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DEVELOPMENT OF A RESEARCH-TRAINING STAND AND INVESTIGATION OF THE RELATIONSHIP BETWEEN THE OUTPUT POWER OF A SOLAR PANEL AND LIGHT INTENSITY

ОҚУ-ЗЕРТТЕУ СТЕНДІН ӘЗІРЛЕУ ЖӘНЕ КҮН ПАНЕЛІНІҢ ШЫҒЫС ҚУАТЫ МЕН ЖАРЫҚ ИНТЕНСИВТІЛІГІ АРАСЫНДАҒЫ БАЙЛАНЫСТЫ ЗЕРТТЕУ

РАЗРАБОТКА УЧЕБНО-ИССЛЕДОВАТЕЛЬСКОГО СТЕНДА И ИССЛЕДОВАНИЕ ВЗАИМОСВЯЗИ МЕЖДУ ВЫХОДНОЙ МОЩНОСТЬЮ СОЛНЕЧНОЙ ПАНЕЛИ И ИНТЕНСИВНОСТЬЮ СВЕТА

Abstract. *In the 21st century, the global energy system has been moving towards renewable energy sources. Solar energy, as an environmentally friendly and inexhaustible resource, is becoming a strategic source of electricity production. The efficiency and performance of solar panels are determined by their dependence on external factors, especially the intensity of incident light and the panel's tilt angle. Therefore, studying the relationship between the output power of a solar panel and light intensity is a relevant scientific direction for optimizing solar energy systems, reducing costs, and increasing efficiency. By developing a special educational and experimental stand, the dependence of the solar panel's output power on light intensity was experimentally investigated; the panel's current-voltage (IV) characteristic was plotted, and the fill factor and efficiency indicators were determined. The research was carried out using a research-training stand consisting of a photovoltaic panel, a control panel, projectors, variable loads, voltage/current sensors, and a lux meter. During the experiment, the light intensity was gradually varied, and the panel parameters Voc, Isc, Vmax, and Imax were measured. Based on the obtained data, the fill factor (Fill Factor) and the efficiency coefficient were calculated. The experimental results showed that the output power of the solar panel is approximately directly proportional to the light intensity. The short-circuit current increased linearly with increasing illumination, while the open-circuit voltage changed only slightly. The IV curves at different light levels and the calculated fill factors corresponded to the operating patterns of the photovoltaic panel. In addition, it was observed that the effect of the panel's tilt angle on power complies with the cosine law. The obtained results can serve as a basis for improving the efficiency of solar panels, ensuring their reliable operation under various conditions, and developing new engineering solutions.*

Keywords: *solar panel; photovoltaic system; light intensity; output power; current-voltage (IV) characteristic; fill factor (Fill Factor); efficiency coefficient; educational and experimental stand.*

Аңдатпа. *XXI ғасырда жаһандық энергетика жүйесі жаңартылатын энергия көздеріне көшуге бет бұрды. Күн энергиясы экологиялық таза әрі сарқылмайтын ресурс ретінде электр энергиясын өндірудің стратегиялық көзіне айналып келеді. Күн панельдерінің тиімділігі мен жұмыс өнімділігі олардың сыртқы факторларға, әсіресе түсетін жарық қарқындылығы мен панельдің орналасу бұрышына тәуелділігімен анықталады. Сондықтан күн панелінің шығыс қуаты мен жарық интенсивтілігі арасындағы байланысты зерттеу – күн энергетикасы жүйелерін оңтайландыру, шығындарды азайту және тиімділікті арттыру үшін өзекті ғылыми бағыт болып табылады. Арнайы оқу-тәжірибелік стенд әзірлеу арқылы күн панелінің шығыс қуаты мен жарық қарқындылығы арасындағы тәуелділікті тәжірибелік тұрғыдан зерттеу, панельдің ток-кернеу (IV) сипаттамасын тұрғызып, толтыру коэффициентін және тиімділік көрсеткіштерін анықтау. Зерттеу жұмысы фотоэлектрлік панель, басқару панелі, прожекторлар, айнымалы жүктемелер, кернеу/ток датчиктері және люксометрден тұратын оқу-зерттеу стенді арқылы жүргізілді. Эксперимент барысында жарық қарқындылығы кезең-кезеңімен өзгертіліп, панельдің Voc, Isc, Vmax және Imax параметрлері өлшенді. Алынған деректер негізінде толтыру коэффициенті (Fill Factor) мен тиімділік коэффициенті есептелді.*

