reaching the set point r, the process variable $x(t)$ does not change. The characteristics described above favorably distinguish the use of a neurocontroller from a PI-controller. For the cases, indicated in Figure 2b, 2c, the process variable $x(t)$ has only slight change.

A comparison of the qualitative indicators of control, which are given in Table 5, shows that the neurocontroller allows to significantly decrease the settling time. The relative value of such an increase in speed for all cases of transfer functions $G_1(s)...G_4(s)$ is within 6.1...96.2%. Larger values of the specified range refer to third-order plants, which are described by the transfer functions $G_2(s)$ and $G_3(s)$. Such an increase in the control performance (by settling time) occurred at the expense of a slight deterioration of other control quality indicators. For example, the mean error value when using a neurocontroller increased by 2.7...13.7%, and the mean control value – by 18.0...44.7% (Table 5).

Comparing the obtained results on the indicator of the settling time with other studies of Yu. Romasevych *et al.* (2019), it may be concluded that the neurocontroller shows better efficiency by 21.8...71.2% than the PI-controller, the coefficients of which were found as a result of solving the optimization problem (1)-(4). A comparison of this indicator was also carried out with PI-controllers tuned by methods widely used in engineering practice. They are classical Ziegler-Nikols (Ziegler & Nichols, 1942) method and some of its recent variations: Kappa-Tau (Åström & Hägglund, 1995), AMIGO (Åström & Hägglund, 2004). Comparison was carried out based on other methods: Chien-Hrones-Rewick (Chien *et al.,* 1952), Cohen-Coon (Cohen & Coon, 1953), Lambda (Eriksson, 2008). Skogestad (Skogestad, 2003), Tures-Luyben (Luyben, 1997) methods also were used for comparison purposes (Table 6).

Table 6. Increasing of control speed of neurocontroller comparing to PI-controllers tuned by engineering methods, times

Plant transfer function	Methods of PI-controller tuning							
	Ziegler-Nichols	Kappa-Tau	AMIGO	Chien-Hrones-Reswick	Cohen-Coon	Lambda Tuning	Skogestad	Tyreus-Luyben
$G_1(s)$	1.68	2.57	3.18	3.35	3.24	7.37	2.18	-
$G_2(s)$	4.18	3.32	4.66	7.84	6.95	5.62	3.08	6.06
$G_3(s)$	5.29	3.56	4.92	9.08	8.14	5.59	2.03	7.93
$G_4(s)$	15.68	4.72	4.21	27.21	-	30.46	2.08	28.53

Source: compiled by the authors

The analysis of the data shown in Table 6 allows us to state that the neurocontroller provides significantly higher performance compared to the PI-controller, which is tuned by using engineering methods. It should be noted that although the specified engineering methods for tuning a PI-controller are quite common in practice, they do not always provide optimal control parameters. At the same time, the purpose of the conducted comparative analysis is to identify reserves for decreasing the settling time. As can be seen, no matter what approaches are used to tune the PI controller – engineering (Table 6) or optimization (Table 5) – in the case of switching to the use of a neurocontroller, such reserves exist.

From the data presented in Table 6 one may conclude, that there is a tendency – the higher a plant order, the bigger the decreasing of the settling time. The only exception is the tuning method developed by S. Skogestad (2003). Providing the comparative analysis of the settling time values referred to the mentioned tuning methods and neurocontroller performance some statements become obvious. The most of the commonly used tuning Ziegler-Nikols method (Ziegler & Nichols, 1942) shows good settling time value, but only for plant with transfer function $G_1(s)$. Indeed, the difference of this control quality indicator is only 68%. For the rest of the involved in the calculations plants the difference is in magnitudes (especially for the plant with transfer function $G_4(s)$). Similar statements may be done for PI-controller performances, which are obtained by Chien-Hrones-Rewick (Chien *et al.,* 1952), Lambda (Eriksson, 2008), Tures-Luyben (Luyben & Luyben, 1997) tuning approaches. For them settling time differs 27.21...30.46 times (Table 6).

Other domain of PI-controller tuning methods Kappa-Tau (Åström & Hägglund, 1995), AMIGO (Åström & Hägglund, 2004), Skogestad (Skogestad *et al.,* 2003) indicates low influence by a plant order. The varying of the times of settling time increasing for these cases is quite low: for Kappa-Tau (Åström & Hägglund, 1995) is in the range 2.57...4.72; for AMIGO (Åström & Hägglund, 2004) – 3.18...4.21; for Skogestad (Skogestad, 2003) – 2.03...3.08.

Note, that all the numerical experiments (both for PI-controllers and for a neurocontroller) were carried out with plants, which described transfer functions given in Table 1. However, the important difference between neurocontroller performance and PI-controllers, which are tuned with mentioned methods, are in outputs (control function). Such improving of settling time indicator is connected with more flexibility of neurocontroller. It has dozens of adjustable parameters (degrees of freedom). Their proper tuning allows forming the needed control function. In general, it is may be concluded that the developed (trained) neurocontroller has better settling time for all cases - an indicator that was used as an element of the optimal control statement (1)-(4). Such an advantage was obviously achieved due to the fact that the neurocontroller is a non-linear control operator that can do the optimal control strategy quite well. Unlike a PI-controller, it has a much larger number of degrees of freedom (weights and biases). Their purposeful change makes it possible to obtain a significant improvement of one or another quality control indicator. At the same time, in order to fully realize the approximation properties of the neurocontroller, it is necessary to have a powerful optimization algorithm, which can ensure the minimization of the appropriately constructed objective function on multiple degrees of freedom of the neurocontroller. Therefore, the solution of the problem of optimal control (by settling time) largely depends on the applied optimizer. It is likely that this conclusion can be extended to a number of other optimization criteria and other plants. However, this thesis is not asserted – within the framework of this study, it remains only a hypothesis that will be proven or disproved in further research by the authors.

CONCLUSIONS

This study presents the results of a comparative analysis of the work of the PI-controller and the neurocontroller for four test plants of second- and third-order. Optimization approaches for tuning PI-controller and training the ANN for control problems (the ANN acts as a control operator) makes it possible to obtain a significant increase in the speed of control. This thesis is based on a comparison of the performance of optimally tuned controllers and PI-controllers that are tuned by using engineering methods. The use of a neurocontroller makes it possible to increase the speed of operation in the range of 6.1...96.2% for the plants, which are described by the transfer functions $G_1(s)...G_4(s)$. To a greater extent, the improvement of this indicator is associated with the third order plants. At the same time, it is necessary to note a certain increase in other undesirable indicators (the mean error value by 2.7...13.7%, the mean control value – by 18.0...44.7%). Therefore, the optimization of the settling time is associated with a certain decrease in other qualitative indicators of control, which quite naturally leads to the idea of using complex optimization criteria. The latter will be used in further research by the authors. The use of ANNs for the control problem requires a justified choice of the optimization algorithm. Within the framework of this work, the VCT-PSO algorithm made it possible to solve all optimization problems, and therefore it may be recommended it for solving problems of this kind. Cases of more complex problems (larger number of ANN parameters, higher orders of control plants, their nonlinearity, etc.) will require careful adjustment of the parameters of the VCT-PSO method (the number of particles in the swarm – 30...50, the number of iterations – more than 1000).

In addition to the above, it is may be indicated other prospects for further research in this direction: the use of more complex models of neurocontrollers for delayed and unstable plants; taking into account other significant constraints that affect the dynamics of control (for example, constraints on the rate of change of the control function , which is caused by the electromagnetic and mechanical inertia of the executive device of the control system); optimization of other control modes (for example, neutralization of external disturbances).

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Порівняльний аналіз роботи ПІ-регуляторів та нейрорегуляторів у задачах оптимального за швидкодією регулювання

Анотація. При розробці систем автоматичного регулювання важливе питання вибору оператора для керуючого впливу на об'єкт можна вирішити за допомогою стандартних ПІ- чи ПІД-регуляторів або навчання штучної нейронної мережі, що потребує порівняльного аналізу їхніх переваг і недоліків. Мета роботи полягала у проведенні порівняльного аналізу роботи ПІ-регулятора та нейрорегулятора за комплексом оціночних показників для об'єктів регулювання другого та третього порядків. Таке порівняння проводилось із застосуванням єдиного підходу щодо синтезу обох регуляторів, який передбачав мінімізацію складної цільової функції. Остання отримана у результаті зведення задачі оптимального регулювання із обмеженнями до задачі безумовної оптимізації. Результати аналізу показали, що за показником швидкодії (критерій оптимізації) нейрорегулятор на модельованих об'єктах регулювання має перевагу на 6,1…96,2 %. Разом з тим, за іншими показниками якості регулювання переважає ПІ-регулятор. Синтез нейрорегулятора у плані відшукування мінімуму цільової функції є складнішою задачею, для вирішення якої необхідна більша кількість ітерацій оптимізаційного алгоритма VCT-PSO. При цьому раціонально задавати кількість ітерацій більше 1000 та розмірність рою 30…50 частинок. Порівняльний аналіз швидкодії нейрорегулятора та ПІ-регуляторів, які налаштовані за інженерними методиками показав значні резерви покращення цього показника. Таким чином, якщо вимоги максимізації швидкодії регулювання є досить жорсткими, то доцільно застосовувати нейрорегулятор. Отримані результати дадуть змогу виконати раціональний вибір оператора регулювання при вирішенні практичних задач синтезу систем регулювання

Ключові слова: об'єкт регулювання; цільова функція; порівняння; нейрорегулятор; оціночні показники регулювання

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Search for innovative solutions to improve the energy system of Ukraine: World experience

Abstract. This study analyses the global experience of introducing innovations in the energy sector to identify effective solutions that can be applied to improve the energy system of Ukraine. The research methods included a comparative analysis of international experience in the energy sector, an assessment of the possibilities of adapting innovative technologies to Ukrainian conditions, and an examination of technical and economic aspects of integrating new solutions. The study analysed the experience of countries such as Germany, Denmark, the United States, Finland, the Netherlands, Sweden, Japan, China, France, and South Korea, which have succeeded in implementing innovative solutions in the energy sector, in particular, in the integration of renewable energy sources (RES), the development of smart networks, energy decentralisation, energy storage technologies, and energy efficiency improvement. It is identified that the most efficient approaches include the integrated use of renewable energy sources in combination with energy storage, which ensures

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the stability of energy supply even in conditions of uneven electricity production. The importance of smart networks for optimising energy distribution and reducing losses is also emphasised. The decentralisation of energy and the development of energy cooperatives contribute to improving energy security and community engagement. The study also showed that the introduction of smart energy management systems at the consumer level helps to increase the flexibility of the energy system and effectively respond to fluctuations in demand. In addition, it is determined that the successful implementation of innovative projects in the energy sector requires state support through subsidies and regulatory incentives. Based on international experience, it is concluded that combining technical solutions with effective management and political initiatives is key to ensuring the sustainable development of the Ukrainian energy system

Keywords: supply stability; smart networks; decentralisation; sustainable development models; subsidies; policy initiatives

INTRODUCTION

In the context of the global energy crisis, the need for stable energy supplies and the challenges caused by shelling, Ukraine faces an important task of modernising its energy system. Substantial reliance on traditional energy sources and low energy efficiency jeopardise national energy security. It is critically important to consider the global experience of implementing innovative solutions that contribute to the development of renewable energy sources (RES), energy decentralisation, and the introduction of smart networks and energy storage technologies. The experience of countries that have successfully implemented these approaches can become an important source of knowledge and practical recommendations for improving the energy system of Ukraine and increasing its resilience to the challenges of the modern world.

In the examined area of the Ukrainian energy system, there are several substantial problems that need to be solved. There is a substantial dependence on traditional energy sources, which threatens energy security and the environmental situation (Shahini *et al*., 2024). Insufficient integration of renewable energy into the national energy system and the lack of efficient energy storage mechanisms limit the ability to ensure a stable and sustainable energy supply. C. Lamnatou *et al*. (2022) focus on the integration of renewable energy sources into national energy systems, especially their impact on reducing CO_2 emissions. In addition, the study examines problems and solutions for integration in the context of existing infrastructure. D.K. Panda & S. Das (2021) examine the efficiency of smart networks, in particular, their ability to optimise energy distribution and reduce energy costs. Their paper also focuses on the practical aspects of implementing such networks in different regions. S. Sahoo & P. Timmann (2023) analyse current energy storage technologies, especially their impact on the stability of energy supply in irregular production. Their study includes evaluating the efficiency of various types of energy storage systems.

J. Fouladvand *et al*. (2022) explore the role of decentralisation in energy, focusing on the impact of energy cooperatives on improving energy security at the local level. They also explore the benefits and challenges of decentralised energy supply models. Y. Shao & Z. Chen (2022) examine the impact of government subsidies and regulatory incentives on innovation in the energy sector. In the study, they considered the impact of these mechanisms on the development and implementation of new technologies. M. Meliani *et al*. (2021) demonstrate how smart energy management systems can increase the flexibility of energy systems. The study also showed how these systems help adapt to changes in energy demand. U. Datta *et al*. (2021) describe in detail the benefits of integrated renewable energy use together with energy storage to ensure supply stability. The study includes an analysis of various approaches and their impact on energy stability.

A. Kumar *et al*. (2021) focus on improving energy efficiency through the latest technologies in construction and industry. The study highlights the importance of innovation in reducing energy consumption and reducing costs. M. Fowlie & R. Meeks (2021) analyse the experience of countries that have successfully implemented energy efficiency programmes. They emphasise the importance of adapting such practices to the conditions of other countries to improve the energy situation. M. Guertler & N. Sick (2021) emphasise the importance of international partnerships and the exchange of experience in implementing innovative projects in the energy sector. Their study also examines the role of international cooperation in the introduction of new technologies. Gaps that require further study include the lack of adaptation of smart networks to the specific conditions of Ukraine and the lack of detailed studies on the effectiveness of various energy storage technologies in the context of local climatic and economic realities. In addition, it is necessary to explore more deeply the possibilities of energy decentralisation through energy cooperatives and local initiatives and to examine the impact of regulatory and financial incentives on the development of innovative solutions in the energy sector of Ukraine.

The purpose of the study was to investigate the world experience of innovations in the energy sector for further use in Ukraine. Objectives of the study:

- analyse the world experience of implementing innovative solutions in the energy sector to identify the most effective practices;
- evaluate technologies and approaches that contribute to the integration of renewable energy sources and improve energy efficiency;

consider the possibilities of adapting these innovative solutions to the conditions of the Ukrainian energy system and their impact on ensuring a stable energy supply and improving economic efficiency.

MATERIALS AND METHODS

The study examined key aspects of renewable energy integration, the use of smart grid technologies, the decentralisation of the energy system, the introduction of energy storage technologies, and improving energy efficiency.

The study compared different types of electricity generation in Ukraine to assess their efficiency and impact on the country's energy system. The analysis included aspects such as power, efficiency, CO_2 emissions and the cost of electricity for each type of generation. This allowed determining the most efficient and environmentally friendly solutions for ensuring Ukraine's energy security.

The experience of Germany, which is actively developing programmes to support wind and solar power plants, has been of considerable interest in analysing the regulatory mechanisms and technical integration of renewable energy into the national energy system (Krug *et al.*, 2022). The experience of Denmark was considered, which has achieved success in the development of offshore wind farms that can have potential for the coastal regions of Ukraine (Harguindéguy and Wokuri, 2024). An important aspect was the investigation of the possibilities of technical integration and ensuring the reliability of the power system at the expense of renewable energy sources.

The introduction of smart grid technologies that can improve the efficiency of energy supply management is analysed. The experience of the United States was considered, where the introduction of such networks allowed substantially optimising the balance of energy supply and demand, and reduce losses in power grids (Butt *et al.*, 2021). Finland's experience in using smart electricity metering technologies to improve energy consumption control and improve energy supply efficiency (Tuomela *et al.*, 2021).

The decentralisation of the energy system has also become an important element of the study. The experience of the Netherlands (Warbroek *et al.*, 2023) and Sweden (Lundmark *et al.*, 2021), where the development of energy cooperatives and the use of local resources such as biomass contributed to improving regional energy security. The prospects for using these approaches in rural regions of Ukraine were considered, considering the specifics of local energy resources and the need to decentralise energy supply.

The study also focused on energy storage opportunities, which are becoming increasingly relevant in the context of the growing share of renewable energy sources. The experience of Japan, where the development of energy storage technologies allows stabilising energy supply, was reviewed (Zhang *et al.*, 2021). In addition, Chinese experience in the development of large-scale energy storage batteries was considered (Fan *et al.*, 2021).

