BULETINUL INSTITUTULUI POLITEHNIC DIN IAŞI
Publicat de
Universitatea Tehnică „Gheorghe Asachi” din Iași
Volumul 70 (74), Numărul 1, 2024
Secţia
CONSTRUCŢII DE MAŞINI
DOI:10.2478/bipcm-2024-0002

ASSESSMENT OF POLYCRYSTALLINE, MONOCRYSTALLINE, AND AMORPHOUS SOLAR PANELS UNDER DYNAMIC ENVIRONMENTAL CONDITIONS: PERFORMANCE INSIGHTS FOR RENEWABLE ENERGY APPLICATIONS

BY

EDUARD ENASEL* and GHEORGHE DUMITRAȘCU

“Gheorghe Asachi” Technical University of Iași,
Faculty of Mechanical Engineering, Iași, Romania

Received: June 3, 2024
Accepted for publication: August 10, 2024

Abstract. Solar photovoltaic (PV) technology is rapidly expanding as a key renewable energy source. Understanding the long-term performance of various PV technologies under real-world conditions is essential. Since Edmond Becquerel's demonstration of the photovoltaic effect in 1839, solar PV has progressed significantly. Performance is influenced by temperature, wind, irradiance, shading, and panel orientation, with elevated cell temperatures potentially decreasing performance by 8-15%. This study analyzes polycrystalline, monocrystalline, and amorphous (thin-film) PV panels' responses to changing solar irradiance and temperature using sensors monitored by microcontrollers. Preliminary findings indicate each panel type has unique performance traits: polycrystalline panels are cost-effective and stable under direct sunlight but less efficient in low-light; monocrystalline panels are highly efficient, especially in low-light, but degrade at high temperatures; and amorphous panels, though less efficient, are resilient under varying light and

*Corresponding author; *e-mail*: eduard.enasel@student.tuiasi.ro

moderate temperature changes. These insights aim to optimize solar energy generation and inform future solar panel design and deployment strategies.

Keywords: Photovoltaic, panel performance, solar energy, PV panel types, solar irradiance.

1. Introduction

The global surge in energy demand, driven by economic growth and industrialization, has led to a significant rise in CO2 emissions from fossil fuels. Despite this, there's a notable shift towards renewable energy like solar, wind, and hydro, supported by cost reductions and policy changes. International agreements such as the Paris Agreement and technological advancements have accelerated this transition.

In 2022, global CO2 emissions reached 36.8 gigatons, with a 1.1% increase in 2023 attributed to post-COVID-19 economic recovery and geopolitical factors (McKinsey, 2024). Forecasts suggest continued emissions growth until 2050 due to population growth and increased manufacturing.

However, there's hope in clean energy transitions. Projections show a peak in demand for coal, oil, and natural gas by 2030, reducing their global share to 73% by the same year (IEA, 2023). To facilitate this transition, substantial investments in clean energy systems, especially in emerging economies, are crucial for achieving sustainable, low-carbon energy futures.

Solar PV technology has become integral to the global renewable energy landscape, addressing rising energy demands while mitigating environmental impacts. The effectiveness of this technology is influenced by various factors such as temperature, solar radiation, shading, precipitation, panel orientation, geographic location and cleanliness (Green, 2012). These factors emphasize the importance of optimizing PV systems under diverse conditions. This study analyzes the performance of polycrystalline, monocrystalline and amorphous PV panels, aiming to reveal their performance under varying environmental variables. Preliminary findings highlight distinct characteristics for each panel type, guiding strategies for optimizing solar energy generation.

The need of energy produced from PV

The demand for energy is rapidly increasing due to population growth, urban expansion, economic development, industrialization, and technological advancements, all driving higher energy requirements each year.

However, this escalating demand for energy presents a critical challenge: meeting these needs in a sustainable and responsible manner. As humanity strives to manage this growing energy demand, there is a pressing need to minimize environmental impact and reduce reliance on finite and polluting resources (Hammoumi *et al.*, 2022).

Solar PV technology has emerged as a vital solution within the global renewable energy landscape. By harnessing the power of sunlight, PV panels generate clean electricity without producing harmful emissions. This renewable energy source aligns with efforts to mitigate climate change and air pollution, offering a sustainable alternative to fossil fuels.

The versatility and scalability of PV panels make them well-suited for addressing diverse energy needs. They can be deployed in various settings, from residential rooftops to large-scale solar farms, providing decentralized and accessible energy solutions. Off-grid applications of PV panels extend electricity access to remote communities, fostering economic development and improving quality of life.

Moreover, the declining cost of PV technology, driven by technological advancements and economies of scale, enhances its affordability and accessibility. As investments in clean energy systems grow, the PV industry supports job creation and economic growth, contributing to a transition towards a low-carbon economy.

2. Solar cells: the key components of PV systems

The solar cell, also known as a PV cell (Fig. 1), is responsible for converting sunlight into electricity through the photovoltaic effect.

A solar cell device features a P-N junction with a large surface area, where the N-type material is deliberately kept thin to enable light to pass through the junction. As incident sunlight strikes the solar cell, it functions as both a current and voltage source, with its output depending on the intensity of the solar irradiance (Oni *et al*., 2024).

In addition to these key characteristics, solar cells are sensitive to temperature variations, similar to other semiconductor devices. Changes in temperature can impact the efficiency and performance of solar cells, affecting their electrical output (Clean Energy Reviews). Therefore, managing temperature fluctuations is essential for optimizing the operation and longevity of solar cell-based systems (Elsabahy *et al*., 2024).

The solar cell generates an internal current corresponding to the light intensity (Office of E.E. & R.E.), but not all of this current is available to the load. Some of the current (I_D) flows through a parallel diode (D), and some flows through a parallel resistance (Rsh). When there is no load connected (open-circuit condition), the voltage at the terminals is determined by the interaction of the internal current source, the parallel diode, and the parallel resistance (Kirchartz and Rau, 2018). The presence of these components influences the open-circuit voltage. In the equivalent circuit of a solar cell (Fig. 2), it is important to note that the internal current source does not directly interact with the load. Instead, the current distribution is affected by the parallel diode and resistance, which play a role in shaping the characteristics of the solar cell's output.

