



ENHANCING THE EFFICIENCY OF A SMALL-SCALE SOLAR POWER PLANT THROUGH AN AUTOMATED CONTROL SYSTEM

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Abstract. *This article investigates the efficiency of solar energy utilization depending on the installation angle of photovoltaic panels and proposes an advanced method for improving their performance through automated solar tracking. The study analyzes the influence of solar elevation and azimuth angles on relative illumination for vertical and inclined (45° and latitude-based) panel configurations, using astronomical simulation data obtained from Stellarium. The results demonstrate that fixed-position solar panels do not fully utilize available solar radiation, particularly during seasonal variations of the Sun's trajectory.*

To address this limitation, solar tracking systems are considered, including commercially available dual-axis trackers and their inherent disadvantages such as high cost, sensitivity to cloud conditions, and delayed response during sunrise and sunset transitions. As an alternative, an automated solar power plant based on a Raspberry Pi microcontroller is proposed. The system uses a programmatic approach combined with optional GPS-based positioning to calculate the Sun's coordinates in real time and control panel orientation via an electric drive.

The proposed solution ensures continuous alignment of solar panels with the Sun from sunrise to sunset, independent of weather conditions, thereby maximizing energy capture efficiency. The study concludes that software-controlled solar tracking provides a more reliable and efficient alternative to sensor-based systems for small-scale photovoltaic installations.

Keywords: *Solar energy; photovoltaic panels; solar tracking system; relative illumination; solar elevation angle; azimuth; Raspberry Pi; microcontroller*

INTRODUCTION

In recent years, issues related to environmental protection and sustainable resource management have become increasingly significant. At the same time, ensuring a stable supply of energy and fuel for humanity remains a critical global challenge. This problem is largely driven by the limited availability of essential natural resources, including fossil fuels and mineral reserves, as well as the negative environmental impact caused by conventional energy production methods. In this context, the transition to alternative energy sources is considered one of the most effective solutions to the global energy crisis.

Among renewable energy sources, solar energy occupies a leading position due to its availability and environmental safety. It is widely used in various applications, including electricity generation through solar power plants. Today, solar installations of different capacities and configurations are actively deployed worldwide, providing clean energy without harmful emissions.

Small-scale solar power plants are particularly promising for decentralized energy systems. They are well suited for supplying electricity to low-power consumers, especially in remote areas where connection to centralized power grids is difficult or economically impractical. The operation of such systems is based on the conversion of solar radiation into electrical energy using photovoltaic panels.

In many cases, solar panels are installed in a fixed position, typically oriented toward the south. While this approach simplifies the design and reduces mechanical complexity, it leads to inefficient utilization of solar energy. Specifically, during the period between the spring and autumn equinoxes, there are time intervals when the Sun is above the horizon but does not illuminate the panels effectively.

To better understand this phenomenon, it is useful to analyze the daily motion of the Sun on a date close to the summer solstice. Key moments such as sunrise, sunset, and the times when the Sun crosses the eastern and western directions can be determined. These moments also correspond to the beginning and end of effective illumination of the solar panels.

Such data can be obtained using astronomical simulation software, for example, the freely available program Stellarium. Although this method may provide slightly less precise results compared to analytical calculations, its accuracy is sufficient for practical purposes.

As an example, consider June 22, 2022 (summer solstice). Using Stellarium, the following times can be determined:

- sunrise: 5:30 (t_1),
- crossing the eastern direction: 8:50 (t_2),
- crossing the western direction: 18:20 (t_3),
- sunset: 20:50 (t_4).

The duration during which the panels receive direct illumination is defined as:

$$\Delta t = t_3 - t_2$$

Substituting the given values, we obtain 9.5 hours. The total daylight duration is:

$$\Delta T = t_4 - t_1$$

which equals 16.33 hours. Therefore, the fraction of time during which the panels are effectively illuminated is:

$$9.5 / 16.33 \approx 0.58 \text{ (58\%)}$$

To increase the utilization of solar energy, tracking systems that follow the Sun's movement are often proposed. Such systems are particularly suitable for small-scale solar installations. In contrast, large solar power plants typically use fixed panels due to the complexity and cost associated with moving large structures.