Special attention is paid to improving energy efficiency, which is important for reducing the load on the power system. In this context, the experience of France on programmes to improve the energy efficiency of buildings and industrial facilities (Belaïd *et al.*, 2021) and South Korea's experience in implementing subsidies for energy-saving technologies was examined (Park *et al.*, 2023). These aspects are of great importance for optimising the use of energy resources in the industrial and residential sectors of Ukraine.

The study considered a thermal power plant with the following characteristics: mains voltage V = 230 V, current I = 100 A, and power factor Cos(φ) = 0.9. These parameters are typical for medium-power stations that are used to power large industrial enterprises and residential areas (Zhang *et al.*, 2024). The calculation was conducted for a typical thermal power plant that provides consumers with heat and electricity, typical for regions with high demand for stable energy supply. The following formulas were used in the study:

1. Formula for calculating the power plant capacity (1):

$$P = V \times I \times \cos(\phi), \tag{1}$$

where P is power (W); V is Voltage (V); I is current (A); cos(ϕ) – power factor.

2. Formula for calculating generation efficiency (2):

$$\eta = \frac{P_{useful}}{P_{input}} \times 100\%, \tag{2}$$

where η – efficiency; P_{useful} – net power (W); P_{input} – input power (W).

3. Formula for calculating CO_2 emissions per unit of energy produced:

$$E_{CO_2} = \frac{M_{CO_2}}{E_{produced}}, \tag{3}$$

where E_{CO_2} – CO_2 emissions per unit of energy (t/GW·h); M_{CO_2} – mass of CO_2 emissions (t), $E_{produced}$ – produced energy (GW·h).

4. Formula for calculating the cost of electricity:

$$C = \frac{T}{E_{produced}}, \tag{4}$$

where C is the cost of electricity (UAH/kW·H); T – total expenses (UAH).

5. Formula for calculating the return on investment time:

$$T_{payback} = \frac{C_{investment}}{C_{energy\ saved}}, \tag{5}$$

where $T_{payback}$ – payback period (years); $C_{investment}$ – total investment (UAH); $C_{energy\ saved}$ – savings in energy costs for the year (UAH).

The research methods included a comparative analysis of innovative solutions, adaptation of international experience to Ukrainian conditions, and assessment of opportunities for implementing new technologies. Comparing data from different countries allowed forming recommendations for integrating international practices into the national energy system of Ukraine, which can substantially increase its efficiency and stability.

RESULTS

The energy system of Ukraine is a critical component of the national infrastructure that ensures the functioning of the economy, industry, and social sphere. It consists of traditional energy sources such as coal, gas, and nuclear power, and renewable energy sources such as solar and wind power. However, in light of global changes and national needs, the Ukrainian energy sector faces numerous challenges that require urgent solutions and modernisation.

One of the main problems is the high dependence on traditional energy sources, in particular, imported gas, which creates risks for energy security and economic stability. Declining domestic coal reserves and an ageing energy infrastructure are also having a negative impact on the energy sector. In addition, the limited integration of renewable energy sources into the national energy system hinders the development of sustainable and environmentally friendly technologies.

The war with Russia, which has been going on since 2014 and has particularly worsened since 2022, has substantially complicated the situation. The war caused the destruction of critical infrastructure, in particular, energy facilities (Lazor *et al.*, 2024). Damage to power plants, power lines, and gas pipelines has led to frequent power outages and reduced energy security. These factors not only complicate the provision of energy to the population and industry but also substantially increase the cost of infrastructure restoration and modernisation (Table 1).

Table 1. Impact of war on Ukraine's energy system

Impact of war	Description	Consequences	Possible solutions
Infrastructure destruction	Damage to power plants, power lines, and gas pipelines	Frequent power outages, increased recovery costs	Repair and modernisation of damaged facilities, strengthening infrastructure protection
Reducing energy security	Risks of lack of stable energy supply due to fighting	Deterioration of the quality of energy services, economic losses	Development of alternative energy sources, decentralisation of the energy system
Increased recovery costs	High costs for the repair and reconstruction of energy infrastructure	Financial pressure on the state budget, delays in modernisation	Search for international financial assistance, effective resource management
Disruption of energy supply chains	Problems with energy supplies due to blockades and fighting	The emergence of energy shortages, higher prices	Expansion of national production, diversification of suppliers
Environmental impacts	Pollution and damage to environmental systems due to fighting	Negative impact on the environment, additional costs for environmental restoration work	Implementation of environmental standards in restoration, monitoring of the ecological state

Source: compiled by the authors on the basis of data obtained by O. Lazor *et al*. (2024)

Table 2 shows the technical characteristics and economic indicators of various types of power generation in Ukraine. Data include power, efficiency, CO_2 emissions, the cost of electricity, and other characteristics such as flexibility and speed of response. The analysis of these indicators allows assessing the advantages and disadvantages of each type of generation, and their impact on the environmental situation and economic efficiency of the Ukrainian energy system.

Table 2. Comparison of different types of electricity generation in Ukraine

Generation type	Power (MW)	Efficiency (%)	CO_2 emissions (t/GW·h)	Electricity cost (UAH/kW·h)	Other features
Coal-fired thermal power plant	5,000-7,000	33-40	900-1,000	2-3	Less flexibility, higher CO_2 emissions, high pollution
Gas-fired thermal power plant	3,000-5,000	45-55	400-500	2.5-3.5	Higher flexibility, lower CO_2 emissions compared to coal-fired thermal power plants
Nuclear power plant	1,000-3,000	33-37	10-15	1-1.5	Low CO_2 emissions, high safety level, high capital cost
Hydroelectric power station	100-3,000	70-90	0	0.5-1	High flexibility, minimal CO_2 emissions, impact on ecosystems
Wind farms	50-1,500	35-45	0	1.5-2.5	Weather dependence, minimum CO_2 emissions
Solar power plants	10-1,000	15-20	0	2-3	Dependence on solar activity, minimum CO_2 emissions

Source: compiled by the authors

Various analytical tools and mathematical formulas are used to assess the efficiency of electric generating plants and their impact on the economy and environment. They allow calculating such key indicators as generator power, efficiency, carbon dioxide emissions, the cost of electricity production and the payback period for investments in energy-saving projects. The following calculation examples provide a deeper understanding of how to evaluate the efficiency of energy projects and reduce their negative impact on the environment.

Formula (1) is used to determine the power of an electric generator or network. Voltage, current, and power factor are the main parameters for estimating system power. When the voltage in the electrical system is V = 230 V, the current flowing through the system is I = 100 A, and the power factor (phase) cos(ϕ) = 0.9. Then, the power is calculated as:

$$P = 230 \times 100 \times 0.9 = 20.7 \text{ kW}.$$

Thus, the power of the system is 20.7 kW, which means that the power plant can provide consumers with this amount of energy every second. Efficiency shows how much of the input power is converted into useful work. High efficiency indicates the performance effectiveness of the system. If the power plant consumes input power P_{input} = 250 kW and the net power used by consumers is P_{useful} = 200 kW. Then efficiency:

$$\eta = \frac{200}{250} \times 100\% = 80\%.$$

This means that 80% of the incoming energy is converted to usable energy, and the remaining 20% is lost, for example, in the form of heat or other undesirable forms of energy. Formula (3) helps estimate how much carbon dioxide emissions are produced per GW·hour of energy. CO_2 emissions is one of the key indicators of the environmental impact of power plants. If a thermal power plant produces $E_{produced}$ = 2 GW·hour of electricity and emits E_{CO_2} = 500 tonnes of carbon dioxide during its operation, then:

$$E_{CO_2} = \frac{500}{2} = 250 \text{ t/GW} \cdot \text{h}.$$

This means that for each GW·h of energy produced, 250 tonnes of CO_2 are emitted. This indicator can be used to compare different types of energy generation by their impact on the environment. The cost of electricity allows determining how much it costs to produce one kW·hour of energy. This indicator is important for assessing the economic feasibility of various generation technologies. If the power plant produces $E_{produced}$ = 1,000,000 kW·hour of energy and the total cost of its production is T = 500,000 UAH. Then the cost of electricity will be:

$$C = \frac{500{,}000}{1{,}000{,}000} = 0.5 \text{ UAH/kW} \cdot \text{h}.$$

This means that the production of one kW·hour of energy costs 0.5 UAH. Formula (5) allows determining how many years the investment in the project will be repaid by saving on energy consumption. If the project for installing solar panels cost $C_{investment}$ = 1,000,000 UAH and the annual savings in electricity costs are $C_{energy\ saved}$ = 200,000 UAH. Then the payback time of the project will be:

$$T_{payback} = \frac{1{,}000{,}000}{20{,}000} = 5 \text{ years}.$$

Consequently, the investment will pay off in 5 years, after which the project will begin to bring a net profit. The results of the study show that the efficiency of a thermal power plant with an efficiency of 80% and an emission index of 250 t/GWH is substantially lower compared to modern technologies implemented in other European countries. For example, German renewable energy-based power plants achieve substantially higher efficiency through the use of innovative energy storage technologies and reduced heat losses. In addition, CO_2 emission indicators in Germany are substantially lower due to the active introduction of "green" technologies and the rejection of the use of fossil fuels (Ibrahim *et al*., 2024). Consequently, the calculation results emphasise the need to modernise power generation systems and introduce renewable energy sources to improve energy efficiency and reduce environmental impact.

In the context of current challenges, two main strategies are important: the modernisation of existing capacities and the implementation of innovative solutions (Treshchov, 2024). Modernisation of the energy infrastructure is aimed at improving efficiency and reducing the cost of energy resources. Important aspects include upgrading equipment in thermal power plants, improving energy storage technologies, and integrating smart grids to optimise energy distribution. Special attention should be paid to the restoration and protection of the energy infrastructure affected by the fighting.

Implementing innovative solutions is another important component of the strategy. In particular, the development of renewable energy sources, such as solar and wind, can substantially reduce dependence on imported resources and reduce the environmental footprint. In addition, decentralising the energy system through energy cooperatives and local initiatives can help improve energy security and involve local communities in energy resource management. It can also help reduce the system's vulnerability to external threats.

Government policies and regulatory initiatives play an important role in this process. The introduction of subsidies and tax incentives for investors in innovative technologies, and the creation of favourable conditions for solving bureaucratic obstacles, can substantially accelerate the transition to sustainable energy. In particular, state support for the restoration of infrastructure and ensuring the safety of energy facilities is critical in the current conditions. Thus, the energy system of Ukraine is at an important stage of transformation, which is complicated by the war. It is necessary to actively implement innovative solutions, modernise infrastructure, and provide state support to ensure its stability and development. Only through an integrated approach to solving these problems can the efficient and sustainable functioning of the energy system be ensured, which will meet the needs of the economy and society in the face of military threats and global challenges.

The energy system of Ukraine faces challenges that require not only the modernisation of existing technologies but also the introduction of innovative solutions. One of the key areas is the integration of renewable energy sources. In this context, the experience of Germany and Denmark can provide valuable lessons for Ukraine. Germany is a leader in renewable energy due to its ambitious Energiewende programme, which was introduced to gradually move from fossil energy sources to renewable energy sources (Krug *et al.*, 2022). The main aspects of this programme are the expansion of wind and solar energy, which reduces dependence on traditional energy sources and reduces greenhouse gas emissions. One of the key elements of Germany's success is the regulatory system, which includes substantial subsidies for renewable energy investors. This allowed to reduce financial risks and make investments in renewable energy more attractive. The system of maintaining prices for electricity produced from renewable sources also encourages the development of new projects.

The technical integration of renewable energy into the national energy system is another important aspect. Germany is actively developing energy storage infrastructure and improving networks to effectively cope with the unpredictability of renewable energy production. Network management systems that allow the integration of large volumes of renewable energy are an important component of this strategy. Germany is a leader in the introduction of renewable energy sources. Since 2010, the share of renewable energy sources in the country's electric grid has increased from 20% to 47% in 2023. Modernisation of electrical networks, including the introduction of new transformers and high-voltage lines, allowed increasing the capacity by 15%. For example, the introduction of new standards for power lines has increased their capacity from 5,000 MW to 5,750 MW. Ukraine can use the experience of Germany to create its own strategy for the development of renewable energy sources. The German model of subsidies and regulation can provide an opportunity to build reliable support for investors. In addition, the modernisation of the energy infrastructure, including energy storage, is important for the integration of new energy sources into the Ukrainian system.

Denmark also demonstrates substantial progress in the development of wind energy, in particular, in the use of offshore wind farms (Harguindéguy & Wokuri, 2024). Denmark is one of the pioneers in this field, and its experience can be extremely useful for Ukraine, especially in coastal areas. Denmark's offshore wind farms allow efficient use of offshore winds, providing a stable and powerful energy source. Denmark has developed advanced technologies for the construction and operation of such parks, including innovative solutions to reduce the impact on the marine environment and increase the cost-effectiveness of projects. Denmark is actively developing offshore wind farms. In 2023, the share of wind farms in total electricity production reached 61%. The introduction of new energy storage systems, such as large-scale batteries, has helped stabilise the power supply, reducing dependence on wind fluctuations by 20%. The Black and Azov Seas have potential for offshore wind power in Ukraine. Denmark's experience can help create efficient wind farms that will expand the renewable energy sector. The use of modern technologies will ensure minimal impact on ecosystems and increase the productivity of energy production.

RES integration is an important component of the strategy for the sustainable development of the Ukrainian energy system. The experience of Germany and Denmark in the field of renewable energy development can provide Ukraine with valuable guidelines for adapting its own energy strategy. Borrowing successful practices such as the German regulatory system and Danish offshore wind farm technology can substantially improve the efficiency and stability of Ukraine's energy system, contributing to its independence and sustainable development.

The modern energy system faces new challenges that require innovative solutions to improve the efficiency and reliability of electricity supply. One such solution is smart grids, which can substantially improve the management of energy systems. The experience of the United States and Finland in implementing these technologies can become an important guide for Ukraine in its efforts to modernise its energy infrastructure. In the United States, smart grids have become an important component of energy infrastructure due to their ability to improve energy efficiency, reduce energy losses, and improve system management (Butt *et al.*, 2021). Smart networks in the United States integrate the latest technologies into traditional electrical networks, which reduces energy costs and increases its reliability.

The main elements of smart networks are sensors, automated control systems, and real-time data acquisition systems. These components provide the ability to monitor and analyse the state of the power system in real time, which allows responding faster to failures and optimising energy distribution. The introduction of smart grids in the United States has reduced energy losses, improved the quality of electricity supply, and ensured more efficient use of renewable energy sources. The introduction of smart grids in the United States has reduced power losses by 7-10% due to automated management and monitoring. Currently, about 25% of American households use smart meters, which can reduce energy costs by 5%. An important area for Ukraine is the introduction of smart networks. They can improve the efficiency of renewable energy integration and ensure the stability of the power system. Such networks help to better manage non-constant electricity generation and ensure uninterrupted supply even during failures.

Finland demonstrates successful experience in implementing smart electricity metering technologies (Tuomela *et al.*, 2021). Smart metering technologies allow consumers to control their electricity consumption and improve energy efficiency better. Smart meters used in Finland provide detailed monitoring of electricity consumption in real time and provide consumers with information regarding cost optimisation. The smart accounting system in Finland includes integration with energy networks for automatic data collection and analysis, which allows identifying trends and anomalies in consumption. This, in turn, helps to manage energy resources more efficiently and reduces the cost of energy services. Such technologies also allow consumers to better understand their energy consumption and make better-informed decisions about saving it. In Finland, the use of smart electricity metering has reduced energy costs by 12% in a number of cities due to accurate monitoring and management of consumption. The introduction of new energy storage technologies has helped reduce peak load costs by 15%.

Smart accounting technologies will help Ukraine improve energy efficiency at both the household and industrial levels. They provide consumers with the opportunity to control electricity costs and implement energy-saving measures, which, in turn, will have a positive impact on the country's economy. The integration of smart grids into the Ukrainian energy system is an important step towards its modernisation and efficiency improvement. The experience of the US in implementing smart networks and Finland's experience in developing smart accounting technologies can serve as important guidelines for Ukraine. Following these practices and adapting them to national conditions will allow Ukraine to substantially improve the management of energy resources, reduce costs, and increase the stability of the energy system.

Current trends in the development of energy systems increasingly point to the importance of decentralisation and active participation of local communities in energy production and consumption. The approaches implemented in the Netherlands and Sweden are of considerable interest to Ukraine, where the issue of energy security and stability remains relevant. Energy cooperatives and decentralised energy models implemented in these countries can become important elements in the formation of an efficient and sustainable energy infrastructure in Ukraine. The Netherlands is an example of a country where energy cooperatives are actively developing (Warbroek *et al.*, 2023). In this context, local communities take the initiative to produce and consume energy, which contributes to the decentralisation of energy systems and improving energy security. Energy cooperatives in the Netherlands allow citizens to pool their resources, creating and managing local energy sources such as solar panels and wind turbines.

