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Determination of the Installation Efficiency of Vertical Stationary Photovoltaic Modules with a Double-Sided "East–West"-Oriented Solar Panel

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Abstract: The objects of this research are double-sided stationary vertical photovoltaic modules (PV-modules) with an "East–West"-oriented solar panel. The tilt angles of the Sun's rays on PV-modules at a latitude of 50° were determined, and the installation efficiencies of both double-sided stationary vertical PV-modules with an "East–West" oriented panel and PV-modules installed at an angle of latitude with a "South" oriented panel were compared. The horizontal azimuth of the fall of the Sun's rays during the day when using PV-modules with an "East–West"-oriented panel reaches a minimum at noon. The vertical azimuth of the Sun's rays remains constant throughout the day and can vary from 66.55° to 113.45°. The weighted average daily installation efficiency of PV-modules with an "East–West"-oriented panel has the same value as that of PV-modules with a "South"-oriented panel, and can vary between 45.87 and 50% on different days. However, these installation options have a "mirror" value of the cosines of the Sun's rays falling on the surface of the PV-modules and can have values from 0.917 to 1. The results can be used as a basis for evaluating the efficiency of double-sided vertical stationary solar PV-modules with an "East–West"-oriented panel.

Keywords: PV-module; "East–West"-oriented solar panel; module installation efficiency; double-sided vertical PV-module; "South"-oriented solar panel

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1. Introduction

In modern conditions, most of the countries in the world are moving towards the decarbonization of their energy systems. The European Union has taken a course towards a green transition, the goal of which is to achieve climate neutrality by 2050, with the replacement of fossil fuels with renewable energy sources by 2035 [1]. As a result, the capacity of installed photovoltaic systems (PVSs) is growing rapidly in various sectors of agriculture, transport, industry and the private sector. Building-integrated photovoltaic systems are also increasingly being used, although there are barriers to their wider uptake [2,3]. This is due to the geographical distribution of solar energy and its high availability during the year—from 4.8 to 6.0 kWh/m^2 [4]. If at the end of 2018, the total capacity of the PVS was 515 GW (world capacity data), then at the end of 2023 it will have reached a value of 1400 GW [5], continuing to grow to the present time.

The use of PVSs has several advantages in various sectors of the economy. In particular, they are easy to install and maintain, do not create noise, are equipped with automatic control and monitoring systems, and work both in autonomous mode and as a part of a network [6].

However, the widespread application of PVSs is difficult due to the variable intensity of solar radiation (depending on the day, season, climatic conditions, etc.) and the limited time of sunlight absorption during sunrise and sunset [4,6]. In order to overcome these difficulties, it is necessary to develop innovative technologies and appropriate designs of the PV-modules, which will allow them to function as efficiently as possible in the given climatic conditions and ensure the maximum production of electricity with minimal capital investments [7].

Although significant progress has been made in recent years in the development of technologies and equipment for converting solar energy into electricity [8], the conventional efficiency of solar cells, as well as of the entire PV module, remains at a low level. The conventional efficiency of industrial solar cells barely exceeds the 25% threshold. For example, the ISC Constance has produced solar cells with efficiencies above 21% using only industrially proven equipment [9]. More advanced solar cell architectures include the so-called passivated emitter and rear cell (PERC), heterojunction (HTJ) and interdigitated back contacted (IBC) solar cells. The leader in the production of IBC c-Si solar cells is SunPower Corporation, which has achieved 25.15% cell efficiency on 121 cm^2 [10]. According to commercial PV-module manufacturers such as AIKO and Trina Solar, the maximum conversion efficiency of IBC solar cells is near 24.1% and 24.4%, respectively [11,12]. In the case of the joint development pursued by Trina Solar and Australian National University, the IBC solar cells were at a small scale (2×2 cm^2) [12]. Conversion efficiencies of 23%, 23.1% and 23.3% have also been achieved at the Fraunhofer Institute for Solar Energy Systems (ISE) [13], the Institute for Solar Energy Research Hameln (ISFH) [14] and IMEC [15] at the 2×2 cm^2 scale.

Therefore, in addition to structural improvements, other ways to increase the efficiency of PV-modules should be explored. One of the ways to increase the efficiency of PV-modules is to determine the optimal angle of inclination of the panels to the horizon, and the method of installing the PV-module on the Earth's surface [16].

For example, scientific work [17] is devoted to the study of the average annual installation efficiency of PV-modules with five different tracking options. The average annual installation efficiency of the PV-modules on an arbitrary latitude can reach 47.93%, i.e., be equal to the average annual installation efficiency of a module on the equator with the angle of inclination of the PV-module solar panel to the horizon equal to the value of this latitude. An increase in the average annual installation efficiency of the PV-module up to 50% is achieved with the use of vertical-plane tracking. In turn, tracking in the horizontal plane ensures the achievement of module installation efficiency at the level of 97.93%. However, it is impossible to generalize the obtained results for further use by other authors, since the average annual installation efficiency of the modules is determined only for the options for installing PV-modules on the Earth's surface from the equator to the latitude of 66.55°. Also, the calculated values of the optimal installation angles of PV-modules, the values of which are equal to the values of the geographical latitude of the place of their installation, show deviations from their real values. The justification for this difference is given in scientific works [18].

The authors proposed a methodology for calculating the annual installation efficiency of PV-modules at different geographical latitudes, depending on the adjusted value of the angle of their installation to the horizon. It has been proven that the deviation of the PV-module's installation angle to the horizon from the value of geographical latitude increases with the increase in the numerical value of geographical latitude. In the work [19], the results given in the scientific work [18] were experimentally confirmed. The authors, based on the conditions of monthly and average annual insolation of solar radiation, determined the values of optimal inclination angles of PV-module solar panels for four cases in different climatic zones of Senegal. In all cases, the maximum installation efficiency of PV-module electricity generation occurred at smaller values of the installation angle of the module panels to the horizon, and the values of the geographical latitude were less important.

The results of large-scale research on determining the values of optimal angles of inclination of PV-module solar panels are presented in a scientific work [20]. The work was carried out in ninety different capitals of countries located in both hemispheres of the Earth, during the winter and summer seasons. The values of the optimal angles were in the ranges of 41° to 105° and 11° to 90° for the winter and summer seasons, respectively. The authors proposed a method for determining the optimal angle of inclination of the PV-module solar panels at any point on the Earth's surface, at a given value of geographical latitude, and at the coordinates of the desired location of the PV-module's installation.

The results of the analytical calculations are confirmed by numerous experimental data, and they show that the maximum production of electricity by PV-module panels occurs when the angle of inclination of the PV-module panels to the horizon is slightly less than the value of the geographical latitude, which is indicated in works [18,19]. However, scientific works [17–20] do not indicate how to adjust the angle of inclination of the module panels depending on the season.

Such studies are presented in scientific works [21–35]. In particular, the author of a scientific work [21] provided technical recommendations for the values of the optimal angles of inclination of PV-module panels for each month of the year, for each season for different regions of the city of Medina, which is in Saudi Arabia. Adjusting the angle of inclination of the PV-module panels depending on the season increased the installation efficiency of electricity production by 8%. The expediency of adjusting the optimal inclination angle of the PV-module solar panels depending on the season was also confirmed by research conducted in the winter period on the territory of Athens, Greece [22].

