Method of orientation of solar panels of solar power plant

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Abstract. The generation of electricity by solar photovoltaic batteries depends on the angle of incidence of sunlight and is maximum when this angle is 90 degrees, i.e., rays fall strictly perpendicular. The greater the deviation from the 90-degree angle, the more radiant energy is reflected rather than extinguished by the solar modules. Therefore, it is especially important to correctly orient the surface of solar modules and set the desired inclination angle. To place photovoltaic panels on the site of a solar power plant, it is necessary to calculate their mutual shading, considering the design and dimensions of one solar cell panel and the method of its installation on the ground at a certain calculated angle.

1 Introduction

The efficiency of a photovoltaic system depends on the level of solar radiation. The main component of photovoltaic systems are modules into which photocells are combined. Modules are designed for any voltage, up to several hundred volts. If the system has AC loads, then inverters are included in the system to convert to AC.

It is known that the efficiency of a photocell is the ratio of the energy falling on the photocell to the electricity supplied to the electricity consumers. There is a practical value in efficiency, theory, and laboratory. The practical value of the efficiency of industrial photocells is: from single-crystal silicon - 16-17%; from polycrystalline silicon - 14-15%; from amorphous silicon - 8-9% [1-2].

The electricity generation by solar photovoltaic cells depends on the angle of incidence of the sun's rays and is maximum when this angle is 90o, i.e., beams are fed strictly perpendicular. The greater the deviation from the 90° angle, the more radiant energy is reflected rather than absorbed by the solar modules. Therefore, it is especially important to correctly orient the surface of solar modules and set the desired inclination angle [3].

To place panels of photovoltaic converters (PVC) on the SPP site, it is necessary to calculate their mutual shading, taking into account the design and dimensions of one PV panel and the way it is installed on the ground at an angle, calculate the panel shadow depending on the time of year and hour of the day and determine the shading coefficients [3-5].

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2 Methods

Analyzing the power of solar radiation, one should estimate the length of the shadow L for four characteristic points - the summer and winter solstices and the spring (autumn) equinox. The maximum amount of shading corresponds to the morning hours on the winter solstice day, and the minimum shading - half a day on the summer solstice day [5-6].

Shading coefficients αij should be presented in fractions of the height h of the panel installation above the ground (Fig. 1).

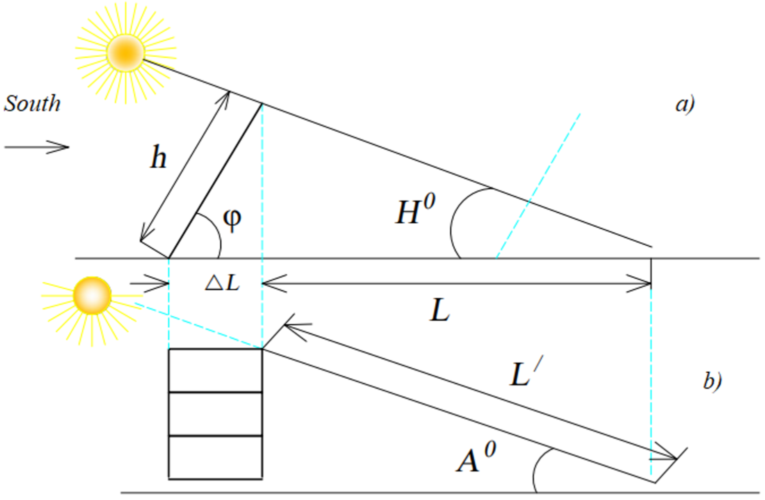

Fig. 1. Layout of FP panels for calculating mutual shading: a) side view; b) top view. The dashed line shows the placement of panels with shading at a distance less than L

To calculate the angles of the Sun and the length of the shadow, the relations [7-9] are used:

$$\alpha = arccos\left\{0.3979 \cdot \cos\left[\frac{2\pi(N-173)}{365}\right]\right\} \quad (1)$$

where N is the number of the day from the first of January;

$$H^o = \arcsin(sin\alpha \cdot cos\delta \cdot cos\tau + cos\alpha \cdot sin\varphi) \quad (2)$$

where $\tau = \frac{(t-12)\cdot 2\pi}{2x}$ is hour angle; t is time in hours from midnight; φ is latitude;
$L' = \frac{h\cdot sin\varphi}{tgH^o}$ is slanted shadow line length; h is photo panel height from ground level;

$$cosA^o = \frac{\cos\alpha - \sin\delta \cdot \sin H^o}{\cos\delta \cdot \cos H^o} \quad (3)$$

where A^o is azimuth angle;
L is the length of the shadow in the direction perpendicular to the photo panel rows,

$$L = L' \cos A^o$$

where A^o is azimuth angle; L is the length of the shadow in the direction perpendicular to the rows of solar modules.

