

Research Article

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Integrated assessment of irradiance and temperature effects on the electrical performance of contemporary photovoltaic technologies

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Highlights

- Integrated PVGIS-SARAH3 and PSIM framework for realistic PV performance evaluation.
- TOPCon modules achieved the highest efficiency (28.8%) and thermal stability.
- Irradiance increased PV power by about 261%, while temperature reduced it by 23–28%.
- Voltage remained nearly constant, whereas current strongly depended on irradiance.
- Seasonal analysis predicted an annual energy yield of 16,272.7 kWh in central Türkiye

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ABSTRACT

This study presents a comprehensive performance assessment of a 10 kWp grid-connected photovoltaic (PV) system located in Kayseri, Türkiye focusing on the coupled effects of irradiance and temperature on electrical output characteristics. PVGIS-SARAH3 climatic data were employed to model long-term solar resource availability, while PSIM-based single-diode simulations were used to analyze the dynamic electrical and thermal behavior of different PV technologies under operating conditions ranging from 300-1000 W/m² irradiance and 10-90 °C cell temperature. The investigated modules include polycrystalline, monocrystalline, heterojunction (HJT), and advanced N-type TOPCon technologies. Results indicate that the highest conversion efficiency of 28.80% is achieved by the TOPCon module, whereas polycrystalline technology exhibits the lowest performance at 17.74%. Irradiance variation leads to a power increase of approximately 261%, while temperature rise causes up to 23–28% power degradation depending on module type. Voltage output remains relatively stable within 38-42 V, whereas current is highly sensitive to irradiance changes. Seasonal analysis reveals an annual energy yield of 16,272.70 kWh, with approximately 55% of production concentrated between May and September. The findings confirm that N-type and TOPCon technologies provide superior thermal stability and higher energy yield under high-irradiance climates. The proposed integrated PVGIS-PSIM framework offers a robust methodology for realistic PV system performance prediction and technology comparison under field-relevant environmental conditions.

Keywords: Photovoltaic module, Solar panel, Temperature effects, Irradiance

INTRODUCTION

Photovoltaic (PV) modules have become one of the most critical technologies among renewable energy systems, offering sustainable and environmentally friendly solutions for electricity generation. However, the performance and long-term reliability of PV modules are significantly influenced by various environmental and structural factors. In this context, module efficiency and thermal stability are strongly dependent on design parameters such as geometrical dimensions and cell density. Effective thermal management plays a crucial role in controlling module operating temperature and, consequently, in enhancing electrical efficiency. An increase in cell temperature negatively affects electrical performance, leading to significant efficiency losses. Therefore, optimizing PV module design through appropriate geometrical configuration, cell arrangement, and the integration of active and passive cooling strategies is essential to improve thermal stability and system performance.

Recent studies in PV technology have focused both on enhancing material properties to improve temperature-dependent efficiency behavior and on minimizing thermal losses during operation. While some research efforts aim to improve intrinsic material performance and long-term efficiency evolution [1, 2], others concentrate on reducing operational temperature fluctuations through advanced thermal management strategies [3-6].

PV cells typically convert only 5–25% of the incoming solar radiation into electrical energy, while the remaining portion is dissipated as thermal energy, increasing module surface temperature. Since PV conversion efficiency is inversely proportional to temperature, operating conditions above the nominal temperature of 25 °C (under 1000 W/m² standard test conditions) result in a significant performance degradation. It is widely reported that each 1 °C increase in cell temperature leads to an approximate 0.4-0.5% reduction in electrical efficiency [7]. Therefore, thermal stability is defined as the ability of PV modules to maintain operating temperatures within acceptable limits while resisting fluctuations induced by environmental conditions. PV performance varies dynamically throughout the day due to changes in solar irradiance, ambient temperature, tilt angle, and shading conditions [8]. Numerical investigations have further confirmed that operating temperature is one of the most sensitive parameters affecting PV electrical output. For instance, active air cooling systems have been shown to improve electrical efficiency by approximately 7-13% through effective reduction of thermal loads [9].

From a system perspective, PV thermal management strategies can be classified into two hierarchical levels Figure 1. The first is the “material-scale approach,” which focuses on micro-scale improvements such as material modification and structural enhancement at the cell level. The second is the “application-scale approach,” which involves system-level strategies such as cooling techniques, module arrangement, and environmental heat mitigation. While both approaches aim to enhance system efficiency, the former targets microscale material optimization, whereas the latter focuses on macroscopic system performance improvement.

