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DETERMINING THE INFLUENCE OF SEASONAL TILT ANGLE ON THE EFFICIENCY OF FIXED SOLAR PHOTOVOLTAIC MODULES

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The object of this study is photovoltaic modules with different seasonal tilt angles at different geographical latitudes. The average annual efficiency of photovoltaic modules with different seasonal angles set at different geographical latitudes has been determined as the annual weighted average value of the cosine of the angle of incidence of solar rays on the plane of the photovoltaic module. The influence of seasonal tilt angles of photovoltaic modules at different geographical latitudes on their average annual efficiency was analyzed.

Approximate values of the seasonal tilt angles of photovoltaic modules at different geographic latitudes take values that differ from the geographic latitude value by plus 15° for the winter period and minus 15° for the summer period.

Modeling the average annual efficiency of photovoltaic modules depending on the seasonal tilt angles at different geographical latitudes made it possible to obtain refined values of the seasonal tilt angles of photovoltaic modules. Thus, at the latitude of 0°, 10°, 20°, 30°, 40°, 50°, and 60°, the tilt angle of photovoltaic modules for the winter period will be 14.8°, 24.6°, 34.5°, 44.4°, 54.1°, 63.6°, and 73°, respectively, and for summer – minus 14.5°, minus 4.6°, 5°, 15.1°, 25.1°, 34.9°, and 44.7°. Dependences were obtained for determining the seasonal tilt angles of photovoltaic modules depending on the value of geographic latitude.

The difference in the average annual efficiency of photovoltaic modules, which are installed at seasonal angles, and photovoltaic modules, which track the position of the Sun in the vertical plane, is 0.4 %.

The results could be used as a basis for evaluating the efficiency of photovoltaic modules when determining the seasonal tilt angle at different geographic latitudes

Keywords: photovoltaic module, angle of incidence of solar rays, module installation efficiency, geographical latitude

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1. Introduction

Solar energy is the most common renewable energy source that can be converted directly into electricity using solar panels. The most affordable, practical, and widespread in the world are solar panels with a fixed tilt angle, which makes it possible to avoid significant financial costs for expensive solar trackers [1]. However, in order to achieve significant indicators of the efficiency of electricity generation with such solar panels, it is necessary to carefully calculate the angle of their inclination to the horizon in order to establish its optimal value [2]. The above substantiates the importance of scientific research into improving the efficiency of electricity generation by solar panels of photovoltaic modules through increasing the efficiency of their installation [3, 4].

In the field of research of modern technologies of production and conversion of solar energy into electricity, there is a sufficient number of scientific works on methods for increasing the efficiency of the installation of photovoltaic modules [5–7]. However, a significant part of those studies is exclusively local in nature and cannot be applied under other experimental conditions, for example, at a different latitude, in a different climate zone under different weather conditions, etc. Seasonality also has a significant impact on the efficiency of solar photovoltaic modules. Scientists from different countries have experimentally proven that the efficiency of photovoltaic modules increases when the seasonal tilt angle of the module panel is smaller for the summer period, and larger for the winter season [8]. However, there is no universal analytical justification of the obtained results.

Therefore, the task of analytically substantiating the dependence of average annual efficiency of the installation of solar photovoltaic modules at different geographical latitudes depending on the seasonal angle remains relevant.

2. Literature review and problem statement

Although there has been significant progress in the field of technologies and means of solar energy generation and conversion over the last decade, the efficiency of modern photovoltaic modules still remains low, being only 18–22 %. The main direction of improving the efficiency of photovoltaic modules, in addition to structural perfection, is still the establishment of the optimal value of their tilt angle to the horizon.

In particular, various options for installing photovoltaic modules were investigated in [9]: fixed, installed at an angle to the horizon; fixed horizontal at the equator; with full tracking; one that performs tracking in horizontal (vertical) planes. It has been proven that the highest efficiency of electricity generation is achieved provided that the tilt angle of the panel of the photovoltaic module is equal to the latitude at which the module is installed. Tracking in the vertical plane makes it possible to increase the efficiency of the module installation by up to 50 %. Tracking in the horizontal plane at an angle of latitude, compared to full tracking, provides a PV module installation efficiency value of 97.93 %. The cited work also gives mathematical dependences that make it possible to generalize the results. The limitation of the study is that the obtained results regarding the efficiency of the installation of the modules allow establishing a relationship between the annual efficiency of the installation of photovoltaic modules and the option of their installation on the earth's surface from the equator to the value of latitude 66.55°. Also, there is no explanation in the paper for the slight deviation of the values of the optimal tilt angles of the modules, obtained experimentally, from the tilt angles determined by this method. We are talking about the tilt angles of photovoltaic modules, the values of which correspond to the values of the geographical latitude of the place where they are installed.

