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DETERMINING THE INFLUENCE OF DESIGN FEATURES IN AGRIVOLTAICS SYSTEMS ON TRACKING EFFICIENCY

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The object of this study is agrivoltaics systems. The task addressed relates to determining the tracking efficiency of agrivoltaics systems. The subject of the study is the dependence of the tracking efficiency of agrivoltaics systems on their design features and the dependence of the area coverage efficiency of photovoltaic panels on the distance between the arrays in an agrivoltaics system during the highest solar activity.

It was established that the tracking efficiency of an agrivoltaics system with a horizontal axis of rotation and the orientation of the axis of rotation "East-West" is 34.75%, and for an agrivoltaics system with an orientation "North-South" – 52.89%. The tracking efficiency of an agrivoltaics system with an orientation "North-South" and the axis of rotation set at an angle of latitude (50°) is 67.95%. At the same time, with the rotation axis set in such a way that the photovoltaic modules track the flow of sunlight also in the vertical plane, this value is 69.5%. The length of the day during the operation of the agrivoltaics system varies from 12 hours on March 21 and September 21 to 16 hours on June 21. This combination of the time of switching on and off the agrivoltaics system and the length of the day leads to the fact that the angle of inclination of the photovoltaic modules relative to the plane of their axis of rotation is 45°.

The obtained value of the angle of inclination of the photovoltaic modules relative to the plane of the axis of rotation in the agrivoltaics system has made it possible to determine the distance between agrivoltaics arrays, which was 3.79 m. If one takes into account the specified distance between the agrivoltaics arrays, the efficiency of covering the area with photovoltaic modules during the highest solar activity will be 52.8%.

The research results could be used as a basis for designing agrivoltaics system structures at different latitudes as well as assessing their economic efficiency

Keywords: agrivoltaics, photovoltaic module, angle of incidence of solar rays, tracking, photovoltaics

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1. Introduction

As more countries join the Paris Agreement to achieve net-zero emissions by 2050, the use of renewable energy technologies, including solar, has increased significantly. Solar energy is the fastest-growing sector of the economy, due to its low present value in many regions compared to other renewable energy sources [1]. However, the increase in the number of photovoltaic installations leads to extensive land use, which contradicts the UN Sustainable Development Goals on land conservation [2]. Land conservation and restoration are the basis of sustainable agricultural production, which is designed to address food security. A promising solution to resolve the contradiction between ensuring balanced land use, promoting food security, and sustainable energy supply is the use of agrivoltaics systems, which contribute to achieving zero CO_2 emissions [3].

Agrivoltaics is a technology aimed at the efficient dual use of agricultural land: for crop production (first priority) and for electricity generation (for additional income) owing to photovoltaic modules installed on these lands [4]. There are two types of agrivoltaics systems: those that involve agricultural activities on available lands of existing photovoltaic facilities; agrivoltaics systems specially installed for combined crop production (livestock, forestry) and energy production. Agrivoltaics systems can improve the efficiency of electricity generation and enable an increase in land productivity by 60–70% compared to their use only for energy generation [5].

The last decades are characterized by a rapid increase in the number of installed agrivoltaics systems of different sizes, power, and level of structural complexity [6]. However, the increasing complexity and size of agrivoltaics systems is often accompanied by a decrease in the efficiency of such systems due to a number of technical, agronomic, and environmental problems. In particular, one of the common factors reducing the efficiency of agrivoltaics systems is shading and uneven light distribution [7]. While partial shading helps protect crops from intense solar radiation, excessive shading (due to incorrect installation and tilting of solar panels) is the cause of crop losses [8].

The increase in the size of agrivoltaics systems complicates the processes of energy conversion and its supply to the power grid. To compensate for the imbalance between the variable generation of electricity by agrivoltaics systems and the needs of the agricultural consumer, it is necessary to design electricity distribution and storage systems. The lack of effective control is the cause of either the appearance of excess electricity or its shortage during periods of peak loads, which disrupts the operation of the entire system [9].

Another important factor in reducing the efficiency of agrivoltaics systems with an increase in their size is the lack of proper extensive infrastructure, including mounting structures, inverters, and network equipment [10]. Therefore, servicing such systems, especially in large areas, becomes more difficult.

It is also necessary to note climatic and environmental factors, which, on the one hand, are the cause of a decrease in the stability of agrivoltaics system structures, and on the other hand, worsen the conditions for agricultural production [11].

Therefore, current agrivoltaics systems require improvement, which is associated with solving a number of practical scientific tasks. Also, the results of research on agrivoltaics systems presented to the general public are mainly limited to experimental conditions. It is important for practitioners to have generalized results for different operating conditions of agrivoltaics systems, which could allow for high efficiency in obtaining both energy and agricultural produce.

Therefore, research aimed at improving the efficiency of agrivoltaics systems is of scientific relevance. This is due to the fact that such systems enable the sustainable development of energy systems and agricultural production, which meet current and future requirements.

