EVALUATION OF THE EFFICIENCY OF SOLAR PANELS DEPENDING ON THE ANGLE OF INCIDENCE OF SUNLIGHT

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Abstract
The study examines the efficiency of solar panels depending on the angle of incidence of solar radiation, with an emphasis on practical applications in agrivoltaic systems. A special experimental setup was developed using a bifacial monocrystalline photovoltaic module with a nominal power of 435 W, which was tested under controlled illumination. The experiment involved systematic variation of vertical and horizontal incidence angles within a range from 0 to 90 degrees in 30-degree increments. Maximum power point parameters were recorded using a specialized measuring device, and statistical analysis confirmed a significant relationship between relative power and both angles. The maximum value of 100% was recorded at a horizontal angle of 90 degrees and a vertical angle of more than 80 degrees, while at angles below 20 degrees the relative power decreased to 32–47%, making panel operation energetically inefficient. The results indicate high angular sensitivity of bifacial modules and emphasize the importance of considering incidence angles to maximize energy yield and land-use efficiency in agrivoltaic systems.

Key words: *solar panels, incidence angle, efficiency, bifacial modules, agrivoltaics, regression analysis.*

INTRODUCTION

The use of photovoltaics (solar panels) in agricultural production is considered both relevant and promising (*Singla et al., 2024; Barron Gafford et al., 2019; Pascaris et al., 2021*) and is commonly referred to as agrivoltaic systems. One of the ways to implement solar panels in agriculture is to install them on elevated structures above crop fields (*Pascaris et al., 2021; Soto Gómez et al., 2024; Bruhwyler et al., 2023*). Such use of solar panels enables dual land use, combining electricity generation with crop production. It also protects crops from heat stress during periods of extreme temperatures. Shading from solar panels slows soil drying, which is especially important in arid regions. However, this configuration complicates the operation of agricultural machinery, particularly tractors and harvesters. Moreover, these systems require stronger supporting structures, which significantly increases their cost. Yield reductions are also possible for light-demanding crops. Therefore, solar panels installed above fields are suitable for crops tolerant to partial shading and for regions with high solar irradiance and water scarcity. They contribute to improved land-use efficiency and higher farm revenues but demand significant investment and careful adaptation of agronomic practices. Another promising approach is the vertical installation of solar panels (*Pascaris et al., 2021; Dupraz, 2024; Badran & Dhimish, 2024*). This solution is particularly convenient in agriculture, as vertical panel rows do not interfere with the movement of tractors and harvesters. Such systems are easier to integrate with conventional farming operations compared to elevated structures. Vertically oriented panels accumulate less dust, dirt, and snow. They also perform efficiently in winter and during morning or evening hours, when energy demand is often highest. Additionally, they help reduce wind erosion of soils by acting as windbreaks and can serve as farm fencing. However, these advantages are accompanied by certain drawbacks. Peak power generation is shifted to morning and evening hours, while output at midday is lower than with conventional tilted installations. Moreover, not all types of solar panels are equally suitable for vertical orientation in agrivoltaic systems. Vertical agrivoltaics therefore represent a compromise between energy efficiency and agricultural convenience. They are especially applicable in areas with land scarcity, livestock farms and pastures, crops tolerant to partial shading, and regions with high winds. Research conducted over a one-year period showed that vertical installation of bifacial solar panels can achieve higher energy efficiency compared to traditional monofacial configurations, although this advantage applies mainly to modules with heterojunction technology (*Badran & Dhimish, 2024*). Another study compared vertical bifacial panels with single-axis trackers and found that vertical systems provided more uniform ground illumination, promoting stable crop growth, and achieved higher energy performance with lower maintenance requirements (*Willockx, Lavaert & Cappelle, 2023*). It has also been noted that certain types of solar panels installed in portrait (vertical) orientation experience morning and evening shading that cannot be fully compensated by bypass diodes, causing the upper and lower halves of the modules to operate at different current levels, which may accelerate degradation (*Rucker & Birnie, 2023*). Comparative analysis of various vertically oriented modules revealed that their energy yield may vary significantly, ranging from 7% to 22% depending on panel type (*Badran & Dhimish, 2024*). These findings demonstrate that vertical solar panels can provide substantial energy yield gains, particularly under low-irradiance conditions, while offering practical advantages in agriculture. However, the creation of effective agrivoltaic systems with vertically mounted panels requires comparative evaluation of the most suitable technologies. It is also essential to assess panel efficiency with respect to the angle of incidence of solar radiation (*Golub et al., 2025*).

