Improving the energy efficiency of using solar panels

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Abstract. The article describes a method for increasing the efficiency of using solar panels when using a two-axis system for tracking the sun. A mathematical model of solar panel operation has been developed for the following applications: stationary installation of solar panels and the use of a two-axis solar tracker. The solar tracker has the ability to rotate the solar panel by the azimuth angle from 0 to 170 degrees, by the Zenith angle from 0 to 90 degrees. The paper presents a method for calculating power generation by solar panels using a solar tracker and a variant of stationary installation of solar panels. Plots of the PV panel as a function of time at stationary position of the solar panels and using a solar tracker. As a result of mathematical modeling, when using a solar tracker, compared with a stationary installation of a solar panel, electricity generation increases by 89.9% on the example of June 22, and by the example of December 22, the increase in electricity generation is 19.6 %. Using a solar tracker during the year increases the efficiency of electricity generation by solar panels by an average of 45-55%. Data on azimuth angles of sunrise and sunset, as well as the Zenith angle depending on the time of day for the 22nd day of each month are given in the table below. The results obtained are presented for coordinates: 45 degrees 3 minutes North latitude 41 degrees 59 minutes East longitude, which corresponds to the locality of the city of Stavropol in the Russian Federation.

1. Introduction
To increase the energy efficiency of using a solar panel, it is assumed to use a two-axis system for tracking the sun [1–5, 6–9].

Let’s present a mathematical model of how solar panels work for the following applications: stationary installation of solar panels and the use of a two-axis solar tracker.

Data on azimuthal angles of sunrise and sunset, as well as the Zenith angle depending on the time of day for the 22nd day of each month are given in the table below. Data is given for coordinates 45 degrees 3 minutes North latitude 41 degrees 59 minutes East longitude, which corresponds to the locality of the city of Stavropol in the Russian Federation.

Table 1. Azimuth and Zenith angle of the sun depending on the time of day.

| Time of day | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 |
|-------------|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|
| January     | 79| 90| 100|110|121|132|145|159|174|189|204|218|230|242|252|262|272|
|             | -39|-28| -18|-8 |2 |10 |17 |22 |25 |22 |16 |9 |0 | -10| -20| -31|
| February    | 70| 82| 93 |103|114|126|140|155|172|190|207|222|236|247|258|269|280|
Table 1 shows that the maximum azimuth angle of sunrise for the selected point of installation of the solar generator is 61°, sunset – 305°. The minimum Zenith angle corresponding to the month of December is 21°, and the maximum Zenith angle (June) is 68°.

Based on the analysis of the data in table 1, when stationary solar panels are installed for year-round operation, the optimal azimuth angle is 183°, the Zenith angle is 44.5°.

Light day in June is 16 hours, light day in December – 9 hours.

The average daily installation of solar energy is shown in table 2.

**Table 2.** Average daily value of solar energy installation per surface unit.

| Month            | Solar insolation, kWh/m² |
|------------------|--------------------------|
| January          | 2.90                     |
| February         | 3.37                     |
| March            | 3.75                     |
| April            | 4.55                     |
| May              | 5.60                     |
| June             | 5.85                     |
| July             | 6.09                     |
| August           | 5.49                     |
| September        | 4.56                     |
| October          | 3.56                     |
| November         | 2.62                     |
| December         | 2.25                     |
| Average per year | 4.22                     |

The table shows that the average daily installation per surface unit for July is 6.09 kWh/m², the minimum value corresponds to December and is 2.25 kWh/m².
2. Materials and methods

The power of the solar panel as a function of time is determined from the expression

\[ P_{sp}(t) = P_{in}(t)\eta_{sp} - P_{pot}(t) \] (1)

where

- \( P_{sp}(t) \) - solar installation capacity, W/m\(^2\);
- \( P_{in}(t) \) – solar radiation installation, W/m\(^2\);
- \( \eta_{sp} \) - efficiency of the solar panel;
- \( P_{pot}(t) \) - power loss of the solar installation, W/m\(^2\).

The power loss of a solar installation depends on the angle of deviation from the normal to the solar panel and is determined by

\[ P_{pot}(t) = P_{in}(t)\eta_{sp}(1 - \cos\gamma) \] (2)

where \( \cos\gamma \) - the cosine of the angle of deviation from the normal to the solar panel.

The angle of deviation from the normal to the solar panel is determined by

\[ \gamma = \sqrt{\alpha^2 + \beta^2} \] (3)

where

- \( \alpha \) - angle of deviation from the normal to the solar panel in azimuth;
- \( \beta \) – Zenith angle of deviation from the normal to the solar panel.

The angle of deviation from the normal to the solar panel by azimuth is determined by

\[ \alpha = \alpha_{az} - \alpha_z(t) \] (4)

where

- \( \alpha_{az} \) - azimuth angle of solar panel installation;
- \( \alpha_z(t) \) - azimuth angle of the sun's position.