The further development of this research is covered in work [10]. The authors presented a mathematical relationship that makes it possible to determine the deviation of the tilt angle of photovoltaic modules to the horizon from the value of the geographical latitude at which they are installed. A mathematical expression is proposed that allows determining the annual efficiency of photovoltaic modules depending on the corrected value of the tilt angle to the horizon for different values of geographical latitude. It is also noted that at larger values of geographic latitude, the deviation of the tilt angle of photovoltaic modules to the horizon from the value of this latitude should increase. The indicated results of analytical calculations are confirmed by numerous examples of experimental studies by other authors. But the issues related to taking into account the seasonal insolation of solar radiation remained unresolved.

The fact that the optimal tilt angle of photovoltaic modules is somewhat different from the value of the geographical latitude at which they are installed was experimentally confirmed in [11]. The task that the authors tried to solve is to maximize the production of electrical energy of photovoltaic modules. The paper presents a mathematical model for determining the optimal tilt angle of solar panels of photovoltaic modules in Senegal, based on the conditions of monthly and average annual insolation of solar radiation. The data obtained were refined and adjusted through a careful study of four specific cases in different climatic zones of Senegal. The results of the experiments showed that installing the module panels at angles equal to the latitude did not increase the average annual efficiency of the photovoltaic modules. The authors note that the maximum energy generation by the modules was obtained at a smaller value of the tilt angle to the horizon than the value of the geographical latitude. The authors also noted that in order to produce more energy, it is desirable to adjust the tilt angle of the module panels depending on the season. However, the study does not take into account the influence of seasonal tilt angles of photovoltaic modules at different geographical latitudes on their average annual efficiency.

This issue was partially resolved in [12]. Using the Solar Irradiance Calculator program, the authors calculated the optimal tilt angles of solar panels of photovoltaic modules for 90 capitals in 90 countries, which are located in both the northern and southern hemispheres of the Earth. The optimal tilt angles of the module panels for the studied capitals ranged from 11° to 90° for the winter season, from 41° to 105° for the summer season, and, on average, from 26° to 90° throughout the year. The work also provides generalized mathematical expressions that make it possible to get results close to those calculated using the Solar Irradiance Calculator program. The authors note that in order to determine the optimal value of the tilt angle of the panel of the photovoltaic module at any point of the globe, it is necessary to know only the value of the geographical latitude of the place of its installation. An unsolved issue of the study is that the results of calculations based on the generalized mathematical expression and the Solar Irradiance Calculator program do not always coincide with the actual optimal tilt angles of the module panels obtained experimentally. Also, the given mathematical expression does not take into account the fact that the actual optimal tilt angle of the module panel is not equal to the geographical latitude of the place of its installation, but is somewhat smaller, as indicated in [11]. This fact also affects the total error of calculations.

The need to adjust the tilt angle of the photovoltaic module panel to the horizon for the summer period is indicated in [13]. It has been experimentally confirmed that the installation of panels of photovoltaic systems at a smaller angle to the horizon reduces the requirements for their inter-row distances, contributing to a higher level of electricity generation during the day in summer. The energy generation of photovoltaic modules at the recommended optimal tilt angle of the solar panels of the modules and at lower values of the inclination angles (5°, 10°, 15°, etc.) for different latitude zones of India were compared. At a tilt angle of 10°, the monthly generation during June was 8.5 % higher, but this led to a slight decrease in the annual level of electricity generation. Therefore, based on the results of the study, it is recommended to reduce the tilt angles of PV panels in order to meet the high demand in the summer season for electricity and mitigate other related challenges. The obtained work results are incomplete since similar studies were not conducted in other seasons of the year. However, the experimental data presented for the summer period can be used by the authors of other works to compare the results.