To evaluate solar panel performance, researchers typically apply numerical modeling (*Sharma, 2019*), conduct long-term monitoring (*Kissell, 2021*), or employ other advanced methods. In this study, we propose a dedicated experimental methodology for assessing solar panel efficiency depending on the angle of incidence of sunlight. The objective of this study was to validate a simplified methodology for assessing the performance of solar panels as a function of the angle of incidence of solar radiation and to identify the optimal operating conditions for a specific type of photovoltaic module in agrivoltaic systems.

MATERIALS AND METHODS

To evaluate the effect of the angles of incidence of sunlight on the efficiency of photovoltaic panels, a specially designed experimental setup was used (Fig. 1).

The setup consisted of a frame structure on which the photovoltaic module was mounted. For the experiment, a bifacial monocrystalline photovoltaic module Runergy HY-DH108N8-435 (Jiangsu Runergy New Energy Technology Co., Ltd., China) was used. The module consisted of 108 half-cut n-type cells in a glass–glass configuration (Fire Class A, Safety Class II) and had a nominal power of 435 W at a maximum voltage of 33.0 *V* and current of 13.2 *A*. The rear side provided an additional 9–12% of power. The dimensions of the module were 1727 × 1134 × 30 *mm*, with a weight of 24 *kg*. As the control light source, five identical portable halogen floodlights (Ninghai Senrun Electronics, China) were used, each designed for 230 *V*, 50 *Hz* supply, with IP44 protection class and a lamp rating up to 400 *W*. All fixtures were equipped with BELLIGHT R7s linear halogen lamps (300 *W*, 118 *mm*, 5200 *lm*), providing a total luminous flux of about 26,000 *lm* and ensuring uniform optical loading for photometric comparison.

The electrical parameters of the module were recorded using a portable Solar MPPT Meter UNI-T UT673 PV (Uni-Trend Technology Co., Ltd., Shenzhen, China), a handheld device that automatically performed sweep-tests of the current–voltage curve and determined the maximum power point (Fig. 2). During the experiment, the vertical angle of incidence was varied from 0 to 90°, and the horizontal angle from 0 to 90° , both in 30° increments. The efficiency of the photovoltaic module was evaluated based on relative electric power, expressed as a percentage of the maximum. At least three power measurements were taken for each angle combination. To express the analytical relationship between the incidence angles of light and the power output of the panel, a second-order regression equation was used:

$$N = b_1 + b_2\alpha + b_3\beta + b_4\alpha^2 + b_5\beta^2 + b_8\alpha\beta , \quad (1)$$

where N – power (% of maximum), α – vertical incidence angle (°), β – horizontal incidence angle (°), b_i – equation coefficients.

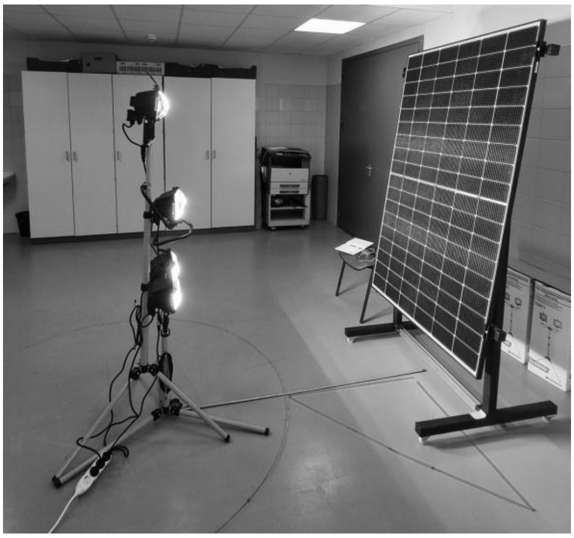

Fig. 1. Experimental setup for studying the efficiency of solar panels depending on the angle of incidence of sunlight

