

Experimental and TRNSYS-Based Evaluation of PV Temperature Effects on Energy Output

Eksperymentalna i symulacyjna (TRNSYS) ocena wpływu temperatury modułów fotowoltaicznych na uzysk energii

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This study investigates the impact of temperature on the performance of three photovoltaic technologies: monocrystalline, polycrystalline, and amorphous silicon. Laboratory tests were conducted under two irradiance levels (500 and 830 W/m²) and temperatures ranging from 30°C to 70°C. Key electrical parameters were measured to determine temperature coefficients. TRNSYS simulations based on the experimental data were performed to assess annual energy yield. Results show that monocrystalline panels have the highest efficiency but are the most sensitive to temperature, while amorphous panels exhibit greater thermal stability despite lower power output. Effective cooling is essential to maintain performance, especially in warm climates.

Keywords: solar energy, photovoltaic panels, temperature coefficient, dynamic simulation, monocrystalline, polycrystalline, amorphous

W niniejszej pracy przeanalizowano wpływ temperatury na wydajność trzech technologii fotowoltaicznych: monokrystalicznej, polikrystalicznej oraz amorficznej. Testy laboratoryjne przeprowadzono przy dwóch poziomach natężenia promieniowania (500 i 830 W/m²) oraz w zakresie wartości temperatury od 30°C do 70°C. Zmierzono kluczowe parametry elektryczne w celu wyznaczenia współczynników temperaturowych. Na podstawie danych eksperymentalnych wykonano symulacje w programie TRNSYS, pozwalające oszacować roczny uzysk energii. Wyniki wykazały, że moduły monokrystaliczne charakteryzują się najwyższą sprawnością, lecz są najbardziej wrażliwe na wzrost temperatury, podczas gdy moduły amorficzne cechuje większa stabilność temperaturowa, mimo niższej mocy wyjściowej. Skuteczne chłodzenie jest kluczowe dla utrzymania wydajności, szczególnie w ciepłym klimacie.

Słowa kluczowe: energia promieniowania słonecznego, panele fotowoltaiczne, współczynnik temperaturowy, symulacja dynamiczna, monokrystaliczny, polikrystaliczny, amorficzny

Introduction

The growing urgency to transition from fossil fuels to renewable energy sources has propelled solar power into the forefront of sustainable energy strategies. Among various solar energy technologies, photovoltaic (PV) systems have garnered particular attention [1] due to their ability to convert sunlight directly into electricity without mechanical components, emissions, or significant environmental disruption. This technology has become increasingly viable owing to the falling cost of PV panels, rising global investments, and continuous improvements in cell efficiency [2]. However, while PV systems offer promising potential in decarbonizing electricity generation, their performance remains highly sensitive to environmental conditions, especially temperature [3]. Unlike irradiance, which provides the energy input for solar conversion, temperature acts as a performance-

modifying factor that often degrades efficiency rather than enhancing it. The dual influence of these parameters, irradiance and temperature, makes comprehensive analysis essential for both the design and operational optimization of solar installations [4].

Photovoltaics is a key topic in contemporary energy research, driven by climate goals and rising electricity prices. In Poland, PV holds a dominant position among renewable energy sources, comprising 60% of installed RES capacity as of 2023. The profitability of PV micro-installations, especially in single-family houses, has been a focus of recent studies. Recent analyses [5] indicate that while direct investment in PV systems yields significant long-term savings, even greater benefits may be achieved by combining PV installation with reinvestment of the savings into long-term funds. Such an integrated approach nearly doubles the overall financial benefit over a 30-year period, demonstrating the complex

optimization possible in household investment strategies regarding renewable energy.

A particularly critical challenge in PV technology is the negative temperature coefficient associated with the electrical characteristics of PV panels. As temperature rises, the open-circuit voltage (V_{OC}) of a PV panel typically decreases at a faster rate than the short-circuit current (I_{SC}) increases, resulting in an overall drop in the power in maximum power point (P_{MPP}) [6]. This effect can lead to substantial energy yield losses, especially in climates characterized by high ambient temperatures or intense solar radiation. According to [7], an increase in photovoltaic panel temperature results in efficiency losses that vary by cell technology: approximately 0.4-0.5%/°C for monocrystalline and polycrystalline silicon, around 1.1%/°C for amorphous silicon. These losses are mainly attributed to temperature-induced reductions in open-circuit voltage, making thermal effects

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a critical factor in PV performance, especially in high-temperature environments. This highlights the necessity for targeted studies investigating how different PV technologies, such as monocrystalline, polycrystalline, and amorphous silicon, respond to thermal stress. Understanding this thermal behaviour is crucial for system integrators, designers, and policymakers aiming to maximize energy output and ensure cost-effective deployment of PV infrastructure in diverse climate zones.

In recent years, numerous scientific investigations have addressed the impact of temperature on photovoltaic performance, leveraging both empirical data and simulation models. As demonstrated by [8], the open-circuit voltage of crystalline silicon solar cells decreases significantly with increasing temperature, contributing to overall power losses. The experimental data show that as the panel temperature rises from 25 °C to 60 °C, V_{OC} drops from 42.18 V to 34.75 V, corresponding to a power loss of approximately 0.65% per degree Celsius.

It should be noted that the temperature of photovoltaic panels is closely correlated with the intensity of solar irradiance, which directly affects both the thermal load on the panel and its electrical performance. According to [9], increasing the surface temperature of PV panels leads to a decrease in open-circuit voltage, which has a dominant effect in reducing the panel's power output under elevated temperature conditions. For example, in laboratory tests without any cooling, the V_{OC} of a 50 Wp panel dropped from 21.6 V at 298 K to 18.5 V at 349.1 K, while the power output decreased by approximately 12% during a 15-minute exposure under 750 W/m² irradiance.

The mounting configuration of a photovoltaic installation significantly influences its energy yield, as the installation's positioning and surrounding environment can affect both temperature regulation and solar irradiance exposure, thereby impacting overall system performance. As demonstrated by [10], the open-circuit voltage of crystalline silicon PV panels decreases significantly with increasing temperature, approximately 2.3 mV/°C, which results in a power loss of around 0.4%/°C. Their experimental study further showed that integrating vegetation into roofing systems (PV-green roofs) effectively reduces panel temperature and enhances electrical performance, with the Sedum-based configuration achieving up to 3.33% higher power output compared to a conventional gravel roof.

Cooling of PV panels is essential for maintaining their efficiency, as elevated temperatures can reduce the amount of electricity generated. Annual analysis [11] of a 410

W PV panel in Polish conditions showed that without cooling, cell temperatures reached up to 57 °C, resulting in lower conversion efficiency and energy output. Adding fins to the back of the panel dropped the maximum temperature to 35.2 °C and achieved a relative increase in yearly electricity production by 3.1% (for temperature coefficient – 0.34%/°C) and 4.6% (for – 0.5%/°C). Installing an air-based cooling system reduced the maximum temperature to 41.2 °C and increased output by 2.1% and 3.1%, respectively, for the same coefficients. Cooling also reduced thermal variations, which may extend the PV panel lifespan and provide even greater long-term benefits

Environmental conditions, particularly temperature and solar irradiance, have a critical impact on the electrical performance of PV panels, primarily due to reductions in open-circuit voltage at elevated temperatures. Active air-cooling systems offer a feasible mitigation approach. A prototype cooling solution developed at AGH University of Krakow [12], employing air fans mounted on the rear of a 70 Wp PV panel, was tested under controlled laboratory conditions (770 W/m² irradiance). Without cooling, the panel's power dropped to 40.09 W as surface temperature reached 60 °C, while the cooled system achieved 44.37 W, representing a 10.7% gain. A validated ANSYS Workbench model was used to analyse and optimize the fan configurations, identifying that a 7° vertical and 10° horizontal tilt yielded a cost-effective improvement of approximately 3.1% in net power. This confirms that even low-cost active cooling methods can be tailored to meaningfully improve PV efficiency in practical applications.

Various hybrid solutions have been explored to reduce the operating temperature of PV panels and improve overall system efficiency. These include integrating PV panels with heat exchangers, phase change materials, or nanofluids to recover waste heat and enhance cooling performance. Recent experimental research [13] has demonstrated that a dual-tank configuration in photovoltaic/thermal (PVT) collectors can significantly enhance performance. Under outdoor conditions in Beijing, the system reduced the average cell temperature by 12.3 °C at 572 W/m², increasing electrical efficiency by 8.2% compared to a standard PV panel. Incorporating a graphite-enhanced heat exchanger further raised the average thermal efficiency to 34.41%, a 57.1% improvement over conventional designs. Additionally, using the Whale Optimization Algorithm (WOA) to adjust tank volume led to a 5-20% increase in daily energy output.