2. Literature review and problem statement

In [12], the authors analyzed research over the past five years to establish ways to optimize photovoltaic systems with the possibility of further using the results obtained in future developments. To establish optimization factors, studies on the use of innovative engineering technologies related to tracking systems, as well as on the use of new generation photovoltaic elements, were considered. The work also considered various layout schemes for agrivoltaics systems and how distance, height, and density affect the degree of shading under the panels. The authors note that one of the leading ways to increase the efficiency of agrivoltaics systems of the future is their engineering optimization. Scientific problems remained unsolved, regarding improving the designs of tracker systems, rational selection of the type of photovoltaic elements, substantiation of schemes for installing PV module arrays, determining the orientation of solar panels and their angle of inclination to the horizon.

The authors of [13] note that commercially available are silicon elements for photovoltaic systems; however, their use in agrivoltaics is limited due to their opaque structure, which blocks the type of radiation required for photosynthesis. Therefore, the use of silicon elements requires careful calculations of the intervals between the panels depending on the type of agriculture. The authors of [14] propose using highly concentrated PV systems in agrivoltaics, which are capable of splitting the light flux into two types of radiation: for the photosynthesis process and for the purpose of electricity generation. However, it is quite difficult to implement this in practice in large-scale agrivoltaics systems due to the limited functionality of such highly concentrated systems and their high cost. In turn, in [15], the possibility of spectral separation of light using ultrathin amorphous germanium (a-Ge : H) solar cells was investigated. And although in [15] the possibility of transmitting active radiation required for the photosynthesis process was confirmed, the efficiency of electricity generation usually does not exceed 5%. In [12–15] it is indicated that effective methods for engineering optimization of agrivoltaics systems are the development of a rational scheme for installing PV module arrays, substantiation of their angle of inclination to the horizon, tracking, and spatial orientation of solar panels.

In particular, the effectiveness of installing a large-scale agrivoltaics system for the combined production of electricity and the cultivation of shade-tolerant crops was investigated in [16]. The solar panel installation scheme was determined by modeling based on data on solar radiation in the region. The ground-based agrivoltaics system provided for the installation of solar panels at a height of 1 meter with a row spacing of 6 m. The size of the panel arrays was 20×1 m, and the land plots were 20×5 m. The agrivoltaics system on poles included two schemes: with partial and full panel installation density. In both cases, the panels were installed at a height of 4 m. The partial scheme included two rows of 20×1 m panels installed at a distance of 6.4 m from each other, and the full scheme included 4 rows of modules with a row spacing of 3.2 m. The results show that the incomes of farms that installed agrivoltaics systems exceeded the incomes of those that preferred traditional crop growing technology by 30%. The authors claim that if the cultivation of only lettuce is transferred to the agrivoltaics system, then electricity generation will increase by 40–70 GW. However, the issues of the influence of the variable nature of solar radiation during the year on the productivity of the agrivoltaics system and the determination of the influence of shading on the yield of agricultural crops remained unresolved. Such studies are reported in [17]. The authors compared the efficiency of two systems of the same production capacity: a ground-based photovoltaic system and an agrivoltaics system installed on land intended for growing vegetable crops. The energy required to perform the operations of the technological process for growing vegetables (irrigation, cold storage) was provided by PV modules. Each system was tested under two hypothetical operating modes, where it was assumed that:

1) solar energy productivity will remain constant throughout the operation period;

2) the annual productivity index will decrease by 0.5%.

The work also investigated the effect of shading on the development, growth, and yield of vegetable crops. It was noted that the cost of electricity generated by the agrivoltaics system was 55% lower than that generated by the photovoltaic system.

Although progress in photovoltaic technologies has contributed to the increase in energy production by agrivoltaics systems, the issue of efficient land use still remains open, especially for industrial-scale systems.

The authors of [18] consider the issue of efficient land use through such optimization parameters as power density and energy density. Using the geographic information system ArcGIS, the boundaries of agrivoltaics stations were determined and the power density (MW/acre) and energy (MWh/acre) were calculated for two types of PV modules – tracker and installed at an angle of inclination to the horizon. The calculations include the value of the geographical latitude and illumination of the site. It was found that for modules with a fixed angle of inclination to the horizon, the power density increased by 52%, while for tracker ones – by 43%. The energy density increased by 33% and 25%, respectively. The authors summarize that the use of land has become more efficient. However, if we talk about even a small agrivoltaics system, then, taking into account the high energy density, a plot of about 6 hectares is required for its installation.