Such cooperatives not only provide local residents with clean energy but also contribute to economic development at the local level. Members of cooperatives have the opportunity to control energy costs and benefit from the sale of excess energy. In addition, energy cooperatives help reduce dependence on centralised energy suppliers and increase the sustainability of the energy system. The Netherlands has focused on the decentralisation of the energy system. The development of energy cooperatives and the use of biomass allowed increasing the share of renewable energy sources to 20% in 2023. It also helped reduce energy security costs by 10%. Ukraine can borrow the experience of the Netherlands in creating energy cooperatives, which will help increase energy autonomy at the local level. This is especially important for regions where there is a need to reduce dependence on centralised suppliers and encourage local development.

Sweden has successfully applied models of decentralised energy, in particular, in the use of local resources such as biomass (Lundmark *et al.*, 2021). The Swedish model is based on the principle that local resources can meet the energy needs of regions, reducing dependence on external energy sources and increasing the sustainability of the system. The use of biomass, agricultural waste, and other local resources allows Sweden to create efficient energy supply systems that meet the specific conditions of each region. This not only helps reduce greenhouse gas emissions but also encourages rural development by creating new jobs and supporting local businesses. Sweden has made substantial strides in introducing biomass as an energy source, increasing its share to 35% in total production. The introduction of new biomass combustion technologies has reduced CO_2 emissions by 25% over the past 10 years. The use of Swedish practices in processing biomass and agricultural waste for energy production is a promising path for Ukraine. This can reduce emissions, increase energy efficiency, and boost economic development in rural areas.

Energy cooperatives and decentralised energy models implemented in the Netherlands and Sweden represent valuable experience for Ukraine. The integration of these approaches can substantially improve the efficiency and sustainability of energy systems in Ukraine, ensure a more even distribution of energy resources, and promote the development of local communities. The use of local resources and the participation of communities in energy production can be important factors in improving energy security and stability in Ukraine.

In the context of the global transition to renewable energy and the growing demand for energy stability, energy storage technologies have become an important component of modern energy systems (Shram & Kachan, 2023). Japan and China are leaders in this area, and their achievements can serve as a guide for Ukraine, which seeks to reduce its dependence on traditional energy sources and ensure the stability of its energy system. Japan is one of the leading countries in the development of energy storage technologies. Japanese companies are actively investing in the latest battery systems that allow efficient storage and use of energy from renewable energy sources (Zhang *et al.*, 2021). One of the key technologies is the use of lithium-ion batteries, which provide high energy density and long service life.

Japanese developments in this area not only improve the efficiency of renewable energy use but also contribute to the stability of the energy system. They allow storing energy during periods of low consumption or excessive production and using it when consumption exceeds production. This helps reduce dependence on traditional energy sources and ensures an uninterrupted power supply. Japan is actively developing energy storage technologies. Large-scale batteries introduced after Fukushima can store up to 10 GW·hour of energy that helps stabilise the energy system. This reduces fluctuations in energy supply by 30%. Japanese energy storage technologies can be useful for Ukraine in the context of improving the stability of the energy system. Considering the Japanese experience will help reduce the risks associated with fluctuations in energy production from renewable sources and ensure the smooth operation of networks.

China is also actively investing in developing and producing high-capacity batteries (Fan *et al.*, 2021). The Chinese approach focuses on large-scale production and improvement of energy storage technologies. Chinese company Contemporary Amperex Technology Co. Limited is a global leader in the production of lithium-ion batteries used in electric vehicles and energy storage systems. China is a world leader in the development of large-scale energy storage batteries. Investment in this area allowed the country to install 30 GW of energy storage capacity in 2023. This reduced energy infrastructure costs by 15%. With a large amount of investment and technological innovation, China has the ability to provide high-quality batteries at competitive prices. This makes energy storage technologies more accessible to developing countries, including Ukraine. The introduction of Chinese technologies can help Ukraine create energy storage systems that will ensure a stable supply of electricity even in conditions of uneven production from renewable energy sources.

Energy storage technologies developed in Japan and China can substantially affect Ukraine's energy infrastructure. Japanese experience in the development of high-efficiency batteries and Chinese achievements in large-scale production of high-capacity batteries represent a substantial potential for improving the stability and efficiency of the Ukrainian energy system. Adapting and implementing these technologies can reduce dependence on traditional energy sources, ensure reliable electricity supplies, and contribute to the sustainable development of the country's energy sector.

In today's world, the growing emphasis on sustainable development and energy security forces countries to look for ways to reduce energy consumption and improve energy efficiency. France and South Korea are prime examples of countries successfully implementing energy efficiency programmes, and their experience can serve as a valuable guide for Ukraine in this direction. France is one of the European countries that actively implements energy efficiency programmes in both the construction sector and industry (Belaïd *et al.*, 2021). The French approach to energy efficiency is based on an integrated approach that includes regulations, financial incentives, and technological innovations. One of the main initiatives is the Plan Bâtiment Durable programme, which aims to reduce energy consumption in buildings through the introduction of new construction standards, modernisation of existing buildings, and the use of energy-saving technologies.

France also implements support programmes that promote the energy modernisation of industrial facilities, through the provision of subsidies and tax incentives for enterprises implementing energy-saving technologies. These initiatives not only reduce energy consumption but also energy costs and the negative impact on the environment. In France, energy efficiency programmes for buildings have reduced energy consumption by 20% in a number of new projects. This was achieved by introducing the latest thermal modernisation technologies, such as energy-saving windows and insulation. Ukraine can use the French experience to develop energy-efficient regulations and support innovations in industry and the construction sector. This will reduce energy consumption and increase the overall efficiency of using energy resources.

South Korea is another example of a country that is actively developing energy efficiency programmes (Park *et al.*, 2023). An important part of the Korean strategy is to provide subsidies and encourage the introduction of energy-saving technologies through various financial instruments, such as compensation programmes and tax breaks for companies implementing energy projects. Korea is also actively implementing energy efficiency technologies in construction and industry. In particular, the programmes promote the use of highly efficient heating and cooling systems, the introduction of modern energy management systems, and infrastructure modernisation. This allows reducing energy consumption at all levels, reducing the load on the energy infrastructure and energy costs. South Korea has introduced subsidies for energy-saving technologies, which has reduced energy costs by 18% in the industrial sector. The introduction of new accounting technologies has reduced the cost of energy resources by 10%. Ukraine can consider the experience of South Korea, which has made substantial progress in improving energy efficiency through financial incentives and technological innovations. The introduction of subsidies and compensations for energy-saving technologies will contribute to improving energy efficiency at the national level.

Reducing energy consumption and improving energy efficiency are critical aspects of ensuring energy security and sustainable development. The experience of France and South Korea in implementing energy efficiency programmes provides Ukraine with the opportunity to implement proven practices to achieve these goals. Learning and adapting these approaches can substantially improve a country's energy efficiency, reduce the burden on energy infrastructure, and promote sustainable development. Thus, innovative solutions, such as the integration of renewable energy sources, the introduction of smart networks, the development of energy storage technologies, energy decentralisation, and energy efficiency improvement, are critical to improving the energy system of Ukraine (Table 3).

These solutions will not only help ensure the stability and efficiency of the energy system but also contribute to the economic and environmental development of the country in the face of modern challenges.

Table 3. Key innovative solutions for improving the energy system of Ukraine

Innovative solution	Description	Advantages
RES integration	Introduction of solar, wind, and hydroelectric power plants	Reducing dependence on imported energy carriers, reducing CO_2 emissions
Smart networks	The use of digital technologies for monitoring and managing the energy network	Optimising energy distribution, reducing losses, and improving efficiency
Energy storage technologies	Introduction of battery systems and other storage technologies	Ensuring the stability of power supply, supporting renewable energy sources
Energy decentralisation	Creation of local energy cooperatives and independent energy sources	Improving energy security, involving communities in management
Improving energy efficiency	Introduction of new technologies in construction and industry to reduce energy consumption	Reduce overall energy consumption, reduce costs

Source: compiled by the authors on the basis of L. Mykhailova & O. Dumanskyi (2024)

Adaptation and implementation of international experience in the energy system of Ukraine can be a crucial factor in ensuring its sustainability, efficiency, and independence. Innovative solutions, such as renewable energy integration, smart grid development, energy decentralisation, energy storage, and energy efficiency improvement, can substantially change the energy landscape of Ukraine, making it more adaptive to modern challenges.

DISCUSSION

As a result of the analysis of innovative solutions for improving the energy system, it was determined that the integration of renewable energy sources is a key aspect for ensuring energy stability. The identified data confirm that the use of solar and wind power plants contributes to reducing dependence on traditional, imported energy carriers, and substantially reducing greenhouse gas emissions. This approach allows for a more sustainable energy environment and meets international environmental standards. However, it is also necessary to consider potential risks, such as instability in renewable energy production, which may affect the reliability of energy supply. This was also investigated by M. Farghali *et al*. (2023), where the results confirmed that the integration of renewable energy sources, such as solar and wind energy, reduces the negative environmental impact of traditional fuels by reducing emissions of polluting gases. However, RES can affect local ecosystems, for example, wind turbines can harm birds, and hydroelectric power plants can alter river ecosystems. It is important to conduct environmental assessments and take measures to minimise negative impacts. A study by S. Erdoğan *et al*. (2021) also showed that switching to renewable energy can substantially reduce dependence on traditional energy resources such as oil, gas, and coal. This not only reduces greenhouse gas emissions but also the economic dependence on imported fuels, which can improve the country's energy security. Notably, this transition also has economic advantages since renewable energy sources often have reduced operating costs compared to traditional sources. Despite the advantages of renewable energy sources, their integration into energy systems requires careful planning and investment in new technologies. The effectiveness of renewable energy sources may depend on the geographical location, climatic conditions, and level of infrastructure development (Stoliarov, 2024). In addition, it is necessary to consider potential environmental impacts, such as the need for backup systems to ensure the stability of energy supplies. Existing challenges can be overcome through innovations in energy storage technologies and improved management practices.

The second important aspect is the introduction of smart networks, which has been confirmed by the results of the study. Smart grid technologies allow managing energy flows more efficiently, reducing energy losses, and increasing overall system efficiency (Selvakumar *et al*., 2024). However, the implementation of such systems requires substantial investment and adaptation to the specific conditions of the Ukrainian market, which can be a challenge for large-scale implementation. M. Judge *et al*. (2022) concluded that the introduction of smart grids ensures the integration of modern technologies into energy systems to improve their efficiency and reliability. Smart networks use sensors, automated systems, and data analytics to monitor and manage electrical networks in real time. This allows optimising energy distribution, reducing the likelihood of supply disruptions, and improving response to changing consumption conditions. Key benefits include increased fault tolerance, the ability to integrate renewable energy sources, and improved load management. T. Ahmad & D. Zhang (2021) established that smart grids show high efficiency in reducing energy costs by being able to accurately measure and monitor energy consumption. They provide more precise control of electrical loads, which reduces energy costs and optimises the operation of generators. The use of data analytics is used to predict demand and adjust energy generation in accordance with the needs of consumers, which reduces the cost of maintaining excess capacity. These results support the above study, as they demonstrate the benefits of smart grids in reducing energy costs and improving system efficiency. They show that such networks optimise energy distribution, reduce costs, and improve the reliability of energy supply, confirming their role in ensuring economic and energy efficiency.

Energy storage technologies have also demonstrated their importance. Battery systems ensure a stable power supply, compensating for periods of low renewable energy production (Amidu *et al.*, 2023). The study results showed that such systems were successfully implemented in the Kyiv region, where they helped to save excess energy and ensure its availability during peak periods. Therewith, the cost of implementing and maintaining battery systems remains high, which requires additional funding and support from the state. A paper of Q. Wu *et al.* (2021) is notable, who also determined that energy storage technologies such as batteries, pumped storage stations, and systems based on new materials play a vital role in ensuring the stability of energy systems. They provide for storing excess energy obtained during periods of high generation or low consumption and its usage at times of peak load or shortage. This helps equalise fluctuations in renewable energy generation, such as wind and sun, which can be unstable. In turn, M. Hannan *et al.* (2021) concluded that battery systems have a substantial impact on ensuring the stability of power supply since they provide the ability to store and distribute energy depending on needs. These systems allow reducing the load on the network during peak consumer periods and provide backup energy sources in the event of interruptions. Batteries also facilitate the integration of renewable energy sources by loading the network during periods of high generation and unloading it during periods of low generation. These data are consistent with the theses presented in the previous section, as they confirm the critical role of energy storage technologies in ensuring the stability of energy systems. In particular, it is shown that battery systems effectively smooth out fluctuations in energy supply and help maintain a balance between generation and consumption. This confirms that increased use of such technologies can reduce dependence on traditional, less stable energy sources and improve the overall reliability of energy infrastructure.

Energy decentralisation, which was analysed in detail, also proved to be an effective tool for improving energy security. The creation of energy cooperatives and the development of local energy sources reduces dependence on centralised suppliers and ensures greater participation of local communities in the management of energy resources (Stepanov *et al.*, 2023). For example, in the Cherkasy region, implemented projects on energy cooperatives have demonstrated a positive impact on the energy independence and economic development of local communities. However, scaling up such initiatives requires a comprehensive approach to state funding and support. A. Berka & M. Dreyfus (2021) also conducted a study that confirmed that energy decentralisation involves the transition from centralised power supply systems to distributed models where energy resources are produced and managed locally. This can have a substantial social impact, in particular, contribute to improving the energy independence of the community, creating new jobs, and developing local economies. However, decentralisation can also lead to uneven access to new technologies and resources, especially in remote or economically weaker regions. M. Rabbi *et al.* (2022) also established that energy cooperatives play an important role in improving energy security through collective ownership and management of energy resources at the local level. Such cooperatives allow communities to invest together in renewable energy sources, such as solar or wind installations, and provide reliable energy supplies, especially in remote or poorly connected areas. It also helps reduce energy costs and increase resilience to energy crises. Comparing the data obtained in the course of the study, it can be argued that the decentralisation of energy and energy cooperatives substantially increases social and economic sustainability. Decentralised systems provide greater energy independence and create new jobs, improving the social structure. Energy cooperatives increase energy security by reducing costs and stabilising supplies, especially in remote regions. Data confirm that these models effectively contribute to development and stability but their success depends on equal access to new technologies.

Improving energy efficiency, as the results of the study showed, is crucial for reducing overall energy consumption. Projects for the thermal modernisation of buildings in large cities, such as Kyiv and Kharkiv, have confirmed that the latest technologies can substantially reduce the cost of heating and air conditioning, which has a positive impact on the economic situation and environmental balance. However, the successful implementation of such projects requires ensuring the appropriate level of qualification of performers and compliance with high quality standards. H. Sun *et al.* (2021) concluded that the latest technologies, such as intelligent energy management systems, high-performance thermal insulation materials, and state-of-the-art automation systems, play an important role in improving the energy efficiency of buildings and industrial processes. In particular, the introduction of intelligent control technologies allows optimising energy consumption in real time, reducing costs, and improving the overall efficiency of energy systems. Highly efficient materials and automation systems provide a substantial reduction in energy consumption for heating and cooling, which also has a positive impact on economic performance. R. Blazy *et al.* (2021) note that thermal modernisation, which includes updating thermal insulation, replacing old windows and doors, and improving heating and ventilation systems, has a substantial impact on overall energy consumption. It reduces heat loss and the need for energy for heating or cooling buildings. This, in turn, helps reduce energy costs and improve living comfort. When analysing the results of the study, it is clear that the latest technologies and thermal modernisation substantially increase energy efficiency. Intelligent control systems and efficient materials reduce energy consumption, resulting in economic and environmental benefits. Thermal modernisation also substantially reduces overall energy consumption and reduces costs, confirming its effectiveness in reducing heat loss and improving comfort.

In general, the results obtained highlight the need to integrate innovative solutions into all aspects of the Ukrainian energy system. Despite the positive trends demonstrated by various innovative approaches, there are substantial challenges associated with financing, technological adaptation, and state support. In the future, to achieve sustainable development of the energy system, it is necessary to continue research, improve existing solutions, and adapt them to the specific conditions of Ukraine.

CONCLUSIONS

A comparative analysis of international experience shows that the introduction of innovative solutions in the energy sector can substantially improve the efficiency and stability of energy systems. For Ukraine, where modernisation of energy infrastructure is critical, it is advisable to adapt successful practices from other countries, in particular, optimise networks, integrate renewable energy sources, and use modern energy storage technologies. This will ensure the sustainability of energy supplies and reduce energy infrastructure costs.

The integration of renewable energy sources, such as solar and wind power plants, has demonstrated its effectiveness in reducing dependence on traditional energy resources and reducing greenhouse gas emissions. The introduction of such technologies ensures environmental stability and meets international standards.