Another promising approach for reducing PV panel temperature involves coupling photovoltaic systems with phase change materials (PCMs), forming PV-PCM hybrid structures. These systems have been shown to improve thermal regulation by absorbing excess heat during peak solar hours. A recent TRNSYS-based numerical and experimental study [14] investigated PV-PCM roofs across various climatic regions in China. The findings revealed that optimal PCM phase change temperatures differ by location, ranging from 23 °C to 33 °C, closely aligned with outdoor air temperatures. The optimal PCM thickness was typically 4 cm. Depending on the region, the use of PCMs reduced PV back surface temperature by up to 21.5 °C and peak heat flux into the building by as much as 26.5 W/m². Notably, while increasing PCM thickness improved indoor thermal comfort, it had minimal effect on PV panel temperature, underscoring the importance of precise PCM temperature selection in hybrid solar applications.

In addition to PCM and dual-tank approaches, optical and structural enhancements play a critical role in improving PV/T system performance. One such strategy [15] involves the use of beam-splitting concentrators coupled with nanofluids. Using a fully coupled optical-thermal-electrical model, the system was evaluated through discrete ordinates radiation modelling, validated against Monte Carlo Ray Tracing results. The integrated system, operating with nanofluids at 25 °C and a flow rate of 0.03 kg/s, achieved an electrical efficiency of 22.13%, thermal efficiency of 71.85%, and exergy efficiency of 20.77%. Moreover, comparative analysis revealed that series configurations enhanced exergy efficiency, while parallel arrangements favoured thermal performance. These results highlight the effectiveness of beam-splitting and spectral management strategies in achieving high-performance PV/T operation under concentrated solar input.

Among the simpler yet effective thermal management strategies for PV systems, forced water cooling using a heat exchanger has proven to be a practical solution, particularly in large-scale applications. In an experimental and simulation study [16] conducted in Jerash, Jordan, a copper pipe heat exchanger was attached to the back of a PV panel and combined with forced water circulation. Compared to an uncooled reference panel, this setup achieved an average temperature reduction of 4.62 °C, resulting in an 8.08% increase in electrical power output and an efficiency of 10.41%. Over six consecutive days, the cooled panel generated 377 Wh more electricity, with TRNSYS simulations confirming the experimental trend. The system's simplicity,

cost-effectiveness, and ability to enhance both productivity and panel lifespan make it a viable method for PV performance enhancement in warm climates.

This study combines experimental analysis with numerical simulation to investigate the impact of temperature on the performance of three photovoltaic technologies: monocrystalline, polycrystalline, and amorphous silicon. Laboratory tests were conducted under two irradiance levels (500 W/m² and 830 W/m²) and a temperature range of 30°C to 70°C. Key electrical parameters, such as current, voltage, power output, and efficiency were measured, allowing the determination of temperature coefficients (α , β , γ) for each panel type. The second part of the work involves dynamic simulations using TRNSYS software to model annual energy yield under realistic climate conditions. This simulation uses the experimental data as inputs and helps assess seasonal and long-term performance variations. A regression-based power prediction model is also proposed, linking irradiance and temperature to output power. The study concludes with design recommendations based on comparative thermal performance, offering practical guidance for PV system optimization in varying environments.

Materials and methods

The experimental setup was designed to evaluate the energy yield of various types of PV panels under diverse operating conditions. The measuring stand comprised PV panels, as well as measurement and electricity reception systems. The entire setup was equipped with the following components:

- three photovoltaic panels (parameters given in Table 1):
 - monocrystalline – Singfo Solar SFM-10,
 - polycrystalline – Action Energy AEMF010,
 - amorphous – Conrad Electronic TPS-103,
- Light Source: A halogen lamp with a power rating of 500 W, providing a stable and consistent illumination for testing purposes.
- Temperature Meters:
 - TES-1307: A high-precision temperature meter with a measuring range from – 190°C to 1333°C. The accuracy within the range of 0-1000°C is 0.1% + 0.5°C, with a resolution of 0.1°C.

- AZ8852: A temperature meter with a measuring range from – 200°C to 1370°C, featuring an accuracy of $\pm 0.1\%$ and a resolution of 0.1°C.
- Temperature Sensors: Four type K thermocouples with a measuring range from – 50°C to 250°C, offering an accuracy of $\pm 0.5^\circ\text{C}$. These sensors are crucial for precise temperature monitoring during the experiments.
- Electronic Load (Array 3711A):
 - Power range: 0 to 400 W (accuracy: 0.1% + 600 mW)
 - Current range: 0 to 40 A (accuracy: 0.05% + 8 mA)
 - Voltage range: 0 to 80 V (accuracy: 0.1% + 8 mV)
 This load device ensures accurate simulation of operational conditions for PV panels.
- Insolation Meter (Benning SUN 2): An instrument for measuring solar irradiance with a range from 100 to 1250 W/m² $\pm 5\%$, essential for assessing the incident solar power.
- Multimeters:
 - AXIOMET AX-594: A current meter with an accuracy of $\pm 1\%$.
 - V&A Instrument VA20C: A voltage meter with an accuracy of $\pm 0.7\% + 2\text{ V}$.
- Cable Set: A set of cables necessary for connecting the various components and ensuring stable and reliable data acquisition.

The general configuration of the experimental stand, including the arrangement of photovoltaic panels and measurement equipment, is presented in Figure 1.

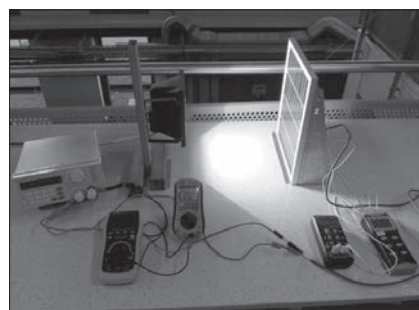


Figure 1. The general view of the experimental stand with polycrystalline PV panel

The parameters of the photovoltaic panels used in the experiment are presented in Table 1. Both the monocrystalline and polycrystalline panels have a nominal power rating of 10 Wp. The monocrystalline panel is

characterized by a higher I_{MPP} and a higher V_{MPP} . In contrast, the polycrystalline panel exhibits a higher I_{MPP} as well as a higher short-circuit current.

While the monocrystalline and polycrystalline panels have comparable surface areas, the amorphous panel features a significantly larger surface area. To ensure consistency and comparability of the results, the measured power gains were normalized to a unit area of 1 m².

The experimental tests were conducted under two distinct irradiance levels generated by a halogen lamp positioned perpendicularly to the active surface of the PV panels. The irradiance intensity was controlled by adjusting the distance between the panel and the light source, allowing for precise regulation of the radiation incident on the PV panel surface. As a result of the measurements, the average irradiance on the surface of each panel was determined, yielding the following values:

- 500 W/m²
- 830 W/m²

The selection of these two irradiance levels was motivated by the need to analyze the performance of PV panels under varying simulated sunlight conditions. In practical applications, PV panels are exposed to fluctuating solar irradiance due to changes in weather conditions, the angle of incidence of sunlight, and atmospheric factors. Therefore, it is essential to investigate how different irradiance intensities affect the electrical parameters and overall efficiency of the panels.

By examining PV panel performance at both moderate (500 W/m²) and higher irradiance levels (830 W/m²), the study aims to gain insights into the thermal and electrical behavior of various PV technologies. This approach not only reflects real-world operating conditions but also helps to determine the temperature sensitivity and efficiency variations under diverse environmental scenarios.

Table 2 presents an overview of the measurement series conducted under different irradiance levels. The table provides a detailed explanation of the experimental conditions and the specific irradiance values applied during each series.