The issue of improving the efficiency of the agrivoltaics system while simultaneously achieving minimum land use is also raised in [19]. The parameter influencing the level of soil illumination and energy production in the agrivoltaics system was the density of PV modules (vertical, oriented "East-West" (E/W) and installed at an angle to the horizon, oriented "North-South" (N/S)). At high installation density, N/S-oriented PV modules produced more energy compared to E/W-oriented modules but were characterized by a lower indicator of the level of soil illumination. The spatial distribution of illumination remained non-uniform in both cases. However, the level of illumination became more uniform after raising the E/W-oriented panels of vertical PV modules by 1 m above the surface. For N/S-oriented modules, under the same conditions, the distribution of illumination did not change. Also, during long-term operation without cleaning, E/W-oriented modules had lower losses in electricity generation than N/S-oriented modules and were better suited for the operation of agricultural machinery. Therefore, according to the authors, E/W-oriented PV modules are the best solution for agrivoltaics systems.

A comparison of the efficiency of two agrivoltaics systems (with vertical E/W-oriented PV modules and N/S-oriented modules installed at an angle to the horizon) is also given in study [20]. The authors built a mathematical model that makes it possible to determine the energy efficiency of the agrivoltaics system, the optimal shading scheme, and predict the yield of shade-tolerant crops. In contrast to what was stated in work [19], the authors of the study claim that the agrivoltaics system with vertical E/W-oriented PV modules is inferior to the system with N/S-oriented modules in terms of overall efficiency. Although they also note that the agrivoltaics system with vertical E/W-oriented PV modules is more convenient when using agricultural machinery. Additional advantages are that the agrivoltaics system provides a more uniform distribution of sunlight and precipitation to plants and is also less prone to dust contamination.

Despite the advantages of the studies described above, the disadvantage is that they only compare two types of agrivoltaics systems, so they have a rather limited application. Those works did not investigate the efficiency of an agrivoltaics system when combining several different types of photovoltaic systems. This issue was partially resolved in subsequent studies.

In particular, in [21], an agrivoltaics system (with a capacity of 10.5 kW) with vertical bifacial PV modules installed on an area of 85 m^2 intended for growing vegetables was investigated. The efficiency of the agrivoltaics system was compared with traditional farming and a rooftop solar station of the same capacity installed with a slope to the south. The yields of okra and calabash decreased by 15.97% and 38.17%, respectively, while the yield of potatoes increased by 8%, which indicates the need for careful selection of shade-tolerant crops for the agrivoltaics system. It is noted that the annual electricity generation decreased by 25% compared to the rooftop station, which is explained by the different angles of inclination and orientation of the panels. The advantage is that the agrivoltaics system made it possible to retain 26% more moisture in the soil compared to conventional agriculture and reduce the air temperature by 0.5°C. The results certainly have practical value, but as in previous works, their application is very limited.

A more extensive study on the efficiency of an agrivoltaics system located on a plot of 175 m^2 (Ankara, Turkey) is reported in [22]. The first stage of the study involved determining the annual, monthly, and seasonal optimal angles of inclination of the PV panel. The second stage involved modeling eight variants of agrivoltaics systems with different installation angles and PV panel efficiency, followed by calculating the energy produced and net profit. The third stage involved determining the potential coefficient of functional land use for seven crops for the eight models. The highest yield increase (11.2%) was demonstrated by model M1 ($\beta = 31.33°$), while the lowest yield loss (33.2%) was demonstrated by model M4 ($\beta = 90°$). Among the crops, kiwi had the highest yield (with a coefficient of 2.07), and bok choy had the lowest (0.25). The maximum electricity generation and net profit were 15674 kWh and USD 1286, respectively. As indicated in the work, the results could become a basis for the development of technical guidance for designing agrivoltaics systems in mid-latitude regions. However, the issues of optimal tracker design and rational placement of PV modules in photovoltaic arrays remained unexplored.

The issue of rational placement of PV modules in photovoltaic arrays was partially addressed in study [23]. The authors report an innovative approach to determining the optimal distance between PV modules that could contribute to achieving a sufficient level of solar radiation for the proper development of agricultural crops. The agrivoltaics station was built on the basis of the existing photovoltaic station "El Molino" (Cordova, Spain), equipped with two-axis solar trackers with a reverse tracking function. Between the modules, pentagonal plots of land were created with a width of 10.5 m and a minimum height of 1.31 m (on the sides) and a maximum height of 2.81 m (in the center). Several options for growing different crops on these plots were proposed. The influence of plant height on the required area of the plot for their cultivation was established. The results show that with a plant height of 1.4 m, about 74% of the land plot area is suitable for cultivation. As the plant height increases, the area of the land plot decreases. The above confirms the high efficiency of land use and the feasibility of converting existing photovoltaic stations into agrivoltaics systems, thereby contributing to meeting the population's needs for food and combating climate change.