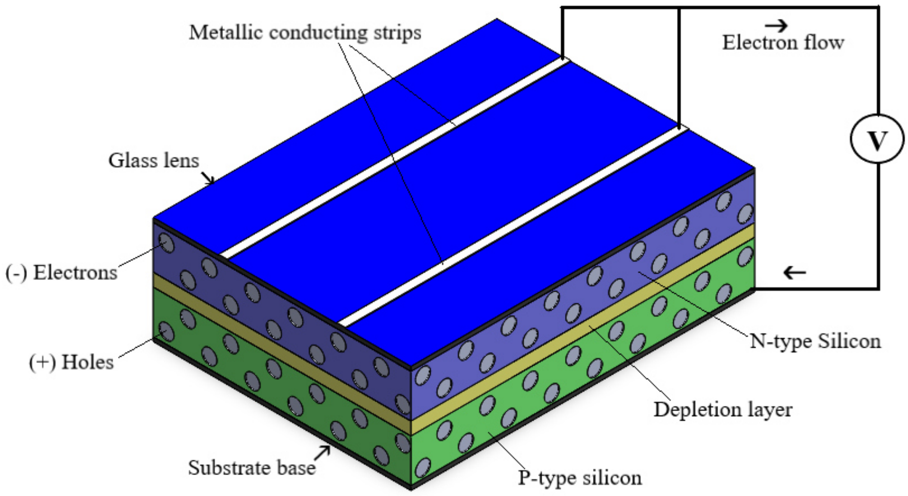

Fig. 1 – Basic diagram of photovoltaic solar cell.

The electrical performance of a solar cell can be expressed and modeled with the Shockley diode equation (Mohamed and Abd El Sattar, 2019), that describes the current-voltage (I-V) characteristics of an ideal p-n junction diode under different operating conditions.

$$I_D = I_S \left(e^{\frac{V_D}{nV_T}} - 1 \right) \tag{1}$$

The main equation for analyzing the solar cell with single-diode model is derived from the Shockley equation:

$$I = Iph - Is \left[exp\left(\frac{q(V + Rs)}{nKT} \right) - 1 \right] - \frac{V + Rs}{Rsh} \tag{2}$$

where:

I - is the output current of the solar cell;

Iph - is the photocurrent generated by the solar cell due to incident sunlight;

I_D - is the diode current;

I_S - is the reverse bias saturation current;

V_D - is the voltage across the diode;

V_T - is the the thermal voltage;

Rs - is the series resistance;
Rsh - is the shunt resistance;
n - is the ideality factor (quality factor or emission coefficient);
k - is the Boltzmann constant;
T - is the absolute temperature of the P-N junction;
q - is the elementary charge;

The Eq. (2) extends the Shockley diode equation by including terms for series resistance, shunt resistance, wich are common elements in modeling the behaviour of real-world solar cells.

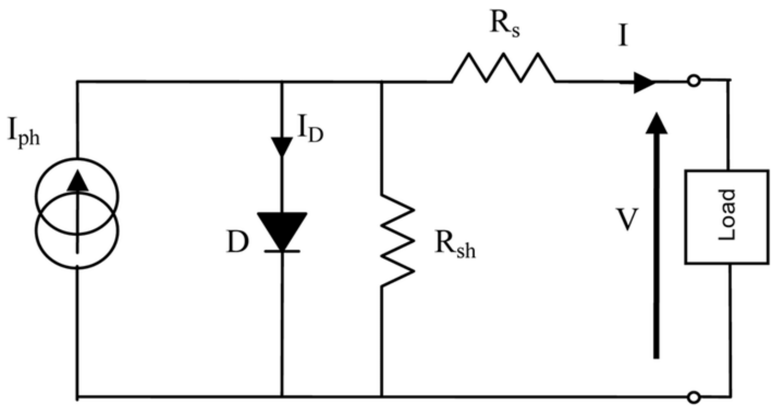

Fig. 2 – The equivalent circuit of a solar cell.

To fully understand the behaviour and performance of a solar cell, there are some additional aspects to consider:

- Isc - the short circuit current, occurs when the load resistance is reduced to 0 ohms. In this condition, the current through the solar cell reaches its maximum value, with no external resistance limiting the current flow. The voltage across the solar cell in this condition is close to 0 volts, resulting in zero power output.
- Voc - the open circuit voltage, occurs when the load resistance (R_L) aproaches infinity, creating an open circuit. In an open circuit condition, no current flows through the load (I=0) and the power output is also zero.
- MPP - maximum power point (Fig. 3), is the operating point of the solar cell where it delivers the maximum power output. The MPP occurs at a specific combination of voltage (Vmp) and current (Imp) values, corresponding to a specific load resistance (R_L). The R_L at the MPP is typically determined as R_L = Vmp/Imp.

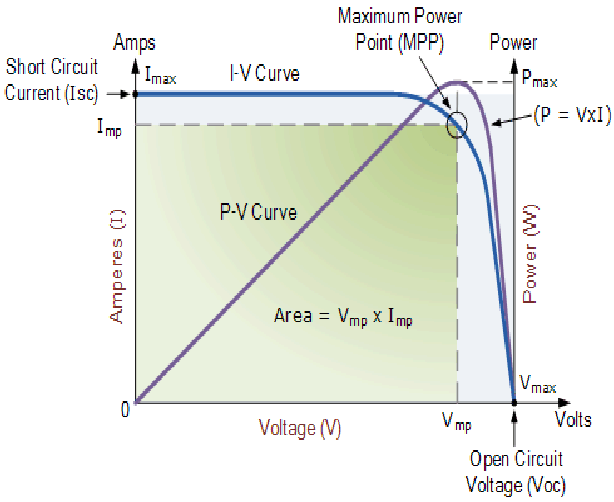

Fig. 3 – The I-V and P-V curves for a solar cell/ panel.

- FF - fill factor, a measure of how efectivelly the solar cell converts sunlight into electrical power, is an important parameter used to evaluate the performance of a solar cell (Javier *et al.*, 2023). A higher fill factor indicates better performance, as it represents less loss due to factors like series resistance, shunt resistance, and other non-ideal characteristics of the device.

$$FF = \frac{I_{mp}V_{mp}}{I_{sc}V_{oc}} \tag{3}$$

Typically, fill factors for commercial solar cells and panels range from 0.60 to 0.85. Factors that can affect the fill factor include the quality of the materials and manufacturing processes used in the solar cell or panel, as well as environmental conditions such as temperature and sunlight intensity.