During the experimental measurements, the rear surface temperature of each PV panel was continuously monitored using four thermocouples attached to the rear side of the PV panel. The thermocouples were strategically positioned at a distance of 7 cm from the corners of each panel to ensure accurate and representative temperature readings across the rear panel surface. The current-voltage (I-V) characteristics of the PV panels were assessed at five distinct temperatures: 30°C, 40°C, 50°C, 60°C, and

Table 1. PV panels technical parameters used in experimental tests

Type of panel	P_{max} [W _p]	V_{MPP} [V]	I_{MPP} [A]	V_{OC} [V]	I_{SC} [A]	Surface [m ²]
Monocrystalline	10	18	0.55	21.6	0.61	0.065
Polycrystalline	10	16.8	0.6	21	0.68	0.0675
Amorphous	6	17.5	0.342	21	0.45	0.1465

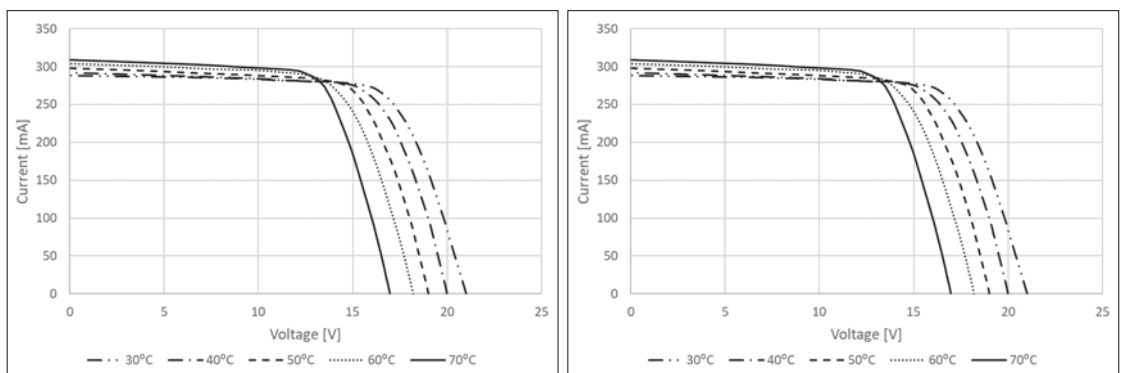
70°C. To achieve the desired temperature levels, the panels were heated using a halogen lamp. The current-voltage characteristic measurements were initiated once the average rear surface temperature of the panel stabilized and reached the predetermined target value. This approach ensured that the temperature conditions were consistent and accurate throughout the testing process.

In this study, all temperature values used in the analysis refer to the average rear surface temperature of the PV panel, determined as the mean value from four thermocouples placed symmetrically on the back side of each panel. Therefore, the presented results should be interpreted in the context of surface temperature effects on electrical parameters, rather than as an analysis of internal cell-level temperatures.

Table 2. Explanation of measurement series

Type of panel	Irradiance [W/m ²]	Series
Monocrystalline	500	Monocrystalline-500
	830	Monocrystalline-830
Polycrystalline	500	Polycrystalline-500
	830	Polycrystalline-830
Amorphous	500	Amorphous-500
	830	Amorphous-830

Figure 2. Current-voltage (left – a) and power-voltage (right – b) characteristics – Monocrystalline-500



It should be noted that the experimental setup represents a simplified model of real-world PV operating conditions. The use of a halogen lamp as both a heat and irradiance source enabled controlled and repeatable heating of the PV panels but does not fully replicate dynamic outdoor factors such as wind-induced cooling, variable irradiance, or environmental convection. Despite these simplifications, the laboratory conditions ensured high precision in thermal and electrical measurements, which was essential for isolating the temperature effects on PV performance.

The use of multiple temperature points allows for a comprehensive analysis of how temperature variations influence the efficiency and power output of the PV panels, offering valuable insights into the thermal behaviour and performance stability under simulated operational conditions.

The current-voltage characteristic measurement involved setting a specific current value on the electronic load, operating in constant current mode. This approach ensured precise control over the current flowing through the photovoltaic panel during testing. The corresponding current and voltage values were measured using electrical multimeters.

Results and discussion

The following chapter presents the results of experimental research conducted on PV panels under varying operating temperatures and irradiance levels. The primary objective of these experiments was to investigate the influence of temperature fluctuations and differing irradiance intensities on the performance characteristics of various types of PV panels. The obtained results provide valuable insights into the thermal and electrical behaviour of PV panels, which is critical for optimizing their efficiency in real-world applications.

The experiments were designed to replicate practical conditions in which PV systems operate, including variations in solar irradiance and temperature that typically occur due to changing environmental factors. To ensure

output, which is a well-documented phenomenon in PV technology.

Electrical characteristics

The following subsection presents the experimental results of current-voltage (I-V) and power-voltage (P-V) characteristics obtained from a monocrystalline photovoltaic (PV) panel. The measurements were conducted under two irradiance levels: 500 W/m² and 830 W/m², simulating moderate and high solar radiation conditions, respectively. For each irradiance level, the I-V and P-V curves were recorded at five distinct average rear surface temperatures of the PV panel: 30°C, 40°C, 50°C, 60°C, and 70°C. The curves presented in the current-voltage (I-V) and power-voltage (P-V) characteristic plots were obtained based on experimental data and subsequently approximated using curve fitting methods to facilitate analysis and enhance the clarity of the trends.

The first two graphs (Figures 2a and 2b) represent the current-voltage (I-V) and power-voltage (P-V) characteristics of the monocrystalline PV panel measured at an irradiance of 500 W/m². As the temperature of the PV panel increases, a noticeable decrease in the open-circuit voltage is observed. The I-V char-

acteristic curves shift to the left with increasing temperature, indicating a reduction in voltage. This behavior can be attributed to the increased charge carrier recombination occurring at elevated temperatures, which reduces the potential difference across the cell. The short-circuit current shows a slight increase with rising temperature, which can be explained by enhanced thermal generation of charge carriers. However, this increase in current is not sufficient to counterbalance the voltage drop, leading to a reduction in the maximum power point. Consequently, the maximum power output of the PV panel decreases as the average rear surface temperature rises, demonstrating the negative impact of thermal conditions on PV efficiency.

The results presented in this chapter encompass key performance parameters such as voltage, current, power output, and efficiency at specified temperatures (30°C, 40°C, 50°C, 60°C, and 70°C) and irradiance levels (500 W/m² and 830 W/m²). The data were collected through systematic experimentation and were carefully analysed to assess the correlation between temperature increase and the decline in power

output, which is a well-documented phenomenon in PV technology.

The corresponding P-V curves also confirm this trend. At lower temperatures, the peak power output occurs at higher voltage

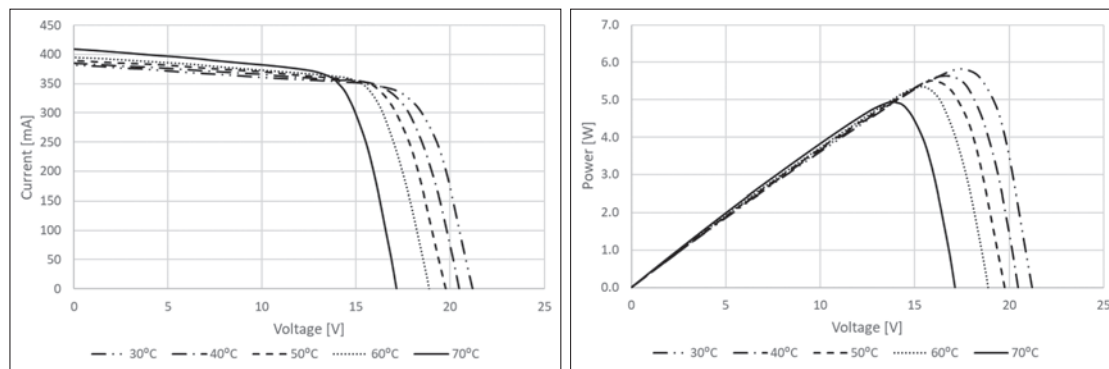


Figure 3. Current-voltage (left – a) and power-voltage (right – b) characteristics – Monocrystalline-830

values, while as the temperature increases, the power peak shifts towards lower voltage values. This indicates a significant decline in the power generation capacity of the PV panel at elevated temperatures. The power curves become noticeably flatter as temperature of rear side of PV panel rises, indicating reduced power output efficiency.

The next two graphs (Figures 3a and 3b) depict the I-V and P-V characteristics measured at a higher irradiance level of 830 W/m². As in the previous case, an increase in average rear surface temperature leads to a significant decrease in the open-circuit voltage. However, at this higher irradiance, the short-circuit current values are noticeably higher than those recorded at 500 W/m², reflecting the increased solar energy input. Similar to the previous set of characteristics, the I_{SC} shows a slight upward trend with temperature, but the voltage drop remains the predominant factor affecting the power output.