In the scientific literature, there are a number of studies [14–17] in which, depending on the season, the optimal tilt angle of panels of photovoltaic modules is calculated by using isotropic and anisotropic models.

Thus, in study [14], by using isotropic and anisotropic models, data on monthly and annual values of optimal tilt angles of panels of photovoltaic modules in five cities of the Kingdom of Saudi Arabia are given. It was established that the annual optimal tilt angle of the panel is close to the geographical latitude of the studied cities. Considerable attention is also paid to the effect of ambient temperature on the performance of the photovoltaic system. In the study, as in work [12], it is not taken into account that the actual optimal tilt angle of the module panel is not equal to the geographical latitude of the place of its installation but is somewhat smaller. Therefore, it would be more convenient for the consumer not to apply the monthly correction of the tilt angle of the panel to the horizon but to use integrated data. For example, seasonal values, or ranges of optimal tilt angles of panels of photovoltaic modules to the horizon.

Work [15] reports the results of the study for the city of Medina, located in the Hejaz region in the west of Saudi Arabia. The annual optimal tilt angle of the panel of the studied module was approximately equal to the value of the geographical latitude of the place of its installation. Using a fixed module panel tilt angle resulted in a loss of about 8 % of the harvested energy compared to the energy harvested when adjusting the tilt angle of the PV module panels depending on the season.

Study [16] also confirmed the expediency of applying the adjustment of the optimal tilt angle of the photovoltaic module panel depending on the season. The research was conducted in Izmir, Turkey. According to the results of experimental studies, which confirmed the calculations based on the model, the tilt angle of the panel of the photovoltaic module was: for the winter months – 55.7°; for spring – 18.3°; for summer – 4.3°; for autumn – 43°. The use of a mathematically and experimentally substantiated seasonal tilt angle of photovoltaic module panels increased the average annual efficiency of energy generation by modules by 10.3 %.

A similar study is reported in [17], in which the optimal tilt angle of solar panels of photovoltaic systems installed in Hannover, Germany was determined. The solar modules were installed at different tilt angles from 0 to 70° in steps of 10°. The maximum energy generation by the modules took place at the tilt angles of the module panels in the winter months from 50 to 70°, and in the summer months from 0 to 30°. The value of the annual optimal tilt angle of the module panels was close to the values of the angles of the summer months. However, if we compare the average annual energy generation efficiency of the modules and the average value of the energy generation efficiency of the modules in the summer season, the difference between these indicators does not exceed 6 %. For the winter season, the difference between the average annual efficiency and the average value of the efficiency of energy generation by modules in winter was about 10 %. However, as the authors of the study themselves note, it is necessary to continue work in this direction and determine the optimal value of the tilt angle of the module for other seasons. Also, the authors question the application of the correction of the tilt angle of the module panel depending on the season because they believe that the difference of 6 % and 10 % could have been caused by inaccuracy of the calculations.

In general, the mathematical expressions given in works [14–17] for determining the optimal tilt angle of the module panel depending on the season and the average annual efficiency of photovoltaic modules are complex and inconvenient to use. The results of calculations of the average annual efficiency of photovoltaic modules, obtained by the equations given in those works, differ. It would be appropriate to generalize the results and reduce the given equations to simplified mathematical expressions that are convenient to use.

A specific research method that has shown high accuracy is the regression analysis reported in [18]. This type of analysis is used to build a predictive model of the total amount of energy produced by photovoltaic modules of ground installations under variable operating conditions. 31 objects in Dnipropetrovsk and Zaporizhzhia oblasts were selected for obtaining empirical data. The authors calculated the weighted average amount of energy produced over the entire lifetime of the modules under variable conditions. Based on the regression analysis, a model of the dependence of the total amount of produced energy on the number of photovoltaic modules and the weighted average amount of produced energy was built. It was determined that the influence factor of the model «number of photovoltaic modules» has a positive influence on the resulting factor (productivity of photovoltaic modules), while the influence factor «weighted average amount of energy produced» has a negative influence. Also, the influence factor «number of photovoltaic modules» is more significant. The results can be adapted to predict the total amount of energy produced by photovoltaic modules depending on the seasonal tilt angle of the panels of these modules.