When determining the realizable total power of the internal network in the DC circuit $P_{\sum PP}$ for a solar module group at the site of a solar power plant, due to a significant difference in the values of φ_{ij} by quarters, it is advisable to perform separately for the quarters according to:

$$P_{\sum PP} = P_j(\varphi_{ij}) \cdot N_j(1-\alpha_{ij}), W/m^2 \quad (4)$$

where $P_j(\varphi_{ij})$ is the realizable power of the photo panel; N_j is the number of photo panels.

To calculate the average quarterly and average annual electricity generation from a solar power plant W_{PPj} (kWh/quarter, kWh/year) and installed capacity utilization factors (ICU) and with known values of the average number of sunny days d_{ij} and h_{ij} hours of sunshine is produced according to the formula:

$$W_{PPij} = P_{\sum PP} \cdot d_{ij} \cdot h_{ij} \quad (5)$$

It is advisable to calculate the generation of electricity from a solar power plant and the average value of a solar power plant not only for the year but also for quarters, which allows you to more accurately take into account the real power of the solar power plant, for example, for a daily schedule for covering network loads. The average value for a solar power plant can also be calculated by quarters and per year (taking into account sunshine hours h_{ij} per year) and the average value of K_i per year according to the usual calculation for power plants (for h=24 hours a day). W_{cal} calculating the power factor of a solar power plant, the estimated electricity generation W_{ac} solar power plant for the year $W_{cal.year}$ and for the quarter $W_{c.kW}$ is determined, subject to the implementation of the normalized installed power of the photocell - P_{nom}.

$$W_{cal.year} = 365 \cdot 24 \cdot P_{nom} \cdot N \quad (6)$$

$$W_{cal.kW} = D_i \cdot 24 \cdot P_{nom} \cdot N \quad (7)$$

where, N is PV number; D_i is number of days in the corresponding quarter of the year.

The value of the ICF is equal to the ratio of the actual realized annual or quarterly energy generation to the calculated one [9-10]:

$$K_{cal.year} = \frac{W_{year}}{W_{cal.year}} \quad (8)$$

$$K_{cal.KW} = \frac{W_{Kvar}}{W_{cal.KW}} \quad (9)$$

3 Results and Discussion

3.1 Solar Panel Orientation Methods

During the year, the Earth describes an elliptical path around the Sun (Fig. 2). This movement causes changes in the year's seasons and the length of daylight hours. The change in the height of the Sun in the sky during the year is determined by the recession of the Earth's axis, which is responsible for the declination of the Earth's axis relative to the ecliptic plane during the year. During the day, the Earth also rotates around its axis, describing a full circle; this movement is the cause of sunrises and sunsets[11-15].