Эксперимент нәтижелері күн панелінің шығыс қуаты жарық қарқындылығына шамамен тікелей пропорционал екенін көрсетті. Қысқа тұйықталу тогы жарық артқан сайын сызықты өсіп, ашық тізбектегі кернеу аз ғана өзгерді. Әртүрлі жарық деңгейіндегі IV қисықтар мен есептелген толтыру коэффициенттері фотоэлектрлік панельдің жұмыс істеу заңдылықтарына сәйкес келді. Сонымен қатар панельдің орналасу бұрышының қуатқа әсері косинустық заңға сай екендігі байқалды. Алынған нәтижелер күн панельдерінің тиімділігін арттыруға, олардың әртүрлі жағдайда сенімді жұмысын қамтамасыз етуге және жаңа инженерлік шешімдер әзірлеуге негіз бола алады.

Негізгі сөздер: *күн панелі; фотоэлектрлік жүйе; жарық қарқындылығы; шығыс қуаты; ток-кернеу (IV) сипаттамасы; толтыру коэффициенті (Fill Factor); тиімділік коэффициенті; оқу-тәжірибелік стенд;*

Аннотация. *В XXI веке мировая энергетическая система направлена на переход к возобновляемым источникам энергии. Солнечная энергия, как экологически чистый и неисчерпаемый ресурс, становится стратегическим источником производства электрической энергии. Эффективность и производительность солнечных панелей определяются их зависимостью от внешних факторов, особенно от интенсивности падающего света и угла установки панели. Поэтому исследование взаимосвязи между выходной мощностью солнечной панели и интенсивностью света является актуальным научным направлением для оптимизации солнечных энергетических систем, снижения затрат и повышения эффективности. Путём разработки специального учебно-практического стенда проведено экспериментальное исследование зависимости выходной мощности солнечной панели от интенсивности света, построена токово-вольтная (IV) характеристика панели, а также определены коэффициент заполнения и показатели эффективности. Исследование проводилось с использованием учебно-исследовательского стенда, состоящего из фотоэлектрической панели, управляющего блока, прожекторов, переменных нагрузок, датчиков напряжения/тока и люксометра. В ходе эксперимента интенсивность света изменялась поэтапно, измерялись параметры панели Voc, Isc, Vmax и Imax. На основании полученных данных были рассчитаны коэффициент заполнения (Fill Factor) и коэффициент эффективности. Результаты эксперимента показали, что выходная мощность солнечной панели приблизительно прямо пропорциональна интенсивности света. Ток короткого замыкания линейно возрастал с увеличением освещённости, а напряжение холостого хода изменялось незначительно. IV-кривые при различных уровнях освещённости и рассчитанные коэффициенты заполнения соответствовали закономерностям работы фотоэлектрической панели. Кроме того, было выявлено, что влияние угла установки панели на мощность соответствует косинусному закону. Полученные результаты могут стать основой для повышения эффективности солнечных панелей, обеспечения их надёжной работы в различных условиях и разработки новых инженерных решений.*

Ключевые слова: *солнечная панель; фотоэлектрическая система; интенсивность света; выходная мощность; токово-вольтная (IV) характеристика; коэффициент заполнения (Fill Factor); коэффициент эффективности; учебно-практический стенд.*

Introduction

The main trend of the global energy system in the 21st century is the transition from traditional fossil fuel sources to renewable and clean energy sources. This process is directly related to climate change, the increase in greenhouse gas emissions, and the urgency of energy security [1], [2]. In particular, solar photovoltaic systems are widely used as an affordable and environmentally friendly source of electricity generation. Solar energy, as an inexhaustible, stable, and globally accessible resource, holds strategic economic and technological significance [3], [4].

The efficiency and overall performance of photovoltaic (PV) modules are closely linked to external environmental factors, including solar irradiance, ambient temperature, and wind effects [5], [6]. Changes in light intensity significantly affect key electrical parameters of photovoltaic cells, such as short-circuit current, open-circuit voltage, fill factor, and efficiency [7], [8]. Therefore, studying the relationship between the output power of solar panels and light intensity is at the core of scientific research aimed at improving operational efficiency, reducing system losses, and stabilizing energy production [9], [10].