The study also confirmed the importance of smart grids for optimising energy distribution, reducing costs, and improving overall system efficiency. Energy storage technologies, including battery systems, contribute to the stability of the energy supply and help compensate for periods of low renewable energy production.

Decentralisation of energy, including the creation of energy cooperatives and the introduction of innovative technologies, has proven to be an important factor in improving energy security and engaging local communities. Improving energy efficiency through the latest technologies, such as the thermal modernisation of buildings and the use of energy-saving materials, has shown a positive impact on the overall reduction of energy consumption and lower energy costs.

However, the implementation of these innovative solutions in Ukraine requires additional investment and state support. An assessment of international experience shows that success in implementing innovative projects is possible when combining technical solutions with effective management and political initiatives. Thus, to ensure the sustainable development of the Ukrainian energy system, it is important to adjust international practices to the specific conditions of the country and provide the necessary support for the implementation of these solutions.

It is necessary to examine the effectiveness of integrating new technologies in the specific conditions of the regions of Ukraine, including economic and social aspects, to ensure their scalability and sustainability at the national level. A limitation of this study is the lack of a detailed analysis of the economic and social impacts of implementing innovative solutions in different regions of Ukraine, which may affect the overall accuracy of recommendations.

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CONFLICT OF INTEREST

None.

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Пошук інноваційних рішень для вдосконалення енергетичної системи України: світовий досвід

Анотація. Це дослідження аналізує світовий досвід впровадження інновацій в енергетичній сфері для виявлення ефективних рішень, які можуть бути застосовані для вдосконалення енергетичної системи України. Методи дослідження включали порівняльний аналіз міжнародного досвіду в енергетичному секторі, оцінку можливостей адаптації інноваційних технологій до українських умов, а також дослідження технічних і економічних аспектів інтеграції нових рішень. У дослідженні було проаналізовано досвід таких країн, як Німеччина, Данія, США, Фінляндія, Нідерланди, Швеція, Японія, Китай, Франція та Південна Корея, які досягли успіху у впровадженні інноваційних рішень в енергетичній сфері, зокрема в інтеграції відновлюваних джерел енергії (ВДЕ), розвитку розумних мереж, децентралізації енергетики, технологій зберігання енергії та підвищення енергоефективності. Виявлено, що найефективніші підходи включають комплексне використання ВДЕ у поєднанні зі зберіганням енергії, що забезпечує стабільність енергопостачання навіть за умови нерівномірного виробництва електроенергії. Також підкреслено важливість розумних мереж для оптимізації розподілу енергії та зниження втрат. Децентралізація енергетики та розвиток енергетичних кооперативів сприяють підвищенню енергетичної безпеки та залученню громад. Дослідження також показало, що впровадження розумних систем управління енергією на рівні споживачів сприяє підвищенню гнучкості енергосистеми та ефективному реагуванню на коливання попиту. Крім того, виявлено, що успішна реалізація інноваційних проектів у енергетиці потребує підтримки держави через субсидії та регуляторні стимули. На основі світового досвіду зроблено висновок, що поєднання технічних рішень з ефективним управлінням та політичними ініціативами є ключовим для забезпечення сталого розвитку енергетичної системи України

Ключові слова: стабільність постачання; розумні мережі; децентралізація; моделі сталого розвитку; субсидії; політичні ініціативи

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Optimisation of solar power plant parameters for use in sprinklers in Southern Ukraine

Abstract. The study aimed to assess the effectiveness of integrating solar power plants into sprinklers in the Mykolaiv region. Modelling methods, practical tests and analysis of system efficiency were used to optimise the parameters of a solar power plant in the South of Ukraine. The results showed that for sprinklers in this region, a solar power plant should have sufficient capacity to meet the energy needs without significantly increasing the weight of the equipment. The most effective solution was to place the solar panels near the Zimmatic-354M machine, which ensures maximum solar energy production. The analysis showed that the use of batteries allows for uninterrupted operation of the system even with partial shading. Field tests confirmed the theoretical findings and revealed the need to improve the materials of the panels to increase their durability and resistance to dust and temperature fluctuations. Improvements to the design and use of new materials are recommended to increase the efficiency of the system in specific climatic conditions. The study also determined that the integration of solar panels into sprinklers would not adversely affect their manoeuvrability and stability. The results showed that the energy system, designed to meet the specific climatic conditions of southern Ukraine, can ensure the stable operation of sprinklers for a long time. In addition, the study revealed the need for regular maintenance of the panels to maintain their efficiency at the optimum level

Keywords: batteries; energy system; temperature fluctuations; maintenance; solar panel integration; agriculture

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INTRODUCTION

In the South of Ukraine, where the level of solar radiation is quite high for most of the year, the use of solar power plants to power agricultural machinery is gaining relevance. One of the most promising areas is the integration of solar systems into the design of sprinklers. This can significantly reduce energy costs, which is an important factor in reducing the overall cost of farming, and contributes to the environmental friendliness of processes, reducing dependence on fossil energy sources. Solar power plants can provide sprinklers with the energy they need to operate, which can include powering pumps, drive wheels, control systems and other electronic components. However, to achieve maximum efficiency of such systems, specific operating conditions must be addressed. This includes assessing local climatic conditions such as temperature, humidity, rainfall and solar radiation intensity. It is necessary to optimise the parameters of solar systems, such as panel power, panel placement and battery efficiency, to ensure stable and uninterrupted operation of sprinklers. Optimisation of these parameters will not only reduce energy costs but also increase the overall efficiency of the system, which will affect the productivity of agricultural processes and the ecological balance in the region. Thus, research in this area is key to developing effective solutions that meet the requirements of the modern agricultural sector and the specific conditions of southern Ukraine.

Optimising the parameters of solar power plants for sprinklers is an important problem that requires a comprehensive approach to be solved effectively. Various aspects of this problem have been studied by different authors, but certain gaps require further research. A study by C.M. Kumar *et al*. (2023) confirms that solar panels can significantly reduce the energy costs of agricultural machinery while increasing its environmental friendliness. They also note that to maximise the benefits, it is necessary to properly consider local climatic conditions. O. Al-Shahri *et al*. (2021) analysed in detail the methods of optimising the placement of solar panels on machinery to improve their performance. This study shows that the correct positioning of solar panels can increase their efficiency by 20%. P. Chaurasiya *et al*. (2022) studied the impact of partial shading on solar panel performance and found that high-capacity batteries are critical to ensure stable system operation in variable conditions. Z. Quan *et al*. (2021) emphasised the importance of choosing materials for solar panels, in particular their ability to withstand high temperatures and dust. Y. Mases *et al.* (2021) demonstrated that the integration of solar systems into sprinklers can increase their autonomy, reducing the need for traditional energy sources and lowering operating costs. S. Gorjian *et al*. (2021) addressed the impact of different types of batteries on the efficiency of solar systems in the agricultural sector, pointing out the advantages of using modern lithium-ion batteries. M. Ghodki (2022) emphasised the need for regular maintenance of solar panels to maintain their efficiency, which is an important aspect of ensuring the smooth operation of sprinklers. A. Pascaris *et al*. (2021) demonstrated that properly configured solar systems can significantly improve the efficiency of agricultural processes, enabling farmers to reduce their energy costs. M. Jamali *et al*. (2021) highlighted that the integration of solar systems into sprinklers can help reduce greenhouse gas emissions, which has a positive impact on the environment. S. Alsadi & T. Foqha (2021) showed that to optimise the performance of solar systems, specific climatic conditions such as the frequency of sunny days and humidity levels need to be considered, which is particularly important for efficient operation. Thus, although there is a significant amount of research covering various aspects of solar power in agriculture, there are gaps in understanding the impact of the specific climatic conditions of southern Ukraine on the efficiency of such systems that require further study.

The study aims to determine the efficiency of using solar energy to power irrigation systems in the South of Ukraine. The objectives of the study are:

- to analyse the effectiveness of hybrid irrigation systems combining traditional methods with solar energy in the arid climate of the Mykolaiv region;
- to analyse the technical parameters of solar systems and their impact on the performance of sprinklers;
- to develop recommendations for improving the performance and durability of systems in specific climatic conditions.

MATERIALS AND METHODS

The study was conducted at Mykolaiv National Agrarian University in 2024. The study carried out a comprehensive analysis and practical tests to optimise the parameters of a solar power plant for use in sprinklers in the Mykolaiv region of southern Ukraine.

The first step was to calculate the optimal capacity of the solar power plant to meet the energy needs of the sprinkler. This process included considering the insolation variability that is typical for the South of Ukraine. To ensure the smooth operation of the system, seasonal changes in insolation, daylight hours, and potential cloud cover, which can significantly affect the system's efficiency, were addressed. The task was to choose a system capacity that would guarantee the reliable operation of the machine even in adverse weather conditions while reducing energy costs. Calculating the required power of solar panels (1):

$$P_{panels} = \frac{P_{sys}}{H \times \eta}, \tag{1}$$

where P_{panels} – power of the solar panels (kW); P_{sys} – power consumption of the sprinkler (kW); H – average number of sunny hours per day (h); η – system efficiency (dimensionless value).

Calculating the area of solar panels (2):

$$A = \frac{P_{panels}}{Power\ perm^2}, \quad (2)$$

where Power per m² – power of solar panels per unit area (kW/m²). An important part of the study was the determination of the optimal location for the solar panel on the Zimmatic-354M sprinkler (USA). Several options were considered, including the installation of panels on the roofs and sides of the machines. It was necessary to choose the location of the panels, which would minimise shading and maximise solar energy absorption. At the same time, the impact of the weight and size of the panels on the stability and manoeuvrability of the machine was analysed. It was necessary to ensure that the additional components did not reduce efficiency or adversely affect the machine's performance, including its cross-country ability and ability to work on different types of soil.

The study also included the development of an energy storage and management system. Efficient batteries were selected to provide sufficient energy storage to keep the system running during shading or at night. The development of control algorithms optimised the distribution of energy between the various working elements of the machine, as well as between the direct operation of the machine and battery charging. This was aimed at ensuring that the sprinkler operates stably regardless of external conditions, especially during periods of low insolation.

Another important aspect was modelling the system's performance under different climate scenarios specific to the South of Ukraine. Theoretical modelling was used to predict the system's operation during different seasons, which identified potential risks and assessed their impact on overall efficiency. This approach also provided for the possibility of adjusting the system parameters based on the results obtained, which could ensure stable operation even in conditions of partial shading and variable weather factors.

Technical and economic analysis was used to assess the efficiency of using different materials in the construction of solar systems in the South of Ukraine. This method was used to study the effect of materials on the durability and resistance of panels and batteries to dust, moisture and temperature fluctuations. Based on the results obtained, recommendations were developed to improve the design of the solar system, including the use of more efficient materials and improved panel design to reduce the impact of adverse climatic conditions such as dust storms.

RESULTS

Agriculture, especially in southern Ukraine, is in constant need of efficient and reliable energy solutions. In this regard, the introduction of solar power plants to power agricultural machinery, including sprinklers, is one of the key areas for the development of the agricultural sector. However, to achieve maximum efficiency and productivity of such systems, it is necessary to calculate and optimise the capacity of the solar power plant to be used.

One of the most important aspects of this process is to consider the variability of insolation, i.e. the amount of solar energy reaching the Earth's surface in a particular region. In the South of Ukraine, where solar activity is quite high but subject to seasonal fluctuations, this factor is particularly important (Klymenko *et al.*, 2023). To ensure efficient operation of the sprinkler throughout the year, it is necessary to account for changes in insolation in different seasons, as well as the impact of daylight hours and potential cloud cover.

The main step in optimising the capacity of a solar power plant is to determine the energy needs of the sprinkler system. This includes analysing the power consumption in different operating modes and estimating the maximum loads that may occur during operation. It is important that the system capacity not only meets these needs but also provides a reserve in case of reduced efficiency due to deteriorating weather conditions or seasonal changes in insolation.

Seasonal changes in insolation are another important factor to consider when calculating system capacity. In summer, when solar activity is at its highest, the sprinkler can receive enough energy to run smoothly. However, in winter, when daylight hours are shortened and insolation levels decrease, there is a need for additional energy sources or a more powerful energy storage system that can keep the machine running even in partial or full shade (Oudes & Stremke, 2021).

In addition, when choosing the optimal capacity of a solar power plant, it is necessary to account for the possibility of cloud cover, which can significantly reduce the efficiency of the system. In this regard, it is advisable to provide a certain power reserve that will allow the sprinkler to operate stably even in adverse weather conditions.

Thus, choosing the optimal capacity of a solar power plant for sprinklers in Southern Ukraine is a multifactorial process that requires a careful analysis of the machine's energy needs, insolation variability, daylight hours and potential cloud cover. Only when all these conditions are met can the system operate stably and efficiently throughout the year, reducing energy costs and improving the environmental friendliness of agricultural processes.

Modern technologies are trying to ensure the integration of renewable energy sources into various areas of activity, and agriculture is no exception. Incorporating solar panels into the design of sprinklers, such as the Zimmatic-354M (Fig. 1), is one way to improve energy efficiency and reduce energy costs. The main technical parameters of this machine are shown in Table 1.

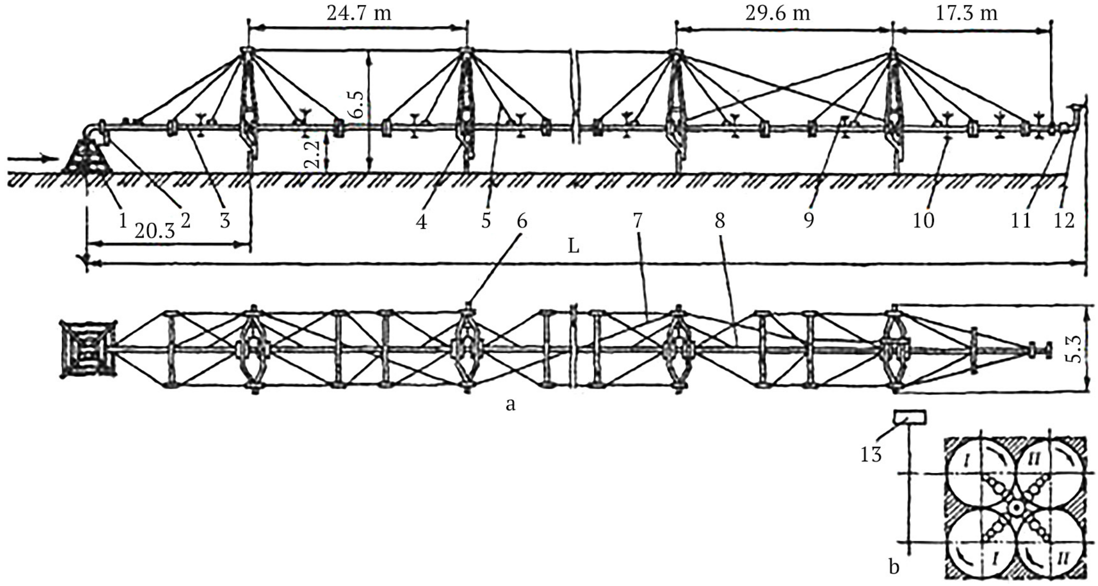

Figure 1. Diagram of the sprinkler Zimmatic-354M

Note: a – general view; b – irrigation scheme of two machines at two positions; 1 – fixed support; 2 – stop device; 3 – water pipeline; 4 – trolley; 5, 6, 7 and 8 – cable systems for automatic control of the trolley speed, as well as mechanical and electrical protection; 9 – sprinklers; 10 – drain valve; 11 – system for shutting down the final sprinkler; 12 – final sprinkler; 13 – pumping station

Source: Spraying Machine Zimmatic-354M (n.d.)

Table 1. Experimental data of the prototype sample of the SEMC

Pressure at the machine inlet, MPa	0.3
Water consumption, l/s	81.4
Operating width, m	354
Productivity, ha per hour of working time (m = 600 m³/hour)	0.49
Specific fuel consumption, l/ha	2.8
Effective irrigation coefficient	0.77-0.84
Average rain intensity, mm/min.	1.1
Rated power of the generator, kW	10
Rated motor power, kW	16.4

Source: Spraying Machine Zimmatic-354M (n.d.)

The sprinkler is designed for irrigation of grain, fodder, industrial and vegetable crops, including tall-stemmed crops, the sprinkler has a power trolley consisting of a support frame, supporting posts and crossbars, which are supported by two pneumatic wheels. This trolley is equipped with a power unit, fuel tank, water supply riser, diesel engine control panel, battery, main machine control panel, furrow guidance devices, limit switches and a flexible water hose.