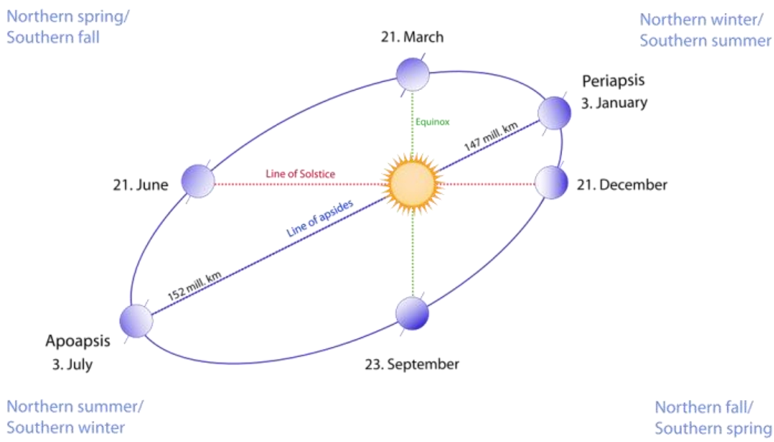

Fig. 2. Rotation of Earth around Sun during the year

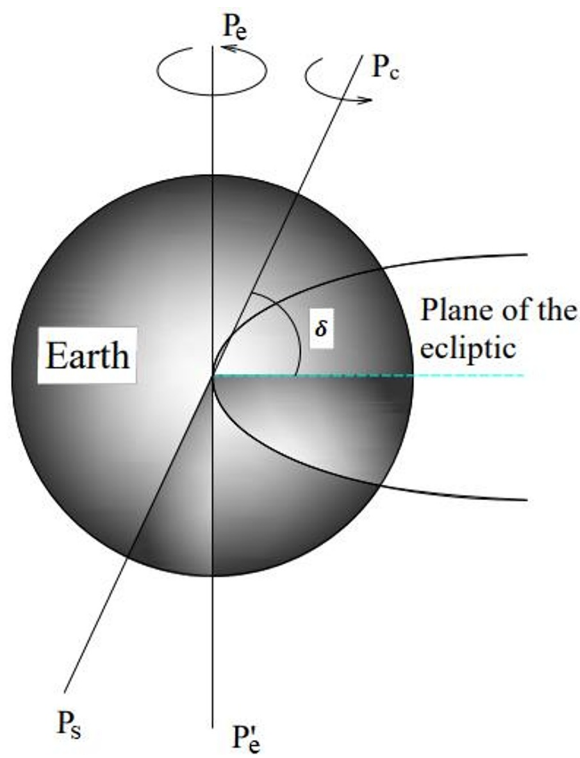

Fig. 3. Schematic representation of precession of Earth's axis

The optimal angle of inclination of solar panels depends on the area's latitude and can also be changed depending on what optimization in energy production needs to be achieved. So, it can be reduced from the optimal value if the photovoltaic station operates in the summer (summer optimum), increased if the photovoltaic station is operated mainly in the autumn-winter period, or taken as an average value if the photovoltaic station is intended for year-round operation.

A simplified formula for calculating the optimal angle of inclination of the solar module:

If the latitude is up to 25 o, multiply the numerical value of the latitude by 0.87;

If the latitude is between 25° and 50°, multiply the numerical value of the latitude by 0.76 plus 3.1 degrees.

The graph below shows the effect of tilt adjustments on performance (Figure 4) [16].

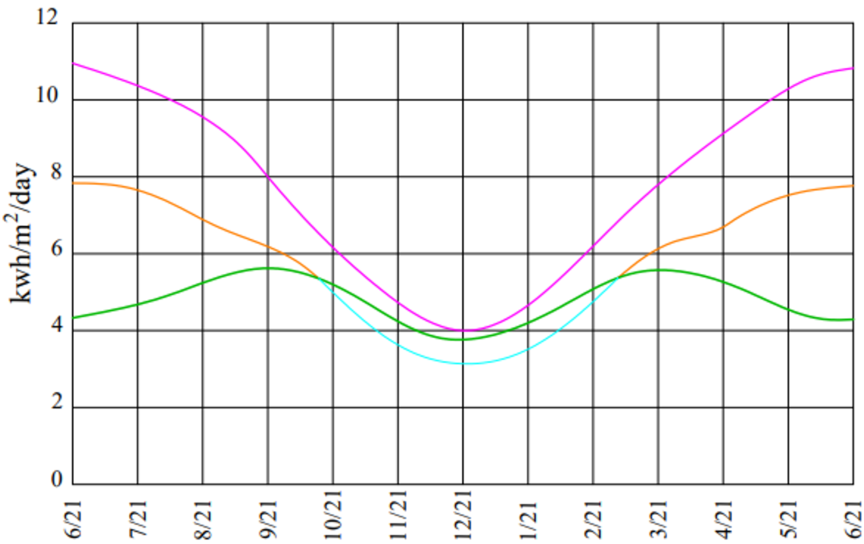

Fig. 4. Impact of tilt angle adjustments on performance

(1) - the line shows the amount of energy that can be obtained every day if the installation of a solar power plant, the installation of a solar battery is made at a fixed optimal angle of inclination;

(2) - the line shows the amount of solar energy that can be obtained by adjusting the tilt angle four times a year;

(3) - the line shows the amount of solar energy per day if the solar battery is set to the winter angle;

(4) - for comparison, shows the energy that could be received from a two-axis tracking system that always orients the panels directly to the sun. Figures are given for 40*latitude (Table 1).