At present, the modeling of photovoltaic systems and the prediction of their performance are increasingly utilizing dynamic physical models, advanced mathematical methods, and artificial intelligence tools (machine learning, deep learning) [11], [12]. These methods enable the assessment of solar panels' real-time performance in different climatic regions, the monitoring of system health, and the early detection of faults [13]. Moreover, studying the relationship between the output power of solar panels and light intensity with high precision through research-training stands allows for comparative analysis of the collected data and integration into system models [14], [15].

The pedagogical significance of developing a research-training stand is also substantial. Such a stand provides future specialists with hands-on experience in the field of solar energy, enables them to learn how to use actual measuring instruments, understand the fundamental laws of energy production, and acquire research methods [16]. Using the stand, the influence of light intensity, panel tilt angles, temperature, and wind effects on the operation of PV modules can be comprehensively studied, thereby developing students' practical skills and research culture [17]. This approach fosters not only engineering skills but also modern scientific competencies such as data collection, processing, analysis, and modeling [18].

Overall, the results obtained from research-training stands form the basis for improving the efficiency of solar panels, ensuring their reliable operation under various conditions, and proposing new technological solutions. This line of research will contribute in the future to the widespread use of photovoltaic systems, strengthening national energy independence, and advancing sustainable development [19], [20].

Methods

During the research, an extensive review of scientific literature related to the development of an educational and experimental stand for studying the relationship between the output power of a solar panel and light intensity was conducted. At this stage, the main terms and keywords relevant to the research topic were identified. The key keywords defined were: “solar panel”; “photovoltaic system”; “light intensity”; “output power”; “current-voltage (IV) characteristic”; “fill factor (Fill Factor)”; “efficiency coefficient”; “educational and experimental stand.”

In the process of searching and selecting literature, international and national scientific databases (Scopus, Web of Science, Google Scholar, etc.) were used. Recently published scientific articles were reviewed, highlighting the importance of experimental stands for improving the efficiency of photovoltaic systems. This analysis provided the basis for selecting experimental approaches, measuring instruments, and calculation methods to evaluate the performance of solar panels.

This study was carried out in an experimental format and was based on a specially designed research-training stand. The stand included a photovoltaic panel, a control panel (voltmeter, ammeter, and switches), light sources (projectors with adjustable intensity), a lux meter, and variable loads. Such an integrated setup made it possible to measure the electrical parameters of the solar panel under different light intensity conditions.

The experimental measurements were carried out in the following stages:

- Preparation and connection of equipment: Mounting the solar panel on the stand's rotation plane and activating the measuring instruments on the control panel.
- Adjustment of light intensity: Using the dimmer of the projectors to set various light levels and measuring them precisely with a lux meter.
- Measurement of main parameters: At each light level, determining the open-circuit voltage (Voc), short-circuit current (Isc), voltage at maximum power point (Vmax), and current at maximum power point (Imax) of the solar panel.
- Data recording and processing: Entering the measured values into a table and plotting the IV (current-voltage) characteristic using Vernier Graphical Analysis or GlobiLab applications.
- Calculation: Using the obtained Voc, Isc, Vmax, and Imax values to compute the fill factor (Fill Factor) and efficiency coefficient, analyzing their dynamics depending on changes in light intensity.

This methodology allows for a comprehensive assessment of the photovoltaic panel's performance under different lighting conditions, comparing its electrical parameters and identifying experimental patterns. In addition, the stand's rotation plane is used to study the effect of the panel's tilt angle on power, enabling the collection of additional data by changing the angle of incident sunlight.

Results and discussion

Solar panels are photovoltaic devices that directly convert the energy of sunlight into electrical energy. Their operation is based on the photovoltaic effect: when sunlight strikes the semiconductor surface of the panel, photoelectrons are released, generating an electric current. The electrical power produced by the panel depends on the intensity of the incoming radiation, as well as on the panel's efficiency, area, temperature, and internal electrical parameters.