Solar tracking can be implemented in several ways. The simplest approach involves rotation of the panel around a vertical axis, which minimizes mechanical complexity while still improving energy capture. In this case, the panel can also be mounted at different tilt angles relative to the horizontal plane.

To evaluate the efficiency of solar energy utilization, it is necessary to consider the relative illuminance, defined as the ratio of the actual illuminance to the maximum possible value when light falls perpendicular to the surface. Two installation configurations are considered: vertical mounting and mounting at a 45° angle relative to the horizon. Calculations are performed for two characteristic dates: the summer solstice (June 22) and the winter solstice (December 22).

At the initial stage, the solar elevation angle above the horizon is determined at regular intervals (e.g., every 30 minutes) throughout the day using Stellarium. Let this angle be denoted as γ . It is well known that when light strikes a surface at an angle, the illuminance decreases proportionally to the cosine of the incidence angle relative to the surface normal.

For a vertically installed panel, the angle of incidence relative to the normal is equal to γ . For a panel tilted at 45° , the incidence angle is defined as $(45^\circ - \gamma)$. These relationships form the basis for further analysis of solar energy efficiency.

Table 1

Values of Relative Illuminance of Solar Panels on the Day of the Summer Solstice

Time (hours)	Solar Elevation Angle ($^\circ$)	Relative Illuminance (Vertical Panel)	Relative Illuminance (45° Tilt Panel)
4-30	1,22	1,000	0,722
5-00	4,95	0,996	0,766
5-30	8,83	0,988	0,807
6-00	13,15	0,974	0,850
6-30	17,22	0,955	0,855
7-00	21,97	0,927	0,920
7-30	26,63	0,894	0,949
8-00	31,55	0,852	0,973
8-30	36,10	0,808	0,988

9-00	40,22	0,764	0,997
9-30	44,67	0,711	1,000
10-00	49,12	0,655	0,997
10-30	52,83	0,605	0,991
11-00	56,50	0,552	0,980
11-30	59,28	0,511	0,969
12-00	61,30	0,481	0,960
12-30	62,07	0,469	0,956
13-00	61,53	0,477	0,959
13-30	59,87	0,502	0,967
14-00	57,48	0,538	0,976
14-30	54,67	0,579	0,986
15-00	51,07	0,629	0,994
15-30	47,07	0,681	0,999
16-00	42,77	0,734	0,999
16-30	38,10	0,787	0,993
17-00	33,62	0,833	0,980
17-30	28,98	0,875	0,961
18-00	24,30	0,911	0,936
18-30	19,77	0,941	0,905
19-00	15,33	0,964	0,869
19-30	10,83	0,982	0,828
20-00	6,83	0,993	0,786
20-30	2,98	0,999	0,743

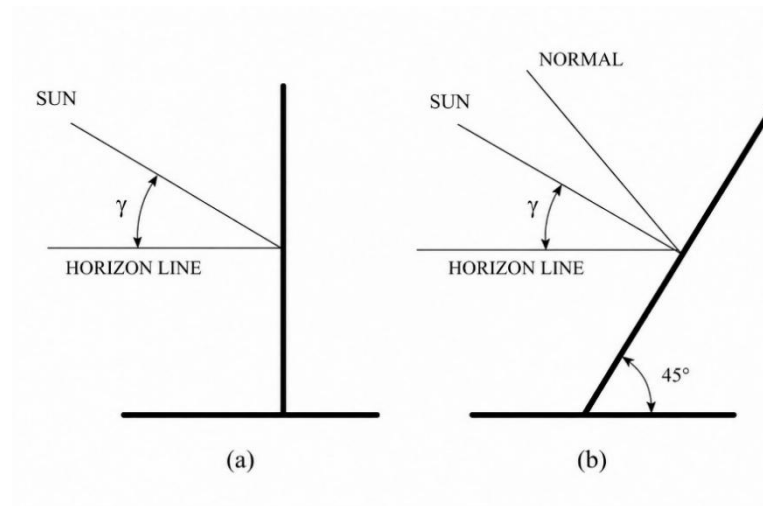


Fig. 1. Types of solar panel installation: (a) vertical, (b) at a 45° angle to the horizon.