Table 1. Relation between latitude and Summer and Winter corner values

Latitude	Summer corner	Winter corner	% of optimal (2-axis tracker)
25^0	2.3	41.1	76%
30^0	6.9	45.5	76%
35^0	11.6	49.8	76%
40^0	16.2	54.2	75%
45^0	20.9	58.6	75%
50^0	25.5	63.0	74%

If the design allows you to change the angle of inclination of the solar panels, then when changing the angle twice a year at a latitude of 41°, the following figures can be taken:

* the best tilt angle for Summer would be the numerical value of the latitude multiplied by 0.93 minus 21°, i.e., 41° 0.93 - 21° = 17.3°;
* the best angle for Winter is the numerical value of the latitude times 0.875 plus 19.2°, i.e., 41° 0.875 + 19.2° = 55.075°;

The optimal time for changing the inclination angle for the summer period is March 30 and for the winter period - September 12.

When adjusting the angle of inclination of solar panels four times a year at a latitude between 25° and 50°, the best angles of inclination will be (Table 2):
*for summer, multiply the numerical value of the latitude by 0.92, and subtract 24.3°;
* for spring and autumn, multiply the numerical value of latitude by 0.98, and subtract 2.3°;
*for winter, multiply the numerical value of the latitude by 0.89, and add 24°.

Therefore, for a latitude of 41° (for Tashkent), you can set the angle of inclination of the solar panels:

Table 2. Relation between Latitude and four season corner values

Latitude	Summer corner	Spring/autumn corner	winter corner
25^0	-1.3	22.2	46.3
30^0	3.3	27.1	50.7
35^0	7.9	32.0	55.2
40^0	12.5	36.9	59.6
45^0	17.1	41.8	64.1
50^0	21.7	46.7	68.5

for Summer, the numerical value will be 41° 0.92 – 24.3° = 13.42°;
for Spring and Autumn, the numerical value will be 41° 0.98 – 2.3° =37.88°;
for Winter, the numerical value will be 41° 0.89 + 24° =60.49°.

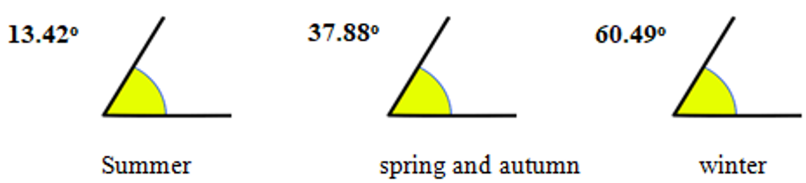

Fig. 5. Angle of inclination depends on time of year.

The optimal time to change the inclination angle for the summer period is April 18, for the autumn period is August 24, for the winter period is October 7, for the spring period is March 5.

Suppose the design of the photovoltaic station allows you to adjust the angle of inclination every month. In that case, the following values are used to calculate its value at a latitude of 41°:

1. From the spring equinox to the autumn equinox:

the angle is (41° -5° =35°) on April 3 and September 9 (including the next 2-week difference);

the angle is (41° -10° =31°) on April 17 and August 26 (including the next 2-week difference);

the angle is (41° -15° = 26°) on May 1 and August 12 (including the next 2-week difference);

the angle is (41° -20° =21°) on May 22 and July 22 (including the next 2-week difference);

the angle is (41° -23,5° - 17.5°) on June 22 (summer solstice).

2. **From the autumnal equinox to the spring equinox** - the angle is equal to the latitude of 41° on March 22 and September 22 (equinox):

the angle is (41° +5° =46°) on October 6 and March 7 (including the next 2-week difference);

the angle is (41° +10° =51°) on October 19 and February 22 (including the next 2-week difference);

the angle is (41° +15° =56°) on November 3 and February 8 (including the next 2-week difference);

the angle is (41° +20° =61°) on November 23 and January 23 (including the next 2-week difference);

the angle is (41° +23,5° = 64,5°) on December 22 (winter solstice).

Solar panels at a winter angle of inclination will be oriented quite efficiently in winter, capturing from 81 to 88% of energy compared to a tracker system. This angle of inclination is a good solution in places where the load is greater in winter than in summer. In spring, summer, and autumn, the efficiency will be lower than 74 - 75% in spring and autumn and 68 - 74% in summer, that in these seasons, the sun passes a large part of the sky, and the fixed panel cannot capture it at angles approaching 90*, a significant part of the day. This is exactly the time of year in which tracker tracking systems have the greatest effect.

3. Determining the distance between rows of solar modules.

When arranging the structure of solar panels in several rows, in addition to the correct orientation and angle of inclination, it is very important to correctly choose the distance between the rows so that there is no mutual shading of the surface of the modules (Fig. 6).