A simple relationship is used to calculate the total output power of the photovoltaic panel (1):

$$P_{out} = \eta A E \qquad (1)$$

Where P_{out} is the electrical power generated by the panel (W), η is the efficiency coefficient, A is the panel area (m²), and E is the light intensity incident on the panel surface (W/m²). This formula shows that the power output of a solar panel is approximately directly proportional to the intensity of the radiation.

To characterize the actual electrical parameters of the panel, the voltage V_{mp} and current I_{mp} at the maximum power point are used. Their product gives the panel's maximum power (2):

$$P_{out} = V_{mp} \times I_{mp} \qquad (2)$$

As the light intensity increases, the number of photoelectrons rises, and consequently the current in the panel increases. This relationship is approximately linear in nature (3).

$$I_{ph} \infty E \qquad (3)$$

That is, the current is directly proportional to the intensity of the incident radiation. The voltage, however, mostly depends on temperature and changes only slightly with variations in light.

The complete description of the photovoltaic cell is given by the following equation (4):

$$I = I_{ph} - I_0 \left(e^{\frac{q(V+IR_S)}{nkT}} - 1\right) - \frac{V+IR_S}{R_{sh}} \qquad (4)$$

Where I_{ph} is the photocurrent (directly proportional to the irradiance), I_0 is the saturation current, q is the electron charge, n is the ideality factor, k is the Boltzmann constant, T is the temperature, and R_s and $R_{sh}$are the internal resistances. This equation provides a complete description of the panel and clearly shows the dependence of the current on light.

As the light intensity increases, the current also increases, while the voltage changes only slightly at a constant temperature. As a result, the power also increases.

Temperature also plays an important role. As the temperature rises, the voltage of the panel decreases (5).

$$V_{mp}(T) = V_{mp}\left(T_{ref}\right) - \beta(T - T_{ref}) \qquad (5)$$

Where β is the temperature coefficient. Accordingly, even at very high light intensities, if the temperature also rises, the voltage may decrease, resulting in a slight reduction in power.

In general, the output power of a solar panel is directly proportional to the irradiance, while the current depends on light and the voltage depends on temperature. In simple form, this relationship can be expressed as follows (1):

$$P_{out} = \eta A E \quad (1)$$

These relationships are considered a fundamental physical principle in solar energy, as well as in the design and modeling of photovoltaic systems.

To experimentally study the relationship between the output power of a solar panel and light intensity, a special educational and experimental stand was developed (Figure 1). This stand makes it possible to measure the main electrical parameters of the panel (voltage, current, power) at different light intensities using either sunlight or an artificial light source.

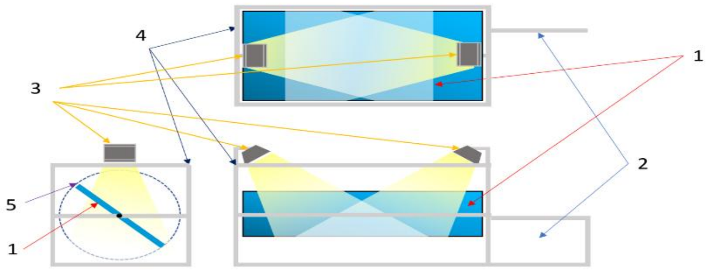

Figure 1. Diagram of the training stand. This diagram shows the layouts of the training stand (top view, side view, and front view). 1 – Solar panel; 2 – Control panel (volt-ammeter, switch, etc.); 3 – Projectors; 4 – Body of the training stand; 5 – Rotation plane of the solar panel.

This training stand is an integrated device designed to experimentally study the relationship between the output power of a solar panel and light intensity. The stand's structure includes key components such as a photovoltaic panel, a control panel, projectors, a housing, and the rotation plane of the solar panel.

The operating principle of the stand is to direct radiation of varying intensity from artificial light sources (projectors) onto the solar panel, measure its electrical parameters (voltage, current, power), and determine the relationship based on the obtained data. Through the control panel, it is possible to record the readings of the voltmeter and ammeter and use switches to connect or disconnect the electrical circuit.