Based on our review of the literature [9–18], it should be noted that changing the tilt angle of photovoltaic modules separately for the summer and winter periods may increase the efficiency of the modules. However, there is still no explanation for this phenomenon. In view of the above, it is advisable to study the degree of improvement of the efficiency of solar photovoltaic modules by installing them at different angles, separately for the summer and winter periods, and depending on the value of the geographical latitude.

3. The aim and objectives of the study

The purpose of our study is to establish the dependence of the average annual efficiency of solar photovoltaic modules on the seasonal tilt angles and the value of geographic latitude. This will make it possible to increase the efficiency of electricity generation by photovoltaic modules.

To achieve the goal, the following tasks were set:

– to determine the seasonal (for winter and summer) values of the tilt angles of photovoltaic modules for different values of geographical latitude;

– to derive generalized expressions for determining the average annual efficiency of installing fixed photovoltaic modules;

– to determine the average annual efficiency of installing stationary photovoltaic modules at a latitude of 50°.

4. The study materials and methods

Photoelectric modules are the object of our research.

The subject of the study is the dependence of the correlation of the seasonal tilt angle of photovoltaic modules on the value of geographical latitude.

The main hypothesis of the study assumes that by adjusting the seasonal (winter and summer) tilt angle of photovoltaic modules for different values of geographical latitude, it is possible to increase the efficiency of installation of solar photovoltaic modules.

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 the angle of incidence of solar rays on the photovoltaic module is not affected).

To achieve the goal of the research, the modeling algorithm was as follows. First, the angular length of daylight was determined from the following expression [9]:

– if:

$$\delta \prec 0 \rightarrow a = 2\mathrm{arctg}\sqrt{\frac{\mathrm{ctg}^2\varphi}{\mathrm{tg}^2\delta}-1};$$

– if:

$$\delta \geq 0 \rightarrow a = 2\pi - 2\mathrm{arctg}\sqrt{\frac{\mathrm{ctg}^2\varphi}{\mathrm{tg}^2\delta}-1}, \qquad (1)$$

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

Next, the angle of incidence of the sun's rays was determined relative to the y-axis, which is located in the equatorial plane and runs parallel to the plane of the panel of the photovoltaic module. The next step was to determine the angle of incidence of the sun's rays relative to the x axis. The specified axis is located in the plane of the solar panel in the meridional plane.

Mathematical expression (2) is used to calculate the angle of incidence of the sun's rays relative to the z axis. The z-axis is perpendicular to the surface of the solar panel. So, according to the geometry of three-dimensional space, the specified angle will be:

$$\cos\theta_Z = \sqrt{1-\cos^2\theta_H - \cos^2\theta_V} = \\ = \sqrt{\sin^2\theta_H - \cos^2\theta_V}, \qquad (2)$$

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

Subsequently, based on the values of the angular length of the daylight and the cosine of the angle of incidence of the sun's rays relative to the z axis, the weighted average daily value of the cosine of the angle of incidence of the sun's rays on the plane of the panel was determined:

$$\cos\theta_{Zi}^d = \frac{\sum_{j=0}^{a_j} a_j \cos\theta_j}{\sum_{j=0}^{a_j} a_j}, \qquad (3)$$

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

The average annual efficiency of installation of photovoltaic modules was determined from expression given in [9]. This parameter is expressed as an annual weighted average value of the cosine of the angle of incidence of the Sun's rays on the plane of the panel of the photovoltaic module:

$$\cos\theta_Z^{an} = \frac{\sum_{i=1}^{365} a_i \cos\theta_{Zi}^d}{\sum_{i=1}^{365} a_i}, \qquad (4)$$

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

This algorithm made it possible to set the tilt angle of stationary photovoltaic modules separately for the summer and winter periods and to determine the average annual efficiency for seasonal options for installing photovoltaic modules. Simulation modeling and generalization of results was carried out in the Microsoft Excel environment (USA).

5. Results of determining the effect of seasonal tilt angles of fixed photovoltaic modules on their efficiency

5. 1. Seasonal values of the tilt angles of photovoltaic modules for different geographical latitudes

The average annual efficiency of photovoltaic modules depending on the difference in their tilt angles at a latitude of 50° for the summer and winter periods is shown in Fig. 1. The simulation results demonstrated an obvious maximum of the average annual efficiency of photovoltaic modules depending on the difference in the tilt angles in relation to the geographical latitude of installation. A similar dependence holds for each value of geographic latitude.