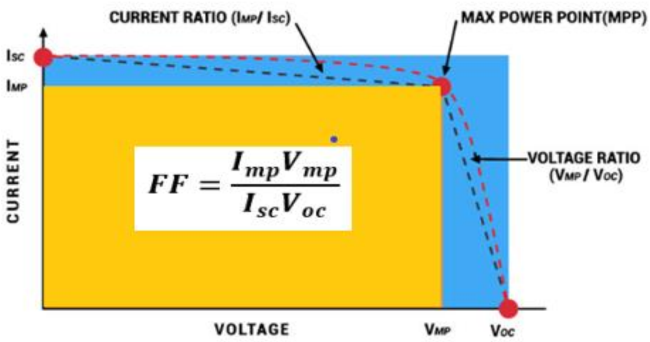

Fig. 4 – The fill factor of a solar cell.

3. Photovoltaic (PV) panels

The photovoltaic panel (PV module) consists of interconnected solar cells arranged in series and/or parallel configurations, enclosed by a glass sheet, and encased within a metal frame. Cables and circuits located behind the cells are used to gather the electric current generated by the solar cells.

In addition to dimensions, shape, and materials used in construction, solar panels have evolved based on the advancement of photovoltaic cell performance, incorporating their advanced technologies. Thus, photovoltaic panels in the industry are classified according to the type of solar cells incorporated, including:

- Monocrystalline solar panels;
- Polycrystalline solar panels;
- Thin-film solar panels.

Monocrystalline solar panels are the most efficient, with an efficiency percentage exceeding 20% (Allouhi *et al.*, 2022). Polycrystalline solar panels are a close competitor, with an efficiency ranging between 15% and 17%. Thin-film panels such as CIGS have an efficiency of 13% to 15%, CdTe thin films have an efficiency of 9% to 11%, and a-Si thin films have an efficiency of 6% to 8%.

The efficiency of the cell should not be confused with the efficiency of the panel, which is always lower due to internal spaces, panel structure, and electrical connection resistance. The cell design plays a crucial role in the efficiency of the solar panel. Key characteristics include the type of silicon used, the configuration of connection bars, the type of junction, and the PERC (passivated emitter and rear contact) feature.

In real life, under solar radiation, the absorbed heat can raise the temperature of solar cells up to 70ºC. Each degree of temperature increase above 25ºC, negatively affects the electrical conversion efficiency of the cell by approximately 0.5%.

Monocrystalline solar panels are made from a single continuous crystal structure of silicon. The manufacturing process involves growing a single crystal of high-purity silicon, which is then sliced into thin wafers to form the basis of solar cells (Chatzisideris *et al.*, 2016). Monocrystalline panels are recognized for their high efficiency and power output due to the uniformity and purity of the silicon crystal. The cells have a distinctive appearance with rounded edges and a uniform dark color.

Polycrystalline solar panels are manufactured using silicon crystals that are melted together to form the solar cell. The process involves pouring molten silicon into a mold and then allowing it to cool and solidify. This results in a panel with multiple silicon crystals of varying sizes, which gives the panel its characteristic blue speckled appearance (Williams *et al.*, 2005). Polycrystalline panels are cost-effective to produce and widely used in the solar industry. While they are slightly less efficient than monocrystalline panels, advancements in technology have narrowed the efficiency gap. Polycrystalline panels are an excellent choice for larger-scale solar installations where cost-effectiveness is a priority.

Amorphous silicon (a-Si) solar panels are thin-film solar panels that use non-crystalline silicon deposited in thin layers onto a substrate such as glass, metal, or plastic (Elibol *et al*., 2017). The manufacturing process involves depositing a-Si onto a surface using techniques like chemical vapor deposition. This results in a flexible and lightweight solar panel that can be used in various applications, including building-integrated photovoltaics and portable devices. Amorphous silicon panels have lower efficiency compared to crystalline silicon panels but offer advantages such as flexibility and lower manufacturing costs. They perform better in low-light conditions and high temperatures, making them suitable for specific environments where traditional panels may not be ideal.

Commercial thin-film solar cells encompass a range of technologies that offer unique advantages (Wijewardane *et al*., 2023). These include amorphous and nanocrystalline silicon (a-Si and nc-Si), which are flexible and lightweight; copper indium gallium diselenide (CIGS) and copper indium selenide (CIS), known for high efficiency; cadmium telluride (CdTe) and cadmium sulfide (CdS), valued for cost-effectiveness and good efficiency; gallium arsenide (GaAs), offering high efficiency; and tandem/multi-junction modules based on silicon, combining materials for improved performance in converting sunlight into electricity (Muteri *et al*., 2020). Each technology has its own strengths, making them suitable for diverse applications within the solar energy industry.

4. Experimental Setup and Instrumentation

The experimental setup presented in Fig. 5. was designed to read and store various values related to solar panels using a combination of hardware components and software. The system comprises three types of solar panels (amorphous, polycrystalline, and monocrystalline), each equipped with a voltage sensor. Additionally, PT100 temperature sensors, RTDs (resistance temperature detector), a pyranometer, a wattmeter, two microcontrollers, two data loggers with SD cards, and various circuits were incorporated into the setup. The panels and the pyranometer are mounted outside, at the same angle (30º) as the horizontal surface, on a building rooftop in Bacău, Romania.