The P-V characteristics for the 830 W/m² irradiance level further highlight the temperature-dependent decline in maximum power output. The power peaks at higher irradiance are significantly greater compared to the 500 W/m² case, but the decrease in power with increasing average rear surface temperature remains evident. The higher irradiance improves current generation, but the overall power output is still negatively impacted by the temperature rise.

When comparing the I-V and P-V characteristics between the two irradiance levels, it is evident that higher irradiance significantly increases the current values, as expected due to the greater incident solar energy. However, the temperature-induced decline in voltage remains consistent across both irradiance conditions. This indicates that while increased irradiance enhances current generation, it does not mitigate the voltage loss caused by average rear surface temperature rise. As a result, the overall power output of the PV panel is significantly affected by temperature, regardless of the irradiance level.

The experimental results clearly demonstrate that average rear surface temperature rise negatively impacts the performance of

monocrystalline PV panels, primarily through a reduction in the open-circuit voltage. Although the short-circuit current shows a minor increase with temperature, it is not sufficient to offset the voltage decrease. Consequently, the maximum power output decreases significantly as the temperature rises, and this effect is consistent across both irradiance levels. These findings emphasize the importance of thermal management in photovoltaic applications, especially in environments with high solar irradiance and elevated temperatures, to maintain optimal energy yield.

The data presented in Table 3 include key electrical parameters, for all PV panels, such as V_{OC}, I_{SC}, and power at P_{MPP} evaluated across an average rear surface temperature range of 30°C to 70°C. The analysis considers two irradiance levels: 500 W/m² and 830 W/m², simulating moderate and high solar radiation scenarios, respectively.

For the monocrystalline panel at an irradiance of 500 W/m², the power at the maximum power point (P_{MPP}) decreases from 4.4 W at 30°C to 3.7 W at 70°C, reflecting a total decrease of approximately 15.9%. The decline in P_{MPP} is relatively consistent across temperature increments, with percentage changes ranging from – 4.55% to – 5.0%. This trend is primarily attributed to a reduction in the open-circuit voltage as temperature increases, while the short-circuit current shows a minor increase, insufficient to offset the voltage loss.

The polycrystalline panel under the same irradiance condition (500 W/m²) exhibits

a similar but slightly less pronounced decrease in P_{MPP} from 4.1 W at 30°C to 3.7 W at 70°C, corresponding to an overall reduction of around 9.8%. The percentage change between temperature increments varies between – 2.44% and – 2.63%, indicating that polycrystalline panels are marginally less sensitive to average rear surface temperature changes compared to monocrystalline panels. Polycrystalline PV panels are less sensitive to temperature increases compared to monocrystalline panels due to their multi-crystalline structure, which reduces the mobility of charge carriers and minimizes the impact of thermal expansion on voltage. Additionally, polycrystalline cells have a slightly lower temperature coefficient, resulting in a smaller voltage drop with rising average rear surface temperature. This structural difference makes polycrystalline panels more thermally stable, while monocrystalline panels, despite higher efficiency, exhibit a more significant power loss at elevated temperatures.

In contrast, the amorphous panel at 500 W/m² shows a significantly smaller reduction in power output, from 1.1 W at 30°C to 1.0 W at 70°C, indicating a total decrease of approximately 9.1%. The percentage changes between temperatures are relatively minor, except for a more significant drop of – 9.09% between 60°C and 70°C. This indicates that amorphous silicon panels exhibit better thermal stability compared to crystalline silicon panels, likely due to the material properties and the lower density of defects that influence charge carrier recombination.

Table 3. Results for open-circuit voltage, short-circuit current and power in MPP

Series	30°C			40°C			50°C			60°C			70°C		
	U _{OC} [V]	I _{SC} [mA]	P _{MPP} [W]	U _{OC} [V]	I _{SC} [mA]	P _{MPP} [W]	U _{OC} [V]	I _{SC} [mA]	P _{MPP} [W]	U _{OC} [V]	I _{SC} [mA]	P _{MPP} [W]	U _{OC} [V]	I _{SC} [mA]	P _{MPP} [W]
Monocrystalline-500	21.0	289.0	4.4	20.0	292.3	4.2	19.0	298.2	4.0	18.2	303.8	3.8	17.0	309.0	3.7
Polycrystalline-500	20.6	285.6	4.1	19.8	289.5	4.0	18.9	295.0	3.9	17.9	301.0	3.8	17.0	306.1	3.7
Amorphous-500	20.9	91.5	1.1	20.1	93.0	1.1	19.0	95.2	1.1	18.3	96.5	1.0	17.1	98.7	1.0
Monocrystalline-830	21.2	382.0	5.8	20.5	385.0	5.6	19.8	389.0	5.5	18.9	395.0	5.4	17.1	409.0	4.9
Polycrystalline-830	21.1	362.0	5.5	20.5	370.0	5.5	19.9	378.0	5.4	19.1	385.0	5.3	17.9	392.0	5.1
Amorphous-830	21.4	110.5	1.3	20.2	112.2	1.3	19.1	114.6	1.3	18.0	116.2	1.2	16.9	117.1	1.2

When analyzing the data for higher irradiance (830 W/m²), the monocrystalline panel again shows a substantial decrease in P_{MPP} from 5.8 W at 30°C to 4.9 W at 70°C, resulting in an overall reduction of approximately 15.5%. The decline is particularly pronounced between 60°C and 70°C, where the percentage change reaches – 9.26%. This enhanced sensitivity at higher irradiance levels can be attributed to increased thermal stress on the panel, leading to more significant reductions in V_{OC}.

The polycrystalline panel at 830 W/m² shows a decrease in P_{MPP} from 5.5 W at 30°C to 5.1 W at 70°C, with an overall reduction of around 7.3%. The changes between temperature increments remain relatively consistent, ranging from 0.0% to – 3.77%. This again confirms that polycrystalline panels are less affected by temperature compared to monocrystalline ones, even at higher irradiance.

The amorphous panel under high irradiance (830 W/m²) shows minimal variation, with P_{MPP} decreasing from 1.3 W at 30°C to 1.2 W at 70°C, corresponding to a total decrease of about 7.7%. The percentage changes remain low throughout, indicating that amorphous panels maintain their power output effectively even under high temperature and irradiance conditions.

When comparing the PV panels under different irradiance conditions, it is evident that the increase in irradiance from 500 W/m² to 830 W/m² significantly enhances the power output of all panel types due to increased current generation. However, the average rear surface temperature sensitivity differs across the technologies. Monocrystalline panels show a more pronounced reduction in power with increasing temperature, particularly at higher irradiance, where the voltage drop is more significant. In contrast, polycrystalline panels demonstrate better temperature resilience, maintaining relatively stable power output even as temperature increases. The most stable performance is observed in amorphous panels, which exhibit minimal changes in P_{MPP} across both irradiance and temperature variations.

Temperature coefficients α , β and γ

To illustrate the impact of the average rear surface temperature on the operation of the tested photovoltaic panels, the temperature coefficients α (short-circuit current, Equation 1), β (open-circuit voltage, Equation 2), and γ (power, Equation 3) were determined. These coefficients are essential for evaluating the thermal performance of photovoltaic panels, as the temperature of the rear side of the PV panel directly affects the power output.

Temperature coefficients provide quantitative insight into how variations in temperature influence key electrical parameters of PV panels. They are particularly important when designing PV systems for environments with significant temperature fluctuations, as they help predict efficiency losses and optimize panel selection.

$$\alpha = \frac{dI_{sc}}{dT} \left[\frac{A}{K} \right] \text{ or } \alpha = \frac{dI_{sc}}{I_{sc}} \left[\frac{\%}{K} \right] \quad (1)$$

$$\beta = \frac{dV_{oc}}{dT} \left[\frac{V}{K} \right] \text{ or } \beta = \frac{dV_{oc}}{V_{oc}} \left[\frac{\%}{K} \right] \quad (2)$$

$$\gamma = \frac{dP_{MPP}}{dT} \left[\frac{W}{K} \right] \text{ or } \gamma = \frac{dP_{MPP}}{P_{MPP}} \left[\frac{\%}{K} \right] \quad (3)$$

The coefficient α represents the change in the I_{SC} per degree Celsius (°C) increase in temperature. Typically, α is positive, indicating that I_{SC} slightly increases with PV panel temperature due to enhanced thermal generation of charge carriers. However, the increase is usually minimal and does not compensate for the losses caused by voltage reduction.