It was established that the maximum of the average annual efficiency of photovoltaic modules is at the difference of the tilt angles in relation to the geographical latitude of installation at the level of about 15°, regardless of the value of the geographical latitude. So, for example, at a latitude of 50°, the tilt angle of photovoltaic modules for the winter period should be about 65°, and for the summer period – 35°.

The calculated values of the tilt angles of photovoltaic modules for the winter and summer periods and for different geographical latitudes of their installation are given in Table 1.

Taking into account the similarity of values of the average annual efficiency of photovoltaic modules depending on the difference in the tilt angles with respect to the geographical latitude of installation, the approximate values of the tilt angles of the modules in winter and summer depending on the latitude were determined.

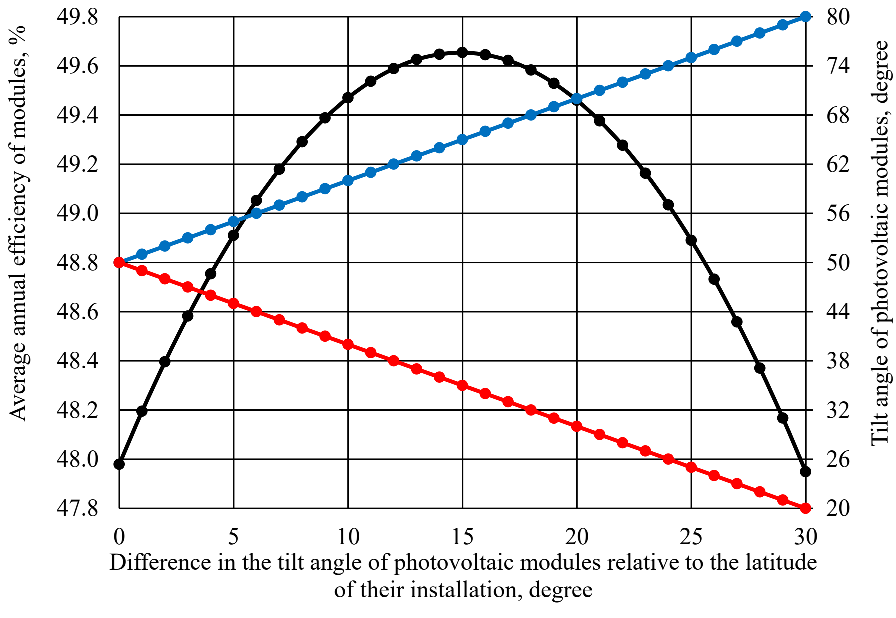

Fig. 1. The average annual efficiency of photovoltaic modules depending on the difference in the tilt angle in relation to the installation latitude at a latitude of 50°

Table 1

Approximate values of the tilt angles of photovoltaic modules for winter and summer periods for different geographical latitudes

Geographic latitude, deg.	Tilt angle of photovoltaic modules, deg.	
	for the winter period	for the summer period
0	15	–15
10	25	–5
20	35	5
30	45	15
40	55	25
50	65	35
60	75	45

The value of the average annual efficiency is the result of a study of the simulation model [9] for a latitude of 50 degrees. This latitude is chosen as the one on which the scientific research laboratory of NUBiP of Ukraine is located with installed photovoltaic modules, the use of which is planned for further research in order to confirm the formed hypothesis.

Based on the data in Fig. 3, dependences were obtained that allow determining the tilt angles of photovoltaic modules for the winter and summer periods, depending on the value of the geographical latitude at which they are installed, and which take the following form:

– for the winer period:

$$\beta_w = 0.973 \cdot \varphi + 14.943; \quad (5)$$

– for the summer period:

$$\beta_s = 0.987 \cdot \varphi - 14.518, \quad (6)$$

where β_W, β_S – tilt angles of photovoltaic modules, respectively for winter and summer periods, degrees; φ – geographical latitude of the point of installation of photovoltaic modules on the earth's surface, degrees.

Thus, the simulation results showed the possibility of increasing the average annual efficiency of photovoltaic modules at different tilt angles of photovoltaic modules for winter and summer periods.