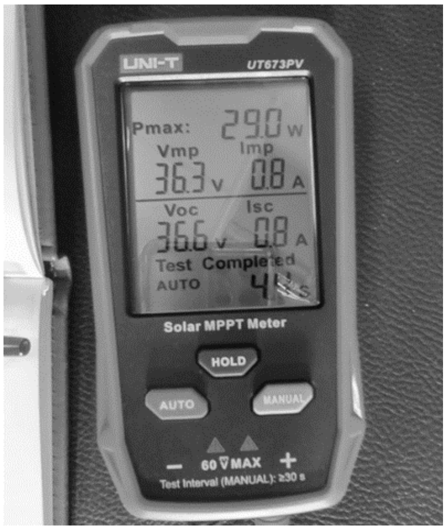

Fig. 2. UT673PV solar MPPT meter

The second-order regression equation was selected because it adequately captures the interaction between independent parameters and their influence on the dependent variable (*Kissell, 2021*). Further analysis of coefficients was performed to identify statistically insignificant terms and simplify the equation. The coefficients were determined using the least squares method (*Kong, Siauw & Bayen, 2021*). The adequacy and statistical significance of the regression equation and its coefficients were assessed using F- and t-tests. For this purpose, the calculated values of the Fisher F-test and Student's t-test were compared with tabulated values. The corresponding statistical calculations were performed in Microsoft Excel using the Data Analysis package (*Romeo, 2020*).

RESULTS AND DISCUSSION

The efficiency values of the tested photovoltaic module at different incidence angles of light are presented in Table 1.

Tab. 1 Dependence of module power output on incidence angles of light

N	Vertical angle α°	Horizontal angle β°	Average absolute power N_a, W	Relative power N, %
1	90	90	31.76	100.00
2	60	90	28.78	90.62
3	30	90	23.56	74.18
4	0	90	3.3	10.39
5	90	60	30	94.46
6	60	60	26.42	83.19
7	30	60	21.1	66.44
8	0	60	3.32	10.45
9	90	30	16.12	50.76
10	60	30	12.38	38.98
11	30	30	10.18	32.05
12	0	30	3.32	10.45
13	90	0	3.3	10.40
14	60	0	3.3	10.39
15	30	0	3.3	10.39
16	0	0	3.3	10.38

Based on the data in Table 1, the coefficients of the regression equation describing the influence of incidence angles on the relative power of the Runergy HY-DH108N8-435 module were determined using the least squares method.

$$N = 0.751\alpha + 0.625\beta - 0.008\alpha^2 - 0.005\beta^2 + 0.011\alpha\beta\ . \qquad (2)$$

According to the obtained regression model, a response surface was plotted to characterize the effect of incidence angles on the efficiency (power output) of the panel (Fig. 3,4). Analysis of the regression equation and graphs shows that at a horizontal angle of 90°, power increases almost linearly with vertical angle and reaches its maximum at about 80°. For incidence angles below 20°, relative power drops sharply: 47% for β = 90°, 44% for β = 60°, and 32% for β = 30°. When both angles are below 30°, operation of the panel is inefficient.

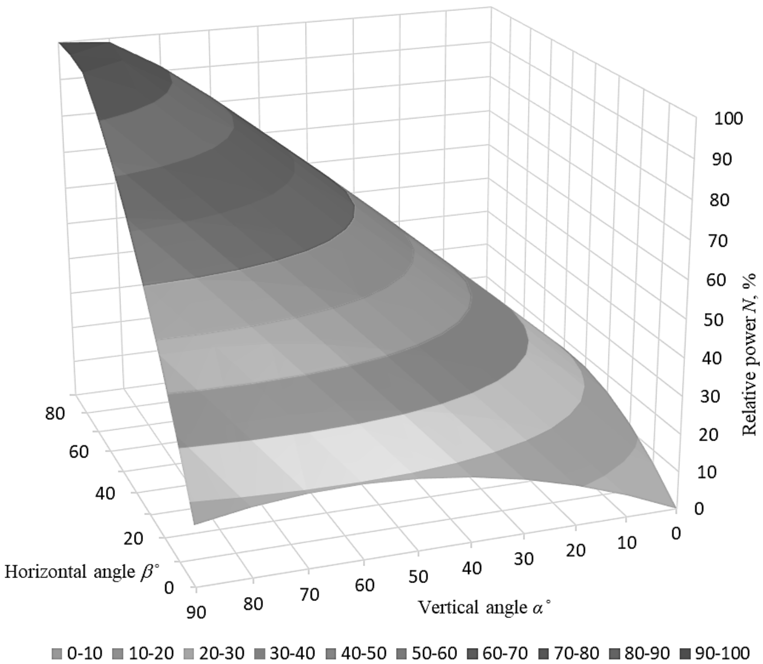

Fig. 3. Effect of incidence angles on panel efficiency: N – relative power (% of maximum), vertical incidence angle (degrees), horizontal incidence angle (degrees)