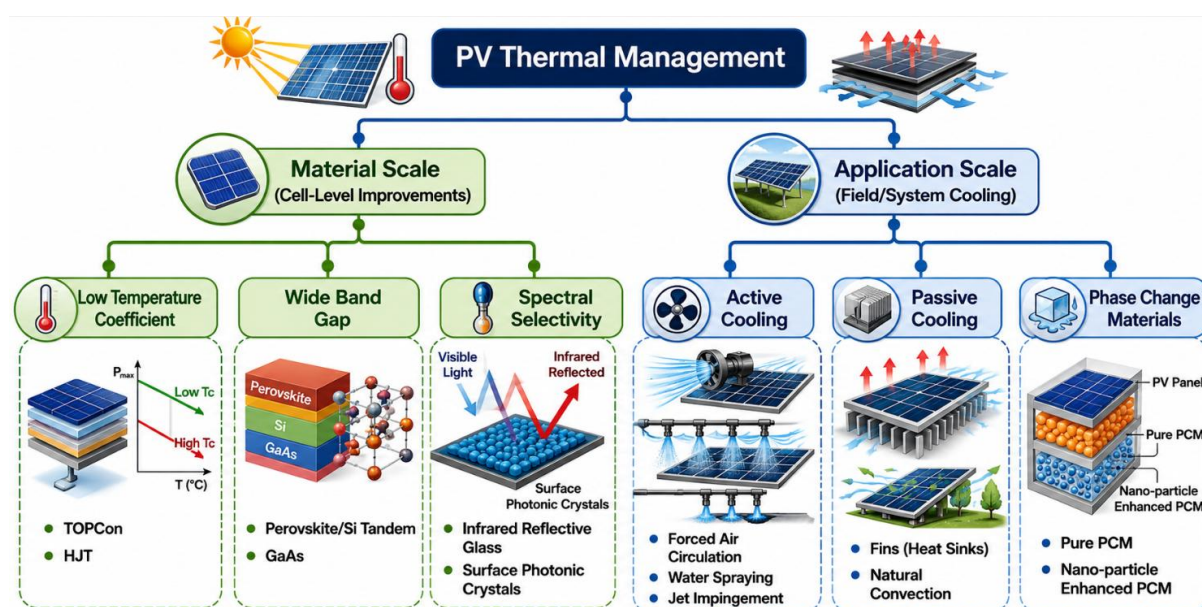


Figure 1. Hierarchical flowchart of photovoltaic thermal management strategies [10]

The influence of geometric parameters on thermal stability is particularly significant. Module surface area, thickness, and cell arrangement directly affect heat transfer mechanisms and temperature distribution. Tilt angle affects natural convection currents, where horizontal positioning reduces convective heat transfer at the lower surface [10]. Furthermore, increasing module length improves heat transfer only up to an optimum value, beyond which thermal accumulation increases module temperature.

Cell density, defined as the spacing and number of cells within a module, also plays a critical role. Although higher cell density increases electrical output potential, it may also intensify heat accumulation, thereby reducing thermal stability. Water-cooled PV modules can achieve up to 15% power enhancement through temperature reduction [11]. Similarly, phase change material

(PCM)-based cooling systems have been reported to reduce module surface temperature by 27–32 °C, resulting in efficiency improvements of 10.9–18.5% [12].

Accurate modeling of temperature-dependent PV performance is also essential. Precise representation of environmental parameters significantly improves energy yield prediction accuracy. PV module temperature can be estimated using empirical equations based on irradiance, wind speed, and wind direction, showing strong agreement with experimental measurements [13]. Material selection also plays a vital role in thermal behavior. Forniés et al. investigated upgraded metallurgical-grade silicon (UMG-Si) cells and reported improved efficiency stability and reduced performance degradation compared to conventional polysilicon-based modules [14]. Similarly, backsheet thermal conductivity significantly influences heat dissipation, where higher conductivity materials reduce temperature rise and improve overall performance [15].

Passive cooling strategies also contribute significantly to thermal regulation. Low wind speeds (<1 m/s) have a strong influence on heat dissipation in HCPV systems, where increasing wind speed reduces maximum cell temperature [16]. However, shading effects remain a critical issue in PV systems, as they increase resistive losses and reduce output power. Moreover, localized hot spots caused by shading can severely degrade module performance [17]. The reliability of performance prediction models is equally important. Marion compared different PV modeling approaches and highlighted the importance of accurate temperature estimation for reliable system performance evaluation [18]. Additionally, the reliability of interconnections between cells is a critical factor, as defects in solder joints and electrical connections can significantly reduce module performance and long-term reliability [19].

Climate-dependent performance variations further emphasize the importance of thermal management. Each 1 °C increase in ambient temperature reduces PV capacity by approximately 0.51%, highlighting the importance of thermal control in hot climates [20]. Long-term degradation effects also play a role in system performance, with annual degradation rates ranging between 0.3% and 0.7% significantly affecting lifetime energy yield and economic performance [21]. Mechanical stress-induced failures further contribute to performance losses, with crack formation leading to measurable power degradation. From an economic perspective, higher efficiency modules reduce levelized cost of electricity, thereby encouraging the adoption of advanced PV technologies [22, 23].

Despite the considerable progress achieved in photovoltaic module design, thermal management technologies, and advanced cell architectures, several important research gaps remain. Most previous studies have primarily focused on either thermal mitigation strategies or the electrical performance of individual photovoltaic technologies under simplified environmental assumptions. Comparatively limited attention has been devoted to the integrated evaluation of irradiance-induced current variation and temperature-induced voltage degradation across different commercially available PV technologies under identical operating conditions. Moreover, comprehensive comparative analyses combining long-term climatic databases with dynamic electrical simulation tools remain scarce. Consequently, a systematic assessment capable of simultaneously quantifying the coupled effects of irradiance, operating temperature, and module technology on photovoltaic electrical performance is still lacking.

To address these limitations, the present study integrates long-term climatic information obtained from the PVGIS-SARAH3 database with detailed PSIM simulations based on the single-diode equivalent circuit model. Four representative photovoltaic technologies, namely polycrystalline silicon, monocrystalline silicon, heterojunction (HJT), and advanced N-type TOPCon modules, are comparatively evaluated under irradiance levels ranging from 300 to 1000 W m⁻² and cell temperatures between 10 and 90 °C. Unlike previous investigations that generally analyze individual performance parameters separately, the proposed framework simultaneously examines the combined influence of irradiance and temperature on power output, current generation, voltage stability, module efficiency, and seasonal energy production. The outcomes provide a comprehensive understanding of the electrical behavior of modern photovoltaic technologies under realistic climatic conditions and offer practical guidance for technology selection and thermal management in regions characterized by high solar irradiance and elevated operating temperatures.