5. 2. Generalized expressions for determining the efficiency of photovoltaic modules taking into account the seasonal tilt angles

The results of modeling the average annual efficiency of photovoltaic modules depending on the seasonal tilt angles at a latitude of 50° are shown in Fig. 2. This made it possible to obtain refined values of the seasonal tilt angles of photovoltaic modules.

The theoretical dependences given in [9] were used to build a simulation model. The simulation modeling procedure is described in [10]. The conformity of the simulation model with the experimental data was confirmed by comparing the data obtained using the simulation model and the data of the results of research conducted by other scientists.

The actual value of the tilt angles of photovoltaic modules for the winter and summer periods, when their maximum average annual efficiency is achieved at different values of geographic latitude, is given in Table 1.

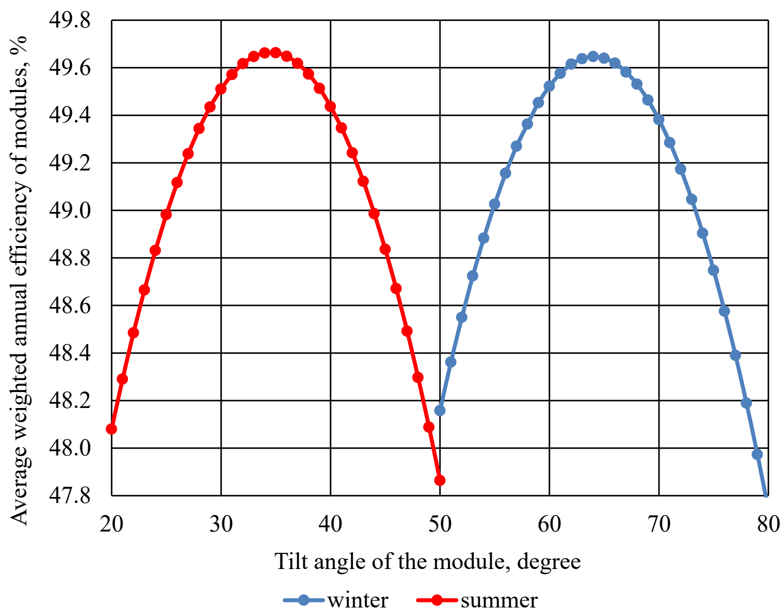

Fig. 2. The average annual efficiency of photovoltaic modules depending on the seasonal tilt angles at a latitude of 50°

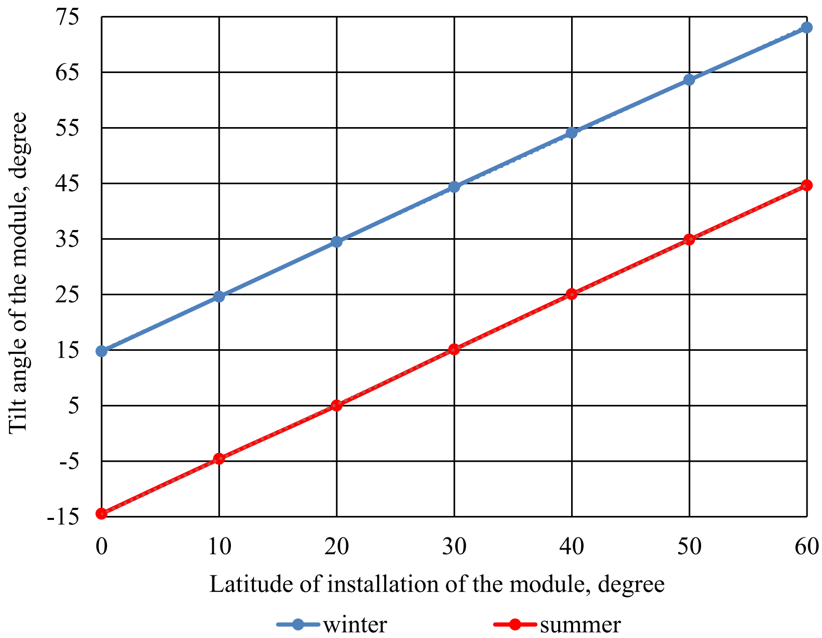

Fig. 3. Actual value of the tilt angles of photovoltaic modules for the winter and summer periods, at which their maximum average annual efficiency is achieved at different values of geographical latitude

5. 3. Average annual efficiency of installing stationary photovoltaic modules at 50° latitude

The graphic relationship of the average annual efficiency of photovoltaic modules depending on the technique of their installation at a latitude of 50° is shown in Fig. 4.

