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Impact of Solar Incidence Angle on Output Power of PV Systems: A Field Study in Turkistan Region, Kazakhstan

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Abstract

This article explores the relationship between the angle of incidence of solar radiation and the output power of solar panels. The object of the study is a 26.1 kW solar power plant installed on the territory of Khoja Akhmet Yassawi International Kazakh-Turkish University. The solar panels at this station are mounted at a tilt angle of 30° and oriented to the south. The main objective of the research is to determine the optimal installation angle of the panels by identifying the effect of the angle of incidence of solar radiation on the output power. During selected time intervals in the spring season, the angle of incidence (θ_i) was calculated based on the sun's altitude and azimuth. The obtained angular values were compared with actual output power data retrieved from the SOLARMAN monitoring system operating in real time, and the correlation between them was analyzed. The results of the study confirmed that the performance of the panels increases as the angle of incidence decreases. In other words, the efficiency of converting solar energy into electrical energy improves when sunlight hits the panel surface more perpendicularly. This research provides valuable practical insights for optimizing the tilt angle of solar panels during the design of solar power plants. Moreover, the results of this study have the potential to enhance the educational process in the field of solar energy and can be integrated into STEM-based learning environments.

Cite

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1. INTRODUCTION

Among these factors, the angle of incidence of solar radiation on the panel surface is of particular importance. Variations in this angle directly influence how effectively the panel absorbs light flux. In other words, the more perpendicular the sunlight falls on the panel surface (i.e., the smaller the angle of incidence), the greater the amount of electricity generated. Since the Sun's position on the horizon changes throughout the day and across seasons, the angle of incidence also varies continuously. Therefore, the correct selection of the panel orientation (azimuth and tilt angles) is a critical condition for maximizing the annual energy yield of solar panels.

In this article, we focus on the relationship between the output power of a solar panel and the Sun's position in the celestial dome. Specifically, based on the solar azimuth and altitude, the angle of incidence (θ_i) on the panel surface is calculated, and its impact on the actual output power of the solar panel is analyzed. This analysis is conducted using the principles of geometrical optics and trigonometric relationships.

The calculation of the angle of incidence is based on the following physical and mathematical principles:

- The position of the Sun in the celestial dome is determined through astronomical calculations based on the Earth's axial tilt and rotational motion (e.g., declination angle, hour angle, solar altitude, and azimuth);

- The effect of the angle of incidence of light is governed by the laws of geometric projection, specifically the projection of radiant flux onto a horizontal surface.

When such research is adapted to the specific geographic coordinates, seasonal characteristics, and climatic conditions of the panel installation site, it offers highly valuable practical recommendations for the design and optimization of solar power plants.

In this article, the angle of solar radiation incidence on the surface of solar panels was calculated based on measurements of solar azimuth and altitude for selected spring days, using a 26.1 kW solar power plant located on the territory of Khoja Akhmet Yassawi International Kazakh-Turkish University. By analyzing the relationship between the angle of incidence and actual power output data obtained from the SOLARMAN Smart monitoring system, the main geometrical factors influencing the efficiency of solar panels are identified.

The output power of photovoltaic (PV) systems is closely related to the incident solar radiation, which is affected by various factors such as panel efficiency, orientation, tracking systems, and environmental conditions. Since solar radiation is the primary energy source for PV cells, its intensity and angle of incidence play a decisive role in determining the amount of electricity generated.

One of the key factors affecting output power is the efficiency of the solar panel. Efficiency refers to the panel’s ability to convert incident solar radiation into electrical energy. Panels with higher efficiency can generate more electricity under identical solar conditions, thereby maximizing energy production [1]. Additionally, the alignment of photovoltaic panels relative to the direction of sunlight is critically important. It has been established that solar panels produce the most electricity when they are oriented perpendicularly to solar radiation. This indicates that optimizing the installation angle of solar panels is essential to improving energy capture [2], [3]. For example, selecting the correct tilt and azimuth angles can significantly increase the solar intensity received by the panels, directly affecting their performance [4].

Moreover, the implementation of solar tracking systems represents an effective strategy for maximizing solar energy utilization. Solar trackers adjust the orientation of panels throughout the day to follow the Sun’s path, thereby maintaining optimal alignment with sunlight. Studies have shown that the use of single- and dual-axis solar trackers can improve energy output by approximately 25–35% compared to fixed installations [5]. This gain is attributed to the trackers’ ability to maintain perpendicular alignment with solar rays, which is crucial for maximizing output power [6].