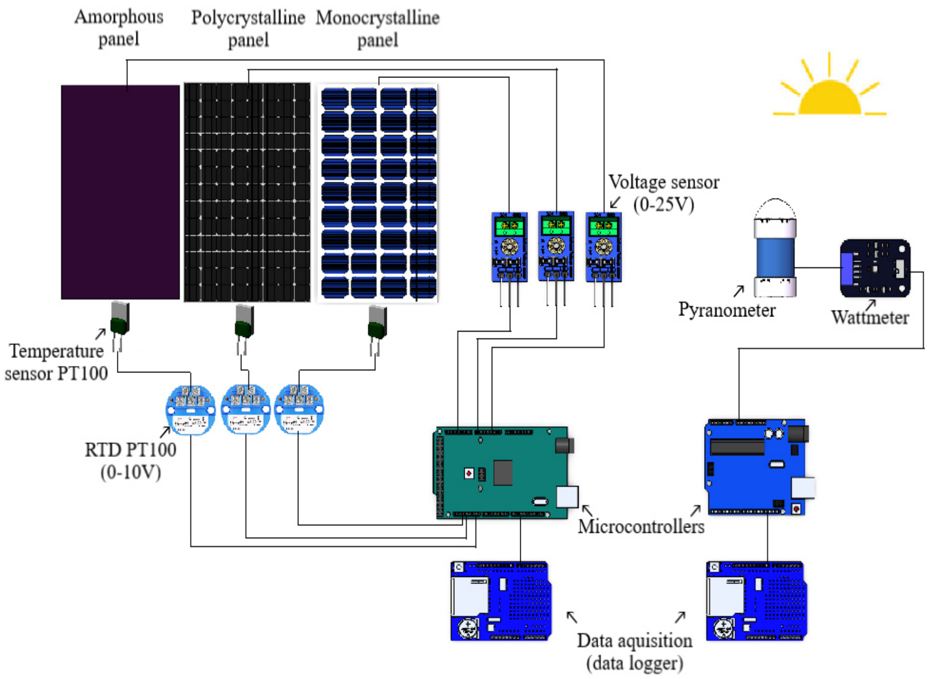

Fig. 5 – Schematic diagram of experimental setup.

4.1. Justification of research setup

The experimental setup described in Fig. 5 was designed to investigate the impact of temperature on the voltage output of different types of solar panels as well as to compare the temperature differences among these PV panels subjected to the same irradiance level. The setup includes a comprehensive array of hardware components and sensors to collect crucial data related to solar panel performance under varying environmental conditions.

Thermal effects, such as temperature-induced efficiency losses, have profound implications for the overall efficiency and power output of solar cells. Understanding these thermal dynamics is essential for developing effective strategies to optimize solar panel performance.

By utilizing PT100 temperature sensors and RTDs integrated into the setup, alongside voltage sensors on each solar panel type, the aim is to gather detailed data on the correlation between temperature variations and changes in the open-circuit voltage. The collected results will provide insights into the critical relationship between temperature and solar panel efficiency.

The findings from this study will inform strategies for managing solar panel temperature to enhance performance and maximize energy conversion efficiency. Effective cooling strategies, such as implementing cooling systems or heat sinks, can be recommended based on the research outcomes to mitigate efficiency losses caused by temperature increases.

4.2. Component explained

1. *Amorphous solar panel* - (Manufacturer: SN Solartechnics, SN-50 series, Nominal Power: 50 W, Voc: 62V, Isc: 1.42A, Vmp: 43V, Imp: 1.17A);

The term "double junction" refers to a specific type of amorphous silicon solar cell structure known as a tandem or multi-junction cell (Ray *et al*., 2002). In a double junction amorphous silicon solar cell, there are two layers of amorphous silicon with differing bandgaps stacked on top of each other. This tandem structure allows the solar cell to absorb a broader spectrum of sunlight, thereby increasing its efficiency compared to single junction amorphous silicon cells.

2. *Polycrystalline solar panel* - (Manufacturer: Solar Jianbao, SA-100 model, Nominal Power: 100W, Voc: 21V, Isc: 6.4A, Vmp: 17.6V, Imp: 5.71A);
3. *Monocrystalline solar panel* - (Manufacturer: Breckner, BK87482 model, Nominal Power: 100W, Voc: 21.1V, Isc: 5.96A, Vmp: 17.6V, Imp: 5.68A);
4. *Voltage sensors* (3 pcs) – (Supply voltage: 5V, maximum VCC input: 25V, resolution: 0.00489V, minimum detected Voltage: 0.02445V, Arduino compatible);
5. *Temperature sensors* (3 pcs) – (Manufacturer: Tewa Temperature, Model TT-PT100B-2050-11-AUNI, resistance: 100Ω, temperature coefficient: 3851ppm/°C, working temperature: -70…400˚C);
6. *Resistance temperature detector* (3 pcs) – (RTD for PT100 type, voltage supply: 24V, voltage output: 0-10V);
7. *Pyranometer* – (Manufacturer: Jiansu, Model: 485, voltage supply: 7~30V, working temperature: -25°C~60°C, measuring range: 0~2000W/m^2, resolution: 1W/m^2, accuracy: ±5%, outputs: 0-10V);
8. *Wattmeter* – (Manufacturer: Gravity, model: SEN-0291, voltage supply: 3.3V~5.5V, maximum input voltage: 26V, voltage resolution: 4mV, current range: 0 ~ ±8A, current resolution, 1mA, power range: 0 ~ 206 W);
9. *Microcontroller ATMEGA328P Arduino Uno R3*- (voltage supply: 7-12V, I/O pins: 14 of which 6 can be used as output PWM pins, analog input pins: 6, operating frequency: 16MHz);
10. *Microcontroller ATMEGA2560 Arduino* Mega *R3*- (voltage supply: 7-12V, I/O pins: 54 of which 14 can be used as output PWM pins, analog input pins: 16, operating frequency: 16MHz);
11. *Data acquisition module* (2 pcs) - (SD card interface, real time clock: RTC, works with Arduino Uno R3 and Arduino Mega R3);

4.3. The workflow of the system

The solar panels, consisting of amorphous, polycrystalline, and monocrystalline types, harness sunlight to generate electrical power. Dedicated voltage sensors are integrated with each panel to capture the key voltage parameters: Voc (open circuit voltage). These sensors return the voltage data to the Arduino Mega R3 through analog input pins, providing real-time insight into the panels' performance. Precise temperature monitoring is achieved through specialized sensors attached to each solar panel. These sensors, leveraging RTDs, gauge the panel temperatures. The RTDs convert temperature variations into 0-10V signals, which are then transmitted to the Arduino Mega R3 for analysis and logging. To quantify solar irradiance intensity, a pyranometer is deployed. This device accurately measures it and translates it into a 0-10V signal. The wattmeter, connected downstream, measures the bus voltage and communicates the calculated signal to the Arduino Uno R3 via I2C communication protocol for comprehensive data collection.