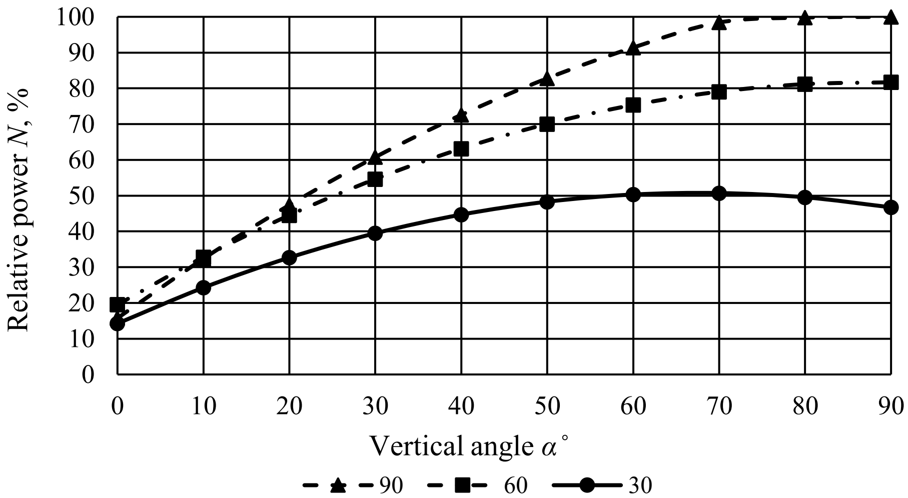

Fig. 4. Effect of vertical incidence angle on panel power for three values of horizontal angle β° (30°, 60°, and 90°).

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These findings are consistent with international studies of vertical and agrivoltaic systems. For example, (Rucker & Birnie, 2023) demonstrated that vertically oriented bifacial panels exhibit strong sensitivity to incidence angles but can achieve high efficiency when properly positioned. Bruhwyler et al. (2023) showed that East–West orientation in vertical agrivoltaic systems enables more uniform daily power generation. Similarly (Willockx et al., 2023) highlighted that vertical and tracker-based systems have complementary advantages: vertical designs are more suitable for integration with agriculture, while trackers maximize generation through dynamic angle adjustment. Badran and Dhimish (2024) confirmed that vertically mounted bifacial modules provide competitive efficiency even in northern latitudes with low irradiance, supporting our conclusions about their applicability in Northern Europe. Dupraz (2024) also emphasized the importance of selecting the correct tilt and orientation in agrivoltaics, as the "angle–power" relationship directly affects both electricity generation and crop productivity. The practical significance of our findings lies in identifying optimal conditions for PV operation in regions with moderate irradiance. The revealed dependencies make it possible to develop recommendations for positioning panels in stationary and vertical agrivoltaic systems. However, some limitations of this study should be noted: the experiment used halogen lamps, whose spectral composition differs from natural solar radiation. This calls for further research under real insolation conditions, including seasonal monitoring of PV performance.

CONCLUSIONS

A special setup was designed and built to measure the efficiency of a solar panel under different incidence angles of sunlight. A bifacial monocrystalline photovoltaic module with a nominal power of 435 *W* was tested using halogen lamps. The main parameter for evaluating efficiency was the relative power output as a function of vertical and horizontal incidence angles (0–90°). A second-order regression equation was used to establish the relationship between incidence angles and power, enabling evaluation of their combined effect on efficiency. The experiment produced data on relative power at different angle combinations. The analysis revealed several key findings: At a horizontal angle of 90°, panel efficiency increases almost linearly and peaks at a vertical angle of about 80°. At vertical angles below 20°, relative power decreases sharply: 47% for 90°, 44% for 60°, and 32% for 30°. When both angles are below 30°, the efficiency of panel use is minimal and not energetically justified. These results allow identifying the most efficient conditions for PV operation, which is important for their large-scale application in agro-energy and other sectors. Future research should expand the analysis by incorporating weather factors, soil surface reflectivity, and integration with energy storage systems. This would enable the creation of comprehensive models that combine experimental and theoretical data and are directly applicable to agricultural production and energy communities.

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