In turn, the authors of a scientific work [23], based on their own research, recommended reducing the angle of inclination of the PV-module solar panels to the horizon in the summer season in order to meet the need for electricity of the consumers in different latitude zones of India. According to the results presented in a scientific work [23], when the optimal angle of inclination of PV-module solar panels was reduced by 10°, the level of monthly electricity generation by PV-module panels increased by 8.5%, although at the same time there was a slight decrease in the indicator of the annual level of electricity generation.

A scientific work [24] analyzed the dependence of the power generated by the PV-module in the western region of Saudi Arabia on the values of the angle of inclination of the solar panels to the horizon and their orientation in space. The studies were carried out for different time periods: a month, two months, a quarter of a year, half a year, and a year. The highest average monthly power output for a 1 kW PV-module panel was 0.225 kW at a panel angle of 0° to the horizon, and it was obtained in June.

The authors recommend adjusting the angle of inclination of the PV-module panel to the horizon in a time frame shorter than a month, in order to maximize the power produced by PV-module panels and increase the installation efficiency of the PV-module.

Similar studies have been described in another scientific work [25]. The authors, by using isotropic and anisotropic models of diffuse solar radiation, determined the optimal tilt angles of the PV-module panels for 44 cities of Ethiopia during different time intervals from a season to a year. The results of numerous studies show that the optimal value of the angle of inclination of the PV-module panel to the horizon should be smaller than the geographical latitude of the PV-module's installation location. It is noted that the use of the annual average fixed value of the optimal angle of inclination of the PV-module panel compared to the monthly optimal angle of inclination value allows one to save from 5.11% to 6.275% (isotopic model) and from 5.72% to 6.346% (anisotropic model) of solar radiation energy.

A scientific work [26] studied and compared the values of PV-module performance at different azimuths and tilt angles of PV-module solar panels to the horizon. The results of the experiments emphasize that the tilt angle of the panel and the values of the azimuth angles have a significant impact on the power generation process, the filling factor and the current strength. Thus, for the province of Konya in Turley, the maximum energy generation took place when the tilt angle of the PV-module solar panel was 32.08°, and the azimuth angle was 0°.

The authors of a scientific work [27] tried to solve the problem of increasing the share of energy generated from the solar source in the energy balance of Bangladesh, in the absence of space for the installation of large-scale power plants. According to the results of simulations in the MATLAB environment, the optimal annual average angle of inclination of the panel should be 27.92°, while the value of the average monthly angle of inclination of the panels varies within rather wide limits of −2.5° to 60°.

At the same time, with the average monthly adjustment of the tilt angle of the panels, the highest energy generation took place in November, and was 79.4% of the nominal. During the annual adjustment of the tilt angle of the panels, the maximum produced power reached 199.09 W, which was 66.36% of the nominal capacity.

A mathematical expression [28] was proposed for determining the average annual installation efficiency of a PV-module with different seasonal tilt angles, set at different geographical latitudes. According to calculations, at latitudes 0°, 10°, 20°, 30°, 40°, 50° and 60°, the PV-module setting angle for the winter period will be 14.8°, 24.6°, 34.5°, 44.4°, 54.1°, 63.6° and 73°, and for the summer it will be -4.6°, -5°, 15.1°, 25.1°, 34.9° and 44.7°. At the same time, the difference in the average annual installation efficiencies of PV-modules installed at seasonal angles and PV-modules that track the position of the Sun in the vertical plane is 0.4%. The authors of the scientific works [29–32] looked at various cases to study the monthly, seasonal and annual performance of a PV-module depending on the angle of inclination of the solar panels to the horizon. However, they all noted that the maximum energy production took place at values of the optimal angles of inclination of the PV-module panels slightly smaller than the values of the geographical latitude. The results of their research show that weather conditions, location and azimuth angles have a significant impact on energy production.

Over the past three years, research has been conducted on determining the orientation in space and the parameters of PV-module installation using artificial intelligence. In particular, the work [33] investigated the use of artificial neural networks (ANN) with various machine learning algorithms for predicting the optimal angle of inclination of a solar power plant's panels installed at different latitudes in order to maximize the photovoltaic power in micro grids.

The use of ANN allowed the more precise determination of the optimal value of the inclination angle of the solar panels towards the horizon under different conditions (latitude, climatic conditions, season, etc.) from 38.59% to 90.72%. The installation of solar panels with tilt angles suggested by ANN increased energy production by 34% compared to PV-modules with fixed installation angles. The authors of the study [34] proposed a model for optimizing the angle of inclination of PV-module solar panels using machine teaching algorithms. It is noted that considering the influence of various factors (dustiness level, weather conditions, aerosol level), the maximization of photovoltaic power was achieved.

In work [35], the annual optimal tilt angle of PV-module panels with a fixed installation was calculated based on global horizontal radiation data collected from 2551 sites across the world. For this, the authors developed a mathematical model that involves the use of regression analysis and neural networks to calculate annual optimum angles as a function of latitude.

However, during the day, a PV-module panel with a fixed angle of inclination to the horizon, or a single axis solar tracker, will receive less energy, since the angle of incidence of the Sun's rays during the movement of the Sun across the sky will increase [36]. Therefore, for the optimal collection of solar energy, it is better to use double-axis solar trackers with the ability to track the direction of the Sun's movement from the North to the South and from the East to the West throughout a day and a year [37]. Designs of two-axis systems with an automatic tracking mechanism oriented "East–West" and "North–South" are complex and expensive, as they contain motors, redundant sensors and other control systems [38]. Also, according to the research of different authors, the difference in the amount of energy generated by biaxial and uniaxial trackers range from 3% [39] to 20% [40,41]. Further, although a two-axis tracker provides better solar energy collection, this additional collected energy may not be worth the cost of installing additional Sun-tracking mechanisms, sensors that also require additional power sources [4]. Based on the above, vertical stationary PV-modules with an "East–West"-oriented solar panel are a good alternative to expensive PV-modules with a two-axis tracker, especially for underdeveloped regions [42]. To increase the efficiency of such PV-modules, it is suggested to install double-sided solar panels with the physical adjustment of their optimal angles of inclination to the horizon depending on geographical latitude, season, and weather conditions [28,43,44].

Based on the analysis of scientific works [36–44], we note that the determination of the optimal design and the angles of inclination of solar PV-module panels to the horizon can significantly increase the installation efficiency of the modules. In view of the above, there is a need to research stationary PV-modules installed vertically, equipped with a double-sided solar panel with an "East–West" orientation to increase their installation efficiency.

Thus, the purpose of the study is to determine the installation efficiency of the vertical fixed PV modules with a double-sided "East–West" orientation of the solar panel.

By "double-sided solar panel", we mean two solar panels mechanically connected to each other, with the working surface of one panel oriented to the East, and the working surface of the second panel oriented to the West. Both panels are installed in a sealed aluminium frame for reliable fixation. The frame with the panels is attached to an iron profile assembled with a slim structure, which ensures the fixed vertical position of the module with an angle of inclination of the attached solar panel to the horizon equal to zero degrees.