The power unit, consisting of a diesel engine and a generator, is equipped with a control and monitoring panel with an emergency protection system for water temperature and oil pressure. The automatic guidance of the machine in the furrow is ensured by the tracking devices. The water pipeline, consisting of seven trusses, transports water to the sprinkler heads and is a prefabricated structure with hinged joints.

The kit includes low-pressure deflector nozzles with circular action and pressure regulators. The gear motor transmits the torque to the wheel gearbox via a propeller shaft. The gimbaled span joint consists of brackets welded to the pipe and a metal ring. The hydraulic connection between the spans is made by a rubber coupling wrapped in a steel cage. The control panel has manual process control and a percentage timer for setting the machine speed. The control system includes a control cabinet, trolley and machine synchronisation devices, stop sensors in a given sector and cable connections to ensure automatic control, monitoring and protection of the machine. The integration of such systems requires a careful approach to choosing the location of the panels, as well as analysing the impact of their weight and size on the machine's performance.

Choosing the optimal location for the solar panels on the Zimmatic 354M is critical to maximising the efficiency of the system. Options include mounting the panels on the roofs or sides of the machine. Placing the panels on the roof tends to maximise solar energy harvesting, as this part of the machine is usually less prone to shading by other objects such as vegetation or buildings (Selvi *et al.*, 2023). The roof also provides a large area for the panels to be placed, allowing for more energy to be captured from sunlight.

However, mounting the panels on the sides of the machine also has its advantages. This option can be useful for sprinklers that often operate in difficult conditions where the roof may be partially shaded or dirty. Side-mounted panels can help in cases where the roof cannot be used due to design or technical limitations. In addition, side panels can be easier to install and maintain. The placement of panels on any part of the machine also has an impact on its overall performance. One of the most important aspects to consider is the impact of the weight and size of the panels on the stability and manoeuvrability of the machine. Heavy solar panels can change the centre of gravity of the machine, which can affect its stability and driving behaviour. This is especially important for sprinklers that often operate on uneven or slippery surfaces.

The analysis of the impact of panel weight on machine stability includes an assessment of changes in the weight distribution and the impact on handling. It is necessary to ensure that the placement of the panels does not compromise the overall stability and manoeuvrability of the machine, which could affect its performance in the field. Technical solutions, such as using lighter materials for panels or weight distribution, can help maintain optimal machine performance (Ahmadnia *et al.*, 2022). Lastly, the integration of solar panels into the design of the Zimmatic-354M sprinkler requires a comprehensive approach to selecting their location and assessing their impact on performance. Carefully planned panel placement will help ensure maximum efficiency of the solar system while maintaining the stability and manoeuvrability of the machine. The successful integration of such systems can significantly improve the energy efficiency of sprinklers and help reduce their environmental impact.

Ensuring the smooth operation of sprinklers in agriculture is critical to maintaining a stable water supply and optimal crop growth. Modern technologies offer solutions to improve energy efficiency, one of which is the integration of energy storage and management systems using solar panels (Tan *et al.*, 2021). In this context, efficient batteries and the development of energy management algorithms that can ensure uninterrupted operation of the system even during shading or at night deserve special attention. Efficient batteries are a key component for storing energy from solar panels (Fagiolari *et al.*, 2022). They can be used to store excess energy during the day, when solar activity is at its highest, and used during periods when sunlight is not available, such as at night or during cloud cover. Choosing batteries with high energy density and long service life is important to ensure the stability of the sprinkler system. The batteries must be able to withstand charging and discharging cycles without significantly reducing efficiency to ensure reliable system operation.

The development of energy management algorithms is the next important step in ensuring efficient system operation. The control algorithms must optimally distribute energy among the various operating elements of the machine, such as pumps, control systems, and other power consumers (Sadeeq & Zeebaree, 2021). This includes developing strategies to prioritise energy allocation, ensure that critical functions have sufficient power, and optimise battery charging processes. This can be done using specialised software solutions that account for the current battery level, the energy needs of the machine and weather forecasts. The integration of energy storage and management systems not only increases the efficiency of solar energy use but also reduces dependence on external energy sources, which can be especially important in remote or hard-to-reach areas (Wang *et al.*, 2022). The smooth operation of the system is critical to ensure the proper functioning of sprinklers, as any decrease in efficiency can lead to insufficient watering of crops and, as a result, lower yields.

The use of efficient batteries for energy storage and the development of control algorithms for optimal energy distribution is integral to the successful integration of solar systems into sprinklers. This ensures stable operation of the equipment even in adverse weather conditions and at night, which significantly increases its efficiency and reliability in the field. Proper management of energy resources is key to ensuring the sustainable development of agricultural production and increasing its efficiency. Evaluating the performance of a solar panel system for sprinklers is a critical step in ensuring its successful implementation in real-world conditions. This includes using modelling to predict system performance under different climate scenarios and conducting field trials to verify theoretical calculations and adjust system parameters.

System performance modelling is the first step in the process of assessing system efficiency. It can be used to predict how the system will perform in different climatic conditions, considering variable factors such as solar radiation intensity, temperature, humidity and seasonal fluctuations. Computer simulations can predict how a system will respond to different scenarios, which can help identify potential problems and adjust the system design before actual testing begins. Modelling can also be used to optimise energy distribution, address changes in operating conditions, and determine the best parameters to ensure maximum efficiency.

To calculate the optimal power of solar panels for sprinklers in the South of Ukraine, the energy needs were first determined. The power consumption of the sprinkler is 5 kW. The following formula (3) was used to determine the required capacity of solar panels, given the average number of sunny hours per day, which is 5 hours in the South of Ukraine, and the system efficiency of 75%:

$$P_{\text{panels}} = \frac{5\ \text{kW}}{5\ \text{hours} \times 0.75} = 1.33\ \text{kW}. \quad (3)$$

The next step was to calculate the area of the solar panels. The average capacity of the solar panels is 300 W/m^2, or 0.3kW/m^2. The area of the panels is calculated using the formula (4):

$$A = \frac{1.33\ \text{kW}}{\frac{0.3\ \text{kW}}{\text{m}^2}} = 4.33\text{m}^2. \quad (4)$$

Thus, to ensure the smooth operation of a sprinkler with a power consumption of 5 kW in the conditions of average insolation in the South of Ukraine, the power of solar panels is about 1.33 kW, and the corresponding panel area will be about 4.43 m^2.

After the theoretical analysis, it was necessary to conduct field tests to confirm the theoretical calculations and identify the actual results of the system. The field tests verified the accuracy of the predictions made during the modelling phase (Table 2). It also contributed to the identification of problems that might not have been noticed during the theoretical calculations, such as unexpected effects from the interaction of solar panels with other machine components or the impact of unforeseen climatic conditions. The field trials provided real-world data on the system's performance that could be used for further improvements.

Table 1. Evaluation of the efficiency of the solar panel system for the Zimmatic-354M sprinkler

Value	Description	Value	Note
Intensity of solar radiation	Average value of solar radiation intensity in different seasons	800 W/m^2 (summer)	According to weather conditions
Temperature	Average temperature in different seasons	30°C (summer)	May affect efficiency
Humidity	Average humidity levels that can affect system performance	60% (humidity)	Affects the performance of the panels
Water consumption	Average water consumption provided by the system	81.4 l/s	Indicated for the main time
Productivity	Total area that can be watered per hour	0.49 ha/hour	Depends on the efficiency of the system
Fuel consumption per unit	Fuel consumption per unit of cultivated area	2.8 l/ha	Depends on the operation of the machine
Effective irrigation coefficient	Ratio of actual watering to planned watering	0.77-0.84	Depends on the accuracy of the system
Average rain intensity	Rain intensity provided by the system	1.1 mm/min	Affects the quality of watering
Rated power of the generator	The power of the generator that provides energy for the system	10.0 kW	Affects system performance
Rated power of the motor	Power of the motor that drives the system	16.4 kW	Impact on work efficiency

Source: compiled by the authors based on A. Matheswaran *et al.* (2021)

Adjusting the system parameters based on the data is the next important step. If the field tests reveal deficiencies or opportunities for improvement, adjustments to the system design or control algorithms should be made accordingly. This may include optimising panel placement, improving batteries, or tweaking software to better manage energy. Flexibility in adjusting system parameters is key to ensuring that the system operates efficiently under conditions that may vary in real-world operating situations.

Evaluating the performance of a solar panel system in real-world conditions is an important process to ensure its success. Using modelling to predict performance and conducting field trials to validate theoretical calculations can ensure that the system is operating at maximum efficiency. It also helps identify possible problems and find solutions to address them, which in turn helps to improve the performance of sprinklers and ensure that they are stable in the real-world operating environment.

Solar systems used in sprinklers have significant potential to improve efficiency and reliability in the specific conditions of southern Ukraine (Atamanyuk *et al.*, 2016). This region is characterised by extreme climatic conditions such as dust storms, high humidity and significant temperature fluctuations. To ensure the durability and performance of solar systems, it is necessary to address these factors and develop recommendations for improving the design and use of materials.

It is important to improve the design of solar panels to meet the specific conditions of southern Ukraine. Dust storms, which are common in the region, can have a negative impact on the efficiency of panels, reducing their performance and service life. To counteract this, it is necessary to use special protective coatings that would reduce the accumulation of dust on the surface of the panels. Additionally, the optimal location of the panels, considering the possibility of self-cleaning during rain or cleaning systems, can significantly increase their efficiency (Stavinskiy *et al.*, 2021; Myyas *et al.*, 2022).

High humidity is also an important factor affecting the efficiency of solar systems. Humidity can lead to corrosion and reduced panel performance. To prevent this, it is recommended to use materials that are resistant to moisture, such as specially treated panel coatings and sealed battery enclosures. This will help ensure the longevity of the system by preventing possible moisture-related problems (Dhass *et al.*, 2022). Temperature fluctuations in southern Ukraine can affect the performance of solar panels and batteries. High temperatures can lead to overheating and reduced panel efficiency, while cold temperatures can reduce battery capacity. The use of heat-resistant materials and cooling systems for panels, such as heat sinks or passive cooling systems, can help maintain optimal temperatures and ensure consistent performance. Batteries should also be equipped with thermal management systems to maintain their efficiency in extreme temperatures.

An important aspect is the use of more efficient materials for the manufacture of solar panels and batteries. Modern materials with improved characteristics can increase the performance and durability of the system. For example, the use of panels with high efficiency can reduce the area required for panel installation while providing greater energy output. Newer generation batteries, with higher capacity and faster charging times, can improve overall system efficiency and reduce maintenance (Rubino *et al.*, 2023). In the South of Ukraine, particularly in the Mykolaiv region, the efficient use of solar energy to power sprinklers is an important task to ensure sustainable crop irrigation. Given the high potential of solar energy in the region, optimising the parameters of a solar power plant is essential to increase the efficiency of irrigation systems and reduce dependence on traditional energy sources.

The first step in optimising a solar power plant is to choose the right capacity. For the Mykolaiv region, where the annual amount of solar radiation is about 1400-1500 kWh/m^2, it is advisable to choose a capacity that will ensure uninterrupted operation of sprinklers throughout the irrigation season (Avdieieva *et al.*, 2022; Shahini *et al.*, 2024). It is recommended to calculate the capacity of the plant accounting for the daily water consumption, pump efficiency and efficiency, as well as energy losses during transmission. For maximum power generation, it is necessary to determine the correct angle of inclination of solar PV modules. In the Mykolaiv region, the recommended angle of inclination should be approximately 30-35° to the horizon, which allows for the highest efficiency throughout the year (Global Solar Atlas, n.d.; Atamanyuk & Kondratenko, 2015). Seasonal changes in insolation and the possibility of adjusting the angle of inclination to increase productivity in summer should be considered. Given the unevenness of solar radiation throughout the day and weather fluctuations, it is advisable to introduce energy storage systems (batteries). This will ensure the uninterrupted operation of sprinklers even in conditions of insufficient power generation. It is recommended to choose batteries with high energy density and long service life to minimise operating costs.

The efficient operation of a solar power plant also depends on proper management and monitoring of its parameters. It is recommended to implement automated systems that monitor the performance of PV modules, the condition of batteries, and the energy consumption of power sprinklers. The use of modern data monitoring and analysis systems will help to quickly identify and eliminate possible malfunctions in the plant. Optimising the parameters of a solar power plant for use in sprinklers in the South of Ukraine requires a comprehensive approach, including the right choice of power, adjusting the angle of the PV modules, implementing energy storage systems and automating the control process. Adherence to these recommendations will increase the efficiency of irrigation systems, reduce operating costs and ensure a stable water supply in the region's unstable climate.

Implementation of these recommendations will significantly improve the efficiency and reliability of solar systems in the South of Ukraine. This will not only increase the productivity of sprinklers but also ensure their stable operation in extreme climatic conditions, which will help to improve the efficiency of agricultural processes in the region.

DISCUSSION

The study on optimising the parameters of a solar power plant for use in sprinklers has yielded results that demonstrate the effectiveness of the proposed solutions. The focus was on calculating the optimal power of solar panels, taking into account the specific climatic conditions of the South of Ukraine. According to the data obtained, the chosen system capacity provided a stable power supply to sprinklers, even under conditions of variable insolation, which proved the effectiveness of the choice in practice. This was also investigated by H. Satria *et al.* (2021), where the results confirmed that the analysis of optimisation results focuses on comparing actual performance with predictions and assessing the impact of factors such as tilt angles and weather conditions. It is important to determine how effective the adjustments made, such as upgrading system components or improving control technologies, were and whether an increase in energy production was achieved. K. Hoffer & G. Savini (2021) also showed that assessing the effectiveness of the designed capacity involves comparing planned and actual performance, using metrics such as system performance factor, and considering financial aspects. It is important to determine how well the system meets energy needs and whether investments in its optimisation are justified. It is worth noting that optimising the capacity of solar panels can have a significant impact on the overall efficiency of the system (Babii & Sologub, 2023). Improving the accuracy of calculations and adjusting system parameters can lead to a significant increase in energy production and a reduction in energy costs. In addition, successful optimisation not only increases productivity but also improves the economic return on investment in solar energy. It is also necessary to consider that regular monitoring and analysis of performance allows for the timely detection and elimination of possible problems, which contributes to the long-term stability and reliability of the system.

After modelling the performance of the system, it was determined that the location of the panels on the roofs of the sprinklers was the most efficient (Stoliarov, 2024). The modelling confirmed that this option minimises shading and maximises solar energy absorption. After implementing the model in real-world conditions, the data confirmed that the optimal location of the panels allows for maximum energy efficiency, which has a positive impact on the overall performance of the sprinklers. S. Shorabeh *et al.* (2022)

concluded that the assessment of the optimal location includes the selection of the correct tilt angles and orientation of the panels to maximise solar radiation absorption. It is important to consider shading from surrounding objects to ensure maximum system performance. V. Gjorgievski *et al*. (2021) found that the location of the panels directly affects their efficiency. Incorrect tilt angle or orientation can reduce the amount of solar energy collected and the overall system performance. Considering seasonal changes in the sun's path is also important to ensure optimal results. These results confirm the above study, as they demonstrate that the optimal positioning of solar panels significantly increases their efficiency. In particular, the correct choice of panel angle and orientation, as well as the consideration of possible shading, confirm the importance of accurate calculations to maximise solar energy collection. This confirms that the results of the study adequately reflect the real conditions and the effectiveness of the proposed solutions.

The use of efficient batteries for energy storage also proved to be important. The batteries ensured uninterrupted operation of the system during periods of shade or night (Amidu *et al*., 2023). Tests confirmed that the selected batteries have sufficient capacity to cover the energy needs of the machines at night and during limited solar radiation, which ensured the reliability of the system. It is worth noting the work of T. Abdul-Jabbar *et al*. (2021), who also determined that batteries are critical to ensuring the smooth operation of solar systems by storing energy for use when the sun is not shining. Their efficiency is determined by capacity, charging and discharging speed, and service life. Modern batteries provide high performance, but their efficiency can vary depending on the type and operating conditions. In turn, D. Kong *et al*. (2021) concluded that the analysis of battery performance in different conditions includes an assessment of their performance when temperature and loads change. Cold temperatures can reduce efficiency, while high temperatures can cause overheating and shorten the service life (Smyk & Arkhypova, 2023). This analysis helps to optimise the system to ensure stable battery performance in different conditions. This data is consistent with the discussion in the previous section, as it confirms that battery efficiency is critical to the smooth operation of the system and demonstrates how different conditions affect battery performance. The results of the analysis confirm that the right choice of batteries and their proper operation are key to ensuring the stability and reliability of the power system. It also confirms the importance of considering variable conditions to optimise system performance.