The effective operation of the solar panel monitoring system relies significantly on specialized C/C++ programs running on both the Arduino Mega R3 and Arduino Uno R3 microcontrollers. Equipped with a dedicated data acquisition module featuring an SD card interface, the Arduino Mega R3 executes a tailored C/C++ program to gather voltage levels and temperatures from the panels. This program efficiently logs the acquired data onto an SD card. Simultaneously, the Arduino Uno R3 is tasked with logging solar irradiance data collected by the pyranometer. With its own data acquisition module and SD card interface, the Arduino Uno R3 operates a custom C/C++ program designed to capture readings from the pyranometer. These readings are then transformed into irradiance levels (measured in Watts per square meter) and stored on the SD card alongside timestamps.

4.4. Experiment carried out

The experiment was conducted from July 1st to July 10th, 2023, utilizing the setup mounted on a rooftop with unobstructed sunlight exposure throughout the day, except for occasional cloud cover. The setup included the three solar panels positioned at the same angle relative to the horizontal surface.

The pyranometer was also installed at this angle to accurately measure the irradiance levels received by the panels. Continuous data collection was performed day and night to capture variations in voltage and temperature, even during low irradiance conditions in the early morning hours. This approach ensured comprehensive recording of sensor readings, including subtle changes during periods of minimal sunlight.

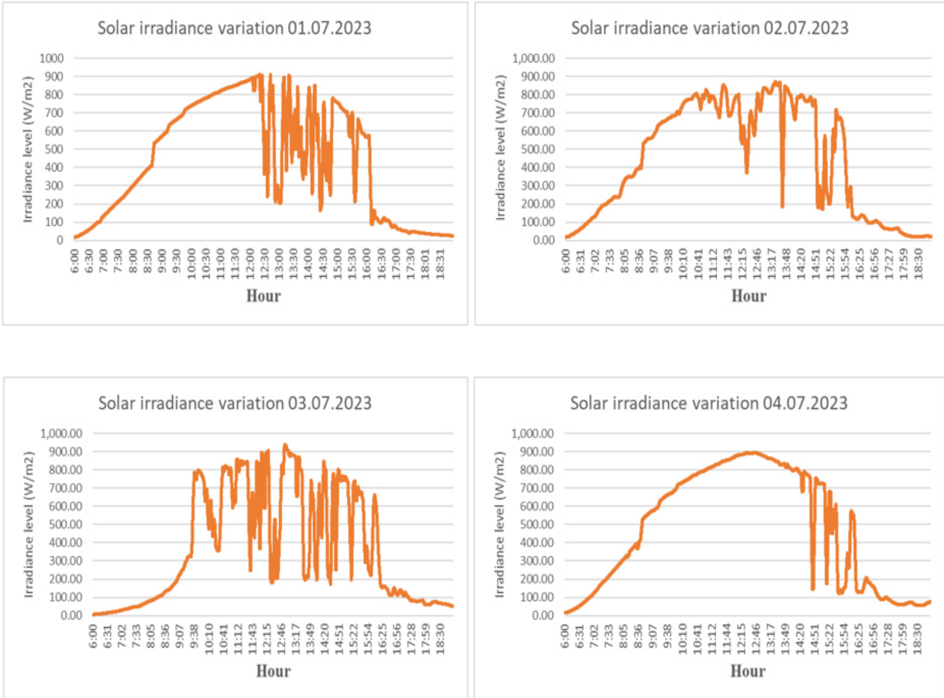

Fig. 6 – Example of daily irradiance fluctuations.

During the experimental period, there were frequent fluctuations in irradiation levels (Fig. 6) due to cloud cover. These fluctuations significantly impacted the temperature variations of the panels. To observe the behavior of the PV panels under conditions of consistent irradiation increase, specific days and hours were selected based on periods of relatively stable irradiance.

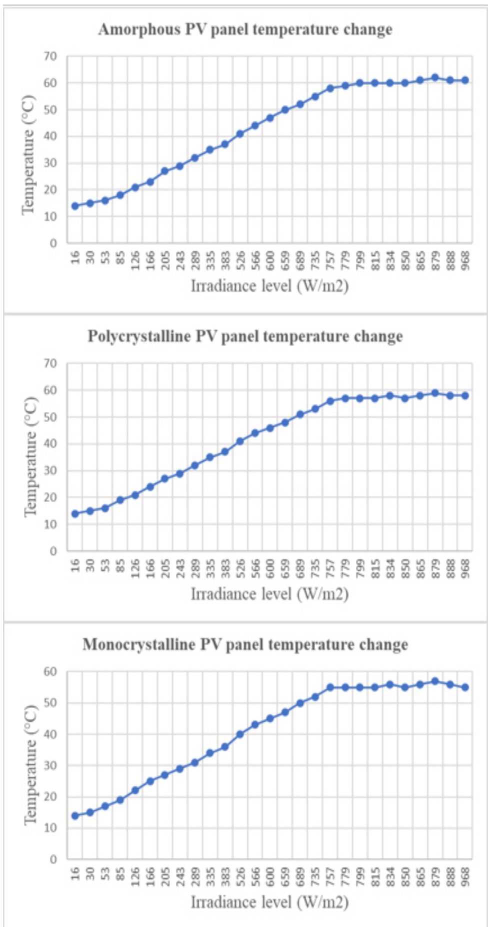

Fig. 7 – PV panels temperature change on July 1st.

With a focus on July 1st, until noon, it was observed a steady increase in irradiance along with a corresponding rise in the temperature of the PV panels (Fig. 7). The iradiance levels ranged from 16 – 970 W/m^2. The temperatures reached at the maximum irradiance level for each panel type were as follows:

Amorphous PV	62ºC
Polycrystalline PV	59ºC
Monocrystalline PV	57°C

When exposed to solar irradiance exceeding 120 W/m², all panels absorb heat at a similarly steep rate (Fig. 8). The monocrystalline panel had the lowest temperature peak. The polycrystalline panel's temperature peak wa 3.5% higher than the monocrystalline. The amorphous panel reached the highest temperature, 8.8% higher than the monocrystalline panel.

The temperature increase is similar for all panels up to an irradiance level of 600 W/m². Beyond this value, the temperatures of the panels begin to differentiate, with the amorphous panel showing the highest increase.