2. METHODOLOGY

The geographic location and site characteristics of the grid-connected PV system investigated in this study are illustrated in Figure 2. The system is located in the Tomarza-1 site of Kayseri Province, Türkiye, within the Central Anatolia Region, at coordinates 38.458° N latitude and 35.810° E longitude.. Long-term solar radiation and meteorological datasets were obtained from the PVGIS-SARAH3 database, which is developed by the European Commission's Joint Research

Centre and provides high-resolution, validated solar resource information. This dataset was used to evaluate the long-term operational performance and to derive monthly and seasonal energy yield profiles of the system based on local climatic conditions. For performance evaluation, PSIM software based on the single-diode equivalent circuit model was employed to simulate the dynamic electrical and thermal behavior of the PV modules. In the simulation environment, module cell temperature (T_{cell}) and incident solar irradiance (G) were defined as independent input variables, while the corresponding electrical outputs, including power (P), voltage (V), and current (I), were analyzed over a wide operating range of 300–1000 W/m² and 10–90 °C. The resulting performance data were systematically extracted from PSIM simulations and summarized in Figure 8-9, enabling a detailed assessment of system behavior under varying environmental conditions. Artificial intelligence-assisted language editing tools were used solely to improve the grammar, language quality, readability, and academic writing style of the manuscript. The study design, methodology, data analysis, interpretation of the results, and final scientific content were developed and verified entirely by the authors.



Figure 2. Geographic location and installed capacity parameters of the PV system [24]

The electrical behaviour of PV modules was simulated in PSIM using a single-diode equivalent circuit model Figure 3. The model consists of a diode characterised by a photocurrent source I_{ph} , a reverse saturation current I_0 and a diode ideality factor (n), as well as a series resistance R_s and a shunt resistance R_{sh} . The electrical characteristics of each photovoltaic module under investigation were characterised under Standard Test Conditions (STC; 1000 W/m² irradiance and 25 °C cell temperature) using the values provided in the manufacturer's data sheet; these

parameters include maximum power P_{max} , maximum power voltage V_{mp} , maximum power current I_{mp} , open-circuit voltage V_{oc} , short-circuit current I_{sc} and the relevant temperature coefficients. The PSIM photovoltaic model parameters were adjusted to reproduce the electrical characteristics specified by the manufacturer for the characteristic points simulated under STC conditions. Following calibration under reference conditions, the calibrated electrical parameters were maintained whilst solar irradiance and cell temperature were varied independently within the ranges of 300–1000 W/m^2 and 10–90 $^{\circ}C$, respectively. This procedure enabled a consistent comparison of the irradiance- and temperature-dependent P–V and I–V characteristics of the photovoltaic technologies under investigation.

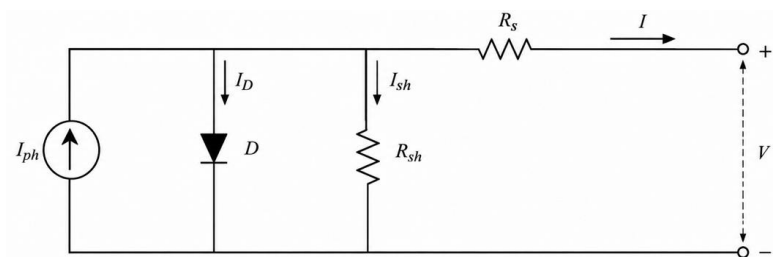


Figure 3. Single-diode model of the PV cell

Within this analytical framework, a comprehensive investigation of PV system performance was conducted by integrating PVGIS-SARAH3 climatic modeling with PSIM-based dynamic simulations. Unlike most previous studies that consider PV performance under either simplified climatic assumptions or isolated electrical and thermal analyses, this work introduces a fully coupled irradiance–temperature–electrical performance evaluation. The main novelty of the study lies in the integrated comparative assessment of multiple commercially available photovoltaic technologies, including polycrystalline, monocrystalline, heterojunction (HJT), and advanced N-type TOPCon modules, under identical environmental conditions. In contrast to existing literature, which typically evaluates efficiency or temperature coefficients independently, this study simultaneously quantifies the combined influence of irradiance variation and thermal stress on key electrical performance parameters, including power output, voltage stability, and current response, thereby providing a more realistic and comprehensive representation of operational PV behavior under field-relevant conditions.

The technical specifications and estimated energy production parameters of a 10 kWp grid-connected PV system are presented in Table 1.

Table 1. Technical characteristics and estimated energy production parameters of the 10 kWp grid-connected PV system obtained from the PVGIS-SARAH3 database.

Parameter	Value
Database Used	PVGIS-SARAH3
Photovoltaic Technology	Crystalline Silicon
Mounting System	Integrated, 1 Section
Installed PV Capacity (kWp)	10.00
Optimal Tilt Angle (Slope)	31°
Optimal Azimuth Angle	-6°
Interannual Variability (%)	3.22
Angle of Incidence Loss (%)	-2.73
Spectral Effects (%)	0.02
Low Temperature and Irradiance Loss (%)	-10.09
Total System Losses (%)	-15.19
Average Daily Energy Production (kWh/day)	44.50
Average Equivalent Production Hours (h/day)	4.50

3. CONCLUSION

Figure 4 illustrates the monthly energy production of the 10 kWp grid-connected photovoltaic system. Annual electricity generation was estimated at 16,272.70 kWh/year, with an interannual variability of 3.22%, indicating stable long-term performance. Energy production is lowest during the winter months, reaching 716.20 kWh in January and 831.52 kWh in December, primarily due to reduced solar irradiance and shorter daylight hours. Energy production increases progressively during the spring, exceeding 1,500 kWh starting in May. The highest monthly generation is observed in August (1,835.74 kWh), closely followed by July (1,827.16 kWh), owing to higher solar radiation levels and longer sunshine durations during the summer. After August, electricity production gradually decreases through the fall and reaches its lowest levels in winter. Overall, approximately 55% of annual energy output is generated between May and September, demonstrating the strong seasonal dependence of photovoltaic electricity production. An analysis of the graph reveals a strong positive correlation between energy production and solar irradiance. While energy production remains limited during the winter months due to low radiation levels, it increases significantly in the spring and summer months as solar radiation increases. In particular, the fact that solar radiation reaches its maximum levels between May and September accounts for

approximately 55% of the total annual production occurring during this period. This clearly demonstrates that solar radiation is one of the key environmental parameters determining the performance of PV systems.