Main components of the stand:

- Solar panel (1): The main module that converts light energy into electrical energy. Through the rotation plane, which allows changing the panel's tilt angle, it can receive radiation at different angles and compare the results.
- Control panel (2): A unit containing instruments for measuring voltage and current (voltmeter, ammeter), switch keys, and protective elements. This panel is designed to control the operating mode of the panel and conduct measurements.
- Projectors (3): Artificial light sources simulating sunlight. By adjusting the intensity and direction of the light, the experimental conditions can be modified.
- Stand housing (4): The frame that integrates all devices and provides stability. It is designed to maintain electrical safety and mechanical strength.
- Rotation plane of the solar panel (5): A movable part that allows changing the panel's tilt angle. This element is used to study the effect of the angle of incidence and to alter the direction of incoming light in order to obtain results.

The stand's design makes it possible to conduct various experiments by changing the light intensity and the panel's tilt angle. In this way, the solar panel's current-voltage characteristics, changes in output power, and efficiency parameters can be determined.

As a result of putting the developed educational and experimental stand into operation, the relationship between the solar panel's output power and the incident light intensity was experimentally studied.

The developed educational and experimental stand allows the experimental determination of the dependence between the solar panel's output power and the incident light intensity. The research results are expected to demonstrate the consistency with the operating principles of the photovoltaic panel.

The electrical power produced by the solar panel depends on the irradiance on its surface and the efficiency coefficient, and this can be expressed simply by the following equation (1):

$$P_{out} = \eta A E \qquad (1)$$

Where P_{out} is the electrical power generated by the panel (W), η is the efficiency coefficient, A is the panel area (m²), and E is the light intensity incident on the panel surface (W/m²).

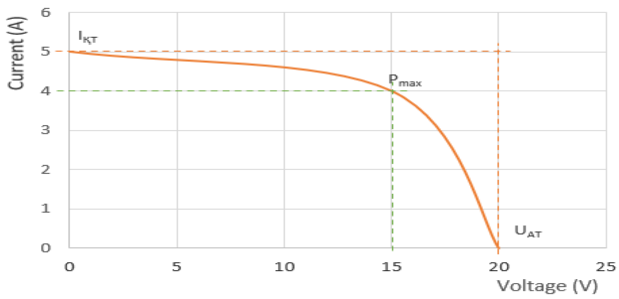

Figure 2. IV curve.

In the upcoming experiment, the panel's open-circuit voltage V_{oc}, short-circuit current I_{sc}, and the voltage and current at the maximum power point (Vmax and Imax) will be measured, and the panel's fill factor (Fill Factor) will be calculated based on these values (6).

$$FF = \frac{V_{mp} \times I_{mp}}{V_{oc} \times I_{sc}} \qquad (6)$$

Additionally, based on the obtained data, the panel's efficiency will be determined using the following expression (7):

$$\eta = \frac{P_{max}}{E * A} = \frac{FF * V_{oc} \times I_{sc}}{E * A} \qquad (7)$$

As expected, as the light intensity increases, the short-circuit current I_{sc} shows an approximately linear increase, while the open-circuit voltage V_{oc}changes only logarithmically. As a result, the power increases almost directly proportionally to the light level (8).

$$P_{max} = V_{mp} \times I_{mp} \text{ and } P_{max} \propto \mathrm{E} \qquad (8)$$

The panel's tilt angle is also expected to affect the power. When the angle of sunlight incident on the panel surface changes, the effective irradiance varies according to the cosine law (9).

$$E(\theta) = E_{\perp} \cos\theta \Longrightarrow P_{max}(\theta) \approx P_{max}(0) \cos\theta \qquad (9)$$

Based on these formulas, using the constructed stand, the panel's current-voltage characteristic will be obtained, its output power dependence on light intensity and angle of incidence will be experimentally determined, and the fill factor and efficiency parameters will also be calculated.

Procedure of the work

- Connection and setup: Connect the energy or voltage sensor to the computer and select the external load mode. Correctly connect the solar panel electrodes to the sensor and launch the graphical analysis software.
- Measuring open-circuit voltage: Fix the panel directed toward the projector and determine the Voc value in the no-load state.
- Measurements at high resistance: Connect the variable load in series and, by adjusting the knobs, record the current and voltage values.
- Measurements at low resistance: Set the load to the minimum parameter, collect additional data points, and complete the IV curve.
- Measuring short-circuit current: Disconnect the load, short the terminals with a wire, and determine the Isc value.
- Measuring illumination: Measure various light levels with a lux meter and enter the values into the data table.