The coefficient β quantifies the change in the V_{OC} with PV panel temperature. It is generally negative, reflecting the significant decrease in V_{OC} as the PV panel temperature rises. This decrease is primarily due to increased recombination rates and reduced bandgap energy at higher temperatures, leading to a decline in the potential difference across the PV cell.

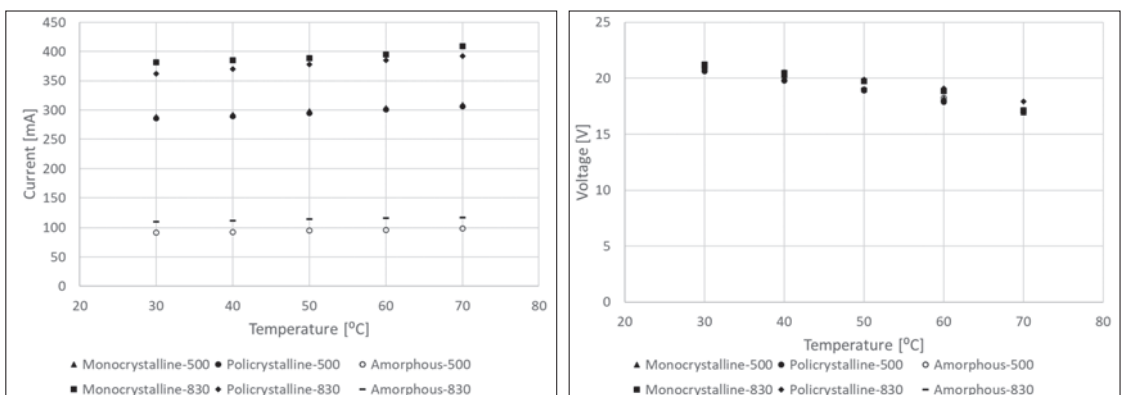
The coefficient γ indicates the change in P_{MPP} with temperature and is also negative. This parameter directly correlates with the reduction in power output as both voltage and efficiency decrease with increasing temperature. Typically, γ is more pronounced in monocrystalline panels compared to polycrystalline or amorphous panels.

The presented graphs (Figures 4 and 5) illustrate the influence of average rear surface temperature on the current, voltage, and power at the maximum power point of various PV panels under different irradiance conditions. The analysis encompasses monocrystalline, polycrystalline, and amorphous PV panels subjected to irradiance levels of 500 W/m² and 830 W/m², with temperatures ranging from 30°C to 70°C.

Figure 4a shows the variation of short-circuit current as a function of average rear surface temperature for the different PV panels. It is evident that for all panel types, the current increases slightly as the temperature rises. This trend is more pronounced for the panels tested at higher irradiance (830 W/m²), particularly for the monocrystalline and polycrystalline panels, where the current values reach approximately 400 mA at 70°C. In contrast, the amorphous panels exhibit significantly lower current values, with a modest increase from around 90 mA at 30°C to about 117 mA at 70°C under the 830 W/m² irradiance. At lower irradiance (500 W/m²), the current levels for monocrystalline and polycrystalline panels are consistently around 300 mA, while the amorphous panel reaches only about 98 mA at the highest temperature. The increase in current with temperature can be attributed to enhanced thermal excitation of charge carriers, which slightly raises the current generation despite the thermal losses. However, the magnitude of the increase is relatively small compared to the decline in voltage observed in the subsequent analysis.

Figure 4b depicts the relationship between open-circuit voltage and average rear surface temperature for the PV panels. It clearly shows a decreasing trend of voltage as the temperature increases, which is consistent

Figure 4. Relation I_{SC} (left – a) and U_{OC} (right – b) as a function of PV panel temperature



across all panel types and irradiance levels. For both monocrystalline and polycrystalline panels, the voltage decreases from approximately 21 V at 30°C to around 17 V at 70°C under both irradiance conditions. Amorphous panels also display a decrease, albeit starting from a slightly lower voltage level. The reduction in voltage with temperature is primarily due to the increased recombination rates of charge carriers and the narrowing of the semiconductor bandgap at elevated temperatures. This decrease in voltage is more critical for monocrystalline panels, where the voltage drop is more pronounced compared to polycrystalline and amorphous types. The relatively stable voltage decrease between the two irradiance levels suggests that the thermal effects dominate over the variations caused by different irradiance intensities.

Figure 5 shows the power at the maximum power point as a function of average rear surface temperature of the PV panel. The

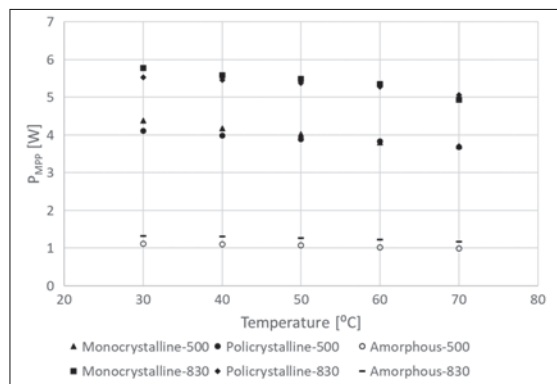


Figure 5. Relation P_{MPP} as a function of PV panel temperature

power output decreases with increasing temperature for all tested PV panels. Monocrystalline panels at 830 W/m² exhibit the highest power at lower temperatures, around 5.8 W at 30°C, but this decreases significantly to 4.9 W at 70°C, indicating a substantial reduction in power efficiency. Polycrystalline panels under the same conditions show a similar trend, though slightly less pronounced, decreasing from 5.5 W to 5.1 W over the same temperature range. For the lower irradiance level (500 W/m²), the power output of monocrystalline panels decreases from 4.4 W at 30°C to 3.7 W at 70°C, while polycrystalline panels drop from 4.1 W to 3.7 W. Amorphous panels, both at 500 W/m² and 830 W/m², exhibit minimal power output variations, with only slight decreases from 1.3 W to 1.2 W across the temperature range. This consistent reduction in power with temperature increase is primarily due to the combination of voltage reduction and the limited increase in current, resulting in an overall negative impact on the panel efficiency.

The presented Table 4 summarizes the temperature coefficients (α , β , and γ) for dif-

Table 4. Temperature coefficients α , β and γ for different values of irradiance

Type of panel	α		β		γ	
	[mA/°C]	[%/°C]	[V/°C]	[%/°C]	[W/°C]	[%/°C]
Monocrystalline-500	0.500	0.162	-0.101	-0.594	-0.017	-0.460
Polycrystalline-500	0.513	0.167	-0.091	-0.535	-0.011	-0.292
Amorphous-500	0.180	0.182	-0.095	-0.552	-0.003	-0.294
Monocrystalline-830	0.675	0.165	-0.102	-0.592	-0.021	-0.430
Polycrystalline-830	0.750	0.191	-0.080	-0.445	-0.012	-0.228
Amorphous-830	0.165	0.141	-0.113	-0.667	-0.004	-0.310

ferent PV panels under two irradiance levels: 500 W/m² and 830 W/m².

The coefficient α represents the change in short-circuit current with temperature. Among the tested panels, the highest values of α are observed for the polycrystalline panel at 830 W/m² (0.750 mA/°C, 0.191%/°C) and monocrystalline at 830 W/m² (0.675 mA/°C, 0.165%/°C), indicating a significant increase in current with rising temperature under high irradiance. In contrast, the amorphous panels exhibit the lowest values

and - 0.102 V/°C (-0.592%/°C) for 830 W/m², highlighting a more pronounced voltage drop compared to polycrystalline and amorphous panels. Polycrystalline panels, particularly at 830 W/m², show less voltage sensitivity with a value of - 0.080 V/°C (-0.445%/°C). Amorphous panels demonstrate intermediate voltage sensitivity with values of - 0.095 V/°C (-0.552%/°C) at 500 W/m² and - 0.113 V/°C (-0.667%/°C) at 830 W/m². This pattern indicates that crystalline silicon, particularly monocrystalline, is more prone to voltage loss at higher temperatures, while amorphous silicon shows a relatively moderate voltage reduction.