The authors of study [24] proposed software that, through modeling, makes it possible to optimize the design of trackers in an agrivoltaics system. An assessment of land productivity in an agrivoltaics system with single-axis trackers located in Germany was also performed. The growth of agricultural crops was simulated under different installation and orientation schemes of trackers (the distance between rows, height above the surface and azimuth were changed). The results indicate that there is a clear relationship between land productivity and the width of the tracker rows. An increase in the height of the trackers, in turn, reduces the efficiency of dual use of the land. However, adjusting only the orientation of the trackers significantly improves productivity. At a 40% density of PV modules in the array, energy production decreased by 42% compared to conventional photovoltaic stations, and crop yields decreased (potatoes by 32%, corn by 66%). The authors presented simplified models for predicting the yield of shade-tolerant and non-shade-tolerant crops, which can be easily integrated into existing software for creating photovoltaic stations, which provides practical tools for their further optimization.

In [25], the ability of PV modules to track sunlight was used for effective spatiotemporal distribution of light between solar panels and crops in an agrivoltaics system. The type of crop and the density of PV modules were chosen as optimization factors. A combined approach was reported, combining classical single-axis tracking and the use of modules without a tracking function to balance the sunlight flow between modules and crops. When modeling the energy productivity of modules and spatiotemporal shading, appropriate coefficients were used, while the response of plants to shading was estimated empirically. It has been experimentally established that 5 hours of standard tracking during the day provides 80% of typical energy generation while maintaining 40% to 80% of crop yield. Increasing the distance between modules improves the yield of shade-loving crops. However, due to higher capital costs, the specified agrivoltaics system requires a 30–40% increase in energy tariffs to be economically competitive. This approach is effective under the conditions of individual design of an agrivoltaics system based on PV modules with the ability to track the sun.

In [26], using the PVsyst and DSSAT programs, various designs of PV modules of agrivoltaics systems with single- and double-sided solar panels, both in fixed and tracker versions, were also investigated. Depending on the location of the PV modules (11 regions of the UK were studied), energy production and crop yield varied significantly (depending on the level of solar radiation, temperature, and rainfall). The study found that tracker PV modules with double-sided solar panels with a capacity of 440 W, on average, produced 24.6% more energy than static PV modules with single-sided panels, but showed a decrease in yield. The functional land use factor was higher for the agrivoltaics system with fixed PV modules with single-sided solar panels. The maximum indicator was 1.39 and reflected the optimal balance between yield and energy production. The financial analysis revealed that tracker PV modules with single-sided panels provide the highest internal rate of return, but the results vary significantly depending on the region – the difference between the lowest and highest indicators reached 41.16%. The lowest cost of electricity was in regions with high levels of solar radiation. The issues of achieving maximum efficiency of the agrivoltaics system by adapting it to local climatic conditions and PV module designs remained unresolved.

The feasibility of using tracking was also considered in work [27], which reported the comparison of two types of agrivoltaics systems in Belgium for growing beet. The systems included both single-axis tracker and vertical PV modules with double-sided solar panels. Field measurements of the amount of energy produced and beet yield lasted for two years. The results show that smart tracking under optimal irrigation conditions provides a significant increase in energy generation (+30%) and land use efficiency (+20%) at lower costs, while maintaining yields at the level of the classical system. As for the proposed empirical plant growth model, its usefulness in practice turned out to be somewhat lower since it does not take into account climatic changes in dry years. The issue of a comprehensive approach to the use of agrivoltaics systems, which includes the analysis of climatic conditions, PV module designs, and crops, assessment of system efficiency, and ways to reduce investment risks, remains unresolved.

Our review of the literature [16–27] makes it possible to reveal one existing problem: despite a significant amount of scientific research, the task of improving the efficiency of agrivoltaics systems still needs to be solved. Summarizing the results reported in [16–27], tracking of various designs of agrivoltaics systems and the degree of coverage of the land area with photovoltaic panels are the most important parameters for improving the efficiency of agrivoltaics systems. Therefore, further research should be conducted on improving the efficiency of tracking of agrivoltaics systems and the efficiency of covering the land area with photovoltaic panels during the lowest solar activity. Despite the complexity of taking into account all the factors influencing the specified parameters of the agrivoltaics system, such research is necessary, and the benefit of results to be obtained is obvious.

3. The aim and objectives of the study

The purpose of our study is to determine the tracking efficiency indicators of agrivoltaics systems depending on their design features. This will make it possible to choose the most acceptable structures of agrivoltaics systems to ensure their effective functioning under specific application conditions.

To achieve the goal, the following tasks were set:

– to determine the tracking efficiency of different designs of agrivoltaics systems;

– to determine the efficiency of area coverage by photovoltaic panels during the lowest solar activity.

4. The study materials and methods

4. 1. The object and hypothesis of the study

The object of our study is agrivoltaics systems.

The subject of the study is the dependence of the tracking efficiency of agrivoltaics systems on their design features and the dependence of the efficiency of covering the area with photovoltaic panels on the distance between the arrays of the agrivoltaics system during the greatest solar activity.