Amorphous panels are fabricated from a thin layer of non-crystalline silicon, which lacks the regular lattice structure characteristic of crystalline silicon panels. In amorphous silicon panels, the silicon atoms are arranged in a disordered manner, which significantly affects their electronic properties. At elevated temperatures, the increased thermal energy causes more pronounced disruptions in charge carrier mobility in amorphous silicon compared to crystalline silicon. This is due to the higher density of localized states and defects in the amorphous structure, which exacerbate the scattering and recombination of charge carriers, thereby impacting the overall efficiency of the panels.

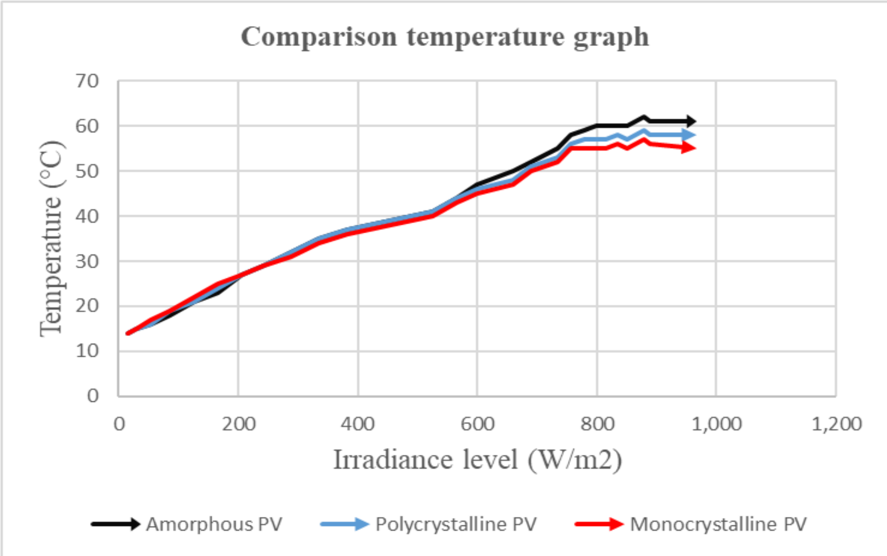

Fig. 8 – Slope comparison of PV panels temperatures.

In this experiment, the effect of temperature on the open-circuit voltage of these three PV panels was investigated and the rates of change among them were compared.

The experimental results indicated that, as the panels temperature exceeded 30°C, a noticeable decline in voltage was observed, with the rate of decrease becoming more pronounced beyond 35°C. This behavior was consistent across all three types of PV panels, though slight variations in the rates of change were noted. The percentage of voltage drop (Table 1) relative to the maximum voltage achieved at lower temperatures was calculated for each type of panel.

The behavior of open-circuit voltage with respect to temperature in photovoltaic panels is influenced by the inherent properties of the semiconductor materials used in each type of panel.

Table 1

Voltage drop and corresponding temperatures for different PV panels

PV panel type	Amorphous	Polycrystalline	Monocrystalline
Maximum Voc reached	53.8V	22.9V	19.9V
Corresponding panel temperature for maximum Voc	32ºC	29ºC	25ºC
Minimum Voc reached	50.9V	22.2V	19.1V
Corresponding panel temperature for minimum Voc	62ºC	59ºC	57ºC
Percentage of voltage drop	5.7%	3.2%	4.2%

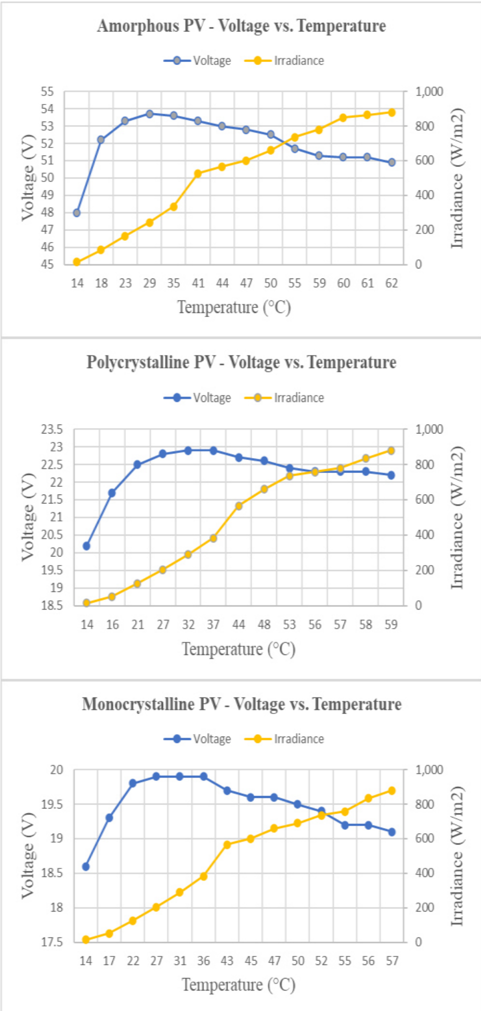

Fig. 9 – Panels voltage drop with temperature increase.

A-Si panel exhibited the highest voltage drop with temperature increase, showing a 5.7% decrease in Voc. This greater sensitivity to temperature changes can be attributed to its higher defect density and lower quality of material, which can lead to more pronounced effects of thermal excitation on charge carriers. Polycrystalline silicon panel consists of multiple small silicon crystals with grain boundaries. This structure results in moderate efficiency due to increased electron scattering at grain boundaries. However, polycrystalline silicon has a better temperature coefficient than amorphous silicon, resulting in a smaller decrease in Voc with temperature increase (3.2%). Monocrystalline silicon panel made from a single, continuous crystal, boast the highest efficiency among the three types due to their uniform crystal lattice, which facilitates better charge carrier mobility and reduced recombination losses.

Despite its efficiency, the monocrystalline PV panel also shows sensitivity to temperature increases, with a 4.2% reduction in Voc observed in the experiment. The highly ordered crystal structure, lower bandgap, and higher purity of monocrystalline silicon, lead to a significant decrease in Voc as temperature rises, reflecting a trade-off between high efficiency and thermal sensitivity.