The developed energy management algorithms have demonstrated their effectiveness in the optimal distribution of energy between the machine's working elements and battery charging. Modelling and field tests have shown that these algorithms reduce energy costs and increase the efficiency of using stored energy. This confirmed the need to fine-tune the control system to ensure stable operation in different conditions. D. Wang *et al*. (2021) also conducted a study that confirmed that the analysis of energy management algorithms helps to evaluate the effectiveness of real-time energy distribution planning and adaptive control. This includes identifying the benefits and limitations of algorithms, such as their ability to respond to load changes and store energy. Optimal algorithms can significantly improve system performance and reduce costs. J. Hu *et al*. (2021) also determined that optimising energy distribution includes the use of algorithms to increase resource efficiency, reduce energy losses, and improve load management. This helps to reduce costs by minimising energy losses and improving overall system efficiency. Comparing the data obtained in the course of the research, it can be concluded that the effectiveness of energy management algorithms has a significant impact on the overall system performance. The analysis shows that optimising energy distribution and using advanced algorithms can reduce costs and increase efficiency. These results confirm that the implementation of such algorithms is key to achieving high energy efficiency and economic benefits in power systems.

Field tests conducted in real-world conditions showed that the solar panel system can operate efficiently even under partial shading and variable weather conditions. This proved to be critical for ensuring the reliability of sprinklers, as variable weather conditions often affect the performance of solar power plants (Serikuly *et al*., 2022). The test results confirmed the theoretical calculations and allowed for timely adjustments to the system parameters. S. Fan *et al*. (2021) concluded that the impact of panels on energy efficiency is assessed through their ability to generate energy under test conditions. Different types of panels can show different performances depending on their characteristics. Tests can identify the advantages and disadvantages of panels, which helps to more accurately predict their performance in real-world conditions. C. Mokhtara *et al*. (2021) determined that determining system performance in a variable climate allows them to assess how changes in temperature and humidity affect solar panel performance. This helps to identify how climate conditions can change system efficiency and what adjustments are needed to maintain optimal performance. When analysing the results of the study, the efficiency of solar panels depends on their characteristics and operating conditions. Tests have shown that different types of panels react differently to changing climatic conditions, which confirms the importance of taking these conditions into account when designing and installing systems. Regular monitoring and adaptation of the system to climate change is essential to maintain stable performance and reduce negative impacts.

CONCLUSIONS

Optimisation of the parameters of a solar power plant for sprinklers in the South of Ukraine is a critical step to ensure the efficient operation of the system in specific climatic conditions. The results of the study showed that the main factors for ensuring proper performance are the calculation of solar panel capacity, consideration of average insolation and system efficiency.

Modern technologies have actively integrated renewable energy sources into various fields of activity, including agriculture. The introduction of solar panels in the design of sprinklers, such as the Zimmatic-354M, has significantly improved the efficiency of energy systems, providing sustainable and reliable power in a specific climate.

The analysis showed that to meet the energy needs of the sprinkler, the solar panels need to have the appropriate capacity. This will provide enough energy for the system to operate smoothly under average insolation. The system's efficiency factor, which considers energy losses, was refined to determine the required panel capacity.

Further calculation of the panel area showed that to meet these needs, an appropriate panel area with optimal efficiency is required. This calculation will help to ensure the optimal placement of the panels for maximum solar energy absorption, considering possible seasonal fluctuations in insolation.

Through modelling and field tests, key aspects were identified to improve system efficiency, including adjustments to panel placement and improvements to the energy storage system. The recommendations made will help to improve the overall efficiency of solar power plants in sprinklers, which will ensure stable and reliable operation in the specific climatic conditions of southern Ukraine.

To further improve the solar power system in sprinklers, it is necessary to address the impact of different types of solar panels and batteries on the overall system efficiency under variable climatic factors and long-term operation. A limitation of the study is that the experimental tests were conducted only in the limited climatic conditions of southern Ukraine, which may not fully reflect the system's effectiveness in other regions with different weather characteristics.

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CONFLICT OF INTEREST

None.

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Оптимізація параметрів сонячної електростанції при використанні у дощувальних машинах в умовах Півдня України

Анотація. Дослідження мало на меті оцінити ефективність інтеграції сонячних електростанцій у дощувальних машинах в умовах Миколаївської області. У дослідженні були використані методи моделювання, практичні випробування та аналіз ефективності системи для оптимізації параметрів сонячної електростанції в умовах Півдня України. Результати показали, що для дощувальних машин у цьому регіоні сонячна електростанція повинна мати достатню потужність для забезпечення енергетичних потреб без значного збільшення ваги обладнання. Найбільш ефективним виявилося розміщення сонячних панелей біля машини Zimmatic-354M, що забезпечує максимальне отримання сонячної енергії. Аналіз показав, що використання акумуляторів дозволяє забезпечити безперебійну роботу системи навіть при частковому затіненні. Польові випробування підтвердили теоретичні висновки та виявили потребу в покращенні матеріалів панелей для підвищення їх довговічності та стійкості до пилу і температурних коливань. Рекомендовано вдосконалення конструкції та використання нових матеріалів для підвищення ефективності системи в специфічних кліматичних умовах. Також було встановлено, що інтеграція сонячних панелей до дощувальних машин не вплине негативно на їх маневреність і стійкість. Результати показали, що енергетична система, спроектована з урахуванням специфічних кліматичних умов Півдня України, здатна забезпечити стабільну роботу дощувальних машин протягом тривалого часу. Крім того, дослідження виявило необхідність регулярного обслуговування панелей для підтримання їх ефективності на оптимальному рівні

Ключові слова: акумуляторні батареї; енергетична система; температурні коливання; обслуговування; інтеграція сонячних панелей; сільське господарство

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Analytical justifications of constructive parameters of bionic colters for vertical soil treatment

Abstract. Bionic coulters imitate natural forms and functions, which help reduce energy costs for soil tillage. The aim of the research was to justify the design and structural parameters of turbo discs (coulters) for vertical tillage based on the principles of bionic reverse engineering. Using this method, an equation for the shape of the turbo discs (coulters) was derived, which was obtained by approximating the shell of the argonaut (*Argonauta argo*). The equation takes into account the main structural parameters of the turbo discs: diameter D_d, cutout height H_m, wave height H_w, number of cutouts n, and spiral coefficient k. As a result of analytical studies on the interaction process between a solid disc and plant residues, the optimal diameter value was determined to be $D_d = 460$ mm under the condition of submerging stems with a thickness of 10-20 mm to a depth of 80 mm. The analytical studies confirmed that the presence of cutouts on the disc prevents stem deflection and ensures better stem capture. In analysing the obtained dependencies using the Wolfram Cloud software package, the optimal values for the cutouts were determined: cutout height $H_m = 40$ mm, number of cutouts $n = 8$. The presence of waves on the disc surface ensures that the interaction with plant residues is independent of their position on the field surface and creates conditions for vertical soil tillage. It was found that, to minimize specific cutting resistance and maximize the degree of soil fragmentation, the optimal wave parameters for the coulter are a wave height of $H_w = 24.4$ mm. The justified parameters of the coulters provide the best balance between soil fragmentation efficiency and reduction in energy consumption for soil tillage. The obtained results can be used to adapt existing agricultural machinery to the new structural parameters of coulters to improve its efficiency

Keywords: vertical tillage; turbo disc; shape; shell; argonauts; analytical studies

INTRODUCTION

Optimization of agricultural machinery helps preserve soil structure, enhancing aeration and water permeability, which is essential for maintaining soil fertility. Bionic colters, designed based on natural analogues, minimize soil erosion and contribute to sustainable agricultural practices. By tailoring the design to different soil types, these colters can be used more effectively in various agro-climatic conditions. Implementing such advanced technologies in

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farming not only increases productivity but also reduces environmental impact, promoting more sustainable and eco-friendly agricultural practices.

Management of crop residues along with compacted soil under intensive farming systems requires highly efficient and well-adapted soil cultivation tools. According to Yu. Belovol (2014), vertical tillage has been gaining popularity involves vertically oriented turbo discs with wavy turbines, also known as colters, which impact the soil in a vertical direction. Due to their wave-shaped cutting edge, they fragment plant residues, and soil loosening occurs through the formation of cracks. G.V. Teslyuk *et al.* (2016) researched that there were many variations of such discs, but their design could be generalized into two main types: with radial waves and waves directed at an angle to the axis of rotation. To enhance the efficiency of fragmenting plant residues and turning the soil, some manufacturers produce discs with serrations on the edge. This type of disc can be successfully used as part of a turbo disc cultivator. Evaluation of such soil cultivation tools requires proper determination of their technical design, as well as the dynamics of their interaction with soil and plant residues.

Some studies on the interaction of turbo discs (colters) with soil and plant residues are considered. In the study of Z. Zeng *et al.* (2021), an experimental comparison of three vertical soil cultivation discs of different shapes, namely toothed, plain, and serrated, was conducted. The analysis found that the serrated disc was the most efficient among the three discs based on measured performance indicators. The results indicate that changing the working depth would be an effective approach to altering soil dynamics and the cutting performance of residues by discs for vertical tillage.

Field tests of vertical tillage tools in of Z. Zeng (2019) demonstrated that serrated discs leave fewer residues on the surface, incorporate more residues into the soil, create a wider furrow, and cover a larger area than plain discs. The impact of working speed was more dominant than the geometry of the openers on the soil processing efficiency of serrated openers.

In the study of I. Torotwa *et al.* (2022), the soil cultivation effort, structural strength, straw cutting performance, and uniformity of soil cultivation depth of a toothed disc with curved edges were evaluated in comparison to a straight-toothed disc. The design of the curved-toothed disc was inspired by the arc-shaped structure of a digger's claw. It was found that using such a disc reduced soil cultivation effort by 22.8%, ensured uniform soil cultivation depth, and increased straw cutting efficiency by 26.3 %.

J.L. Zhao *et al.* (2021) developed a stubble chopper based on the analysis of bionic prototypes. Inspired by the unique mouthpart structure of a locust, the bionic stubble chopping device acquired a new multi-segment toothed bionic structure and symmetrical rotational motion, significantly increasing stubble chopping speed. Also noteworthy is a patented design of a wavy disc (Piccat, 2006), whose wave profile is asymmetric and offset in the direction of rotation.

The article of I.V. Sobolevsky *et al.* (2021) presented methods and results of the bionic approach in the agro-mechanics system, which theoretically substantiated the main parameters of the model of working elements of wavy discs using two bionic prototypes – the digging leg and radial ribs of the bivalve mollusk *Cerastoderma edule*, and the digging leg of the dung beetle *Geotrupes stercorarius*. The model of the working elements of wavy discs helps to maintain soil erosion resistance in the upper cultivated layer to preserve its structure and stubble background during no-till soil cultivation in soil conservation farming systems using Verti-till and Strip-till technologies.

The aim of the research is to justify the design and constructive parameters of turbo discs (colters) for vertical soil tillage based on bionic reverse engineering.

MATERIALS AND METHODS

Taking into account the bionic reverse engineering approach, the shape equation for turbo discs (colters) had been derived by approximating the form of the Argonaut (*Argonauta argo*) shell. The shells of argonaut octopuses (*Argonauta argo*) served as a fascinating example for mathematical analysis in engineering design as M. Oudot *et al.* (2020) emphasized. The geometric complexity of the shell, particularly its wavy shape, had been explored in previous studies. J. Finn & M. Norman (2010) demonstrated that the wave patterns aid in vertical movement through water, while H. Hoving *et al.* (2022) identified the functional significance of these shapes in burrowing into seabed sand. According to analysis of the mathematical description of various shell shapes (Roccatano, 2018; Larsson *et al.*, 2020; Contreras-Figueroa & Aragón, 2023) particular attention particular attention of this reserch was given to spiral forms, while planar wavy forms have been less explored. Based on the reverse engineering method, the boundary of the shell was represented as shown in Figure 1

In analytical form, the equation of the shell surface can be represented as follows:

$$\begin{cases} x(\varphi_u, \varphi_v) = \left(1 - \frac{H_m}{D_d}|sin(n\varphi_u)|\right) sin\left(\varphi_u + k\frac{\varphi_v}{D_d}\right)\varphi_v, \\ y(\varphi_u, \varphi_v) = \left(1 - \frac{H_m}{D_d}|sin(n\varphi_u)|\right) cos\left(\varphi_u + k\frac{\varphi_v}{D_d}\right)\varphi_v, \\ z(\varphi_u, \varphi_v) = H_w\, cos(n\varphi_u)\left(\frac{\varphi_v}{D_d}\right)^2, \\ 0 \le \varphi_u \le 2\pi, \\ 0 \le \varphi_v \le D_d. \end{cases} \quad (1)$$

where φ_u is the parametric angular variable in radians; φ_v is the parametric linear variable in meters.

The graphical interpretation of the equation (1) in Wolfram Cloud with different parameters D_d, H_m, H_w, n and k is shown in Figure 2.

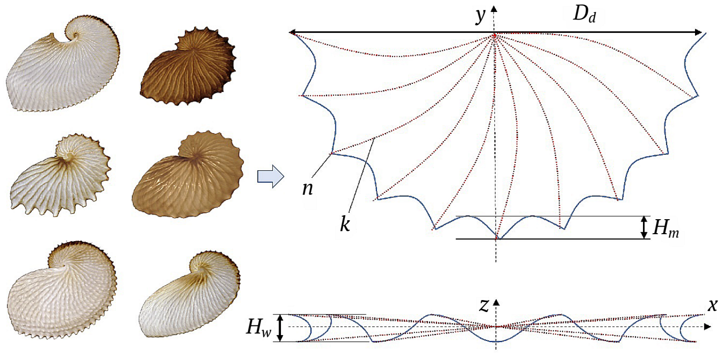

Figure 1. Approximation of the Argonaut Shell (*Argonauta argo*)

Note: D_d – diameter; H_m – notch height; H_w – wave height; n – number of waves; k – spiral coefficient; x, y, z – spatial coordinates in meters

Source: compiled by the authors

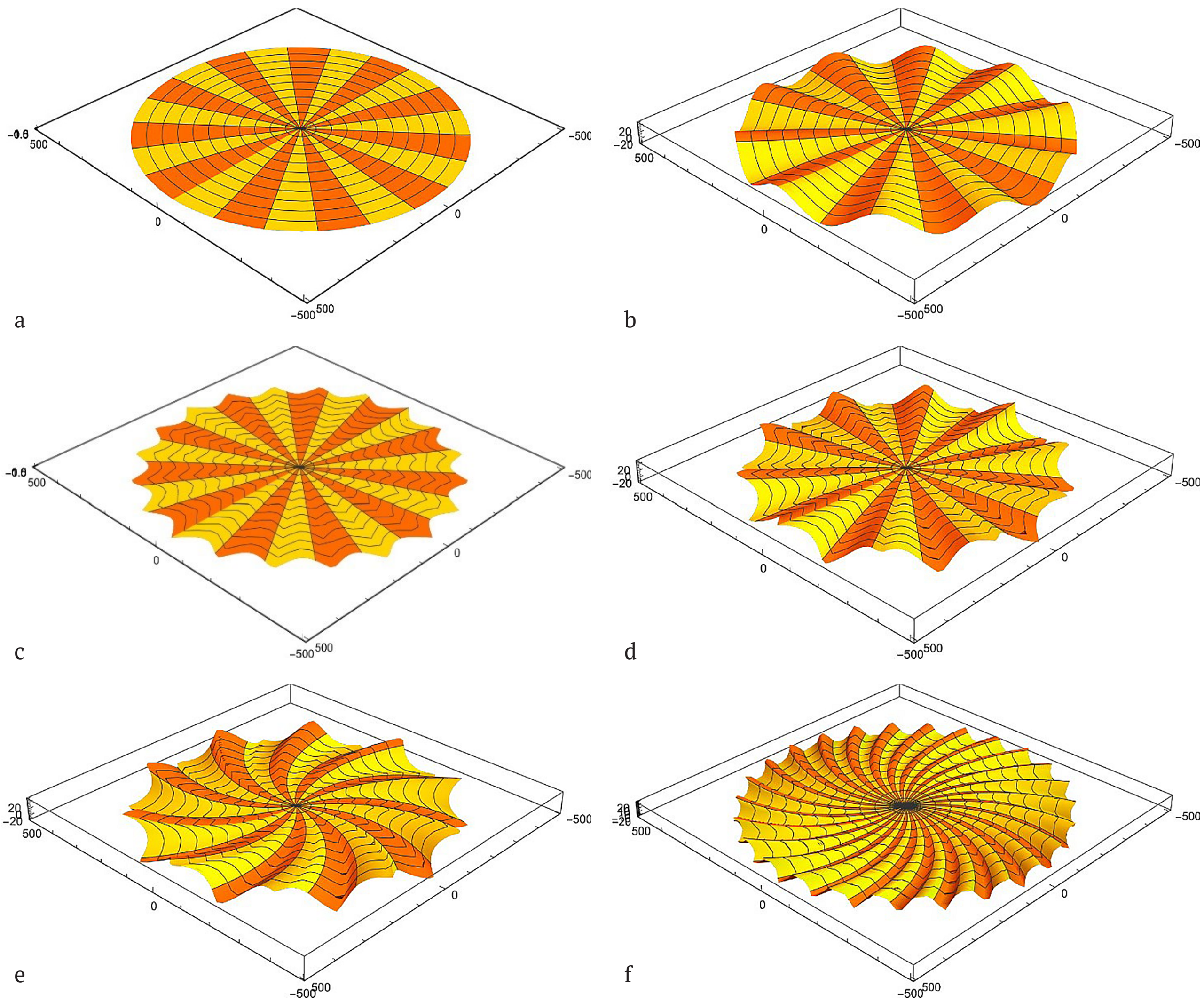

Figure 2. Constructed Variants of Turbo Discs (Colters) Based on the Bionics of Argonaut Shells