The main hypothesis of the study assumes that by complicating the structure of an agrivoltaics system, it is possible to improve its tracking efficiency up to reaching its maximum value.

The main assumptions and simplifications adopted in the work: it was assumed that the Earth is in a parallel flow of solar rays; the phenomenon of cloudiness was ignored (it affects only the intensity of solar radiation and does not affect the angle of incidence of solar rays on the photovoltaic module).

4. 2. Description of the designs of agrivoltaics systems

The studies were conducted on agrivoltaics systems with the orientation of the axis of rotation of photovoltaic modules in the direction of "East-West" and "North-South". Agrivoltaics systems with the orientation of "North-South" differed in the position of the axis of rotation of photovoltaic modules into horizontal, installed at an angle of latitude and adjustable in the vertical plane. Agrivoltaics systems with the orientation of "East-West" were considered only with a horizontal position of the axis of rotation of photovoltaic modules. This is due to the fact that it is too difficult to use such agrivoltaics systems adjustable in the vertical plane since the change in the angle of inclination of the axis during the day must change from 0 to 90° twice a day. The general view of the studied structures of agrivoltaics systems is shown in Fig. 1.

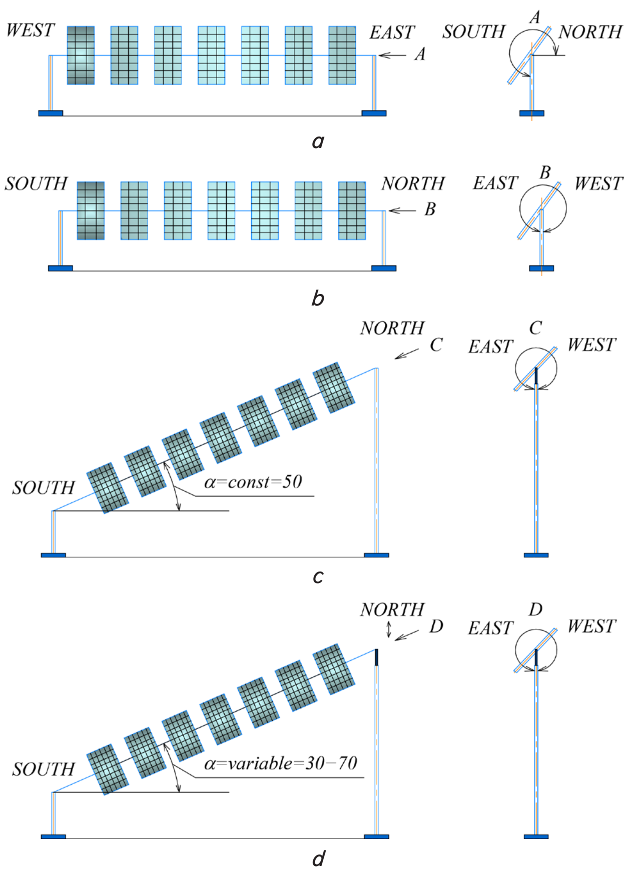

Fig. 1. Schematics showing the studied structures of agrivoltaics systems depending on the orientation of the axis of rotation of photovoltaic modules: *a* – horizontal axis, direction "East-West"; *b* – horizontal axis, direction "North-South"; c – axis installed at an angle of latitude, direction "North-South"; *d* – axis installed with the possibility of adjustment in the vertical plane, direction "North-South"

The above designs were used to study the tracking efficiency of agrivoltaics systems using simulation modeling and the efficiency of covering the surface area with photovoltaic panels during peak solar activity.

4. 3. Methods for conducting research on the designs of agrivoltaics systems

The average annual tracking efficiency of photovoltaic modules in the agrivoltaics system was determined using an expression from [28]. This parameter is the ratio of the annual weighted average value of the cosine of the angle of incidence of the Sun's rays $\cos\theta_Z^{gn}$ on the plane of the photovoltaic module panel installed in the agrivoltaics system to its maximum value $\left(\cos\theta_Z^{gn}=1\right)$. This makes it possible to express the average annual tracking efficiency of photovoltaic modules in relative units or in percentages and determine it from the expression

$$\cos\theta_Z^{gn}=\frac{\sum_{i=1}^{365}a_i\cos\theta_{Zi}^{d}}{\sum_{i=1}^{365}a_i},\tag{1}$$

where $\cos\theta_{Zi}^{d}$ is the average daily efficiency of the photovoltaic module installation in the agrivoltaics system; a_i is the angular length of the i-th day, degrees.