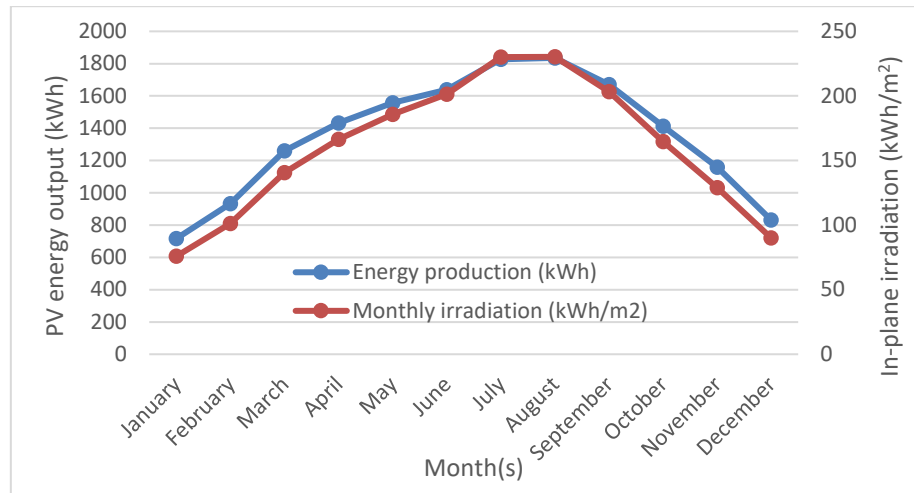


Figure 4. Relationship between monthly solar irradiation and photovoltaic energy output

Figure 5 shows the monthly equivalent full-load operating times of the grid-connected PV system. The equivalent generation time refers to the time period corresponding to the amount of energy that could be generated if the system operated continuously at its nominal power level. The results reveal a distinct seasonal variability in the PV system's energy production performance. During the summer months particularly June, July, and August a notable increase in the system's daily equivalent full-load hours is observed due to longer daylight hours and higher levels of solar irradiance. During this period, the PV system is able to maintain operating conditions close to its nominal power for longer periods.

In contrast, during the winter months, equivalent production hours decrease significantly due to shorter sunshine duration and a reduction in the angle of incidence of solar radiation. This situation causes significant seasonal fluctuations in the system's energy production capacity. The results clearly demonstrate that the PV energy production profile is directly related not only to irradiance intensity but also to meteorological and astronomical parameters such as sunshine duration and solar geometry.

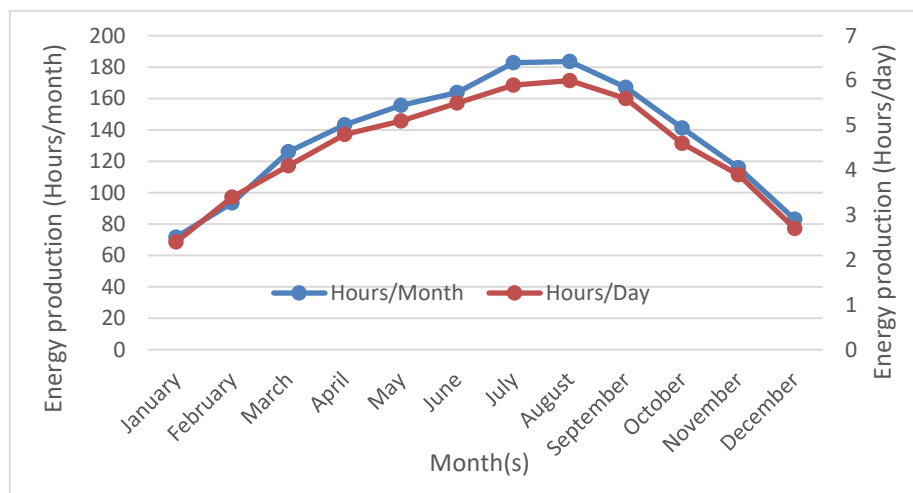


Figure 5. Variation of monthly equivalent photovoltaic production hours throughout the year

Figure 6 shows the relationship between daily energy production and daily equivalent full-load operating hours. The results indicate that the PV system's daily energy production shows a strong correlation with sunshine duration and the diurnal irradiance profile. According to the analysis findings, daily energy production reaches approximately 50–60 kWh/day during the summer, while this value drops to the 20–25 kWh/day range during the winter months. Similarly, daily equivalent production hours approach approximately 6 hours in the summer, while remaining at 2–3 hours during the winter. This confirms that PV system performance varies significantly on a seasonal basis. The results indicate that evaluating only the annual total energy production in PV systems is insufficient; the daily production characteristics are also a critical design parameter. Accurately modeling and accounting for the daily production profile is of great importance, particularly in the development of energy storage systems and load management strategies.

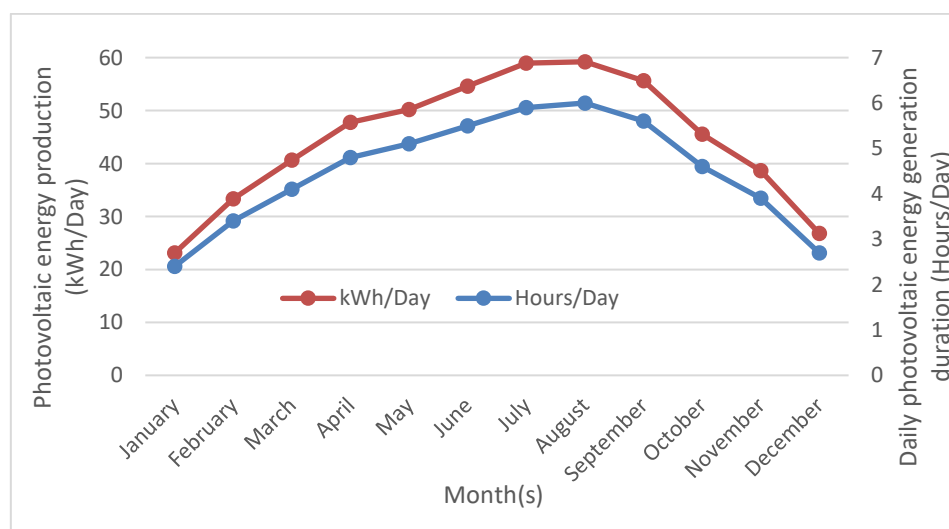


Figure 6. Daily photovoltaic energy production and equivalent operating hours by month