The Zenith angle of deviation from the normal to the solar panel can be found from the expression

\[ \beta = \beta_{zu} - \beta_z(t) \] (5)

where

- \( \beta_{zu} \) - Zenith angle of solar panel installation;
- \( \beta_z(t) \) - Zenith angle of the sun's position.

3. Results and discussion

Delivering value power of solar installation by time and loss of solar installations over time in the expression 1 will construct the graphs of the power solar panel as a function of time at stationary position of the solar panels and using a solar tracker [10].

The solar tracker has the ability to rotate the solar panel at an azimuth angle from 0 to 170 degrees, along the Zenith angle from 0 to 90 degrees.
Figure 1. Power of the solar panel on June 22 with an area of 1 m$^2$ depending on the time of day when installing the solar panel: 1 - on the solar tracker; 2-Zenith angle 68°, azimuth angle 183°; 3-Zenith angle 44.5°, azimuth angle 183°.

Figure 2. Power of the solar panel on December 22 with an area of 1 m$^2$ depending on the time of day when installing the solar panel: 1 - on the solar tracker; 2-Zenith angle 21°, azimuth angle 183°; 3-Zenith angle 44.5°, azimuth angle 183°.

Based on the graphs in figures 2 and 3, it can be concluded that when using a solar tracker in comparison with a stationary solar panel installation, electricity generation increases by 89.9% on the example of June 22, and by 19.6% on the example of December 22. At the same time, for December 22,
the Zenith angle was 21°, for June 22. 68°. The azimuth angle for both graphs is 183°. Changing the Zenith angle leads to a decrease in power generation by solar panels.

Using the solar tracker throughout the year, based on the analysis of graphical dependencies (figure. 1, 2) increases the efficiency of power generation by solar panels by an average of 45–55%.

To determine the effectiveness of using a solar tracker, a system for tracking the sun has been created. The efficiency of using a solar tracker was compared to a stationary solar panel. The experiment to determine the effectiveness was performed in June and December.

The solar tracker is shown in figure 3.

Figure 3. Solar tracker.

Figure 3 a shows a view of a solar tracker with solar panels installed in the front, and figure 3 b shows a view from the back.

In a rigid frame, solar panels 1 are installed, the frame with solar panels is welded to a shaft mounted in housing bearings 2, which allow changing the positions of the solar panels horizontally. The beam with the installed housing bearings is attached by means of a loop 5 to the solar collector rack. Linear drive 3 based on a DC motor connected via a reducer to the rod, one end is attached to the frame with solar panels, the other to the outrigger part of the beam, which provides a controlled change in the position of the solar panels horizontally. The linear drive 4 is attached to the rack and beam of the solar collector, which provides a controlled change in the vertical position of the solar panels.

The sun position sensor is based on four photoresistors separated by partitions, which allows you to position the solar tracker with sufficient accuracy.

The appearance of the experimental installation for determining the efficiency of using solar panels with a solar tracking system is shown in figure 4.
Figure 4. Experimental setup for determining the efficiency of using a solar tracker.

Figure 4 a shows the installation of solar panel 1 permanently for the month of June-Zenith angle 68°. The solar panel 2 is installed on a solar tracker, tracking the position of the sun is performed using the sun position sensor 4 and the control system 3. The sun position sensor itself is shown in figure 4 b and consists of four photoresistors separated by opaque partitions. Depending on the dimming of a particular photoresistor, the solar panel is positioned perpendicular to the sun.

To determine the increase in electric power generation by solar panels using a solar tracker, an experiment was carried out, the results of which are shown in figure 5. The load was a 100-watt incandescent lamp. 100 W solar panel.

Figure 5. Solar panel power over time for June 22, 2019: 1 - when using a solar tracker, 2 - when installing a stationary solar panel.
Figure 5 shows that the power generation of the solar panel installed on the tracker is significantly higher than when it is installed permanently. For June 22, generation of electricity when using solar tracker with one solar panel 100W amounted to 1160 Wh, with permanent installation, solar panel electricity generation amounted to 655 Wh. Thus, the solar tracker allows you to increase the power generation of a solar panel compared to its fixed installation by 76.9%.

On June 22, 2019, there was clear Sunny weather, which allowed for a significant increase in electricity generation when using a solar tracker.

If the weather is overcast or cloudy, the tracker's effectiveness is reduced. The use of a two-axis solar tracker in summer allows an average increase in electricity generation compared to a stationary location of solar panels by 65%, in winter – 17%, the average annual increase in electricity generation is 41%.

4. Conclusion
1. Mathematical modeling of the efficiency of using a solar tracker is carried out. Based on the results of mathematical modeling, it was determined that in winter, the use of a solar tracker can increase the power generation of solar panels by 19.6%, in summer by 89.9%.
2. It is experimentally determined that the use of a two-axis solar tracker can increase the power generation of solar panels in comparison with their stationary installation in the summer by 76.9%, in winter by 17%, and the average annual electricity generation increases by 41%.

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