The average daily efficiency of tracking photovoltaic modules in the agrivoltaics system was determined based on the values of the cosine of the angle of incidence of the sun's rays relative to the z axis and the angular length of daylight. The actual determination was carried out based on the ratio of the average daily value of the cosine of the angle of incidence of the sun's rays on the panel plane to its maximum value $\left(\cos\theta_{Zi}^{d}=1\right)$. This makes it possible to express the average daily efficiency of tracking photovoltaic modules in relative units or in percentages and determine it from the expression

$$\cos\theta_{Zi}^{d}=\frac{\sum_{j=0}^{a_j}a_j\cos\theta_j}{\sum_{j=0}^{a_j}a_j},\tag{2}$$

where $\cos\theta_j$ is the cosine of the angle of incidence of the sun's rays, corresponding to the angular length of the j-th day; a_j is the current value of the angular length of the j-th day from sunrise to sunset, degrees.

The magnitude of the angle of incidence of the sun's rays relative to the z axis, which is perpendicular to the surface of the solar panel, according to the geometry of three-dimensional space will be

$$\cos\theta_Z=\sqrt{1-\cos^2\theta_H-\cos^2\theta_V}=\sqrt{\sin^2\theta_H-\cos^2\theta_V},\tag{3}$$

where θ_Z is the angle of incidence of the sun's rays relative to the z axis; θ_V is the angle of incidence of the sun's rays relative to the x axis; θ_H is the angle of incidence of the sun's rays relative to the y axis.

The angle of incidence of the sun's rays relative to the y axis, which is located in the equatorial plane and runs parallel to the plane of the photovoltaic module panel, was determined according to the relative position of the module and the sun's rays. Similarly, the angle of incidence of the sun's rays relative to the x axis, which is located in the plane of the solar panel in the meridional plane, was determined.

The angular length of daylight was determined using the following expression from [28]:

$$\text{if } \delta \succ 0 \rightarrow a = 2\text{arctg}\sqrt{\frac{\text{ctg}^2}{\text{tg}^2\delta} - 1};$$

$$\text{if } \delta \geq 0 \rightarrow a = 2\pi - 2\text{arctg}\sqrt{\frac{\text{ctg}^2}{\text{tg}^2\delta} - 1}, \quad (4)$$

where φ is the geographical latitude at which the solar panels of the photovoltaic modules of the agrivoltaics system are installed on the earth's surface; δ is the declination angle (the angular position of the Sun at noon relative to the plane of the equator); a is the angular length of the daylight.

This algorithm allowed us to specify the installation angle of the photovoltaic modules in the agrivoltaics system and determine the average annual efficiency of various agrivoltaics systems. Simulation modeling and generalization of the results were carried out in the Microsoft Excel environment (USA).

To determine the efficiency of covering the area with photovoltaic panels during the highest solar activity, the calculation scheme shown in Fig. 2 was used.

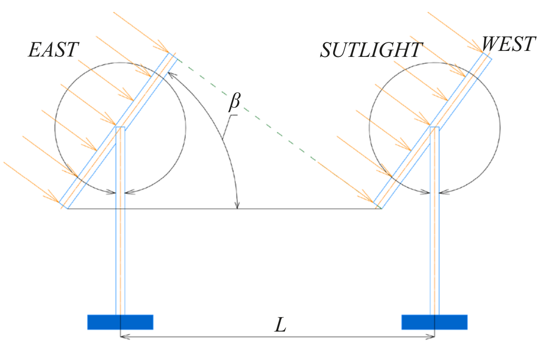

Fig. 2. Calculation scheme for determining the efficiency of area coverage by photovoltaic panels in an agrivoltaics system

Based on this calculation scheme, the distance between the arrays of the agrivoltaics system was determined depending on the time of inclusion of the agrivoltaics system in the plant shading mode according to the expression

$$L = h/\cos\beta,$$

where L is the distance between the arrays of the agrivoltaics system, m; h is the width of the photovoltaic module, m; β is the tilt angle of the photovoltaic module when the agrivoltaics system is switched on under the plant shading mode, rad.

5. Research on the tracking efficiency of agrivoltaics systems depending on their design features

5. 1. Tracking efficiency of different structures of agrivoltaics systems

The dependence of the tracking efficiency of photovoltaic modules in photovoltaic and agrivoltaics systems on the structure of these systems is shown in Fig. 3.

Data on the efficiency of installing photovoltaic modules in photovoltaic systems are given according to [29, 30] and for comparison with agrivoltaics systems of similar design by other authors [21–23].