To achieve the goal, the following tasks were set:

- Determine the characteristic angles of incidence of the Sun's rays on vertically fixed PV-modules with a double-sided solar panel at latitude of 50°;

- To compare the installation efficiency of the vertical stationary PV-modules equipped with a double-sided solar panel with an "East–West" orientation and PV-modules installed at a latitude angle with a "South" orientation.

2. Materials and Methods

The subject of the study is the dependence of the installation efficiency of vertical stationary solar PV-modules, equipped with a double-sided panel with an "East–West" orientation, on the time of the day. The main hypothesis of the study is that the combination of different installation systems of solar PV-modules can increase their efficiency of use.

The main assumption and simplification adopted in the work is as follows: it was assumed that the Earth is in a parallel flow of the Sun's rays, and the phenomenon of cloudiness was ignored (it affects only the intensity of solar radiation, and the angle of incidence of the Sun's rays on the PV-module is not affected).

The specific (per square meter) power of a photovoltaic module is determined by a simple well-known formula, and is

$$P/S = I\,\eta\ \cos\theta_z \tag{1}$$

where P is the specific power of the photovoltaic module, W; S is the area of the photovoltaic module, m^2; I is the intensity of solar radiation, W/m^2; η is the efficiency of the photovoltaic module, rel. units; θ_Z is the angle of incidence of solar radiation (the angle between the direction of incidence of solar radiation and perpendicular to the photovoltaic module), degrees.

This dependence, by its structure, yields three main directions for improving photovoltaic modules, namely, studying the nature of the intensity of solar radiation, increasing the efficiency of the photovoltaic module itself, and increasing the installation efficiency (reducing the angle between the direction of incidence of solar radiation and the angle perpendicular to the photovoltaic module). It is also well known that the intensity of solar radiation is a natural phenomenon, and therefore it is impossible to influence its value. It is possible to influence the value of the specific power of photovoltaic modules by improving the semiconductors involved, and this is a separate approach to their improvement. An important factor influencing the specific power of a photovoltaic module is the angle of incidence of solar radiation on the photovoltaic module, except in cases where a photovoltaic module that tracks the Sun is used. However, photovoltaic modules that track the Sun are rarely used due to their relatively high cost. Therefore, the task associated with determining the angle of incidence of solar radiation on a photovoltaic module (not energy efficiency, but the installation efficiency of the photovoltaic module) remains important and relevant. Based on the above, we can talk about three areas of research in terms of analyzing the efficiency of photovoltaic systems, as follows:

1. Determining the intensity of solar radiation as a natural phenomenon depending on the temperature of the Sun, the radiation spectrum, etc.;
2. Improving semiconductors for photovoltaic modules (increasing the energy efficiency of semiconductors);
3. Determining the angle of incidence of solar radiation on a photovoltaic module (installation efficiency of photovoltaic module).

The task of synthesizing photovoltaic systems involves the need to combine the results obtained in the above three areas to create new systems and determine their energy efficiency in terms of power or the amount of electricity generated. The results obtained in the third area, namely, determining the angle of incidence of solar radiation on a photovoltaic module, will reduce the number and complexity of experimental studies, reduce the time and financial investment in design work, and help to quantitatively assess the installation efficiency of the solar photovoltaic modules at different latitudes with different installation methods.

To model the installation efficiency of the panel, this study used the basic theoretical principles outlined in [17], which are built on the basis of a physical model of the Earth's illumination by a parallel stream of sunlight. The refinement of this physical model and further modeling consists in determining the angle of inclination as the angle between the Earth's inclined axis and its projection onto a vertical plane perpendicular to the line connecting the centers of the Earth and the Sun. This model allows us to determine the average annual efficiency of the photovoltaic module's installation depending on the angle of its installation to the horizon for different values of geographical latitude. The correlation coefficient of the set of experimental data of the deviation of the installation angle of photovoltaic modules from the value of geographical latitude and the corresponding set of calculated data according to the modeling data was 0.83 [18]. The results of mathematical modeling are confirmed by numerical experimental data obtained in different cities of the world at different values of geographical latitude of the place of installation, and are given in the study [18].

A general view of the installation and orientation of the solar PV-modules is shown in Figure 1. One module was stationary, with a vertically installed double-sided solar panel with an "East–West" orientation. The other module was equipped with a solar panel with a "South" orientation.

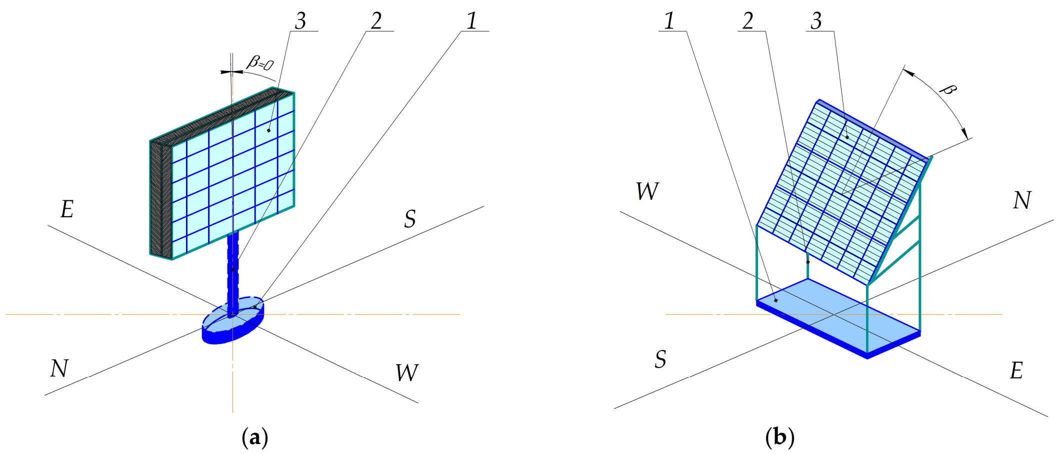

Figure 1. Examples of photovoltaic modules installation: (**a**) vertically mounted double-sided solar panel with "East–West" orientation; (**b**) inclined solar panel with "South" orientation; 1—foundation slab; 2—frame structure; 3—solar panel.

This research was carried out on the geographical latitude of 50°.

The angle of inclination of the PV-module panel with "South" orientation in the winter period is 54.1°, and for the summer period it is −34.9° [28]. The rest of the data, necessary for conducting experimental work on PV-module panels with a "South" orientation, are given in other works [17,18]. The angle of inclination of the double-sided panels of the vertical PV-module to the horizon is equal to zero.

To achieve our research goal, the modeling algorithm was as follows. First, the angular length of daylight was determined using the following expression [17]:

$$\delta \prec 0 \rightarrow \alpha = 2arctg\sqrt{\frac{ctg^2\phi}{tg^2\delta} - 1};\ \delta \geq 0 \rightarrow \alpha = 2\pi - 2arctg\sqrt{\frac{ctg^2\phi}{tg^2\delta} - 1} \quad (2)$$

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

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

The mathematical expression (3) 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. Therefore, according to the geometry of three-dimensional space, the specified angle will be [17]:

$$\cos\theta_Z = \sqrt{1-\cos^2\theta_H-\cos^2\theta_V} = \sqrt{\sin^2\theta_H-\cos^2\theta_V} \quad (3)$$

where θ_H, θ_V and θ_Z are the angles of incidence of the Sun's rays relative to the y, x and z axes, accordingly.