Table 2 presents a comparison of the electrical and thermal performance parameters of PV modules from different manufacturers, including polycrystalline, monocrystalline, half-cut, bifacial, and N-type/TOPCon technologies. It is observed that the maximum power $P_{\max}$ values of the modules under review range from 345 Wp to 745 Wp, and a clear upward trend in power output is evident in parallel with advancements in cell technology. The lowest efficiency value of 17.74% was obtained from the Ödül OSPP72-345 model, which features a polycrystalline structure, while the highest efficiency of 28.80% was recorded in the TommaTech 745 Wp TOPCon Diamond Plus module. This demonstrates that N-type and TOPCon-based cell technologies, in particular, significantly increase energy conversion efficiency. In terms of electrical characteristics, the maximum power voltage V_{mp} ranges from 33.34 V to 55.4 V, while the maximum power current (I_{mp}) ranges from 8.49 A to 17.69 A. High current values are particularly prominent in Jinko 66HL5-BDV and CWT series modules, while higher voltage values are observed in advanced technology modules such as the REC Alpha Pure-RX. These differences stem from cell arrangement, series-parallel connection configurations, and the use of half-cut architecture. An analysis of the temperature coefficients reveals that the power temperature coefficient varies between -0.240 and -0.400 %/°C. The modules with the lowest temperature dependence are the REC Alpha Pure-RX and similar N-type/TOPCon technology panels, which exhibit more stable performance under high-temperature conditions. In contrast, it was determined that polycrystalline modules are more significantly affected by temperature increases due to their higher negative temperature coefficients. Overall, the findings highlight that in PV system design, it is critically important to evaluate not only the nominal power rating but also efficiency, temperature coefficients, and cell technology collectively.

Table 2. Types and features of PV panels

Marka/Model	Cell Type	Max. Power $P_{\max}$ (W _p)	Maximum Power Voltage (V_{mp})	Maximum Power Current (I_{mp})	Power/Temperature Ratio, %/°C	Voltage/Temperature Ratio %/°C	Current/Temperature Ratio %/°C	Module Efficiency (%)	Panel Dimensions (mm)
Ödül OSPP72-345	Polyc. 72-Cell	345	37.39	9.23	-0.400	-0.340	+0.044	17.74	1960x992x40
2-Ödül OSMP72-390	Monoc. 72 Cells	390	41.10	9.49	-0.400	-0.340	+0.044	19.52	1006x1986x40
CWT655-132TNB12R 655 Wp	Monoc. 132 Cells	655	42.42	15.45	-0.300	-0.260	+0.046	24.23	2382x1134x35
CW 620Wp 144TNFB M10 Topcon Black	Monoc. 144 Cells	620	44.55	13.92	-0.300	-0.260	+0.040	24.00	2278x1134x35
TommaTech 745Wp 144TNB M10 TopCon Diamond Plus	Monoc. 144 Cells	744.00	44.55	13.92	-0.300	-0.260	+0.040	28.80	2278x1134x30

TommaTech® 455Wp 108TN M10 TopCon	Monoc. 108 Cells	455	33.34	13.65	-0.300	-0.260	+0.040	23.30	1722x1134x30
Alfa Solar 545 W Watt Güneş Paneli Half Cut Bifacial	Monoc. 144 Cells	550	42.08	13.12	-0.315	-0.230	+0.040	21.16	2295x1132x42
Tiger Neo 66 L6- BDV	N-type Monoc. 264 Cells	650	42.57	15.27	-0.260	-0.240	+0.046	24.06	2382x1134x30
Jinko 66HL5-BDV	Monoc. 132 Cells	725	41.00	17.69	-0.290	-0.250	+0.045	22.90	2384x1303x33
REC ALPHA PURE-RX Half-cut Bifacial	Monoc. 88 Cells	470	55.40	8.49	-0.240	-0.240	+0.040	22.60	1728x1205x30

The variation in electrical power output of a PV panel with a nominal power of 400 W under different solar irradiance (300-1000 W/m²) and panel temperature (10-90 °C) conditions was analyzed using PSIM software, and the results are presented in Table 2. The findings reveal that the PV panel's output power exhibits a positive correlation with solar irradiance and a negative correlation with panel temperature. Under constant temperature conditions, an increase in solar irradiance was observed to significantly boost power generation. Specifically, when the panel temperature was 10 °C, power generation was found to rise from approximately 119 W to 429 W. This corresponds to an increase of approximately 260%, clearly demonstrating the dominant effect of solar irradiance on PV power generation. Power, voltage, and current values in PV modules vary depending on both irradiance and operating temperature. Figure 6 shows the P-V and I-V characteristics of a 660 W PV panel under different irradiance levels (200-1000 W/m²) and a constant cell temperature 25 °C, as simulated using PVGIS.

Upon examining the I-V curves, it can be observed that as solar irradiance decreases, the current produced by the panel (particularly the short-circuit current) decreases significantly in direct proportion to the irradiance, whereas the change in open-circuit voltage remains quite limited Figure 7. This behavior stems from the fact that the current generation mechanism of PV cells is directly dependent on the photon flux. This trend is also directly reflected in the P-V characteristics. As the irradiance level decreases, the P_{mp} decreases rapidly, whereas the V_{mp} corresponding to the maximum power point remains relatively constant in the range of approximately 38-42 V. This indicates that in PV systems, current and consequently power output is highly sensitive to changes in irradiance, whereas the voltage value exhibits more stable behavior.