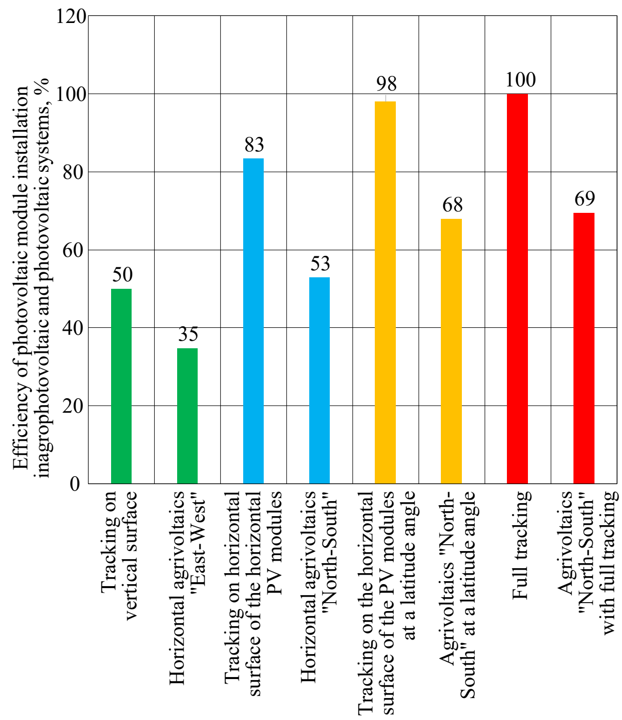

Fig. 3. Dependence of tracking efficiency of photovoltaic modules in photovoltaic and agrivoltaics systems on the structure of these systems

5. 2. Efficiency of covering the area with photovoltaic panels during the highest solar activity

The results of modeling the change in the tilt angle of photovoltaic modules relative to the plane of their axis of rotation in the agrivoltaics system "North-South" with the axis of rotation set at the angle of latitude are shown in Fig. 4.

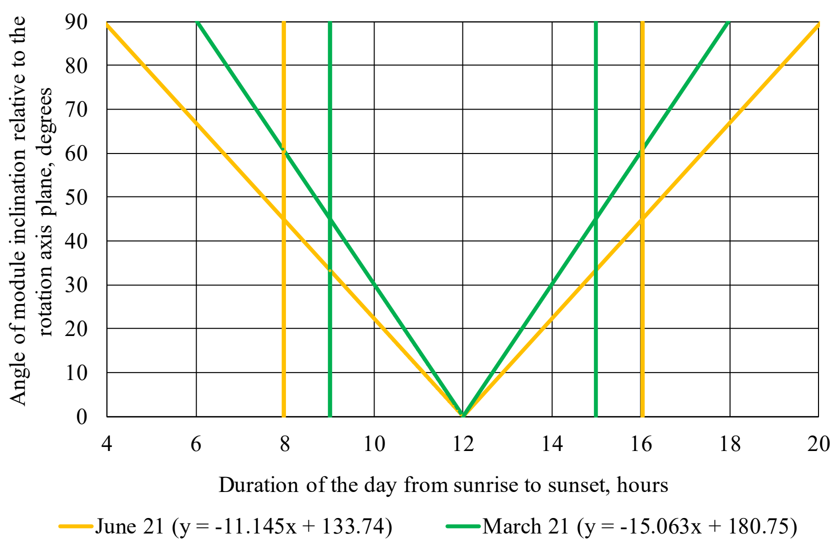

Fig. 4. Dependence of the tilt angle of photovoltaic modules relative to the plane of their axis of rotation in the North-South agrivoltaics system with the axis of rotation set at the latitude angle during the day. The vertical lines determine the time of switching on and off of the agrivoltaics under the electricity generation mode

The results of determining the efficiency of covering the area with photovoltaic panels during the highest solar activity (noon) are given in Table 1.

Table 1

Results of calculating the area coverage by photovoltaic panels during the highest solar activity

Design parameter and units of measurement	Value
The angle of inclination of the module relative to the plane of the axis of rotation, degrees:	
June 21	44.999
March 21 and September 21	44.995
The average value of the angle of inclination of the module, deg.	44.997
Cosine of the angle of inclination	0.528
Length of the photovoltaic module, m	2
Distance between agrivoltaics arrays, m	3.79
Area covered from sunlight, %:	
When turning on agrivoltaics	100
Noon	52.8

The results allow us to determine the minimum distance between individual arrays of the agrivoltaics system.

6. Discussion of results based on the study of the efficiency of tracking indicators of agrivoltaics systems

The results of our study of the efficiency of installing photovoltaic modules in photovoltaic systems and the tracking efficiency of agrivoltaics systems depending on the design of these systems are shown in Fig. 3. The theoretical dependences that underlie the research are generally outlined in [28]. This study proposes a method for determining the tracking efficiency of agrivoltaics systems. Unlike previously conducted studies [29, 30], our study determines the tracking efficiency of photovoltaic modules in agrivoltaics systems depending on the design of these systems. The study allowed us to obtain the tracking efficiency of agrivoltaics systems depending on their orientation and the method of mounting the axis of rotation of photovoltaic modules. This was made possible by determining, by modeling, the annual weighted average value of the cosine of the angle of incidence of the Sun's rays on the plane of the photovoltaic module panel installed in the agrivoltaics system.

As can be seen from Fig. 3, the values of the efficiency of installing photovoltaic modules in photovoltaic systems and the tracking efficiency of agrivoltaics systems vary depending on the structure of these systems. The values of the efficiency of installing photovoltaic modules for photovoltaic systems have higher values than for the tracking efficiency of agrivoltaics systems. This is due to the fact that agrivoltaics systems are switched on only during the hours of greatest solar activity, and accordingly have a shorter operating time compared to photovoltaic systems.