Later, based on the values of the angular length of 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 the Sun's rays on the plane of the panel was determined [17],

$$\cos\theta_{Zi}^{d} = \frac{\sum_{j=0}^{a_j} a_j \cos\theta_j}{\sum_{j=0}^{a_j} a_j} \quad (4)$$

where α_{i}—angular length of the ith day, degrees; $\cos\theta_{Zi}^{d}$—daily installation efficiency of PV-module installation.

Such an algorithm made it possible to set the angle of inclination of the stationary PV-modules to the horizon, and to determine the installation efficiency of such an installation. Simulation modeling and the generalization of the results were carried out in the Microsoft Excel environment.

3. The Installation Efficiency of Vertical Stationary PV-Modules Equipped with a Double-Sided Solar Panel with an "East–West" Orientation

3.1. The Determination of Characteristic Angles of Incidence of Rays on Double-Sided Solar Panels of Vertical Stationary PV-Modules

The calculation of the characteristic angles of incidence of the rays for vertical stationary PV-modules equipped with a double-sided solar panel with "East–West" orientation at a latitude of 50° is shown in Table 1.

Table 1. Characteristic angles of incidence of the rays for vertical stationary PV-modules equipped with a double-sided solar panel with "East–West" orientation.

Moment of Time	Sunrise	At Noon	Sunset
	Angular length of a day at latitude of 50°		
March 21	0.00	89.63	179.25
June 21	0.00	121.13	242.26
December 21	0.00	58.87	117.74
	Horizontal azimuth of the Sun (axis y), θ_H		
March 21	90	−0.31	90
June 21	90	23.45	90
December 21	90	−23.45	90

Table 1. *Cont.*

Moment of Time	Sunrise	At Noon	Sunset
Cosine of the Sun's horizontal azimuth, $\cos\theta_H$			
March 21	0.000	0.99998	0.000
June 21	0.000	0.917	0.000
December 21	0.000	0.917	0.000
The cosine square of the Sun's horizontal azimuth, $\cos^2\theta_H$			
March 21	0.000	0.99997	0.000
June 21	0.000	0.842	0.000
December 21	0.000	0.842	0.000
Vertical azimuth of the Sun (axis x), θ_V			
March 21	89.69	89.69	89.69
June 21	113.45	113.45	113.45
December 21	66.55	66.55	66.55
Cosine of the Sun's vertical azimuth, $\cos\theta_V$			
March 21	0.00549	0.005	0.00549
June 21	−0.398	−0.398	−0.398
December 21	0.398	0.398	0.398
The cosine square of the Sun's vertical azimuth, $\cos^2\theta_V$			
March 21	0.00003	0.00003	0.00003
June 21	0.158	0.158	0.158
December 21	0.158	0.158	0.158

The change in the horizontal and vertical azimuths of the Sun's rays' incidence on a double-sided solar panel of a vertical stationary PV-module during the day is given in Figures 2 and 3.

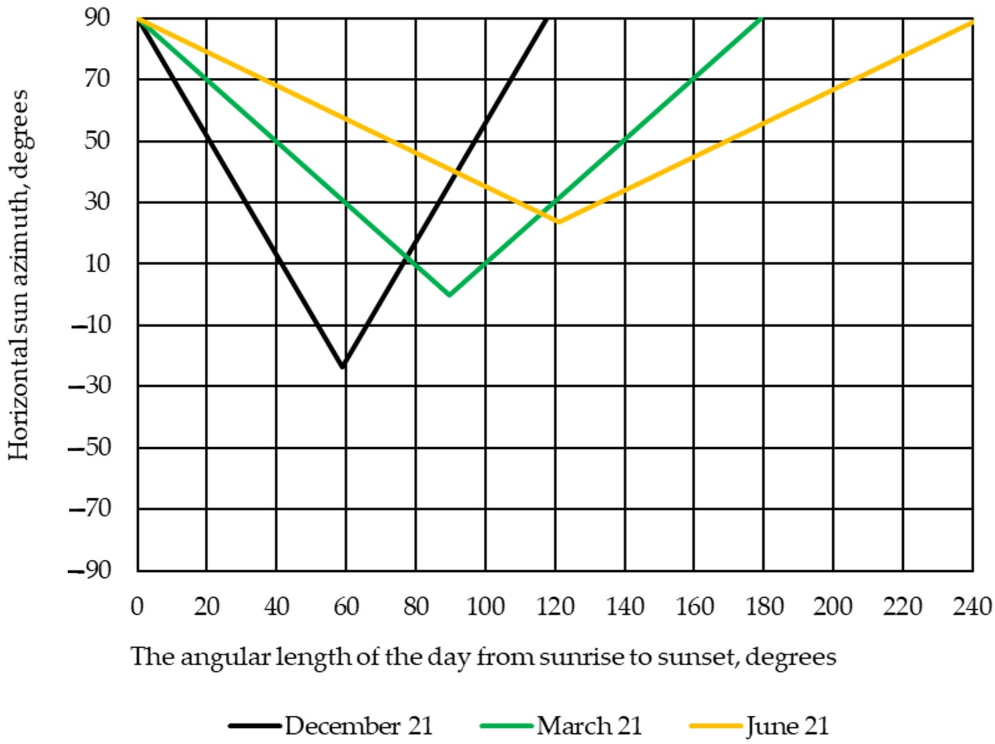

Figure 2. The change in the horizontal azimuth of the Sun's rays incidence on a double-sided solar panel with an "East–West" orientation on a vertical stationary PV-module during a day.

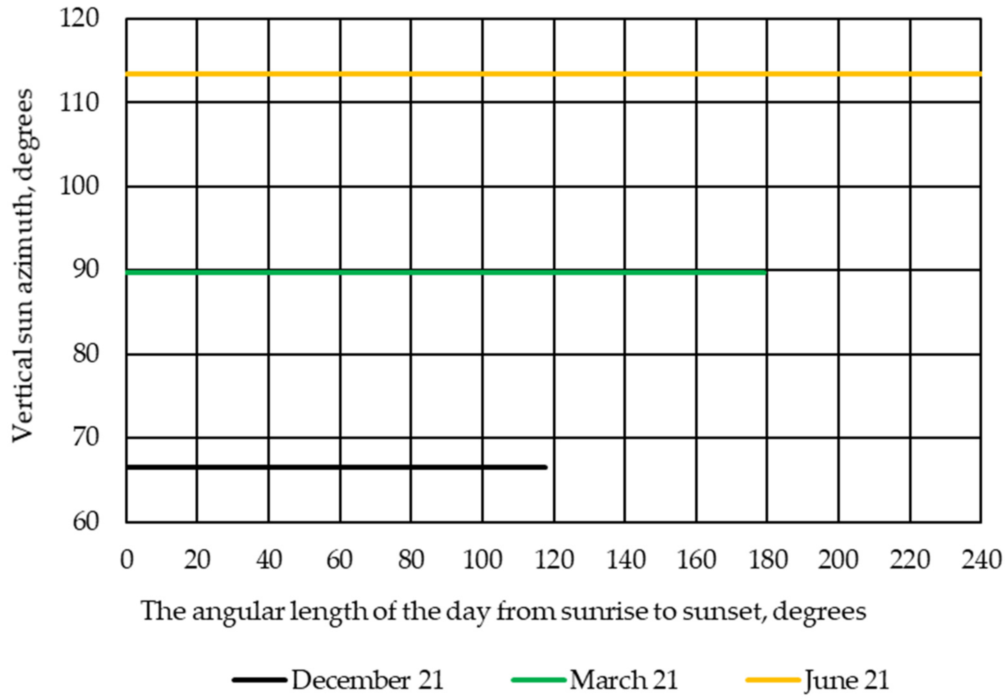

Figure 3. The change in the vertical azimuth of the Sun's rays' incidence on a double-sided solar panel with an "East–West" orientation on a vertical stationary PV-module during a day.