Environmental factors such as shading and temperature also influence the performance of solar panels. Output power depends not only on the intensity of solar radiation but also on temperature, as higher temperatures can reduce efficiency. Consequently, innovative designs incorporating cooling mechanisms or advanced materials are being developed to mitigate these efficiency losses [7]. Tracking systems often include technologies such as fuzzy logic for real-time adjustments, ensuring optimized performance under varying environmental conditions and maximizing solar energy utilization [8].

As for studies linking solar irradiance intensity to electrical output, extensive experiments have shown that an increase in solar irradiance typically leads to a proportional increase in power generation. For instance, at a light intensity of 890 W/m², output power reached a significant level, indicating a direct relationship between solar irradiance and photovoltaic system performance. Additionally, studies have demonstrated that system configurations, including the orientation and tilt angle of PV panels, significantly influence the amount of solar radiation captured, thus affecting overall efficiency [9], [10].

However, there remain several unresolved challenges in the field of efficient solar energy utilization. One such challenge is the lack of field studies on the relationship between the angle of incidence and actual output power. Although the importance of the angle of incidence is well established theoretically, there is a shortage of practical, measurement-based studies that examine the relationship between solar angle and output power under real climatic conditions.

Furthermore, there is a lack of localized models; while international studies are abundant, analytical or predictive models based on Kazakhstan's climatic and geographic conditions are scarce. Therefore, independent methodologies are needed for the design and performance prediction of domestic solar power plants.

This article explores the scientific and methodological foundations, potential applications, and future development prospects related to the solar energy sector. The aim of the study is to analyze the relationship between the output power of solar panels and the angle of incidence of solar radiation on the panel surface. The findings provide the basis for developing recommendations to enhance solar energy generation efficiency through the optimal selection of panel orientation, consideration of seasonal variations, and adaptation to specific climatic conditions.

2. MATERIAL AND METHOD

In this study, the angle of solar radiation incident on the panel surface was determined based on the Sun's azimuth and altitude using an astronomical-geometric calculation method. Through empirical observation and data comparison, the calculated angles were compared with the actual measured output power to analyze their correlation. A comparative analysis method was employed to examine variations at different times of the day and to identify the periods of optimal panel performance. The integrated application of these methods enabled a comprehensive investigation of the key geometrical factors affecting solar panel efficiency.

The astronomical-geometric calculation method involved the use of trigonometric formulas to compute the angle of incidence (θ_i) of solar radiation on the panel surface, based on the Sun's position on the horizon (azimuth and altitude). This method allowed for the determination of the angular relationship between the direction of incoming solar radiation and the spatial orientation of the panel, thereby assessing the panel's ability to effectively capture sunlight. Supporting tools such as the StarWalk2 and Stellarium applications were used to aid in the calculations (Figure 1).

Figure 2. *Azimuth and altitude of The Sun at the local location in the Stellarium and StarWalk2 programs*

The empirical observation and data comparison method involved analyzing real-time operational data obtained via the SOLARMAN Smart monitoring system from a 26.1 kW solar power plant installed on the campus of Khoja Akhmet Yassawi International Kazakh-Turkish University. These data were compared with the calculated angles of incidence for different times of the day. This approach enabled the identification of the correlation between the geometric orientation of the panels and their actual output power.

Using the *graphical analysis method*, the collected data were visualized in the form of graphs with the help of software such as Excel or Python. This visualization clearly illustrated the relationship between the angle of incidence and the resulting output power.

3. RESULTS AND DISCUSSION

The classical formula for calculating the angle of incidence of solar radiation on the surface of a panel is as follows:

$$\theta_i = arccos\left[sinh \times sin\beta + cosh \times cos\beta \times cos\left(A - A_p\right)\right] \quad (1)$$

Where:

β - Tilt angle of the panel (measured from the horizontal; in this case 30°);

A_p - Azimuth angle of the panel (e.g., 180° if facing due south);

h - Solar altitude (angle of the Sun above the horizon);

A - Solar azimuth angle.