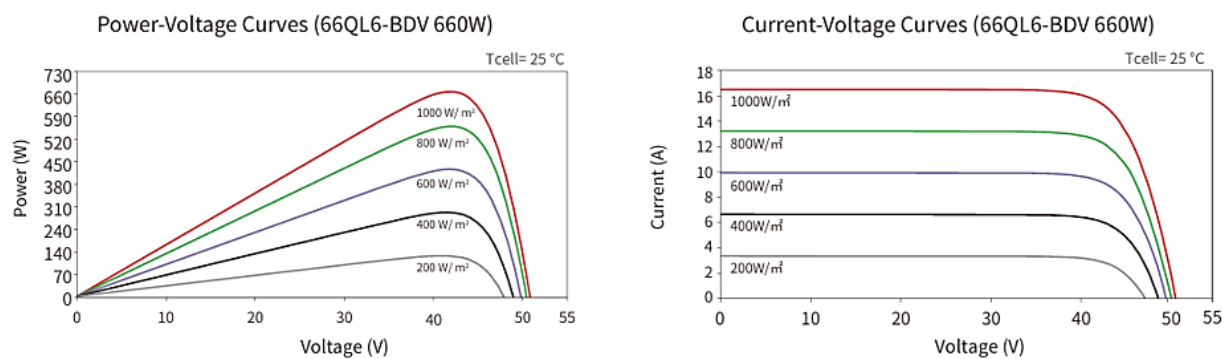


Figure 7. Current-Voltage (I-V) and Power-Voltage (P-V) characteristic curves of a 660 W PV panel at different irradiance levels ($T_{cell} = 25^{\circ}\text{C}$)

Figure 8 shows the variation in the electrical performance of PV systems under different environmental conditions as a function of temperature (T , $^{\circ}\text{C}$) and solar irradiance (W/m^2). In general, an increase in solar irradiance raises the current generated and thus the total power output—because it increases the number of photons reaching the panel, whereas a rise in temperature reduces the voltage, thereby negatively affecting system efficiency. For this reason, while power generation in PV modules tends to increase with rising irradiance, this increase is partially limited under high-temperature conditions. An evaluation of these two opposing effects clearly demonstrates that the highest energy production generally occurs under a combination of high irradiance and lower-to-moderate temperature values.

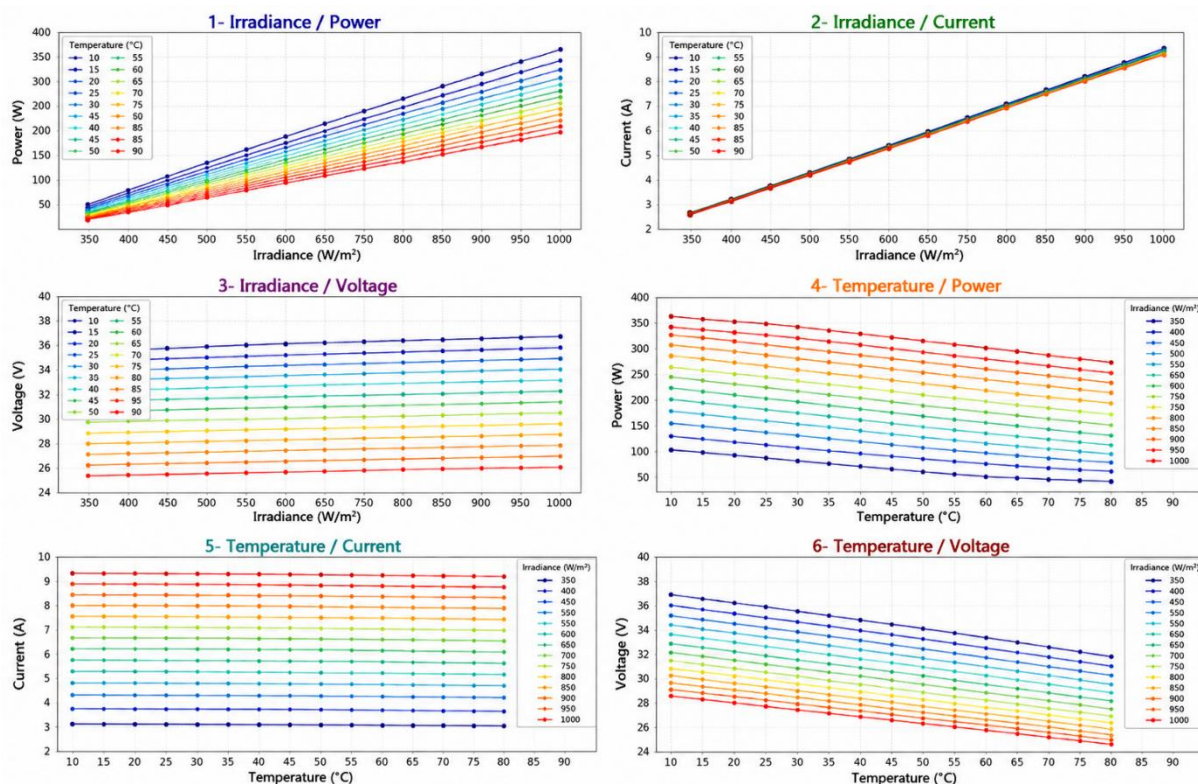


Figure 8. Effect of irradiance and temperature on the electrical performance of a 330 W monocrystalline solar panel

Figure 9 illustrates the effects of solar irradiance (300-1000 W/m²) and module temperature (10-90 °C) on the electrical performance parameters of the polycrystalline PV module, including power output, current, and voltage. The results indicate that power output increases almost linearly with increasing irradiance, while rising module temperature causes a noticeable reduction in power generation. At low temperatures 10 °C, the module achieves its highest power values, whereas power decreases progressively as temperature increases due to enhanced semiconductor losses. Current is strongly dependent on irradiance and exhibits only minor variations with temperature, demonstrating an approximately linear increase as irradiance rises. In contrast, voltage is more sensitive to temperature changes and decreases significantly with increasing module temperature, while showing only limited variation with irradiance. The combined analysis of the P-I-V characteristics confirms that solar irradiance is the dominant parameter governing current generation and overall power output, whereas temperature primarily affects voltage and consequently reduces conversion efficiency.