The change in the cosine of the horizontal and vertical azimuths of the Sun's rays falling on a double solar panel with an "East–West" orientation of vertical stationary PV-modules during the day is shown in Figures 4 and 5.

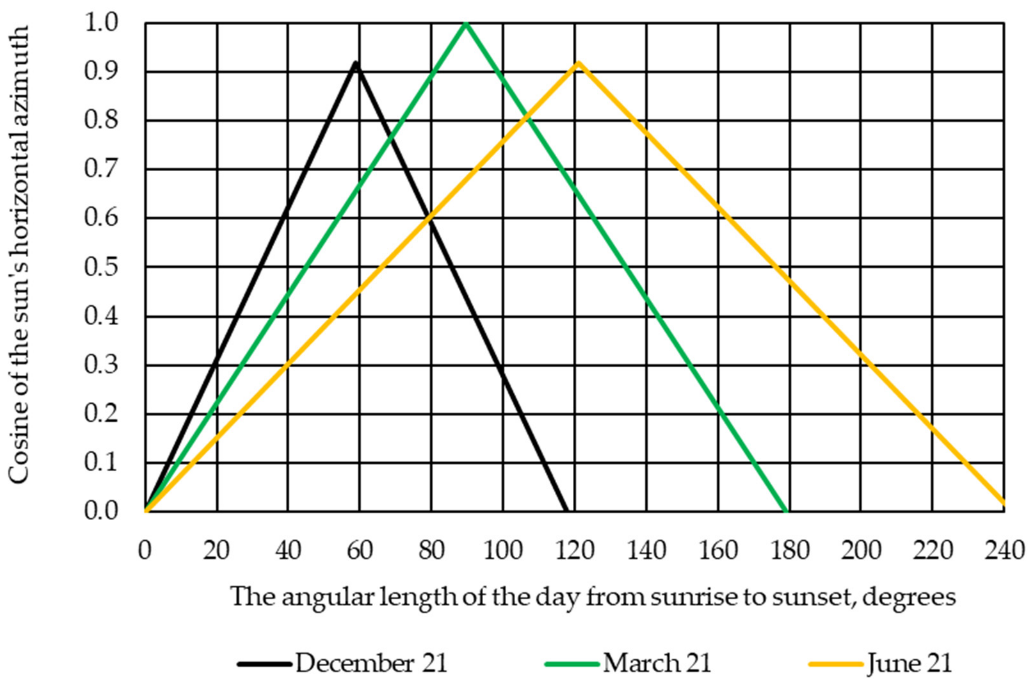

Figure 4. The change in the cosine of horizontal Sun rays falling on a double-sided solar panel with an "East–West" orientation on a vertical stationary PV-module during a day.

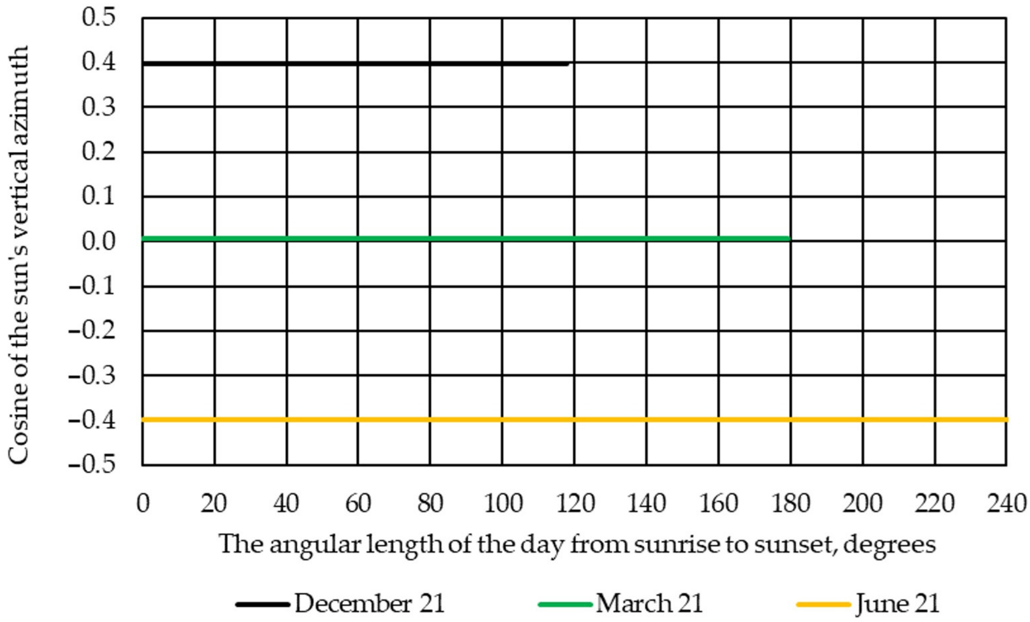

Figure 5. The change in the cosine of the vertical azimuths of the Sun's rays falling on a double-sided solar panel with an "East–West" orientation on a vertical stationary PV-module during the day.

The above calculations allow us to determine the cosine of the angle of incidence of the rays on the double-sided solar panel of the PV-module and the installation efficiency of the vertical stationary PV-module at a latitude of 50°. The developed calculation algorithm makes it possible to determine the installation efficiency of vertical stationary PV-modules equipped with a double-sided solar panel with an "East–West" orientation at the geographic latitudes of the Earth's surface from the equator to the latitude of 66.55°.

3.2. Comparison of the Installation Efficiency of the PV-Modules Equipped with a Solar Panel with "East–West" and "South" Orientations

Based on the received data, regarding the cosine changes of the horizontal and vertical azimuths of the Sun's rays falling on a double solar panel with an "East–West" orientation on a vertical stationary PV-module, further calculations were carried out during the day. Thus, according to Formula (3), the cosine of the Sun's rays falling on a double panel with an "East–West" orientation on a vertical stationary PV-module during the day was calculated (Table 2).

Table 2. Calculation of the angle of incidence of the Sun's rays on a double-sided panel with an "East–West" orientation on a vertical stationary PV-module.