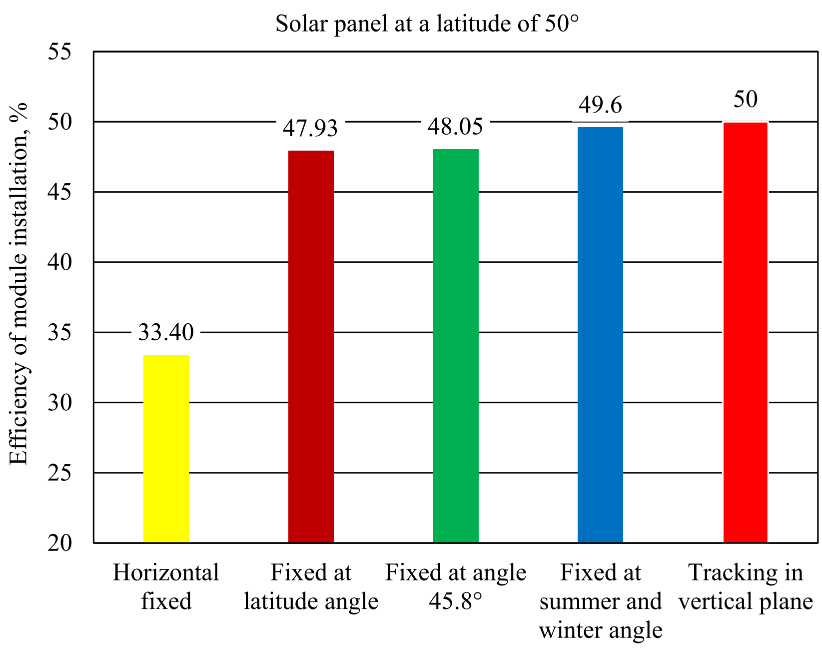

Fig. 4. Average annual efficiency of photovoltaic modules depending on the technique of their installation at a latitude of 50°

In Fig. 4, data on the average annual efficiency of photovoltaic modules when installed horizontally and fixed at an angle of latitude are taken from [9], and when installed fixed at an angle of 45.8° – from [10].

6. Discussion of results related to the influence of seasonal tilt angles of photovoltaic modules on their average annual efficiency

Our results regarding the efficiency of the installation of photovoltaic modules allow establishing a relationship between the average annual efficiency of the installation of photovoltaic modules and the seasonal tilt angle at different values of geographical latitude. To evaluate the efficiency of the installation of photovoltaic modules, the value of the annual average weighted by the cosine of the angle of incidence of solar rays on the plane of the solar panel was used [9].

The research results showed that there is a maximum average annual efficiency of photovoltaic modules depending on the difference in the tilt angles in relation to the geographical latitude of their location. It was determined that the approximate values of the tilt angles of photovoltaic modules for winter and summer periods for different geographical latitudes have values that differ from the value of geographical latitude.

These deviations amount to plus 15° for the winter period (from September 21 to March 21) and minus 15° for the summer (from March 21 to September 21) period (Fig. 1, Table 1). The physical essence of this phenomenon is related to the fact that the Sun is much higher in the vertical plane in summer than in winter. Therefore, the angle of incidence of the sun's rays on the plane of photovoltaic modules installed at an angle of latitude in summer and winter will be far from perpendicular. At the same time, the number of hours during which the Sun in the vertical plane is closer to the state when the sun's rays are perpendicular to the plane of the photovoltaic modules increases. This, in turn, increases both the daily efficiency of the installation of photovoltaic modules (the weighted average daily value of the cosine of the angle of incidence of the sun's rays on the plane of the solar panel), and the average annual efficiency of the photovoltaic modules.

Modeling of the average annual efficiency of photovoltaic modules depending on the seasonal tilt angles at different geographical latitudes made it possible to obtain refined values of the seasonal tilt angles of photovoltaic modules. Thus, at the latitude of 0°, 10°, 20°, 30°, 40°, 50°, and 60°, the tilt angle of photovoltaic modules for the winter period will be 14.8°, 24.6°, 34.5°, 44.4°, 54.1°, 63.6°, and 73°, and for summer – minus 14.5°, minus 4.6°, 5°, 15.1°, 25.1°, 34.9°, and 44.7° (Fig. 3, expressions (5) and (6)).