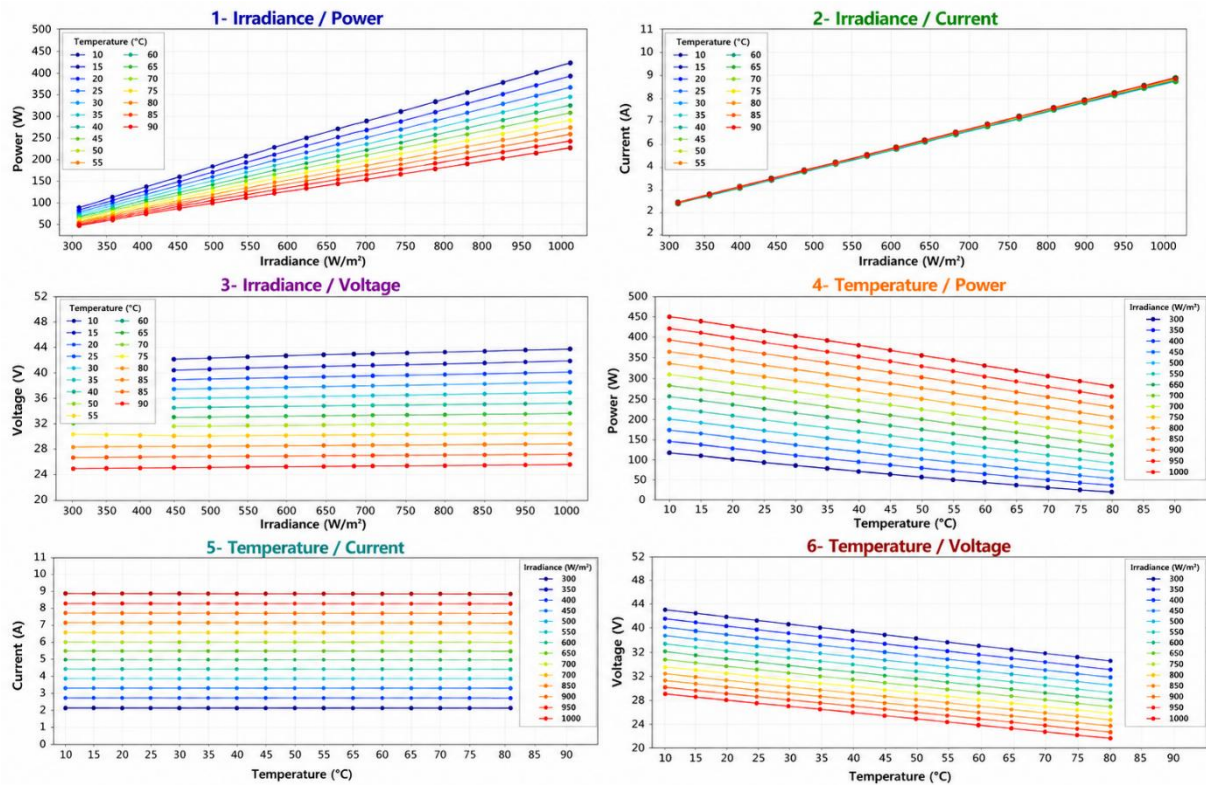


Figure 9. Effect of irradiance and temperature on the electrical performance of a 330 W polycrystalline solar panel

Figure 10 demonstrates, both empirically and graphically, how chemical and structural differences in PV cell technologies affect the relative power output of modules under increasing operating temperatures. Under Standard Test Conditions (STC: 25°C), all panels start operating at 100% of their nominal power capacity; however, as cell temperature rises to extreme levels such as 75°C under field conditions, a linear power decay curve is observed across all technologies. The brown line forming the lowest curve in the graph, with a high-temperature coefficient of $-0.400\% / ^\circ\text{C}$, representing traditional polycrystalline (Ödül OSPP72) and monocrystalline (Ödül OSMP72) cell structures with the lowest thermal stability; these modules lose 20% of their nominal power at 75°C, dropping to an 80% efficiency limit. In contrast, the light blue line at the top of the graph represents heterojunction (REC ALPHA PURE-RX) cell technology, which has the highest thermal resistance thanks to its minimum coefficient of $-0.24\% / ^\circ\text{C}$, and demonstrates its operational stability by retaining 88% of its original power even under the same extreme temperature. N-type TOPCon modules such as Jinko Tiger Neo, TommaTech, and CWT, which are positioned as mid-generation technologies, fall within the range of $-0.26\% / ^\circ\text{C}$ to $-0.30\% / ^\circ\text{C}$ range, significantly limiting thermal losses compared to traditional P-type cells thanks to their

tunnel oxide passivation layers, and exhibit a power retention rate of 85-87% at 75°C. In conclusion, this graphical analysis confirms at an academic level that, regardless of how much panel sizes or cell densities increase, the primary structural parameters determining long-term energy production stability in PV plant designs in high-temperature zones are the cells' semiconductor architecture and thermal coefficients.