It was found that the tracking efficiency of an agrivoltaics system with an East-West rotation axis orientation is 34.75%. This is due to the fact that such a system tracks the flow of sunlight only in the vertical plane. The tracking efficiency of an agrivoltaics system with a North-South rotation axis orientation is significantly higher. Therefore, such systems are able to track the flow of sunlight in the horizontal plane. Thus, the tracking efficiency value of the agrivoltaics system with a North-South orientation and a horizontal axis of rotation is 52.89%. The tracking efficiency value of the agrivoltaics system with the same orientation and the axis of rotation set at an angle of latitude, in this case 50°, is 67.95%. The agrivoltaics system with a North-South orientation and an axis of rotation set in such a way that the photovoltaic modules track the flow of sunlight also in the vertical plane has the maximum tracking efficiency value. In this case, this value is 69.5%. Such a system is the most complex since it provides complete tracking of the flow of sunlight in the horizontal and vertical planes (full tracking).

The agrivoltaics system "North-South" with the rotation axis set at the latitude angle was further analyzed (Fig. 4). The simulation results showed that the angle of inclination of the photovoltaic modules relative to the plane of their rotation axis depends on the time of switching on and off the agrivoltaics system. When the agrivoltaics system is operating from 8–9 to 15–16 hours from March 21 to September 21, the angle of inclination of the photovoltaic modules relative to the plane of their rotation axis will be in the range from 40 to 50°. This is due to the fact that when the agrivoltaics system is switched on and off on March 21 and September 21, the total operating time of the agrivoltaics system is minimal and is 6 hours. The total operating time of the agrivoltaics system on June 21 is maximal and is 8 hours. On all other days, the operating time of the agrivoltaics system is within the above-mentioned limits. The length of the day during the operation of the agrivoltaics system also changes from 12 hours on March 21 and September 21 to 16 hours on June 21. This combination of the time of switching on and off the agrivoltaics system and the length of the day leads to the fact that the angle of inclination of the photovoltaic modules relative to the plane of their axis of rotation is 45° (Table 1). This average value of the angle of inclination of the modules relative to the plane of the axis of rotation occurs for all days of the operation of the agrivoltaics system.

The calculation of the distance between the agrivoltaics arrays was carried out with a width of the photovoltaic module at the level of 2 m. The obtained value of the angle of inclination of the modules relative to the plane of the axis of rotation in the agrivoltaics system allowed us to determine the distance between the agrivoltaics arrays, which was 3.79 m. It is obvious that if this distance is reduced in the agrivoltaics system, the photovoltaic modules of neighboring arrays will be shaded. If we take into account the specified distance between the agrivoltaics arrays, the efficiency of covering the area with photovoltaic panels during the highest solar activity will be 52.8%.

The results obtained (Fig. 3, 4, Table 1) allow us to determine the main indicators of the tracking efficiency of agrivoltaics systems.

Limitations of the study: the results allow us to establish the relationship between the tracking efficiency of different designs of agrivoltaics systems at different geographical latitudes on the Earth's surface from the equator to the latitude of 66.55°.

The main drawback of this study is that it does not take into account the unevenness of the flow of sunlight on the Earth's surface in summer and winter, which applies to a greater extent to geographical latitudes remote from the equator.

Further development of this study should consist in designing the structure of an agrivoltaics system array and conducting experimental studies on various structural solutions.

The practical significance of our research results is that they could be used to design the structure of an agrivoltaics system.

7. Conclusions

1. It has been found that the tracking efficiency of an agrivoltaics system with a horizontal axis of rotation and an East-West orientation of the axis of rotation is 34.75%; for the agrivoltaics system with a North-South orientation – 52.89%. The tracking efficiency of the agrivoltaics system with a North-South orientation and an axis of rotation set at a latitude angle (50°) is 67.95%, and with the axis of rotation set in such a way that the photovoltaic modules track the flow of sunlight also in the vertical plane – 69.5%.

2. It has been established that the length of the day during the operation of an agrivoltaics system varies from 12 hours on March 21 and September 21 to 16 hours on June 21. This combination of the on-off time of the agrivoltaics system and the length of the day leads to the fact that the angle of inclination of the photovoltaic modules relative to the plane of their axis of rotation is 45°. The obtained value of the angle of inclination of the modules relative to the plane of the axis of rotation in the agrivoltaics system allowed us to determine the distance between the agrivoltaics arrays, which was 3.79 m. If we take into account the specified distance between the agrivoltaics arrays, the efficiency of covering the area with photovoltaic panels during the highest solar activity will be 52.8%.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

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Data availability

The data will be provided upon reasonable request.

Use of artificial intelligence

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

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