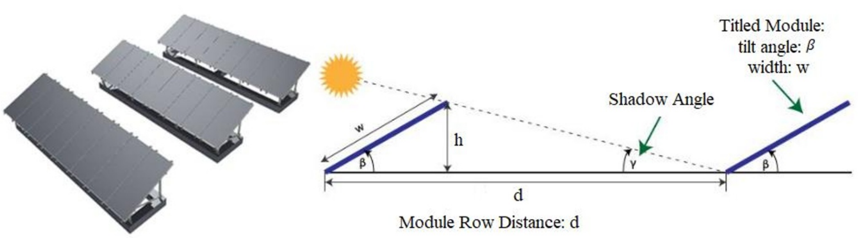

Fig. 6. Choosing the distance between rows

At angles of inclination close to 30*, the site utilization rate for solar power plants is 33%. Most often, solar energy objects are exposed to direct solar radiation for about 5 - 6 pure sun hours per day; therefore, at any cost, they remove objects blocking sunlight from them.

Shading even one corner of a solar module can reduce its productivity by 50%, so it is very important to avoid it. This problem mainly concerns ground fixings and some roof flat supports where rows of panels need to be placed for maximum sufficient space (Fig. 7).

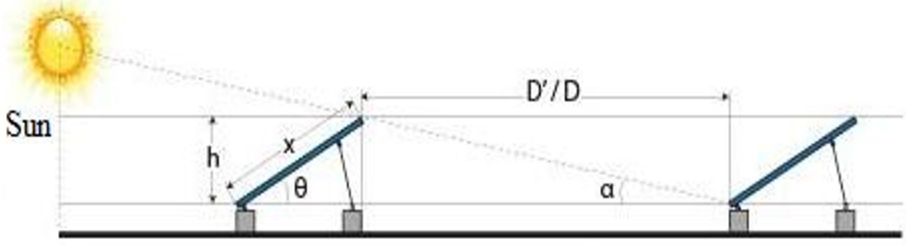

Fig. 7. Placement of rows of panels

The method for calculating the length of the shadow begins with the position of the Sun in the sky during the winter solstice on December 21. It is necessary to obtain the minimum solstice height α, which is the minimum angle at which the Sun passes around the Earth in an unobscured solar window (Fig. 8). During the 4 hours of the solar window, you need to determine the height of the solstice at 10 am, or at 2 pm on December 21, because on this day the Sun is at the lowest point in the sky. Within a 5-hour window, it is necessary to find the height of the Sun at 9.30 or 14.30. When the height of the solstice is found, you can find the azimuth angle of the Sun ψ.

When the position of the Sun deviates from the line of the South (Fig. 8), it is necessary to calculate the minimum allowable distance between the rows.

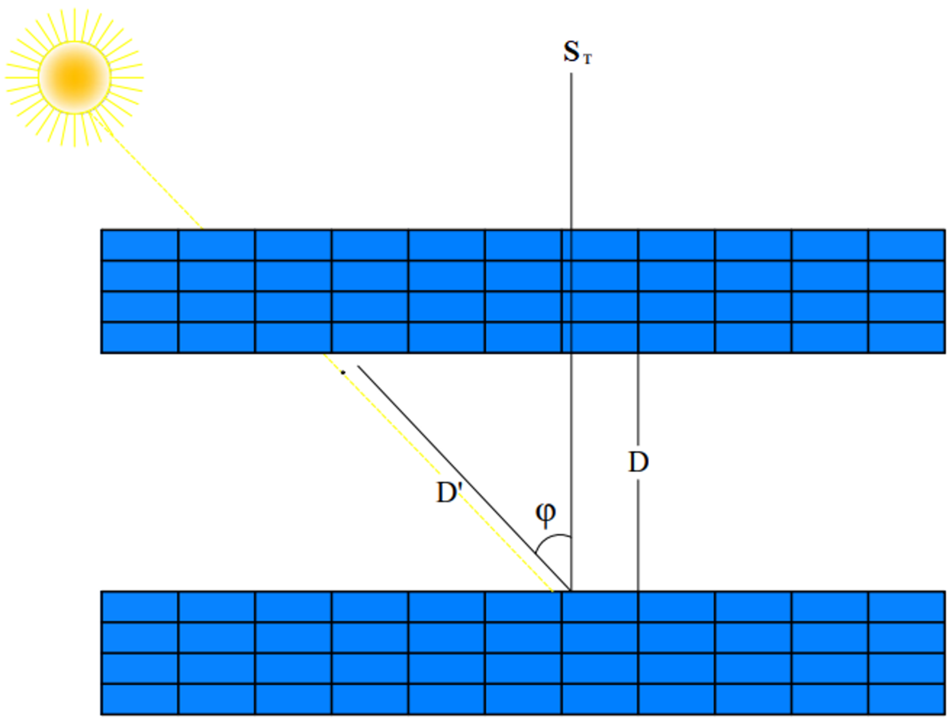

Fig. 8. Correction of azimuth angle of Sun when deviating from line of south (top view)