Based on this, we determine the relative illuminance values for these options and the two calendar dates specified above. The results are presented in two tables.

Time (hours)	Solar Elevation Angle (°)	Relative Illuminance (Vertical Panel)	Relative Illuminance (45° Tilt Panel)
9-00	2,12	0,999	0,733
9-30	5,20	0,996	0,769
10-00	8,07	0,990	0,800
10-30	10,38	0,984	0,823
11-00	12,50	0,976	0,844
11-30	13,88	0,971	0,856
12-00	14,90	0,966	0,865
12-30	15,33	0,964	0,869
13-00	15,12	0,965	0,867
13-30	14,23	0,969	0,859
14-00	12,97	0,975	0,848
14-30	11,13	0,981	0,831
15-00	8,73	0,988	0,806
15-30	6,03	0,994	0,778
16-00	2,83	0,999	0,741

Table 2

Relative illuminance values for solar panels on the winter solstice

For a more visual presentation, the obtained results are shown in graphs (Fig. 2 and Fig. 3).

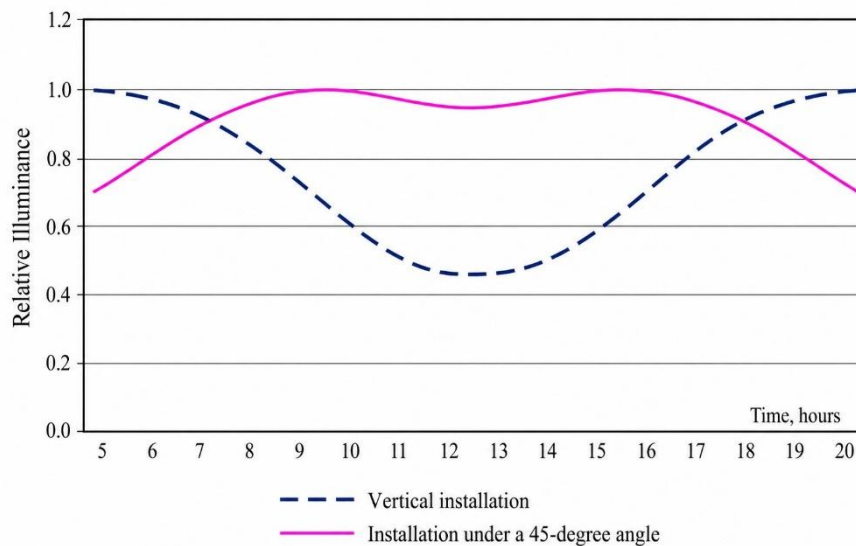


Fig. 2. Graphs of changes in the relative illumination of solar panels for the day of the summer solstice