The coefficient γ reflects the temperature-induced change in maximum power output. It is consistently negative for all panel types, indicating that the power decreases as temperature rises. Monocrystalline panels again exhibit the most significant power loss with increasing temperature, particularly at 500 W/m² (-0.017 W/°C, - 0.460%/°C) and 830 W/m² (-0.021 W/°C, - 0.430%/°C). Polycrystalline panels show a lower decrease, with - 0.011 W/°C (-0.292%/°C) at 500 W/m² and - 0.012 W/°C (-0.228%/°C) at 830 W/m². Amorphous panels exhibit the least power sensitivity with temperature, showing - 0.003 W/°C (-0.294%/°C) at 500 W/m² and - 0.004 W/°C (-0.310%/°C) at 830 W/m². This demonstrates that amorphous panels, while inherently less efficient, maintain more stable power output under varying thermal conditions compared to crystalline silicon panels.

Panels efficiency and fill factor

The next step was to determine the panels efficiency (η) and fill factor (FF). Table 5 summarizes the efficiency and fill factor of different PV panels under varying average

Table 5. Summary of panels efficiency and fill factor

Type of panel	30°C		40°C		50°C		60°C		70°C	
	η [%]	FF [-]	η [%]	FF [-]	η [%]	FF [-]	η [%]	FF [-]	η [%]	FF [-]
Monocrystalline-500	13.5	0.723	12.9	0.715	12.4	0.710	11.7	0.689	11.4	0.706
Polycrystalline-500	12.2	0.699	11.8	0.694	11.5	0.698	11.4	0.713	10.9	0.708
Amorphous-500	1.5	0.582	1.5	0.589	1.5	0.597	1.4	0.578	1.4	0.589
Monocrystalline-830	10.7	0.714	10.4	0.709	10.2	0.715	9.9	0.718	9.2	0.704
Polycrystalline-830	9.9	0.724	9.8	0.720	9.6	0.715	9.4	0.718	9.0	0.722
Amorphous-830	1.1	0.559	1.1	0.576	1.1	0.582	1.0	0.589	1.0	0.594

rear surface temperature conditions (30°C to 70°C) and irradiance levels (500 W/m² and 830 W/m²). These metrics provide crucial insights into the energy conversion capability and the quality of electrical output of the tested PV panels.

The data clearly show that the efficiency of all tested PV panels decreases as the temperature increases, regardless of the irradiance level. This trend is consistent with the typical behavior of solar cells, where elevated temperatures reduce voltage more significantly than they increase current, resulting in a net decrease in power output. For the monocrystalline panel at 500 W/m², the efficiency drops from 13.5% at 30°C to 11.4% at 70°C, representing an approximate reduction of 15.6%. Similarly, the monocrystalline panel at 830 W/m² shows a decrease from 10.7% at 30°C to 9.2% at 70°C, indicating a decrease of around 14%. This indicates that monocrystalline panels are particularly sensitive to temperature increases, which significantly affect their efficiency, especially at higher irradiance.

The polycrystalline panel at 500 W/m² exhibits a reduction in efficiency from 12.2% at 30°C to 11.0% at 70°C, showing a decrease of about 9.8%. Under higher irradiance (830 W/m²), the polycrystalline panel's efficiency decreases from 9.9% at 30°C to 9.0% at 70°C, reflecting a decrease of approximately 9.1%. These results suggest that polycrystalline panels exhibit better thermal stability compared to monocrystalline panels, maintaining relatively higher efficiency as the temperature rises.

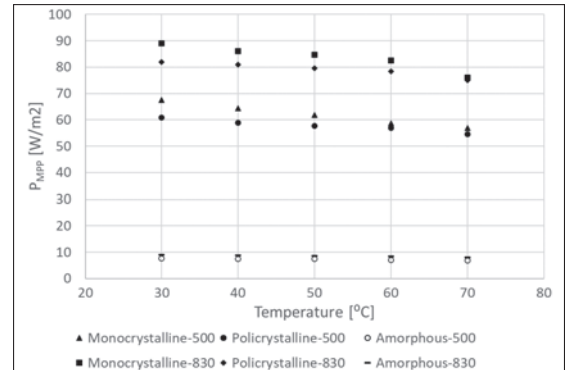
Amorphous panels display significantly lower efficiency compared to crystalline panels. At 500 W/m², the efficiency of the amorphous panel decreases slightly from 1.5% at 30°C to 1.4% at 70°C, showing a reduction of around 6.7%. At 830 W/m², the efficiency remains almost unchanged, fluctuating slightly around 1.1%. This minimal change highlights the thermal resilience of amorphous silicon, which, despite its lower efficiency, exhibits stability in performance across varying temperatures.

The results indicate that the fill factor decreases slightly with increasing temperature for all panel types. The monocrystalline panel at 500 W/m² shows a decrease in FF from 0.723 at 30°C to 0.706 at 70°C, while at 830 W/m², it decreases from 0.714 to 0.704. Similarly, the polycrystalline panel at 500 W/m² exhibits a decrease from 0.699 at 30°C to 0.708 at 70°C, and at 830 W/m², it drops from 0.724 to 0.722. The amorphous panels show a more pronounced reduction in FF at 500 W/m², from 0.582 at 30°C to 0.589 at 70°C, while at 830 W/m², the FF improves slightly from 0.559 to 0.594.

Power in maximum power point per unit area

The presented graph (Figure 6) illustrates the power output per unit area (1 m²) of different photovoltaic panels under varying temperature conditions, ranging from 30°C to 70°C and different irradiance. Since the tested PV panels had different surface areas, standardizing the power output to a unit area was essential to accurately assess the impact of different PV technologies on the results. This normalization allows for a fair comparison between the panel types, regardless of their physical size.

Figure 6.
Relation P_{MPP} as a function of PV panel temperature



The graph clearly shows that monocrystalline and polycrystalline panels tested under higher irradiance conditions (830 W/m²) exhibit the highest power density, reaching around 85-90 W/m² at lower temperatures (30°C). As the temperature increases, the power output per unit area decreases slightly, with a drop of approximately 10% by 70°C. This decline is consistent with the known temperature sensitivity of crystalline silicon panels, where increased temperature leads to a decrease in voltage, and consequently, a reduction in power output.

For monocrystalline and polycrystalline panels tested under lower irradiance (500 W/m²), the power density is significantly lower, starting at approximately 65-70 W/m² at 30°C and decreasing to around 60 W/m² at 70°C. The percentage reduction in power per unit area is similar to that observed at higher irradiance, indicating that while the absolute values differ, the relative effect of temperature on power loss remains comparable.

The amorphous PV panels show distinctly lower power density compared to crystalline panels, both at 500 W/m² and 830 W/m². Their power output per unit area remains relatively constant, ranging between 10 to 12 W/m², with minimal variation across the temperature range. This stability is characteristic of amorphous silicon technology, which exhibits lower temperature sensitivity compared to crystalline silicon. The relatively consistent power density, despite temperature fluctuations, makes amorphous panels more suitable

for applications where maintaining output under variable thermal conditions is critical.

Summary of experimental results

The experimental analysis of photovoltaic panels under varying irradiance levels (500 W/m² and 830 W/m²) and average rear surface temperatures revealed significant differences in performance among monocrystalline, polycrystalline, and amorphous silicon modules.

The current-voltage and power-voltage characteristics revealed that an increase in the rear surface temperature of PV panels signifi-

cantly reduces the open-circuit voltage, slightly increases the short-circuit current, and leads to an overall decline in power output—particularly in monocrystalline panels. Higher irradiance levels increase current, but the relative temperature-induced power loss remains consistent across different irradiance conditions.

Temperature coefficients (α , β , γ) showed that monocrystalline panels are the most sensitive to temperature changes, particularly with more negative β and γ values, indicating significant voltage and power loss. Polycrystalline panels displayed better thermal stability, while amorphous panels demonstrated the least sensitivity, maintaining more stable power output.

Efficiency decreased with rising temperature for all panels, with monocrystalline panels showing the largest decline, followed by polycrystalline, while amorphous panels remained stable. The fill factor also slightly decreased with temperature, particularly in crystalline panels, but remained more consistent in amorphous panels.

Power per unit area (1 m²) showed that monocrystalline and polycrystalline panels at high irradiance (830 W/m²) produced the highest power density, decreasing by about 10% with rising temperature. Amorphous panels, despite lower power density, maintained consistent performance, indicating better thermal resilience.