Finding the values of the local solstice altitude and the azimuthal angle of the Sun during the winter solstice can be quite challenging. Luckily for solar system designers, tools are available to greatly aid the calculation process.

By clicking on the map, you can get information about the coordinates of the area and the time zone, and if you enter the date of the solar solstice, December 21, you can easily get data about the location of the Sun.

After finding the height of the solstice and the azimuth angle of the Sun, you can determine the distance between the rows of solar panels.

The extent of the shadow is determined using simple trigonometry, the following equation:

$$D' = \frac{h}{\tan \alpha} \tag{10}$$

From this, with just one action, the minimum row spacing required to avoid shading in the middle of the sun window is found. This is called "azimuth correction of the Sun". Using the morning position of the Sun, we obtain the equation:

$$D = D' \cos(180 - \psi) \qquad (11)$$

Respectively:

$$D' = \frac{h}{\tan \alpha}$$

We get
$D = D' \cos(180 - \psi)$ before noon; $D = D' \cos(\psi - 180)$ in the afternoon
where T is the duration of the photoperiod for solar panels when they are not shaded during the winter solstice (usually 4-6 hours); α is height of solstice; ψ is azimuth angle of the Sun; h is the height of the obstacle; x is the length of the module in an inclined position; θ is angle of inclination;

$$h = x \cdot sin\theta \qquad (12)$$

D is minimum distance between rows; D' is the maximum length of the shadow.
For the middle strip, with optimal fixation of the inclination angle, the following formula (7) is often used.

$$d = 3h \qquad (13)$$

where d is the distance between rows, m; h is the height of the panel under the optimal slope, m;
If the height of the panel is within 2.05 meters, then for latitude 41 * (Tashkent), it will be:

$$h= 2.05 \cos(90^{\circ} -41^{\circ})=2.05\cos 49^{\circ} = 2.05^{\circ}\, 0.65= 1.333 \text{ m}$$

According to the formula for latitude 41°, the rows between the solar module will be:

$$d = 3 \cdot h = 3 \cdot 1.333 = 3.998\, m.$$

4 Conclusions

1. To place photovoltaic converter panels on the site of a solar power plant, it is necessary to calculate their mutual shading, taking into account the design and dimensions of one photovoltaic converter panel and the way it is installed on the ground at an angle φ, calculate the panel shadow depending on the time of year and hour of the day, and it is necessary to determine the shading coefficients α_{ij} from the height h of the installation of panels above the ground.

2. The optimal tilt angle of the solar panel depends on the area's latitude and can also be changed depending on what optimization in energy production needs to be achieved. So, it can be reduced from the optimal value if the photovoltaic system operates in the summer (summer optimum), increased if the photovoltaic system is operated mainly in the autumn-winter period, or taken as an average value if the photovoltaic system is intended for year-round operation.

3. In winter, the solar panel will be oriented quite efficiently at a winter angle of inclination, capturing from 81 to 88% of the energy compared to the tracker system. This

angle of inclination is a good solution in places where the load is greater in winter than in summer. In spring, summer, and autumn, the efficiency will be lower (74-75% in spring/autumn and 68-74% in summer) because during these seasons, the sun passes through a large area of the sky, and the fixed panel cannot capture it at angles, approaching 90°, a significant part of the day. This is exactly the time of year in which tracker tracking systems have the greatest effect.

4. For the city of Tashkent (local latitude 41°), you can set the angle of inclination of the solar panel: for Summer, the numerical value will be 13.42°; for Spring and Autumn, the numerical value will be 37.88°; for Winter, the numerical value will be 60.49°. If the panel's height is within 2.05 m, then for a latitude of 41° the distance between the rows is 3.998 meters.

5. Despite advances in solar technology, solar energy remains the most expensive form of renewable energy known. The development of solar energy in the future will lead to cheaper photovoltaic cells and tariffs for solar energy.

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