Moment of Time	Sunrise	At Noon	Sunset
The cosine square of the Sun's rays falling on the panel of a PV-module, $\cos^2\theta_Z$			
March 21	0.99997	0.00000	0.99997
June 21	0.84164	0.00000	0.84164
December 21	0.84164	0.00000	0.84164
Cosine of the angle of the Sun's rays falling on the panel of the module, $\cos\theta_Z$			
March 21	0.99998	0.00000	0.99998
June 21	0.91741	0.00000	0.91741
December 21	0.91741	0.00000	0.91741

Table 2. *Cont.*

Moment of Time	Sunrise	At Noon	Sunset
Cosine of the Sun's horizontal azimuth, cosθ_H			
March 21	0.000	0.99998	0.000
June 21	0.000	0.917	0.000
December 21	0.000	0.917	0.000
The angle of the Sun's rays (the angle between the Sun's rays and the axis z), θ_Z			
March 21	0.31	90	0.31
June 21	23.45	90	23.45
December 21	23.45	90	23.45

The change in the cosine of the Sun's rays falling on a double-sided panel with an "East–West" orientation on a vertical stationary PV-module during the day is shown in Figure 6.

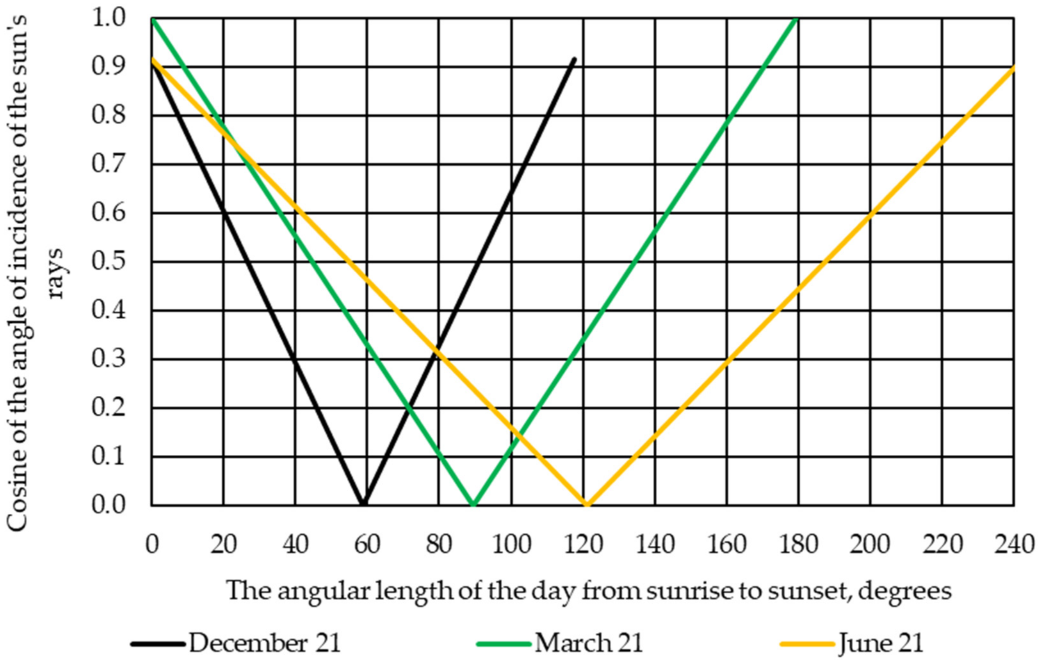

Figure 6. Change in the cosine of the Sun's rays falling on a double-sided panel with an "East–West" orientation of a vertical stationary PV-module during the day.

The weighted average daily installation efficiency of vertical stationary PV-modules with a double-sided solar panel with "East–West" orientation is determined by expression (4), and is given in Table 3.

Table 3. The weighted average daily installation efficiency of solar PV-modules at the latitude of 50°.

Day of a Year	December 21	March 21	June 21
PV-modules with a double-sided solar panel with the "East–West" orientation	45.87	50.00	45.87
PV-modules with the "South" orientation [10]	45.87	50.00	45.87

The results of a comparison of the weighed annual daily installation efficiencies of vertical stationary PV-modules with a double-sided solar panel with "East–West" orientation and PV-modules with "South" orientation are shown in Figure 7.

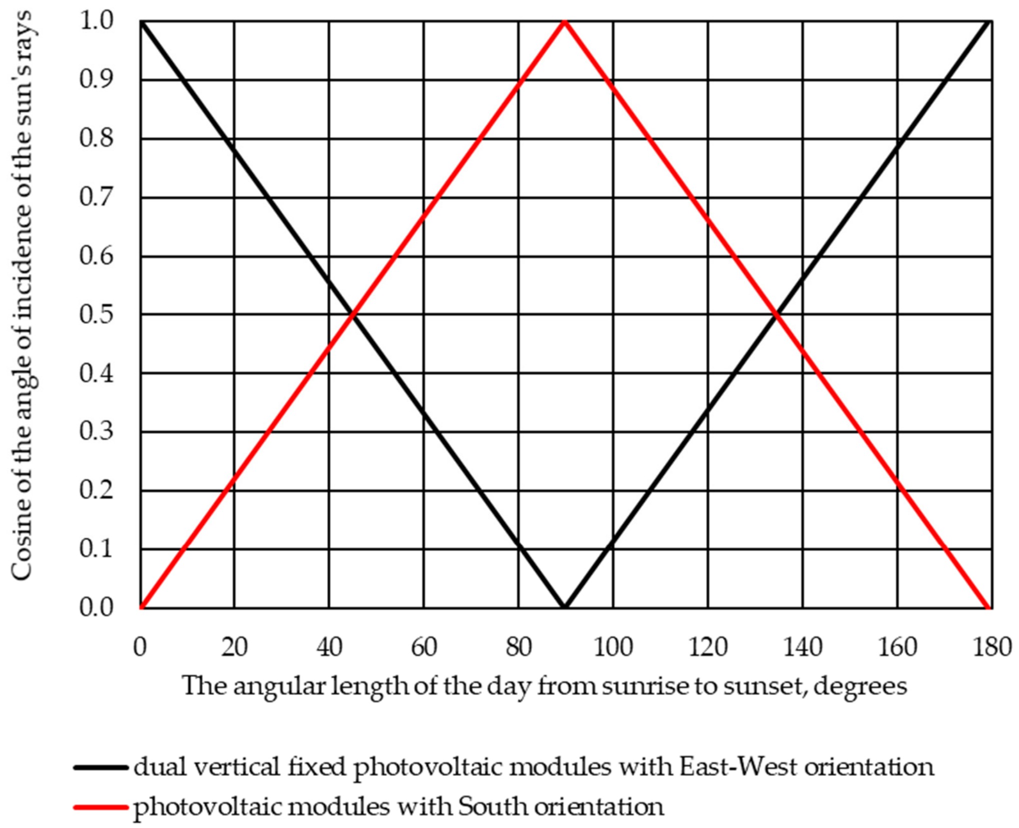

Figure 7. Weighed annual daily installation efficiency of solar PV-modules on March 21 at a latitude of 50°.

The obtained data indicate that the weighted average annual daily installation efficiencies of vertical stationary PV modules with a double-sided solar panel with an "East–West" orientation and PV-modules with a "South" orientation have the same values. However, a change in the cosine of the Sun's rays falling on the surface of the module panels leads to mutually opposite values throughout the day.