Overall, monocrystalline PV panels are highly efficient but more susceptible to temperature-induced power losses, while

polycrystalline panels exhibit moderate stability, and amorphous panels, though less efficient, offer the best thermal performance. This highlights the importance of considering thermal management for monocrystalline systems, especially in high-temperature environments.

Model in the TRNSYS software

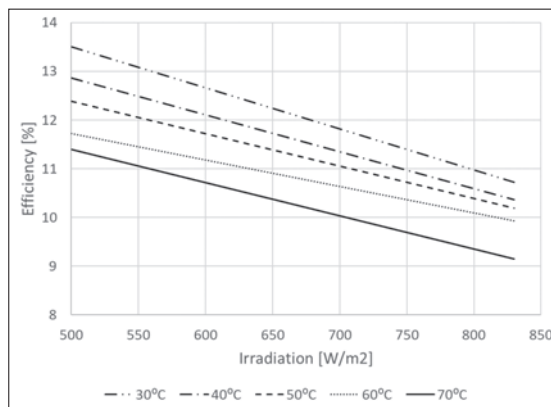
After conducting experimental research and obtaining relevant data, the development of a dynamic model of a simple PV system based on the tested panels was initiated. The experimental results, including current-voltage characteristics, power-voltage characteristics, temperature coefficients, efficiency, and power per unit area, were utilized to create an accurate and realistic model. The primary goal of the modeling process was to calculate the energy yield of each PV panel and compare their performance throughout the year to identify the most efficient configuration.

TRNSYS software was employed for this purpose, offering the capability to simulate energy yield and analyze the performance of PV systems under various climatic conditions. By incorporating experimental data, TRNSYS enabled precise calculations of power generation and energy output, taking into account the effects of rear surface temperature and irradiance variations on PV panel performance. The simulation also allowed the identification of optimal temperature conditions for each panel to maximize energy production while minimizing the need for excessive cooling.

Power generation and energy yield were calculated using the TRNSYS tool, which is widely used for simulating energy systems and operates on component models that incorporate experimental data and manufacturer specifications. The simulation model was developed based on self-prepared PV panel models and utilized meteorological data sourced from the Meteororm database. This approach enabled the determination of annual energy generation for different types of PV panels, considering real-world environmental conditions and allowing for a comprehensive performance comparison.

The Figure 7 shows the change in efficiency for a monocrystalline PV panel under various temperature conditions, illustrating the relationship between efficiency and irradiance for temperatures ranging from 30°C to 70°C. The analysis was conducted using the TRNSYS software to model the dynamic behavior of the PV panel based on the experimental data. The calculations were performed specifically for the city of Krakow, Poland, with the PV panels oriented south

Figure 7. Efficiency of the monocrystalline panel as a function of irradiance



and inclined at an angle of 40°, which is optimal for the location. The time step was 0.125 hours and using solar radiation data obtained from the Meteororm database.

The analysis was conducted for three representative temperatures: 30°C, 50°C, and 70°C, selected to reflect typical operational conditions and extreme scenarios. These temperature levels help to understand how the monocrystalline panel behaves under varying environmental conditions throughout the year. The calculated energy yield from the unit surface of the panel shows that maintaining lower temperatures is crucial for achieving higher efficiency, particularly during periods of strong solar radiation.

The general formula describing the power generated by a photovoltaic panel is expressed as follows:

$$P = \frac{a \cdot I_x^2 + b \cdot I_x}{100} \quad (4)$$

Where:

- P – represents the power output of the PV panel, [W],
- I_x – denotes the solar irradiance incident on the panel surface, [W/m²],
- a and b are empirical coefficients derived from experimental data or simulation results that account for the panel's efficiency and temperature effects.

This Equation 4 reflects the relationship between the solar irradiance and the resulting power output of the PV panel, incorporating quadratic and linear terms to account for the nonlinear behaviour observed in real PV systems. The division by 100 ensures that the power value is appropriately scaled.

Table 6 below presents the parameters a and b that describe the relationship between the power output of each photovoltaic panel and the irradiance at a given temperature.

Table 6. Parameters a and b

Type of panel	30 °C		50 °C		70 °C	
	a	b	a	b	a	b
Monocrystalline	-0.0084	17.7120	-0.0066	15.6980	-0.0068	14.8090
Polycrystalline	-0.0070	15.6800	-0.0059	14.4690	-0.0056	13.7180
Amorphous	-0.0013	2.1715	-0.0013	2.1064	-0.0012	1.9509

These parameters were obtained through regression analysis based on experimental data and reflect the specific characteristics of each panel type under varying temperature conditions. By incorporating these coefficients into the general power formula, it is possible to accurately predict the power output as a function of irradiance, facilitating reliable performance modelling and simulation.

Figure 8 show the power output per unit area (W/m²) of PV panels for a selected day of the year (July 1st) under three different temperature conditions: 30°C, 50°C, and 70°C. The graphs illustrate the diurnal variation in power generation throughout the day, capturing the typical pattern of solar energy production, with a peak around midday. The time on the horizontal axis is expressed in hours (h), and the power on the vertical axis is normalized to unit area. The three graphs correspond to different PV panel types: monocrystalline (Figure 8a), polycrystalline (Figure 8b), and amorphous (Figure 8c).

Figure 8a, representing the monocrystalline panel, shows a clear peak in power output at around midday, with the highest power recorded at 30°C (approximately 90 W/m²), followed by 50°C and then 70°C. The difference between the power peaks is distinct, indicating that as the temperature increases, the power output decreases. This reduction is primarily due to the temperature sensitivity of monocrystalline panels, where an increase in temperature results in a significant drop in V_{OC} and, consequently the V_{MPP}. The characteristic sharp rise and fall of the curve reflect the high efficiency of monocrystalline technology during peak irradiance periods, but also its susceptibility to temperature-induced losses.

Figure 8b, illustrating the polycrystalline panel, follows a similar pattern but with

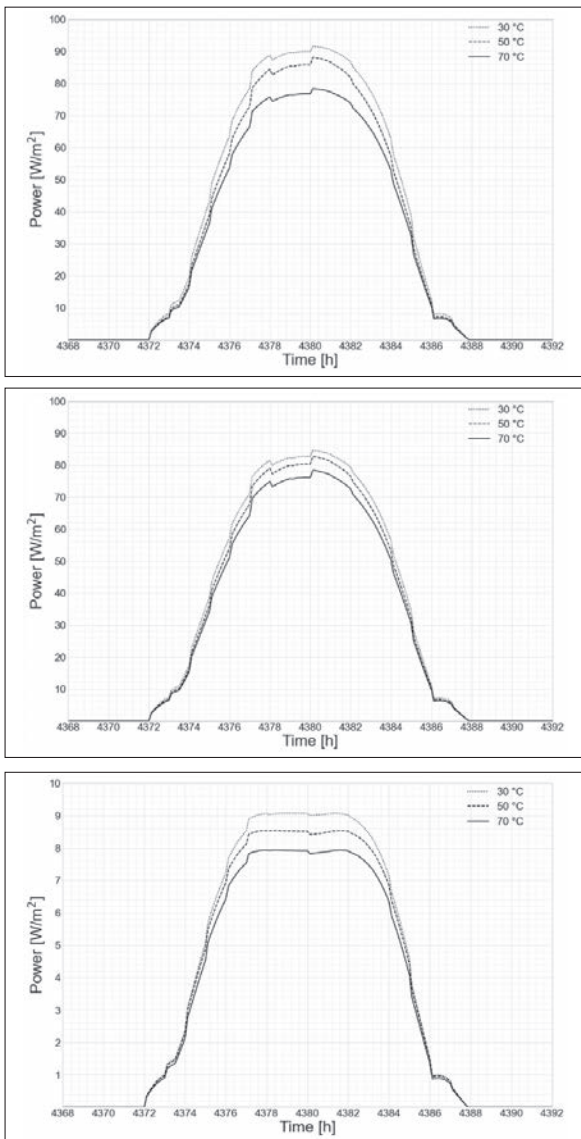


Figure 8. The power of monocrystalline (left – a) polycrystalline (right – b) and amorphous (bottom – c) panels in July 1st