This is explained by the fact that the Sun in the vertical plane is at an angle that varies from the difference between the angles of geographic latitude and the tilt angle of the Earth's axis to their sum. For June 21, the value of the Sun's azimuth in the vertical plane is the sum of the angle of geographic latitude and the tilt angle of the Earth's axis (plus 23.45°). In turn, for December 21, the value of the Sun's azimuth in the vertical plane is the difference between the angle of geographic latitude and the tilt angle of the Earth's axis (minus 23.45°). It follows from this that the average value of the Sun's azimuth in the vertical plane in summer is the sum of the angles of geographic latitude and half the tilt angle of the Earth's axis (11.725°). And in the wintertime, the difference between the angles of geographic latitude and half the tilt angle of the Earth's axis [9]. However, the actual values of the tilt angles of photovoltaic modules for the winter and summer periods exceed the sum of the angles of geographic latitude and half the tilt angle of the Earth's axis. This is due to the fact that the average annual efficiency of photovoltaic modules is affected by the length of the day, which increases with increasing latitude in summer and decreases with increasing latitude in winter. This means an increase in the average annual efficiency of photovoltaic modules due to a longer time of the sun's rays falling on the plane of the solar panel in the summer. In winter, the decrease in the average annual efficiency of photovoltaic modules is caused by a decrease in the time of the sun's rays falling on the plane of the solar panel.

The difference in the average annual efficiency of photovoltaic modules installed at seasonal angles and horizontal modules, modules installed at an angle of latitude, and modules installed at an angle of 45.8°, respectively, is 16.2 %, 1.67 %, 1.55 % at a latitude of 50°. At the same geographical latitude, the difference in the average annual efficiency of photovoltaic modules installed at seasonal angles and modules that perform tracking in the vertical plane is only 0.4 % (Fig. 4).

The practical value of our research is determining the values of the seasonal tilt angles of photovoltaic modules at different values of geographical latitude. This issue is particularly relevant, as follows from [10], for values of geographic latitude less than 40 °. In addition, the replacement of tracking PV modules in the vertical plane, which is quite cumbersome, with their installation at seasonal angles is ensured with a loss of only 0.4 % of the average annual efficiency.

The results are similar to the results reported in [19–21]. In those works, the authors confirm in practice the dependence of the efficiency of installing photovoltaic modules at seasonal angles at different geographical latitudes.

Special feature of our study (Fig. 1–3) is the following two components. The first is the determination of the values of the weighted average daily cosine of the angle of incidence of the sun's rays on the plane of the photovoltaic module. The second is to determine, on this basis, the weighted average annual value of the cosine of the angle of incidence of the sun's rays on the plane of the photovoltaic module. The results could be used to calculate the seasonal tilt angles of photovoltaic modules at different geographical latitudes. The findings have numerous experimental confirmations in the scientific literature [10–17].

Limitations of the study: the results allow us to establish the relationship between the average annual efficiency of installation of photovoltaic modules and the reduction of the tilt angle at different geographical latitudes compared to the value of geographical latitude on the surface of the Earth from the equator to the value of latitude 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 mostly concerns geographical latitudes far from the equator.

The further development of this research should consist in determining the average annual efficiency of groups of photovoltaic modules that rotate around the horizontal axis in different ways of its orientation.

7. Conclusions

1. Approximate values of the tilt angles of photovoltaic modules for the winter and summer periods for different geographic latitudes take values that differ from the geographic latitude value by plus 15° for the winter period and minus 15° for the summer period.

2. It was established that at the latitude of 0°, 10°, 20°, 30°, 40°, 50°, and 60°, the tilt angle of photovoltaic modules for the winter period will be 14.8°, 24.6°, 34.5°, 44.4°, 54.1°, 63.6°, and 73°, and for summer – minus 14.5°, minus 4.6°, 5°, 15.1°, 25.1°, 34.9°, and 44.7°.

3. The difference in the average annual efficiency of photovoltaic modules that are installed at seasonal angles and photovoltaic modules that track the position of the Sun in the vertical plane is 0.4 %.

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 and 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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