So, the simulation results make it possible to determine the weighted average daily installation efficiency of vertical stationary PV-modules with a double-sided solar panel with an "East–West" orientation, and to compare it with the installation efficiency of PV-modules with a solar panel with a "South" orientation.

4. Discussion of the Results of Modeling of Double-Sided Panels with an "East–West" Orientation of Vertical Stationary PV-Modules

The obtained results regarding the installation efficiency of double-sided solar panels with an "East–West" orientation of vertical stationary PV-modules and their comparison with the installation efficiency of PV-modules with a "South" orientation allow us to establish the conditions of application of such modules. To evaluate the installation efficiency of double-sided solar panels with an "East–West" orientation on vertical stationary PV-modules, the value of the daily average weighed cosine of the angle of incidence of the Sun's rays on the plane of the solar module was used [17].

The results of the calculations of the characteristic angles of incidence of the Sun's rays for double-sided panels with an "East–West" orientation on vertical stationary solar PV-modules (Table 1) are shown graphically in Figures 2–5.

The results of the research show that when using double-sided solar panels with an "East–West" orientation of vertical stationary PV-modules, the horizontal azimuth of the Sun's rays during the day reaches a minimum at noon (Figure 2). This is due to the fact that such modules at noon, in the flow of sunlight, are located parallel to the flow of the Sun's rays, with a deviation in this parallel flow in summer and in winter.

In the morning and in the evening, the double-sided panels with an "East–West" orientation of vertical stationary PV-modules are located perpendicular to the flow of the Sun's rays, with a deviation in this flow in summer and in winter. Accordingly, the change in the cosine of the horizontal azimuth of the Sun's rays falling on such panels of vertical PV-modules during day (Figure 4) reaches its maximum value at noon. In the morning and evening, the cosines of the horizontal azimuth of the Sun's rays falling on the double-sided solar panels with an "East–West" orientation of the vertical stationary PV-modules will have their minimum values.

As for the vertical azimuth of the fall of the Sun's rays when using double panels with the "East–West" orientation of vertical stationary PV-modules, it remains constant throughout the day (Figure 3). This is due to the fact that such modules, due to their design, do not change their position relative to the parallel flow of the Sun's rays in the vertical plane. Therefore, during each day, the vertical azimuth of the Sun's rays will remain constant. The change in the vertical azimuth of the Sun's rays throughout a year is due to the change in the angle of inclination. This angle is the angle between the inclined axis of the Earth and its projection on a vertical plane, perpendicular to the line connecting the centers of the Earth and the Sun [17]. According to this, the cosines of the vertical azimuth of the Sun's rays falling on a double-sided panel with an "East–West" orientation on a vertical stationary PV-module throughout the day (Figure 6) remain unchanged.

The values of the cosines of the horizontal and vertical azimuths of the Sun's rays falling on double-sided panels with "East–West" orientation on vertical stationary PV-modules during the day are used for further calculations. The purpose of these calculations is to determine the cosine of the angle of incidence of the Sun's rays on the panel of the PV-modules (Table 2) and the weighted average daily installation efficiency of double-sided panels of vertical stationary PV-modules (Table 3).

The results of the calculations show that the cosine of the Sun's rays falling on double-sided panels with an "East–West" orientation of the vertical stationary PV-modules during the day reaches a minimum at noon (Figure 6). This is due to the fact that such modules at noon, in the flow of the Sun's rays, are located parallel to the flow of the Sun's rays, with a deviation in this parallel flow in summer and in winter. In the morning and in the evening, the cosine of the Sun's rays falling on the double-sided panels with an "East–West" orientation of the vertical stationary PV-modules reaches its maximum value. This is because, in the morning and in the evening, double-sided panels with an "East–West" orientation on vertical stationary PV-modules are located perpendicular to the flow of the Sun's rays. The deviation of their location in the flow of the Sun's rays occurs both in summer and in winter.

It was established that the weighted average daily installation efficiency of double-sided panels with "East–West" orientation on vertical stationary PV-modules have the same value as that of PV-modules with a "South" orientation (Table 3). However, greatest interest is given to the fact that these installation options have a value that mirrors that of the cosines of the Sun's rays falling on the surface of the solar panels on PV-modules (Figure 7).

For double-sided panels with an "East–West" orientation on vertical stationary PV-modules, the maximum values of the cosines of the angles of incidence of the Sun's rays on the surface of such a panel will occur in the morning and in the evening. At the same time, PV-modules with a "South" orientation reach their maximum value for the cosine of the Sun's rays falling on the surface of the vertical stationary PV-module panel only at noon. It should be noted that there is a significant disadvantage suffered by vertical stationary

PV-modules with double-sided panels with an "East–West" orientation compared to PV-modules with a "South" panel orientation. It consists in the fact that the production of the same amount of electricity requires twice the number of PV-modules.

The daily positions required to reach the maximum values of the cosines of the Sun's rays falling on the surface of the panels of the PV-modules determine the practical value of using vertical stationary PV-modules with a double-sided panel with "East–West" orientation. Namely, such solar PV-modules are recommended for consumers who have morning and evening load peaks. First of all, these include household consumers. It should be noted that, for domestic electricity consumers, the morning peak of electricity consumption coincides with the peak of electricity production by vertical stationary PV-modules with a double-sided panel with an "East–West" orientation.

However, the evening peak of electricity consumption is shifted relative to the electricity production by such PV-modules later during the day, when the solar panel of the module is no longer exposed to sunlight. Another option for the use of vertical stationary PV-modules with a double-sided panel with "East–West" orientation is their location along highways that run perpendicular to the parallels. In this case, their compactness is useful. There may also be an option of combining vertical stationary PV-modules with a double-sided panel with an "East–West" orientation with PV-modules with a "South" orientation.

The results of our analytical calculations (Tables 1 and 2, as well as Figures 2–7) are indirectly confirmed by the results of experimental studies by the authors of [38,45,46].

Papers [38,45] provide a comprehensive evaluation of PV-modules with the "East–West" orientation using a modeling approach. The model integrates the geographical location of the PV-modules and the corresponding solar irradiance data. A comparative analysis is carried out between "South"- and "East–West"-oriented PV- modules, focusing on energy cost efficiency and technical requirements. The authors highlight several advantages of an "East–West" PV-modules orientation, such as the reduced costs associated with substation interconnection (especially when PV-modules are slanted at high tilt angles) and the reduced costs for steel structure and mounting piles. A notable disadvantage of the "East–West" configuration is its comparatively lower energy yield compared to the "South"-orientated modules. The authors conclude that in scenarios requiring significant power input, "South"-orientated PV-modules are preferable. Conversely, an "East–West"-oriented PV-module with a direct grid connection can provide a smoother power input to the grid with fewer harmonics and less reactive power.

The efficiency of the PV-modules described in [46] was assessed using key indicators such as energy production, capacity factor and annual income. The results of the numerical modeling carried out using the Sunny Design software (SMA Solar Technology AG) are confirmed by experimental data obtained in three cities—Nicosia (Cyprus), Maiduguri (Nigeria) and Stuttgart (Germany)—selected for their position relative to the equator. The results indicate that "East–West"-oriented PV-modules offer advantages in terms of energy production and capacity factor compared to "South"-orientated PV-modules. The distribution of solar radiation over the day improves energy production during peak demand hours. On the contrary, "South"-orientated PV-modules show higher annual yields due to their better capturing of solar radiation during certain periods.