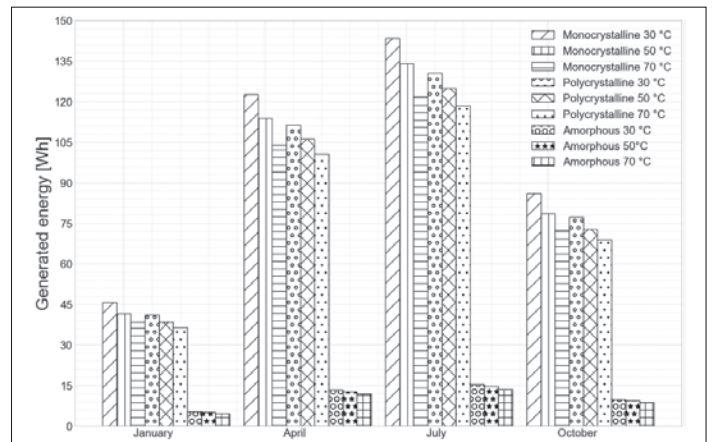


Figure 9. Energy yield for typical days

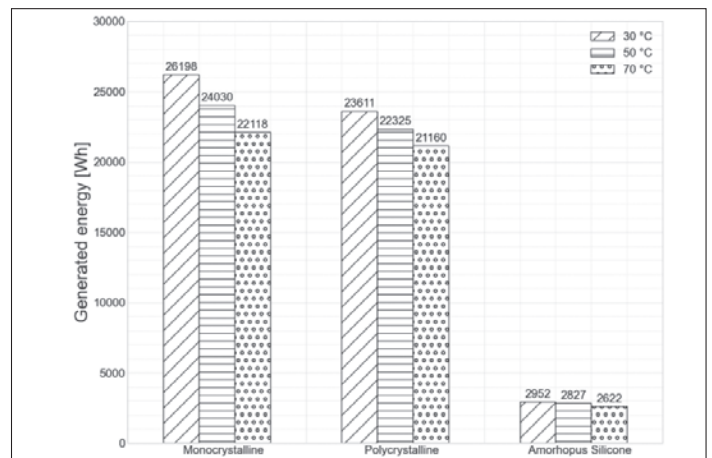


Figure 10. Energy yield in whole year

slightly lower peak power values compared to the monocrystalline panel. At 30°C, the peak power reaches around 85 W/m², while at 70°C, it drops to approximately 75 W/m². The decrease in power with temperature is evident, but the gap between the power curves for different temperatures is somewhat smaller than that observed in the monocrystalline panel. This indicates that polycrystalline panels, while also affected by temperature rise, maintain a relatively more stable power output compared to monocrystalline panels, which aligns with their known characteristics of better thermal resilience.

Figure 8c shows the power output of the amorphous panel. The peak power values are significantly lower, reaching about 9 W/m² at 30°C, 8.5 W/m² at 50°C, and around 8 W/m² at 70°C. The power difference between temperature levels is less pronounced compared to crystalline panels, indicating that amorphous silicon panels exhibit higher thermal stability. The curve shapes are similar, but the relatively flat peak suggests that amorphous panels do not respond as sensitively to

temperature changes, maintaining more consistent power output throughout the day.

Figure 9 shows the energy yield of different PV panels (monocrystalline, polycrystalline, and amorphous) for four typical days (January, April, July, October), considering three temperature conditions (30°C, 50°C, 70°C). Monocrystalline panels consistently generate the highest energy, followed by polycrystalline, while amorphous panels produce the least. The energy yield decreases as temperature rises, particularly for crystalline panels, with the largest difference observed in July, reflecting the negative impact of high temperatures on efficiency.

Figure 10 presents the total annual energy yield for each PV technology under the same temperature conditions. Monocrystalline panels achieve the highest annual output, ranging from 26,198 Wh at 30°C to 22,118 Wh at 70°C. Polycrystalline panels also perform well, generating between 23,611 Wh and 21,160 Wh. Amorphous panels produce significantly less, ranging from 2,952 Wh to 2,622 Wh. While monocrystalline panels are

the most efficient, they are more sensitive to temperature increases, whereas amorphous panels maintain relatively stable performance despite lower overall yields.

The analysis performed using the TRNSYS software clearly indicates that the monocrystalline panel operating at a maximum temperature of 30°C is the most efficient, achieving the highest annual energy yield. However, maintaining such a low temperature during summer and transitional periods is challenging, even with intensive cooling. Therefore, it appears more practical to aim for a panel temperature of around 40°C, which is more achievable under typical conditions.

Cooling the monocrystalline panel to approximately 40°C would result in an estimated annual energy yield of around 25,100 Wh, which is only about 4% less compared to maintaining the ideal temperature of 30°C. In comparison, using a polycrystalline panel at 40°C would generate approximately 22,950 Wh annually, which is about 9% lower than the monocrystalline panel under the same temperature conditions. These findings suggest that

while monocrystalline panels offer the best performance, maintaining optimal temperatures through feasible cooling strategies is crucial to maximizing energy yield, especially in warmer climates.

Conclusion

This study combined laboratory experiments and TRNSYS-based simulations to evaluate the temperature-dependent performance of three photovoltaic technologies: monocrystalline, polycrystalline, and amorphous silicon. The key findings are as follows:

1. Monocrystalline PV panels exhibited the highest efficiency under standard conditions but were the most sensitive to temperature increase. Their power output dropped by approximately 15.5-15.9% when the surface of the PV panel temperature rose from 30°C to 70°C.
2. Polycrystalline panels showed better thermal resilience than monocrystalline ones. Their power losses over the same temperature range were lower, ranging from 7.3% to 9.8%, making them more stable under elevated temperatures.
3. Amorphous silicon panels had the lowest efficiency but demonstrated excellent thermal stability, with power reductions limited to 7.7-9.1% across the full temperature range and minimal changes in efficiency and fill factor.
4. Temperature coefficients (α , β , γ) derived from measurements confirmed these trends, with the most negative values found for monocrystalline panels and the least negative for amorphous panels, indicating distinct temperature sensitivities across technologies.
5. Efficiency and fill factor decreased with rising temperature for all technologies. The largest declines were recorded for monocrystalline panels, while amorphous panels maintained nearly constant values, reinforcing their suitability in thermally challenging environments.
6. TRNSYS simulations showed that monocrystalline panels achieved the highest annual energy yield under favorable thermal conditions. A panel temperature of 40°C resulted in only approx. 4% energy loss compared to the ideal 30°C scenario, demonstrating the practical feasibility of partial thermal management.
7. The selection of PV technology should be guided not only by nominal efficiency but also by temperature-dependent performance characteristics. In hot climates or installations with limited cooling potential, technologies with lower thermal sensitivity may offer superior long-term energy yield. The findings of this study clearly confirm that PV module performance is highly sensi-

tive to surface temperature variations. While monocrystalline panels provide the highest efficiency, they also suffer the greatest performance decline under thermal stress. Amorphous panels, though less efficient, offer greater output stability at elevated temperatures. These findings emphasize the need to consider both electrical efficiency and thermal behavior when selecting PV technologies and designing systems for real-world conditions, particularly in warm or poorly ventilated environments.

Future research should focus on optimizing PV system design by integrating predictive temperature management strategies. One promising approach is to develop adaptive algorithms that dynamically adjust panel orientation and cooling mechanisms based on real-time weather data, maximizing energy yield while minimizing thermal losses. Additionally, exploring innovative materials for PV panels that inherently possess lower temperature coefficients could significantly enhance performance stability under fluctuating temperature conditions.

Moreover, long-term field studies across diverse climatic regions are essential to validate laboratory and simulation findings, providing insights into real-world performance variability. Investigating hybrid systems that combine PV technology with passive cooling elements, such as phase change materials (PCMs) or natural ventilation systems, could offer sustainable and cost-effective solutions for maintaining optimal operating temperatures.

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Nomenclature

- α , β – line parameters
- FF – fill factor
- I_{MPP} – current at MPP, [mA]
- I_{SC} – short-circuit current, [mA]
- I_x – irradiance [W/m^2]
- MPP – maximum power point
- PV – photovoltaic
- P_{MPP} – maximum power, [W]
- T – temperature, [K]
- V_{MPP} – voltage at MPP, [V]
- V_{OC} – open-circuit voltage, [V]
- α – short-circuit current temperature coefficient, [mA/K], [%/K]
- β – open-circuit voltage temperature coefficient, [V/K], [%/K]
- γ – power temperature coefficient, [W/K], [%/K]
- η – efficiency, [%]

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