This experiment aims to measure the output power of the solar panel by varying the load resistance. Such an approach makes it possible to determine the optimal load resistance for increasing the output power in experiments with solar panels.

The proposed experiment is an improved version of the procedures in previous editions of this book. The original experiment has been revised and introduced as Experiment 18B. In this version, it is possible to determine the fill factor (Fill Factor) of the solar panel by constructing its current-voltage (IV) characteristic.

The fill factor is an important indicator that makes it possible to assess the efficiency of a solar panel without separately measuring its illumination level or calculating the power produced per unit area. This factor is one of the main parameters frequently used in the field of solar energy to characterize solar cells.

It is also possible to find several alternative versions of this experiment online for various data collection software (for example, Graphical Analysis 4, Logger Pro, LabQuest). Students or users should be offered the version that corresponds to the hardware and software they are using.

Results

The load resistance at which the solar panel delivers maximum power mainly depends on the illumination intensity of the radiation incident on the solar panel and on the wavelength of the incoming light. It also depends, to some extent, on the temperature of the solar panel. For this experiment, a halogen projector attached to the stand, with brightness controlled by a dimmer, is used.

The measured value of the short-circuit current is significantly dependent on the illumination level during the measurement. At low light levels, the measured value may be considerably lower. However, even at low illumination, the open-circuit voltage and the shape of the IV curve remain similar to those obtained under higher illumination conditions.

When constructing the IV curve, very low loads—possibly as low as 1–2 ohms—are needed to obtain good results and reach low voltages. The student should connect two variable loads in parallel to reduce the total resistance.

Using a lux meter, we calculated the light intensity at four positions of the rheostat. For this, we placed four marks on the knob of the rheostat controlling the projector brightness. Then, at each mark, we covered the panel surface with cloth to prevent external light and measured the illumination. In our case, the illumination levels were 850 lm, 1390 lm, 8000 lm, and 12,200 lm.

The following results were obtained during the experiment.

Table 1. Data table

Illumination (lm)	$V_{\text{ат}}$ (B)	$I_{\text{кт}}$ (mA)	V_{max} (B)	I_{max} (mA)
850	15.721	20.013	5.16	19.9695
1390	17.745	57.221	13.508	50.928
8000	18.705	149.277	17.931	128.144
12200	19.173	189.304	18.741	186.677

Using the obtained results, it is possible to calculate the maximum power at different illumination levels. It is determined by the following formula (10):

$$P_{max} = V_{mp} \times I_{mp} \tag{10}$$

Using the results obtained, draw the current-voltage characteristic (IV curve) of the solar cell.

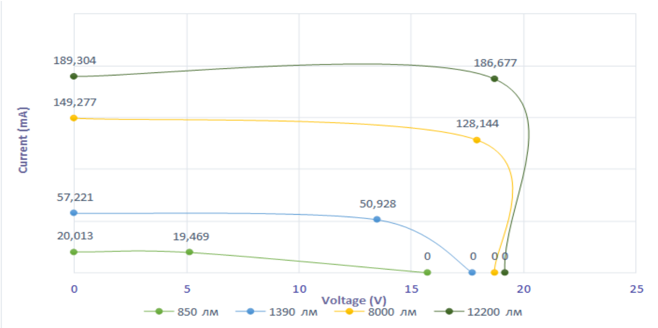

Figure 3. Data sample for the experiment

Summarizing this experiment, it can be observed that the output power of solar panels directly depends on illumination. The IV curves at four different illumination levels clearly demonstrate this dependence.

As a result of the conducted research, it was experimentally proven that the output power of the solar panel is clearly dependent on the intensity of the incident light. The developed educational and experimental stand made it possible to measure the panel's voltage and current at different light levels, to plot the IV (current-voltage) characteristic, and to determine the parameters at the maximum power point.

Based on the Voc, Isc, Vmax, and Imax values obtained during the experiment, the fill factor (FF) and the efficiency coefficient were calculated, and their dynamics under changing light intensity were analyzed. The results showed that as the light level increases, the short-circuit current grows linearly, while the open-circuit voltage changes only slightly. As a result, the output power increases almost proportionally to the light intensity.