Note: a – Flat solid disc ($D_d = 460$ mm; $H_m = 0$ mm; $H_w = 0$ mm; $n = 10$; $k = 0$), b – Wavy disc ($D_d = 460$ mm; $H_m = 0$ mm; $H_w = 30$ mm; $n = 10$; $k = 0$); c – Flat notched disc ($D_d = 460$ mm; $H_m = 50$ mm; $H_w = 0$ mm; $n = 10$; $k = 0$); d – Wavy notched disc ($D_d = 460$ mm; $H_m = 50$ mm; $H_w = 30$ mm; $n = 10$; $k = 0$); e – Wavy spiral notched disc ($D_d = 460$ mm; $H_m = 50$ mm; $H_w = 30$ m; $n = 10$; $k = 0.6$); f – Wavy spiral notched disc ($D_d = 460$ mm; $H_m = 20$ mm; $H_w = 30$ mm; $n = 26$; $k = 0.6$)

Source: compiled by the authors

The next step involved analytical studies of the interaction process between the turbo disc (colter) and the soil environment, as well as plant residues. In determining the forces acting within the model soil environment, the following simplifications and assumptions were made: the soil was conditionally modelled as a medium with internal friction and specific cohesion that did not depend on external pressure. The likelihood of this assumption being valid was confirmed by (Semenyuta, 2014). The soil environment was considered anisotropic in its various properties (Shevchenko, 2001). At pressures of 0.4-0.6 MPa, and for soils with significant compaction up to 0.9 MPa, the relationship between pressure and deformation was considered linear. Thus, to establish the forces acting in the soil environment, elasticity theory was used. The propagation of cleavage lines (cracks) in the soil occurred in a vertical-transverse plane at an angle of $\varphi_2 + \pi/2$ to the cutting edge of the tool, where φ_2 was the internal friction angle of the soil (Kobets *et al.*, 2011). The predominant direction of crack propagation remained unchanged throughout the process (Kobets *et al.*, 2009). The specific cohesion of soil particles was a key indicator that encompassed other mechanical and technological properties. Analytical studies were conducted for different types of colters: flat solid, flat notched, and wavy notched discs. The research was carried out in the software package Wolfram Cloud (Wolfram company, USA).

RESULTS AND DISCUSSION

A mulcher made up of flat solid discs (H_m=0 mm; H_w=0 mm; k=0) can perform cutting of plant residues and surface loosening of the soil environment without mixing and rotating its layers. The scheme for calculating the interaction of the disc with the soil and plant residues is shown in Figure 3.

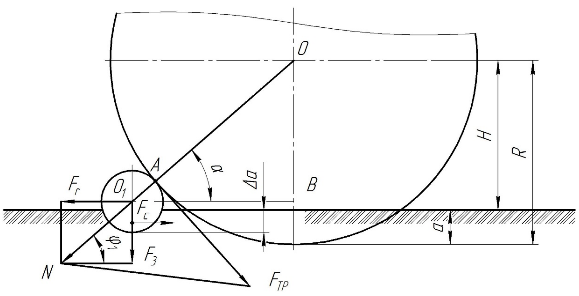

Figure 3. Interaction of a flat solid disc with soil and plant residues

Note: O, A, B, O_1 – points on the drawing; *a, H, R,* Δa – length in meters; α, φ_1 – angles in radians; F_{TP} – the force of friction between the disk and plant remains in Newtons; N – the force of normal pressure between the disc and plant remains in Newtons; F_c – soil resistance in Newtons; F_3 – disc reaction force in Newtons; F_r – the force of inertia in Newtons

Source: compiled by the authors

Consider the conditions for cutting plant residues (using a stem as an example) with a disc. The interaction of the disc with the stem can have four possible outcomes:

- forward displacement: this option is unacceptable as it excludes the possibility of cutting;
- side displacement: this occurs with short stems of 5-8 cm in length (which meets agronomic requirements);
- pulling under the disc: although this option does not guarantee cutting of plants, it meets agronomic requirements (Fig. 4), as part of the stem is buried to the depth at which the disc operates;
- stationary stem: this option ensures guaranteed cutting of the plant.

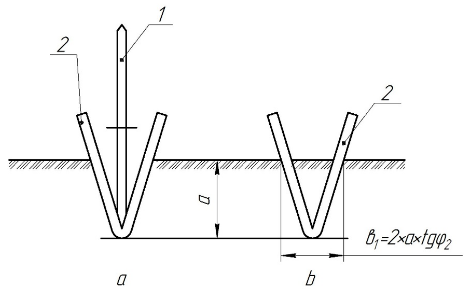

Figure 4. Interaction of the flat solid disc with soil and plant residues

Note: 1 – disk; 2 – stem; a – moment of interaction between the disk and the stem; b – after the disk passes; *a*, b_1 – length in meters; φ_2 – angles in radians

Source: compiled by the authors

The achievement of cutting a stationary stalk can be accomplished in two ways: by cutting without support at increased cutting speeds or by creating conditions for supported cutting. Unambiguously supported cutting can be achieved with a blade speed up to 15 m/s for crops with thin stalks and up to 60 m/s for crops with thick stalks (Kirichenko *et al.*, 2011). The specified speeds are not achieved by passive working elements, so analytical studies need to be considered under the scheme of supported cutting without moving the stalk by the disc (Fig. 3).

As indicated by informational analysis, there is no excessive need for cutting thin-stemmed plant residues (the option shown in Figure 4 is sufficient), but the problem of shredding residues of coarse-stemmed crops is present. Unshredded residues decompose slowly and significantly complicate the operation of seeders. Therefore, it is worth examining the interaction of the disc with crops with thick stalks.

Assumptions made: The stalk to be cut is cylindrical; stalk characteristics are homogeneous and isotropic throughout its length; the strength parameters of the stalks are proportional to the square of their diameters (Kobets *et al.*, 2011); the interaction of the disc with the soil is determined by the wall support law (Kozachenko *et al.,* 2021).

The forces acting on the stalk by the disc are: normal pressure force N; resistance force from the soil F_C; friction force F_{TP}. The condition for cutting the stalk is the zero sum of the horizontal components of all forces acting on it (Fig. 3). The most rational option is a small displacement of the stalk backward along the disc's path. The stalk will be pressed into the soil until the pressure force of the blade exceeds the critical cutting force. This depth of immersion is denoted as Δa. The value Δa will determine the coefficient of volumetric soil displacement. According to the calculation scheme (Fig. 5), the volume of the stalk immersed in the soil is calculated by the equation:

$$V = 0.5LS_{BCD} =$$
$$= 0.5L\left[R^2 \, arccos\frac{R-\Delta a}{R} - (R-\Delta a)\sqrt{R^2-(R-\Delta a)^2}\right], \quad (2)$$

where R is the stem radius; L is the stem length; Δa is the penetration depth.

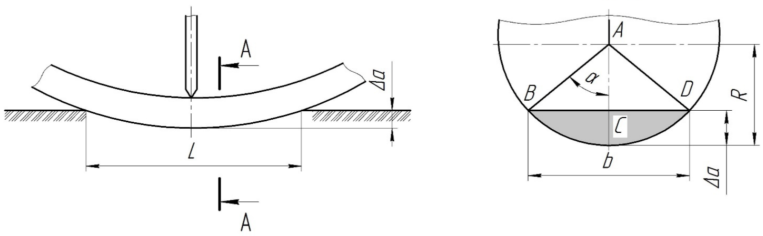

Figure 5. Diagram for calculating stem immersion parameters under the action of the disk
Note: A-A – designation of the section on the drawing; A, B, C, D – points on the drawing; **Δ*a, L, b, R*** – length in meters; ***α*** – angles in radians
Source: compiled by the authors

The relationship for determining the immersion depth is as follows:

$$qV = 0.5qL$$
$$\left[R^2 \, arccos\frac{R-\Delta a}{R} - (R-\Delta a)\sqrt{R^2-(R-\Delta a)^2}\right] > [P], \quad (3)$$

where $[P]$ – stem shear resistance; q – soil volume change coefficient.

Solving equation (3) in the Wolfram Cloud software yields a graph showing the relationship between the stem immersion depth in the soil and its diameter under the action of a solid disk (Fig. 6). The analysis of this relationship indicates that, for real values of stem radius and the force acting on its cross-section, the immersion depth ranges from 4 to 6 mm. In other words, stems with diameters less than 4 mm will be reliably driven into the soil. It is important to note that the plastic deformation of the stem itself does not affect the immersion depth, as this aspect is already accounted for in the stem resistance. According to Figure 3, the balance of forces acting in the horizontal plane can be expressed as:

$$N \cdot cos\alpha + f_1 \cdot N \cdot sin\alpha = f_2 \cdot F_3, \quad (4)$$

where f_2 – coefficient of friction between the stem and the soil; f_1 – coefficient of friction between the stem and the steel; α – angle of embedding.

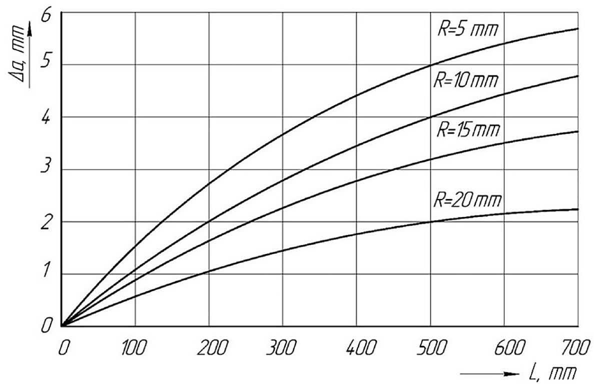

Figure 6. Relationship between stem immersion depth in the soil, its radius and length at q=900 kN/m³
Note: Δa – the penetration depth; R – the stem radius; L – the stem length
Source: compiled by the authors

The mass of the stem is small enough to be neglected. Then, the force reaction of the disk can be determined from the following relation:

$$F_3 = N \cdot sin\alpha - f_1 \cdot N \cdot cos. \quad (5)$$

By substituting (4) into (5) and performing the mathematical transformations, the following expression is obtained:

$$tg\alpha = \frac{1+tg\varphi_1 \cdot tg\varphi_2}{tg\varphi_2 - tg\varphi_1} = ctg(\varphi_1 - \varphi_2) = tg(\frac{\pi}{2} - \varphi_1 - \varphi_2). \quad (6)$$

Taking into account Figure 5, the following is obtained:

$$\alpha = arcsin\frac{OB}{R_d+R} = arcsin\frac{R_d-a-R+\Delta a}{R_d+R}, \quad (7)$$

where R is the stem radius and R_d is the disk radius. By substituting (7) into (6) and performing mathematical transformations, the following is obtained:

$$D_d = 2R_d = 2\frac{R\cdot cos(\varphi_1+\varphi_2)+a+R-\Delta a}{1-cos(\varphi_1+\varphi_2)}. \quad (8)$$

Graphical interpretation of equation (8) is shown in Figure 7. The parameter Δa is obtained from equation (3), Figure 6. Given a soil penetration depth of 80 mm, the optimal diameter of the disc for equation (1) is D_d = 460 mm. It should be noted that plain solid discs are rarely used in their pure form, as their functional capabilities are limited to merely crushing plant residues and clods on the soil surface. In this context, they are considered an intermediate stage for determining the parameters of a turbo-disc (colter).

The solid disc has several drawbacks that limit its capabilities in soil processing, especially in the context of organic farming systems. One of these is the negative entry angle into the working medium. However, for effective stem cutting, it is necessary for the blade's action to be directed vertically during the initial stages. This allows the stem to be partially embedded in the soil and fixes it in place, preventing movement during cutting.

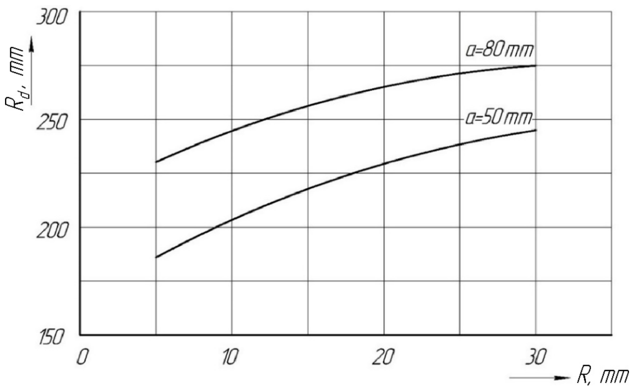

Figure 7. Dependence of the minimum disk radius on the depth of penetration and the coefficient of volumetric soil compression

Note: R_d – the disk radius; a – penetration depth of the disc; L – the stem length

Source: compiled by the authors

The calculation scheme for such a disc is examined, and the working process is broken down into stages according to the number of cuts on the disc (Fig. 8). Each stage corresponds to Fig. 8a-Fig. 8f. The beginning of the stage (Fig. 8a) is determined by the vertical downward movement of the cutting blade. The end of the stage corresponds to the moment when the blade starts moving towards the soil surface (Fig. 8f).

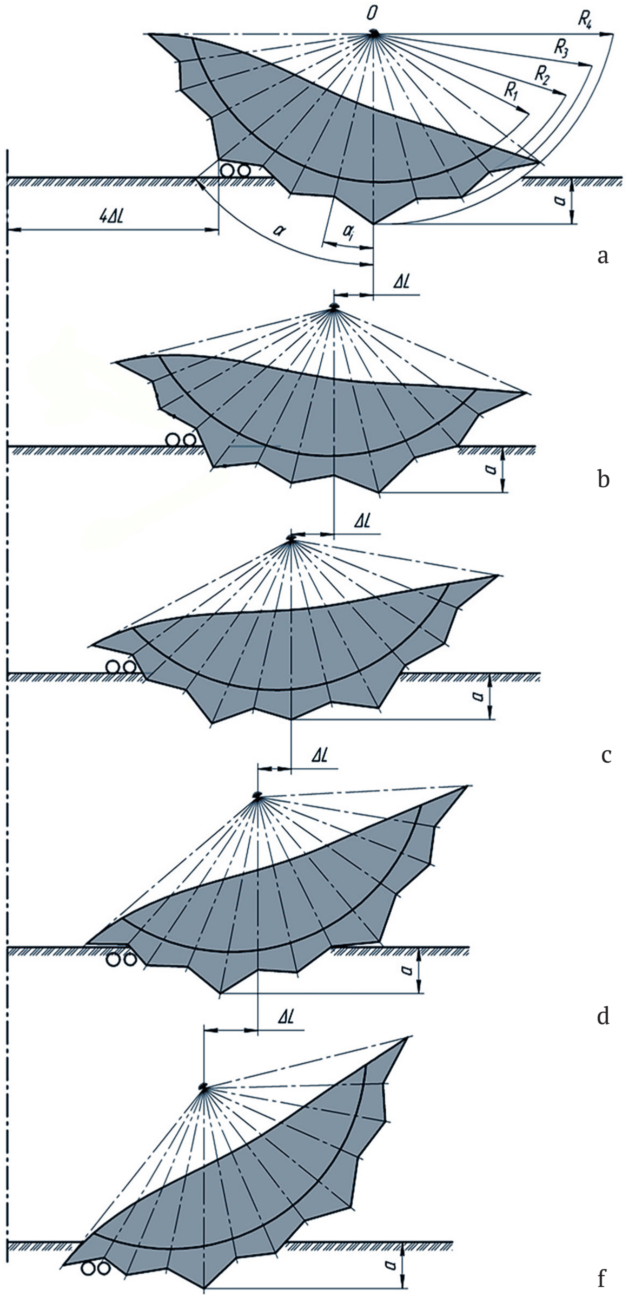

Figure 8. Diagram for calculating the action of a notched disc on soil and stem

Note: a–f – stages of the work process; O – axis of rotation; a, ΔL, R_1, R_2, R_3, R_4 – length in meters; α, α_i – angles in radians

Source: compiled by the authors

From the calculation scheme, the angular step of the cuts can be determined:

$$\alpha < arccos\frac{R_4-a-d}{R_4}, \quad (9)$$

where a – penetration depth of the disc; R_4 – radius of the circumscribed circle; d – diameter of the stem. This allows for the determination of the number of cuts. Calculations are performed using the following data: R_4 = 230 mm, corresponding to a disc diameter of 460 mm; a = 50-80 mm (standard values accepted in most known aggregates); $d = 2\text{-}35$ mm – diameter of the stem. Given the requirement for full immersion of the disc cuts in the soil during operation, the radial parameters of the disc are set as follows: $R_1 = 230 - 80 = 150$ mm, $R_2 = 230 - 50 = 180$ mm, $R_3 = (R_1 + R_4)/2 = 190$ mm. Thus, for equation (1), $H_m = R_4 - R_3 = 40$ mm.