Below, based on data from March 18, with the panel installed at a 30° tilt angle relative to the horizontal and oriented exactly to the south (azimuth angle of 180°), the actual values of the Sun's altitude (h) and azimuth (A) are provided. Using these data, the angle of incidence (θ_i) of solar radiation on the panel surface was calculated (Figure 2).

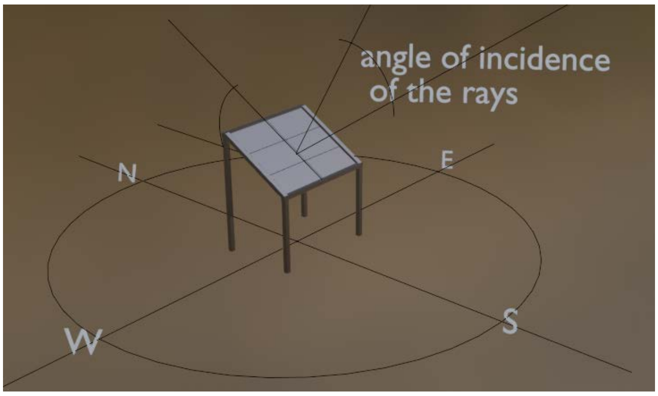

Figure 2. *Installation view of solar panels*

In this study, in order to investigate the dependence of solar panel performance solely on the angle of incidence, we selected a clear and sunny day. Given our geographical location, the solar azimuth and altitude values throughout the day were obtained using the Stellarium and StarWalk2 applications. The collected values are presented in Table 1 below.

Table 1. *First Data Table*

Time	**Solar azimuth** ***A*** **(°)**	**Solar altitude** ***h*** **(°)**
08:00	105.67	14.75
09:30	123.95	29.57
11:00	147.95	41.07
12:30	178.45	45.88
14:00	209.37	41.92
15:30	233.97	31.03
17:00	252.77	16.42

Let us demonstrate one sample calculation using data recorded at 12:30 PM

Solar azimuth: $A = 178°\,27' \approx 178.45°$

Solar altitude: $h = 45°\,53' \approx 45.88°$

Panel tilt angle: $\beta = 30°$

Panel azimuth: $A_p = 180°$

All values are converted into radians for the calculation.

1. $h_{rad} = 45.88° \times \frac{\pi}{180} \approx 0.801\ rad$

2. $\beta_{rad} = 30° \times \frac{\pi}{180} \approx 0.5236\ rad$

3. $A_{rad} = 178.45° \times \frac{\pi}{180} \approx 3.115\ rad$

4. $A_{p,rad} = 180° \times \frac{\pi}{180} \approx 3.1416\ rad$

We put these values in the Formula (1) Above.

$$\theta_i = arccos[sin0.801 \times sin0.5236 + cos0.801 \times cos0.5236 \times cos(3.115 - 3.1416)]$$

$$\theta_i = arccos[0.718 \times 0.5 + 0.695 \times 0.866 \times 1] = 0.28\, rad$$

$$\theta_i = 0.28 rad \times \frac{180}{\pi} \approx 16°$$

In this sequence, we calculate at the remaining angles of incidence (Table 2).

Table 1. *Angles of descent for specific times*

Time	Solar azimuth A (°)	Solar altitude h (°)	Angle of incidence θ_i (°)
08:00	105.67	14.75	69.30
09:30	123.95	29.57	48.13
11:00	147.95	41.07	28.13
12:30	178.45	45.88	15.93
14:00	209.37	41.92	26.41
15:30	233.97	31.03	46.03
17:00	252.77	16.42	67.21

After determining the angle of incidence, we retrieved output power data for March 18 from the SOLARMAN Smart server. To access the data, we logged into the SOLARMAN Smart platform, selected the appropriate inverter by clicking the “Device” button on the main page, and navigated to the “Historical Data” section to choose the specific date and download the corresponding information. Below is a graph showing the time-dependent output power on March 18 (Figure 3; Table 3).

Figure 3. *Data received from SOLARMAN Smart server at 12:30 PM*

Table 3. *Data table from SOLARMAN Smart server*

Time	Angle of incidence θ_i (°)	Output power (kW)
08:00	69.30	1.38
09:30	48.13	11.24
11:00	28.13	22.26
12:30	15.93	24.20
14:00	26.41	22.31
15:30	46.03	16.83
17:00	67.21	5.78

Using the data of this Tab.3., we plot the relationship between the angle of incidence and the output power (Figure 4).