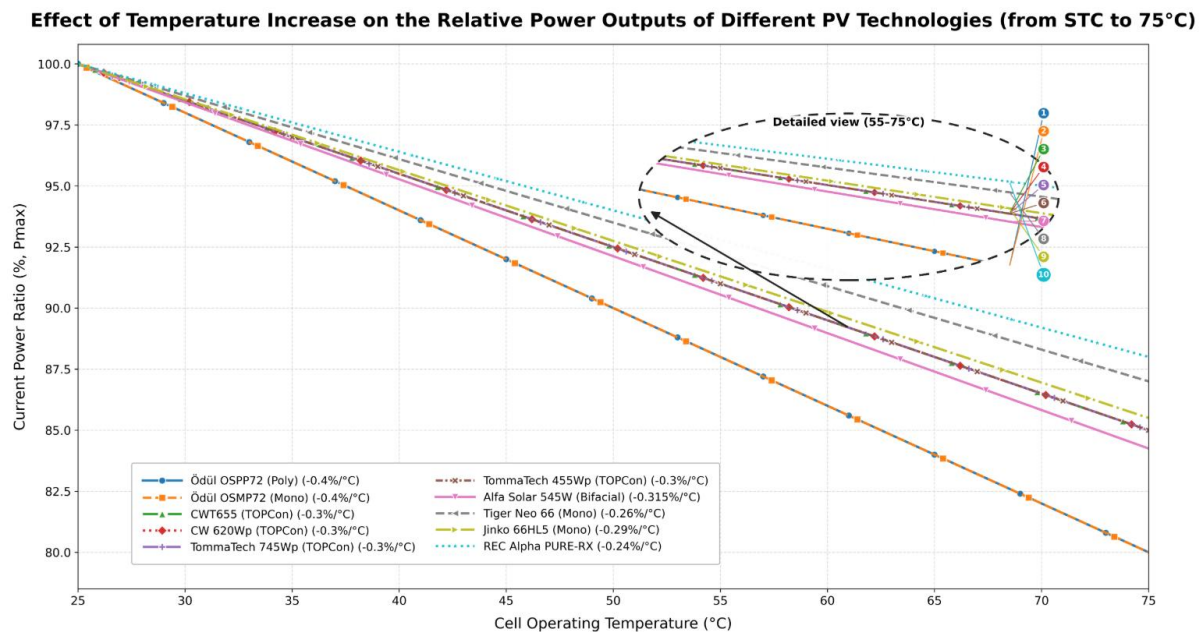


Figure 10. Effect of temperature increase on the relative power Outputs (from STC to 75 °C)

For the long-term performance optimisation of the 10 kWp grid-connected PV system in Kayseri-Tomarza, module configuration and installation geometry-particularly the tilt angle-are key parameters that influence annual energy yield and operating conditions. Previous studies have shown that mathematical and graphical optimisation approaches can improve PV energy production by determining suitable geometric and installation configurations [26]. Although new technologies such as transparent and semi-transparent PV modules and perovskite-silicon tandem cells offer further opportunities for architectural integration and performance enhancement [27], these technologies fall outside the primary scope of the present study. In this study, therefore, emphasis has been placed on the effects of irradiance, temperature and system configuration on the electrical performance of the grid-connected PV system under investigation. Prediction and simulation-based approaches provide an effective framework for evaluating these parameters and predicting PV power output under varying environmental conditions [29, 30]. Such analyses also contribute to a better understanding of the relationship between module operating conditions, thermal behaviour and long-term system performance [8, 18, 25].

In this study, the electrical and thermal performance characteristics of a 10 kWp grid-connected photovoltaic system designed for the Kayseri–Tomarza-1 location were investigated using PVGIS-SARAH3 climatic data and PSIM simulation tools, and the main findings are summarized as follows:

The correlation between seasonal irradiance and energy generation indicates that the optimized system is expected to produce a total annual electricity yield of 16,272.70 kWh/year with a relatively low interannual variability of 3.22%, according to PVGIS-SARAH3 data. The results further reveal that approximately 55% of the total annual energy production is concentrated in the May–September period, when solar irradiance reaches its peak levels. During these months, the system operates closer to its nominal capacity, achieving approximately 6 equivalent full-load hours per day, which confirms the strong dependence of PV output on seasonal solar availability.

Regarding the relationship between PV cell technology and thermal stability, comparative analysis shows that conventional polycrystalline silicon modules exhibit the lowest thermal performance due to a high negative temperature coefficient of approximately $-0.400\%/^{\circ}\text{C}$, resulting in significant power losses under elevated operating temperatures. At high field temperatures approaching 75°C , these modules may experience up to 20% reduction in nominal power output. In contrast, heterojunction (HJT) and advanced N-type architectures demonstrate superior thermal stability, with temperature coefficients as low as $-0.24\%/^{\circ}\text{C}$, allowing them to retain approximately 88% of their nominal power even under harsh climatic conditions. Similarly, N-type TOPCon technologies significantly mitigate thermal losses compared to conventional P-type silicon cells, primarily due to the presence of tunnel oxide passivation layers, with reported coefficients in the range of -0.26 to $-0.30\%/^{\circ}\text{C}$.

In terms of irradiance sensitivity and voltage stability, PSIM-based dynamic simulations confirm that the current output of PV modules and consequently the P_{mp} is highly dependent on variations in irradiance levels between 300 and 1000 W/m^2 , as a direct function of photon flux. However, the voltage at V_{mp} remains relatively stable, exhibiting only minor fluctuations within the 38–42 V range, which indicates that voltage is significantly less sensitive to irradiance variations compared to current.

Finally, thermal regulation requirements are strongly emphasized by simulation results, which demonstrate that an increase in module temperature from (10-90) °C under constant irradiance conditions leads to approximately 23% power degradation in monocrystalline PV modules. This finding clearly indicates that high solar irradiance potential alone is insufficient for maximizing system efficiency. Therefore, the integration of active cooling systems, passive heat dissipation mechanisms, or PCM based thermal management strategies is essential for maintaining electrical performance and ensuring long-term operational stability in PV installations located in high temperature environments.

DECLARATION OF ETHICAL STANDARDS

The author of the paper submitted declares that nothing which is necessary for achieving the paper requires ethical committee and/or legal-special permissions.

CONTRIBUTION OF THE AUTHORS

Ramazan Kayabaşı: The author contributed to the conceptualization and design of the study, carried out the analytical procedures, and undertook the comparative analysis.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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