During the experimental period, extreme values were reached for the temperatures and corresponding open-circuit voltages of the three types of PV panels (Figs. 10, 11, 12).

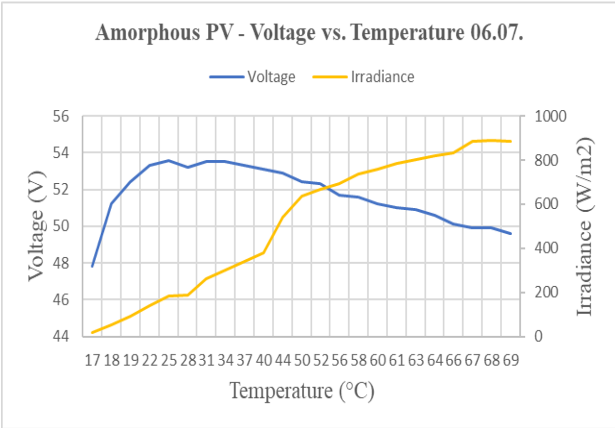

Fig. 10 – Amorphous PV panel voltage vs. temperature – 6.07.2023.

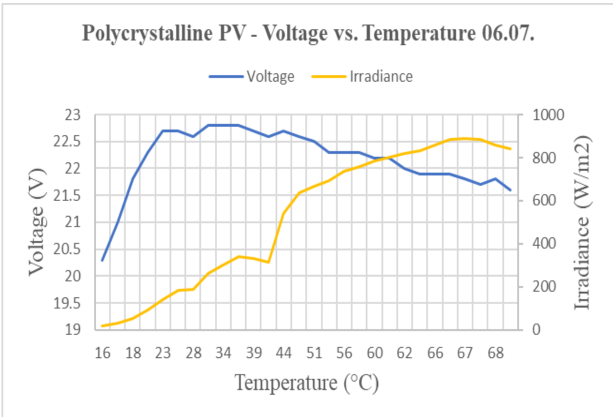

Fig. 11 – Polycrystalline PV panel voltage vs. temperature – 6.07.2023.

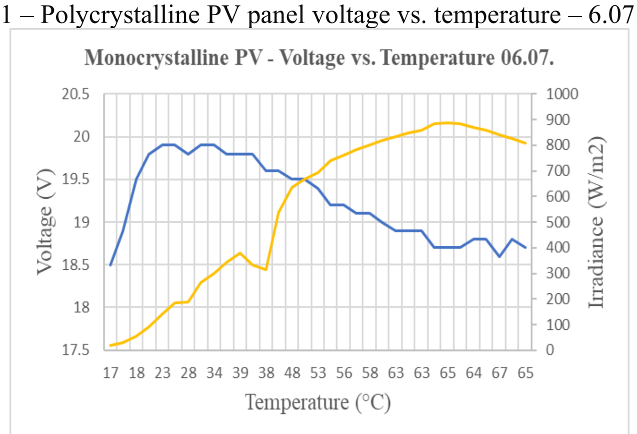

Fig. 12 – Monocrystalline PV panel voltage vs. temperature – 6.07.2023.

The highest temperatures recorded (Table 2) were 69°C for the amorphous PV panel, 68°C for the polycrystalline PV panel, and 67°C for the monocrystalline PV panel. At these temperatures, the corresponding Voc values were 49.5 V for the amorphous PV panel, 21.7 V for the polycrystalline PV panel, and 18.6 V for the monocrystalline PV panel.

Table 2
Extreme values reached in the experiment period for each PV panel

PV panel type	Amorphous	Polycrystalline	Monocrystalline
Maximum Voc reached	53.8V	22.9V	19.9V
Minimum Voc reached	49.5V	21.7V	18.6V
Corresponding panel temperature for minimum Voc	69ºC	68ºC	67ºC
Percentage of voltage drop	8.7%	5.5%	7%

The percentage voltage drop for each PV panel, due to temperature increase, was also analyzed. For the amorphous PV panel, the voltage drop was significant, reflecting the sensitivity of this panel type to high temperatures. The polycrystalline PV panel showed a moderate voltage drop, indicating a better stability compared to the amorphous type. The monocrystalline PV panel, while highly efficient, also exhibited a notable voltage drop, illustrating the trade-off between efficiency and thermal sensitivity.

5. Conclusions

Temperature impact on voltage drop. The study confirms that PV panels experience a significant voltage drop as temperature increases. This phenomenon directly affects the efficiency of power generation, leading to reduced overall power output from the PV system.

Panel performance variability. Among the panel types studied, monocrystalline panels demonstrate superior thermal performance, exhibiting the lowest temperature peaks compared to polycrystalline and amorphous panels. This characteristic translates to more stable voltage output under temperature variations.

Trade-offs in panel selection. While amorphous panels may offer higher initial voltage output, they are also the most sensitive to temperature changes, which can compromise their efficiency and longevity in high-temperature environments. On the other hand, monocrystalline panels excel in managing heat while maintaining decent voltage output, making them a favorable choice for applications where temperature control is important.

Considerations for cooling systems. Implementing cooling technologies in PV systems presents both opportunities and challenges. While cooling systems can improve the power curve of PV panels, designing a system with low initial cost and tailored to specific needs remains a real challenge. Factors such as location, weather conditions, orientation, shading, space availability, consumer requirements, and budget constraints must be carefully considered in the design and implementation of cooling systems.

REFERENCES

Allouhi A., Rehman S., Buker M.S., Said Z., *Up-to-date literature review on Solar PV systems: Technology progress, market status and R&D*, Journal of Cleaner Production **362**, (2022).

Chatzisideris M.D., Espinosa N., Laurent A., Krebs F.C., *Ecodesign perspectives of thinfilm photovoltaic technologies: a review of life cycle assessment studies*, Sol Energy Mater Sol Cells **156**, 2-10, (2016).

Clean Energy Reviews https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels

Elibol E., Ozmen O.T., Tutkun N., Köysal O., *Outdoor performance analysis of different PV panel type*, Renew. and Sust. En. Rev. **67**, 651-661, (2017).

Elsabahy M.M., Emam M., Sekiguchi H., Ahmed M., *Performance mapping of silicon-based solar cell for efficient power generation and thermal utilization: Effect of cell encapsulation, temperature coefficient, and reference efficiency*, Applied Energy 356, (2024).