It was also determined that the panel's tilt angle affects the power: when the angle of radiation changes, the effective irradiance varies according to the cosine law, resulting in a decrease in power. The obtained data can serve as a basis for improving the operational efficiency of solar panels, ensuring their stable performance under different conditions, and developing new engineering solutions.

The results of the conducted research demonstrated experimentally that the output power of the solar panel clearly depends on the intensity of the incident light. The IV (current-voltage) curves constructed on the basis of the obtained Voc, Isc, Vmax, and Imax parameters and the calculated fill factors (FF) correspond to the operational patterns of photovoltaic panels. These results are consistent with the latest studies in the international literature, which provide extensive evidence that the efficiency and power output of solar panels depend on the intensity, spectrum, and temperature of the irradiance.

As the light intensity increased, the short-circuit current showed an approximately linear rise, while the open-circuit voltage changed only logarithmically. This phenomenon, as noted by Hasan et al., is explained by the direct increase in the number of photoelectrons in photovoltaic cells [21]. Manowska et al. also recorded similar dependencies in monitoring systems designed to optimize solar potential, identifying parameters that enable increasing the power output of panels [22].

The experimental results confirm, as described by Jaiswal, the physical and environmental advantages of solar panels. In his work, he highlighted the fill factor as an important metric for assessing the efficiency of solar panels [23]. By comparing the obtained FF values with the standard ranges in the field of solar energy, it became possible to objectively evaluate the panel's performance under changing light levels.

Furthermore, during the study, the effect of the solar panel's tilt angle on power was observed. When the angle of sunlight incident on the panel surface changed, the effective irradiance decreased according to the cosine law, resulting in reduced output power. This phenomenon, as presented by Alqaraghuli & İbrahim, is significant for improving diagnostic and fault detection algorithms in photovoltaic systems [24].

Alsalem also emphasizes in his work that solar energy is geographically unstable and difficult to predict, highlighting the importance of such experiments [25]. Our research findings support this conclusion—measurements at different light levels enable the assessment of the panel's current-voltage characteristics and efficiency, providing an opportunity to model its real operating conditions.

In recent years, extensive research has been conducted to improve photovoltaic materials and energy storage systems. Dada & Popoola demonstrated that the use of new materials and systems in solar energy not only enhances efficiency but also expands energy storage capabilities [26]. The data obtained in our study can serve as a foundation for improving the efficiency of solar panels, predicting their long-term performance, and developing new engineering solutions.

Overall, comparing the research results with international literature clearly highlights the relevance of optimizing photovoltaic system operation, introducing new diagnostic methods, and enhancing the efficiency of solar panels in the future.

Conclusion

As a result of the conducted research, the dependence between the solar panel's output power and the intensity of the incident light was comprehensively studied experimentally. The specially developed educational and experimental stand made it possible to measure the panel's electrical parameters at different light levels, to plot its current–voltage (IV) characteristic, and to determine the indicators at the maximum power point. The modular structure of the stand allowed the experiment to be conducted flexibly, enabling multifaceted analysis by changing the load resistance, light intensity, and the panel's tilt angle.

Based on the obtained data, the open-circuit voltage (Voc), short-circuit current (Isc), and the voltage and current at the maximum power point (Vmax and Imax) were determined. Using these parameters, the panel's fill factor (Fill Factor) and efficiency coefficient were calculated. The results clearly showed that as the light intensity increases, the output power of the solar panel grows approximately linearly, while the voltage changes only slightly. This fully corresponds to the fundamental physical principles of photovoltaic cells.

The research also confirmed the effect of the panel's tilt angle on power. When the angle of incidence changed, the effective irradiance decreased according to the cosine law, and as a result, the panel's output power also decreased. These findings demonstrate the importance of correctly selecting installation strategies for solar panels and adapting them to actual conditions.

Overall, the developed educational and experimental stand is a convenient tool for the experimental evaluation of the performance of photovoltaic systems. It allows for a comprehensive analysis of the current–voltage characteristics, fill factor, efficiency parameters, and the effects of light intensity and angle of incidence on solar panels. The obtained results can serve as a basis for optimizing the operating modes of photovoltaic systems, testing new materials and technologies, and advancing scientific research and educational processes in the field of solar energy.

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