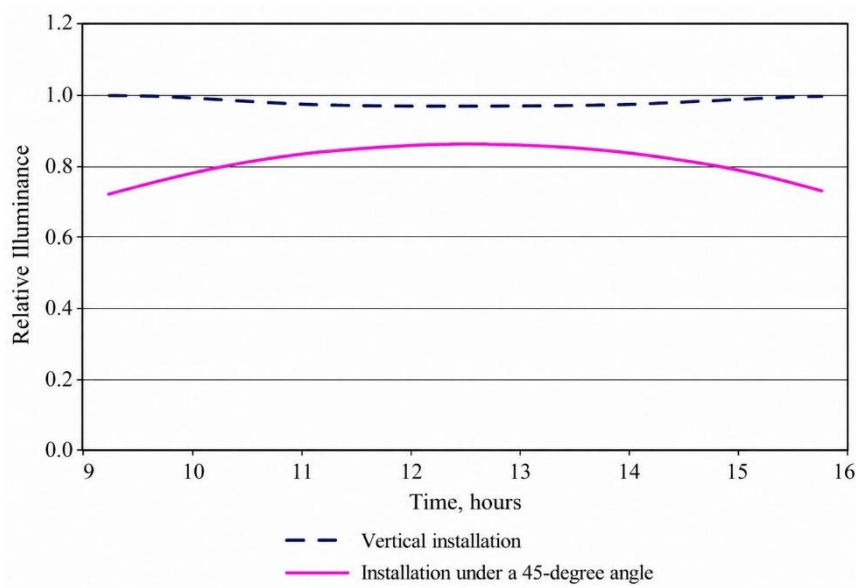


Fig. 3. Graphs of changes in the relative illumination of solar panels for the day of the winter solstice

The data on relative illumination show that in summer, vertical installation of solar panels is less efficient than installation at a 45° angle. An even more efficient configuration is installation at an angle equal to the latitude of the installation site; for Tashkent, this value is 52° .

The presented relative illumination values indicate that, for the most complete utilization of solar energy, it is necessary to use a solar panel positioning control system. Currently, there are many such designs, for example, the “ED-1500 Dual” solar tracker – an automatic rotating structure for solar panels that dynamically orients itself relative to the position of the Sun, ensuring the optimal position of the solar modules. Accurate solar tracking is achieved through systems with one or two tracking axes [energy-ds.ru]. The tracker orientation occurs in two planes: up–down from -10° to 75° ; left–right from -120° to 120° .

The use of two light sensors for solar orientation cannot ensure proper operation of the control system in cases of even short-term solar obstruction by clouds. In such a situation, illumination becomes more uniform than under clear-sky conditions, and control signals for rotating the solar panels may not be generated.

As a result, when the Sun reappears, additional time is required to restore correct orientation. It should also be noted that such a device is relatively expensive.

In addition, it will take some time to orient the system toward the rising Sun if the solar panel remained pointed toward the sunset position from the previous day. The light sensors will be directed away from the Sun, and therefore a certain period is required for sufficient illumination imbalance to develop, enabling the control system to operate and rotate the panels toward the rising Sun.

To eliminate these shortcomings, it is necessary to apply alternative principles for controlling the solar panel position. In the automated solar power plant developed at the Department of Electrical Engineering of TSTU, the solar panel automatically changes its position so that it remains continuously directed toward the Sun, resulting in the angle of incidence of sunlight on the panel surface being close to 90° throughout the day. Panel movement is carried out by an electric drive according to commands issued by the control unit.

To implement such a control unit, a microcontroller based on Raspberry Pi can be used. Unlike existing systems that rely on control signals from light sensors, the operating commands for the electric drive in this solar power plant are generated by a control program. To run the program, the geographical coordinates of the installation site must be specified in advance. This operation can be performed automatically if the equipment includes a GPS module that determines the installation coordinates and current time from satellite signals.

The program determines, for each day, the time of sunrise and the location (azimuth) of the sunrise point. Before sunrise, the program activates the solar power plant from night or “sleep” mode and issues a command to orient the panels toward the sunrise position for the current day.

Then, the program calculates the horizontal coordinates of the Sun (azimuth and elevation) at small time intervals throughout the daylight period. Based on these values, continuous tracking of the Sun’s position is performed, even when it is

obscured by clouds. After sunset, the program stops the electric drive and switches the solar power plant to standby mode.

The proposed automated solar power plant allows maximum utilization of solar energy throughout the daylight period. This is achieved through software-based control of the solar panel orientation. Such a control method ensures continuous alignment with the Sun from sunrise to sunset, regardless of cloud cover and other factors that may reduce the efficiency of systems based on light sensors.

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