Green M.A., *Limiting photovoltaic efficiency under new ASTM International G173-based reference spectra*, Prog. Photovolt.: Res. Appl., vol. **20 (8)**, 954-959, (2012), https://doi.org/10.1002/PIP.1156.

Hammoumi A.L., Chtita S., Motahhir S., Ghzizal A.E., *Solar PV energy: From material to use, and the most commonly used techniques to maximize the power output of PV systems: A focus on solar trackers and floating solar panels*, Energy Reports **8**, 11992-12010, (2022).

IEA 2023, World Energy Outlook 2023, Executive Summary https://www.iea.org/reports/world-energy-outlook-2023/executive-summary.

Javier G.M.N., Dwivedi P., Buratti Y., Perez-Wurfl Y., Trupke T., Hameiri Z., *Improvements and gaps in the empirical expressions for the fill factor of modern industrial solar cells*, Sol Energy Mater Sol Cells **253**, (2023).

Kirchartz T., Rau U., *What makes a good solar cell?* Adv. Energy Material, **vol. 8 (28)**, (2018), https://doi.org/10.1002/AENM.201703385.

McKinsey&Company 2024, Global Energy Perspective 2023: CO_2 emissions outlook, https://www.mckinsey.com/industries/oil-and-gas/our-insights/global-energy-perspective-2023-co2-emissions-outlook.

Mohamed S.A., Abd El Sattar M., *A comparative study of P&O and INC maximum power point tracking techniques for grid-connected PV systems*, Appl. Sci., vol. **1 (2)**, 1–13, (2019), https://doi.org/10.1007/S42452-018-0134-4.

Muteri V., Cellura M., Curto D., Franzitta V., Longo S., Mistretta M. et al., *Review on life cycle assessment of solar photovoltaic panels*, Energies **13**(1):252, (2020).

Office of Energy Efficiency & Renewable Energy https://www.energy.gov/eere/solar/solar-photovoltaic-cell-basics

Oni A.M., Abu S.M. Mohsin, Md. Mosaddequr Rahman, Mohammed B.H. Bhuian, *A comprehensive evaluation of solar cell technologies, associated loss*

mechanisms, and efficiency enhancement strategies for photovoltaic cells, Energy Reports **11**, 3345-3366, (2024).
Ray S., Das R., Barua A.K, *Performance of double junction a-Si solar cells by using ZnO: Al films with different electrical and optical properties at the n/metal interface*, Sol Energy Mater Sol Cells 74, 387-392, (2002).
Wijewardane S., Lawrence L. Kazmerski, *Inventions, innovations, and new technologies: Flexible and lightweight thin-film solar PV based on CIGS, CdTe, and a-Si:H*, Solar Compass **7**, (2023).
Williams S.R., Betts T.R., Vorasayan P., Gottschalg R., Infield D.G., *Actual PV module performance including spectral losses in the UK*, In: Proceedings of the IEEE photovoltaic specialists conference, 1607-1610, (2005).

EVALUAREA PANOURILOR SOLARE POLICRISTALINE, MONOCRISTALINE ȘI AMORFE ÎN CONDIȚII DINAMICE DE MEDIU: EVALUĂRI DE PERFORMANȚĂ PENTRU APLICAȚII CU ENERGIE REGENERABILĂ

(Rezumat)

Tehnologia fotovoltaică solară (PV) se extinde rapid la nivel global ca sursă principală de energie regenerabilă. Înțelegerea performanței pe termen lung a diferitelor tehnologii PV în condiții reale este crucială pentru dezvoltarea și implementarea lor. De la începuturile sale în 1839, odată cu demonstrarea efectului fotovoltaic de către Edmond Becquerel, domeniul PV solar a cunoscut progrese remarcabile. Totuși, performanța reală a sistemelor PV este influențată de factori externi precum temperatura, vântul și iradierea, alături de constrângeri operaționale cum ar fi umbrirea și orientarea panourilor. Temperaturile ridicate ale celulelor, cauzate de absorbția luminii solare, pot scădea performanța cu 8-15%, ceea ce necesită utilizarea sistemelor de răcire pentru optimizarea performanței în condiții ce nu sunt optime. Acest studiu se concentrează pe analiza comportamentului a trei tipuri distincte de panouri PV - policristaline, monocristaline și amorfe (cu peliculă subțire) - în răspuns la variațiile radiației solare și temperaturii. Prin utilizarea senzorilor monitorizați cu microcontrolere, inclusiv senzori de temperatura, senzori de tensiune și un piranometru pentru măsurarea radiației solare, cercetarea își propune să elucideze modul în care aceste panouri răspund la condițiile de mediu dinamice. Obiectivul studiului este de a furniza perspective asupra caracteristicilor de performanță ale fiecărui tip de panou în condiții de radiatie și temperatură variabile, informând astfel strategiile pentru optimizarea generării de energie solară în aplicații reale. Rezultatele preliminare indică faptul că fiecare tip de panou PV prezintă caracteristici de performanță unice influențate de radiația solară și fluctuațiile de temperatură. Panourile policristaline, caracterizate prin rentabilitate și adecvare pentru medii cu temperaturi ridicate, demonstrează un randament stabil sub lumina directă a soarelui, dar prezintă o eficiență redusă în condiții de lumină scăzută. În contrast, panourile monocristaline, cunoscute pentru eficiența și utilizarea eficientă a spațiului, excelează în scenarii de lumină scăzută, dar sunt susceptibile la degradarea performanței la temperaturi ridicate. Panourile amorfe (cu peliculă subțire), deși mai puțin eficiente în general, afișează reziliență în condiții de

lumină variabilă și fluctuații moderate de temperatură. Această investigație cuprinzătoare asupra comportamentului panourilor PV în condiții reale își propune să contribuie cu perspective valoroase în domeniul tehnologiei energiei solare. Prin înțelegerea modului în care diferitele tipuri de panouri răspund la variabilele de mediu, această cercetare își propune să ghideze viitoarele avansuri în designul și strategiile de implementare a panourilor solare, facilitând în cele din urmă adoptarea pe scară largă a surselor de energie regenerabilă pentru un viitor energetic durabil.