The study [47] is an excellent example of the practical implementation of what has been described in [38,45,46]. The authors modeled 40 different grid scenarios and compared two variants of PV modules—with "South" and "East–West" orientations. Two EV charging profiles were also compared for five tilt angles of the "South"-orientated PV-modules—from 15° to 35°—and two assumptions of potential long-term energy storage (LDES). The conclusion of the study is that while the East–West solar orientation is expected to reduce the need for diurnal storage by allowing EVs to be charged early and late in the day, it appears that a better match between seasonal supply and demand is more important for the south-facing orientation.

The present study is characterized by the use of a simplified methodology and results that allow us to complement and explain the studies presented in [38,45–47]. The expression (4) of the mathematical model allows for estimating the weighted average cosine of the angle of incidence of the sunlight on the PV-modules. Calculations based on this expression provide a degree of accuracy comparable to commercial software without the need for financial costs. In addition, the application of the mathematical model developed by us is geographically universal, making it suitable for use in different latitudes with appropriate climatic conditions. In contrast to the approaches presented in [38,46], where the authors study "East–West"-oriented PV-modules and then compare them with "South"-oriented PV-modules, our study proposes to combine "East–West"- and "South"-oriented PV-modules into a single system. This is a rational option for consumers with morning and evening peak loads.

The experimental results presented in studies [38,45–47] confirm the performance of the model developed by us, which will allow it to be widely used to estimate the amount of solar energy received by PV-modules during the day, without significant capital investment in experimental research and the purchase of appropriate expensive equipment.

The peculiarity of the conducted research (Figure 7) relates to the establishment of the following facts. The first is that the weighted average daily installation efficiency of the vertical stationary PV-modules with an "East–West" orientation is the same as that of vertical stationary PV-modules with "South" orientation. The second is that these installation options have a "mirror" value of the cosines of the Sun's rays falling on the surface of the panels of vertical stationary PV-modules during the day. The research results can be used for the calculation of the systems of vertical stationary PV-modules with double-sided panels with an "East–West" orientation.

The peculiarity of the conducted research (Figure 7) lies in the establishment of the following facts. The first is that the weighted average daily installation efficiency of the vertical stationary solar PV-modules with double-sided panels with an "East–West" orientation is not the same as that of a "South"-oriented PV-module. The second peculiarity is the fact that the installation options have a "mirror" value in the cosines of the Sun's rays falling on the surface of the panels of the PV-module during the day. The research results can be used for calculations of the systems of vertical stationary solar PV-modules with double-sided panels facing "East–West".

Thus, the energy productions of double-sided stationary vertical PV-modules with an "East–West" orientation and those of PV-modules installed at a latitude angle with a "South" orientation will have the same values. The peak of electricity production for double-sided stationary vertical PV-modules with an "East–West" orientation will only be in the morning and in the evening. The peak of electricity production for PV-modules installed at a latitude angle with a "South" orientation will be at noon.

The study suggests that double-sided stationary vertical PV-modules with an "East–West" orientation should be installed along roads or sidewalks facing south. At the same time, such modules are easily integrated into the design of the surrounding space. It is impractical to use PV-modules installed at a latitude angle with an orientation of "South" in such a situation, since the area that such modules will occupy will be approximately 10 times larger, and such systems will not be integrated into the design of the surrounding space.

It is also obvious that the cost of a system with double-sided stationary vertical PV-modules with an "East–West" orientation will be double that of PV-modules installed at a latitude angle with an orientation of "South". Based on this, stationary vertical PV-modules with an "East–West" orientation should only be used in power supply systems of facilities with significant morning and evening load peaks. PV-modules installed at a latitude angle with a “South” orientation will, in this case, require a significant number of batteries.

In addition, it has been established that double-sided stationary vertical PV-modules with an “East–West” orientation can be installed in combination with PV-modules installed at a latitude angle with an orientation of “South” in systems that have significant peaks in energy consumption in the morning and evening. At the same time, double-sided stationary vertical PV-modules with an orientation of “East–West” can be installed along fences and sidewalks, and will complement PV-modules installed at a latitude angle with an orientation of “South”, which are installed on the roofs of buildings.

The cost of electricity generated by double-sided stationary vertical PV-modules with an “East–West” orientation installed in combination with PV-modules installed at a latitude angle with a “South” orientation, at a solar radiation intensity of 600 to 1000 W/m^2 and a solar energy conversion efficiency of 22.5%, will be from EUR 65 to 108/kWh. When using PV-modules installed at a latitude angle with a “South” orientation and batteries to supply power consumers during morning and evening peaks of energy consumption, the cost of energy storage will be about EUR 300/kWh. Thus, the use of double-sided stationary vertical PV-modules with an “East–West” orientation is approximately 3 times more efficient than the use of batteries. This will reduce the number of batteries required to provide consumers with power during morning and evening load peaks.

The limitations of the study are as follows. The results of the study allow us to determine the weighted average daily installation efficiency of the vertical stationary solar PV-modules with a double-sided solar panel with an “East–West” orientation at different geographical latitudes of the Earth’s surface from the equator to a latitude of 66.55°. The main shortcoming of this study is that it did not consider the unevenness of the flow of light on the Earth’s surface in summer and in winter, which mostly applies to geographical latitudes from the equator.

The further development of this research will consist in the justification of the creation of systems that combine vertical stationary solar PV-modules with double-sided panels with “East–West” and “South” orientations.

5. Conclusions

1. The horizontal azimuth of the Sun’s rays during the day when using vertical stationary solar PV-modules with double-sided solar panels with “East–West” orientation reaches its minimum at noon. In the morning and evening, such solar modules are located perpendicular to the flow of the Sun’s rays, with a deviation in this flow in summer and winter by ±23.45°. At the same time, the cosine of the horizontal azimuth of the Sun’s rays during the day reaches its maximum level at noon, which is from 0.917 to 1. In the morning and evening, the cosine of the horizontal azimuth of the Sun’s rays has a value of zero. At the same time, the vertical azimuth of the fall of the Sun’s rays remains constant throughout the day, and can vary on different days of the year from 66.55 to 113.45°. Accordingly, the cosine of the vertical azimuth of the Sun’s rays during the day remains unchanged, and can vary on different days of the year within the range of ±0.398.

2. The cosine of the Sun’s rays falling on solar panels with an “East–West” orientation on vertical stationary solar PV-modules during the day reaches its minimum at noon. In the morning and evening, the cosine of the incidence of the Sun’s rays has a maximum value within the range of 0.917 to 1. The weighted average daily installation efficiency of the vertical stationary solar PV-modules with double-sided panels with an “East–West” orientation is the same as that of PV-modules with a “South” orientation, and can vary on different days of the year from 45.87 to 50%. However, these installation options have a “mirror” value of the cosines of the Sun’s rays falling on the surface of the panels of

vertical stationary solar PV-modules, and can have values from 0.917 to 1 on different days of the year.

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