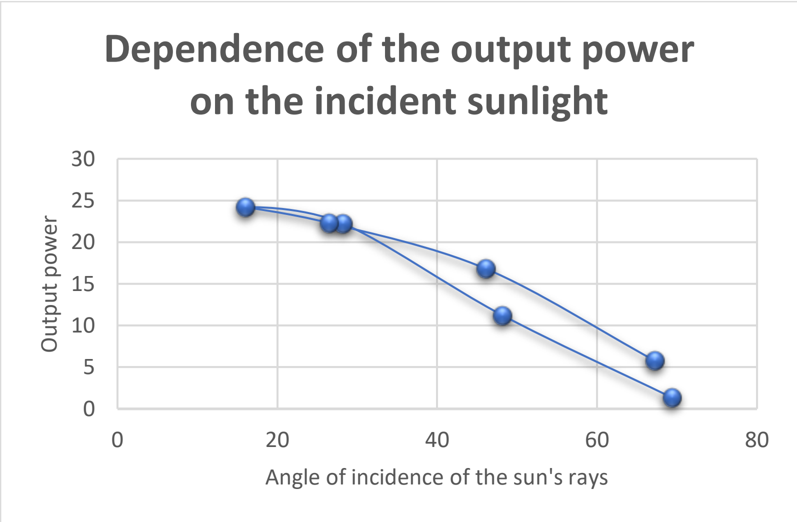

Figure 4. *Dependence of the output power on the incident sunlight*

From the graph, a regression relationship between the angle of incidence and the panel's output power can be observed—namely, as the angle of incidence decreases, the output power increases.

Optimal installation angles for solar panels, specifically tilt and azimuth angles, are critically important for maximizing solar energy collection and power output. The tilt angle refers to the inclination of the photovoltaic (PV) panel relative to the horizontal surface, while the azimuth angle indicates the panel's orientation with respect to true north.

For example, the optimal tilt angle varies depending on latitude and climatic conditions. In regions with distinct seasonal weather patterns, such as those with rainy periods, different tilt adjustments may be required compared to areas with dry climates [11]. Similarly, predictive regression models based on local conditions can help determine the most efficient tilt angles for maximizing solar energy collection [12]. These findings highlight the crucial role of empirical models and simulations in identifying optimal panel orientations.

4. CONCLUSION

The results of this study clearly demonstrate a strong correlation between the output power of solar panels and the angle of incidence of solar radiation on the panel surface. By comparing the incidence angles calculated using the astronomical-geometric method with actual power values obtained from the SOLARMAN Smart system, it was confirmed that as the angle of incidence decreases, the output power of the panel increases. This finding underscores the importance of selecting appropriate angular parameters—tilt and azimuth—during the installation of solar panels.

It was also found that the most efficient angles of incidence correspond to moments when sunlight strikes the panel nearly perpendicularly, whereas larger incidence angles (when sunlight is more oblique) significantly reduce power output. A high level of agreement between experimental data and theoretical calculations reinforces the reliability of the applied model.

The methods employed in this study—astronomical-geometric calculations, empirical observation, and comparative analysis—enabled a comprehensive examination of the geometric and climatic factors influencing solar panel performance.

The outcomes of this research offer practical value for designing solar power plants adapted to Kazakhstan's climatic conditions, optimizing panel orientation, and improving energy efficiency by accounting for solar irradiance directionality. In the future, expanding such studies to include seasonal dynamics and comparisons with tracking systems may further unlock the potential of solar energy.

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AUTHOR CONTRIBUTIONS

Conceptualization, N.Zh. and S.R.; methodology, N.G.; fieldwork, N.Zh.; software, N.Zh.; title, S.R., N.Zh., and N.G.; validation, S.R., N.G., and N.Zh.; laboratory work, N.Zh., S.R.; formal analysis, N.Zh.; research, N.Zh.; manuscript-original draft, N.Zh.; manuscript-review and editing, S.R.; visualization, N.Zh.; supervision, S.R.; project management, S.R.; All authors have read and legally accepted the final version of the article published in the journal.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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