By analysing dependence (9) in the Wolfram Cloud software package, the optimal angular step value of $\alpha = 48.3°$ and the number of notches $n = 8$ is obtained. Considering Figure 8, $\alpha_i = \alpha/4 = 12.1°$, $\Delta L = 2\pi R_4 \alpha_i/360 = 48.5$ mm. Such discs are used in Strip-Till and Mini-Till systems for crushing surface clods and plant residues. However, they are not suitable for soil loosening.

In the previous stages, the disc diameter of 460 mm, the number, and the parameters of the notches on it were justified. According to equation (1) and Figure 1, the number of waves of the colter corresponds to the number of notches. The calculation scheme is shown in Figure 9.

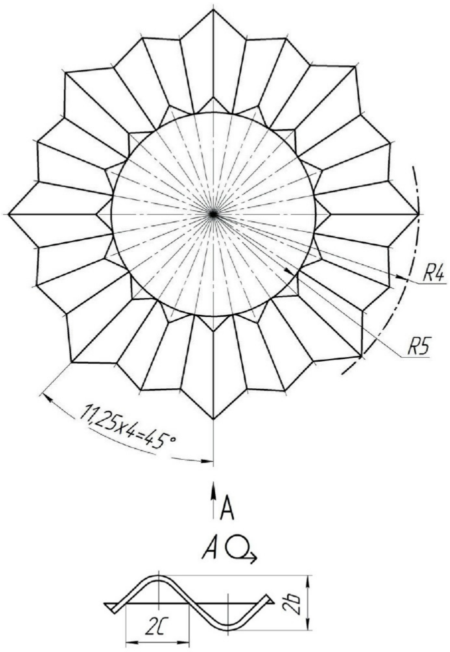

Figure 9. Diagram for calculating the colter
Note: A – reamer on the drawing; *C, R_4, R_5* – length in meters
Source: compiled by the authors

Structurally, this modification of the notched disc is an improvement of the previous version, in which the peaks of the cutting segments are made in the form of bends in a staggered order. The presence of waves ensures independence of the interaction process with plant residues from their location on the field surface and creates conditions for vertical soil processing. In the proposed modification, the waves are arranged radially, although there are options where they are positioned at a certain radius to the axis of rotation (Fig. 1). The main purpose of the colter is to perform vertical processing, i.e., loosening through vertical action. The peculiarity of vertical processing is that the wear lines from the cutting element do not propagate in the vertical-transverse plane. This is not only analytically justified but also confirmed during operation.

The separated soil aggregate from the moment of undercutting to placement in the furrow remains in constant contact with the working surfaces of the disc. Thus, to overcome the internal stress in the soil, it will be sufficient to determine the cutting force. For this, it is necessary to know the coefficient of soil particle cohesion and the surface area of the corresponding prism.

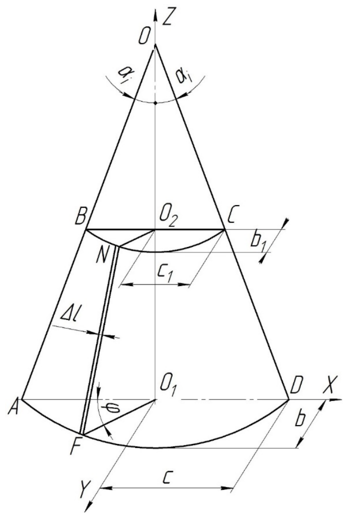

Figure 10. Geometric dimensions of the separated prismatic soil slice
Note: X, Y, Z – spatial coordinates in meters; O, A, B, D, F, N, O_1, O_2 – points on the drawing; Δl, *b, c*, b_1, c_1 – length in meters; α_i, φ – angles in radians
Source: compiled by the authors

The separated prismatic soil slice is a semi-truncated cone ABCD with corresponding parameters (designated according to Fig. 10): $c = R_4\, tg\alpha_i = 49.3$ mm; the constructively accepted value is $b = 35$ mm; $b_1 = b \cdot (R_4 - H_m)/R_4 = 29$ mm. For the lower ellipse, the radius vector value is:

$$R = \frac{b \cdot c}{\sqrt{b^2 \cdot cos^2\, \varphi + c^2 \cdot sin^2\, \varphi}}. \quad (10)$$

For the lower radius vector:

$$r = \frac{b_1 \cdot c_1}{\sqrt{b_1^2 \cdot cos^2\, \varphi + c_1^2 \cdot sin^2\, \varphi}}. \quad (11)$$

The surface area of the separated soil prism is calculated as the sum of the area of the lower semi-ellipse and the area of the lateral surface DABC. The area of the lateral surface is calculated by numerical integration. The surface is then divided into infinitely thin elementary sections of width Δl. The area of each such elementary section is determined as follows:

$$dS = \sqrt{a^2 + (R - r)^2} \cdot dl = \sqrt{a^2 + (R - r)^2} \cdot R \cdot d\varphi. \quad (12)$$

By integrating expression (12), the total area of the lateral surface is obtained:

$$S_B = \int_{\varphi=0}^{\varphi=\pi} \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi. \quad (13)$$

According to Figure 10, the expression for the total surface area is:

$$S_\Sigma = S_B + S_O + S_{PO} = \\ = \int_0^\pi \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi + \pi \cdot b \cdot c + a \cdot (c + c_1). \quad (14)$$

where S_{PO} is the area of the prism cut; S_O is the area of the prism base.

The force required to separate the soil prism can be expressed as follows:

$$F = C_{UD} \cdot S_\Sigma. \quad (15)$$

In turn, the specific cutting resistance can be represented as follows:

$$K_1 = \frac{F}{b \cdot a}. \quad (16)$$

The volume of the separated soil prism is determined for further calculations:

$$V = 0.5 \cdot \frac{\pi \cdot a}{6} \cdot [(2 \cdot c + c_1) \cdot b + (2 \cdot c_1 + c) \cdot b_1]. \quad (17)$$

The degree of soil fragmentation is determined as follows:

$$i = \frac{V}{V_i} = \frac{6V}{\pi d_a^3}. \quad (18)$$

where d_a is the diameter of the formed soil aggregate.

Combining equations (10)-(18) yields the following result:

$$i = \frac{a}{2d_a^3} \cdot [(2 \cdot c + c_1) \cdot b + (2 \cdot c_1 + c) \cdot b_1]. \quad (19)$$

$$K_1 = \frac{C_{UD}}{b \cdot a} \cdot \\ \cdot \left(\int_0^\pi \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi + \pi \cdot b \cdot c + a \cdot (c + c_1)\right). \quad (20)$$

Solving the condition for minimizing the specific cutting resistance and maximizing the degree of soil fragmentation in the Wolfram Cloud software package:

$$\frac{a}{2d_a^3} \cdot [(2 \cdot c + c_1) \cdot b + (2 \cdot c_1 + c) \cdot b_1] \to max \\ \frac{C_{UD}}{b \cdot a} \cdot \left(\int_0^\pi \sqrt{a^2 + (R-r)^2} \cdot R \cdot d\varphi + \right. \\ \left. + \pi \cdot b \cdot c + a \cdot (c + c_1)\right) \to min. \quad (21)$$

The following rational parameters for the colter wave are obtained: $H_w = b = 24.4$ mm; $c = 2b = 48.8$ mm.

The necessity of the spiral shape of the wave cutouts on the disc is difficult to justify analytically, so further research will use numerical modelling methods in the Simcenter STAR-CCM+ software package. The analytical model developed in this study offered further insights into how the geometric features of the disc affected its interaction with soil. By simulating the forces acting on the disc during tillage, the model allowed researchers to predict the performance of different disc shapes under varying field conditions. This proved to be a valuable tool for optimizing the design of the discs and could be used by manufacturers to improve the effectiveness of their products.

Moreover, the wavy disc's unique shape allowed for a more controlled interaction with the soil, reducing the likelihood of soil compaction, which is a significant concern in modern agriculture. Soil compaction can lead to poor root development, reduced water infiltration, and lower crop yields. By reducing the pressure applied to the soil surface, the wavy disc minimized compaction while still performing the necessary tillage functions. Overall, the research demonstrated the potential of using bionic principles to design more efficient agricultural tools. The wavy disc, with its optimized shape, offered a clear advantage over traditional designs, reducing both energy consumption and operational costs while improving soil and residue management. This could have a significant impact on the agricultural industry, particularly in regions where soil health and sustainable farming practices are of paramount importance. By continuing to explore the applications of bionics in agricultural engineering, future research may uncover even more innovative solutions that help farmers meet the growing demands of modern agriculture.

Comparing the proposed designs of the discs (equation (1) and Fig. 2) with the Patent US 2006/0144600 A1 (Piccat, 2006), it could be concluded that the proposed mathematical description of the profile was more universal. With certain parameters, it was possible to achieve known designs. This indicated the generalization of the obtained disc shape.

The application of bionics in justifying the shape of turbo discs, modelled on the basis of the Argonaut shell, improved the capture and cutting of plant residues without repulsion. This approach was further supported by the work of Z. Zeng *et al.* (2021), where bionic prototypes such as the oral apparatus of locusts and the digging legs of mollusks were used. Additionally, this approach was confirmed in the study of I.V. Sobolevsky *et al.* (2021), where bionic prototypes of wavy discs were derived from the radial ribs of the bivalve edible cockle shell (*Cerastoderma edule*) and the digging leg of the common dung beetle (*Geotrupes stercorarius*).

The rational parameters of the wavy disc (wave height of 24.4 mm, number of notches – 8, and diameter – 460 mm) identified in the research aligned with the findings of I. Torotwa *et al.* (2022), where similar designs demonstrated increased efficiency in chopping plant residues and loosening the soil. For example, experiments with fluted discs revealed that they significantly reduced the amount of residue on the field's surface and created a wider furrow, which was similar to the results obtained with wavy discs. Furthermore, the proposed analytical model (3)-(8) could complement the simulation by I. Torotwa *et al.* (2022) and serve as a suitable physical-mathematical tool. The study by I. Torotwa *et al.* (2022) provided a direct comparison of wavy and conventional discs, reinforcing the conclusion that wavy discs are more effective for handling plant residues. In tests, the wavy discs significantly reduced the amount of unprocessed material left on the soil surface, which is critical for ensuring proper seed placement and reducing the likelihood of crop diseases. This was particularly beneficial in no-till or reduced-till systems where crop residues are intentionally left on the surface for moisture retention and erosion control.

The analytical justification for the behaviour of the discs during contact with soil and plant residues demonstrated that the wavy surface of the disc with notches created optimal conditions for vertical soil tillage, as it reduced resistance and promoted uniform chopping of residues. These results were corroborated by the studies of A.M. Semenyuta (2014) and A.I. Shevchenko (2001), which found that fluted discs enhanced soil fragmentation and reduced energy costs for tillage.

The research results presented here supplemented the findings of Z. Zeng (2019), particularly by enabling the development of a methodology for engineering calculations of the structural parameters of turbo discs (colters). In turn, the bionic analogue of the turbo disc, proposed as the basis of the design, confirmed the effectiveness of using the bionic approach in the agro-mechanics system (Kozachenko *et al.*, 2021).

The spiral shape of the wavy disc, proposed in this study, had great potential for reducing the specific cutting resistance and improving the quality of soil treatment. The works of A.S. Kobets *et al.* (2011) and O. Kozachenko *et al.* (2021) also noted that geometric modifications similar to spiral elements could significantly affect the efficiency of soil tillage tools.

By examining the differences between traditional disc profiles and those designed using bionic principles, a more comprehensive understanding of the advantages offered by biologically inspired shapes was gained. The research not only highlighted the utility of imitating natural forms but also validated the effectiveness of applying these forms to agricultural machinery. Traditional flat discs, for example, often struggled to perform optimally when dealing with tough plant residues or compacted soils. The introduction of wavy or spiral designs allowed for better engagement with the soil, leading to improved penetration and more efficient residue cutting.

The use of bionic principles, as seen in this study, aligned with the broader trend in agricultural engineering towards more sustainable and efficient machinery. Bionics, which draws inspiration from nature, offered a novel approach to solving long-standing challenges in the field. In the case of the wavy disc, the inspiration came from natural structures that have evolved to efficiently interact with the environment, such as the shells of molluscs and the limbs of burrowing animals. These natural designs provided a blueprint for creating tools that are both effective and energy-efficient.

CONCLUSIONS

Considering the method of bionic reverse engineering, the equation for the shape of turbo discs (colters) has been determined by approximating the shell of the Argonaut (*Argonauta argo*). As a result of analytical studies of the interaction process of a solid disc with plant residues, the rational diameter value of the disc was determined to be $D_d = 460$ mm, assuming the embedding of stems with a thickness of 10-20 mm to a depth of 80 mm. Analytical studies confirmed that the presence of cutouts on the disc prevents the stems from being pushed aside and ensures better capture. Analysing the obtained analytical dependencies in the Wolfram Cloud software package, rational cutout values were obtained: the cutout height $H_m = 40$ mm, and the number of cutouts $n = 8$.

The presence of waves in the disc plane ensures the independence of the interaction process with plant residues from their location on the field surface and creates conditions for vertical soil cultivation. Thus, according to the results of analytical studies, it was determined that with the condition of minimizing the specific cutting resistance and maximizing the degree of soil fragmentation, the rational parameters of the colter wave are a wave height $H_w = 24.4$ mm.

The substantiated parameters of the colters open new avenues for further research into optimizing agricultural machinery. Future studies could explore the potential for adapting existing equipment to these innovative structural parameters, aiming to achieve a better balance between soil pulverization efficiency and reduced energy consumption. Additionally, further investigation into the integration of bionic principles in machinery design could lead to the development of more efficient and environmentally sustainable soil processing technologies.

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CONFLICT OF INTEREST

None.

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Аналітичні обґрунтування конструктивних параметрів біонічних колтерів для вертикального обробітку ґрунту

Анотація. Біонічні колтери імітують природні форми та функції, які дозволяють знизити енергетичні витрати на обробку ґрунту. Мета досліджень була обґрунтування конструкції і конструктивні параметри турбодисків (колтерів) для вертикального обробітку ґрунту спираючись на принципи біонічного зворотного інжинірингу. Враховуючи цей метод визначено рівняння форми турбодисків (колтерів), яке отримано в результаті апроксимації мушлі аргонавта (*Argonauta argo*). Рівняння враховує основні конструктивні параметри турбодисків: діаметр D_d, висота вирізу H_m, висота хвилі H_w, кількість вирізів n, коефіцієнт спіралеподібності k. В результаті аналітичних досліджень процесу взаємодії суцільного диска з рослинними рештками визначено раціональне значення його діаметра $D_d = 460$ мм при умові занурення стебелів товщиною 10-20 мм, на глибину 80 мм. Аналітичні дослідження підтвердили, що наявність вирізів на диску унеможливлює відштовхування стебла і забезпечує його кращій захват. При цьому аналізуючи отримані залежності у програмному пакеті Wolfram Cloud визначені раціональні значення вирізів: висота вирізу $H_m = 40$ мм, кількість вирізів $n = 8$. Наявність хвиль в площині диску забезпечує незалежність процесу взаємодії з рослинними залишками від їх розташування на поверхні поля та створює умови для вертикальної обробки ґрунту. Встановлено, що при умові мінімізації питомого опору різання і максимізації ступеня подрібнення ґрунту раціональними параметрами хвилі колтера є висота хвилі $H_w = 24{,}4$ мм. Обґрунтовані параметри колтерів забезпечують найкращий баланс між ефективністю подрібнення ґрунту і зниженням енергетичних витрат на обробку ґрунту. Отримані результати можна використати для адаптування існуючої сільськогосподарської техніки під нові конструктивні параметри колтерів для підвищення її ефективності

Ключові слова: вертикальний обробіток ґрунту; турбодиск; форма; мушля; аргонавти; аналітичні дослідження

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