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Solar Photovoltaic Panels Fault Detection Due to Thermal Effects

Mohamed F. Nasr *, Marwa M. Ibrahim, Amal El Berry

Mechanical Engineering Department, Engineering and Renewable Energy Research Institute, National Research Centre (NRC), Cairo 12622, Egypt

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ABSTRACT

The current study investigates the effects of thermal behaviors on PV panels, which are significantly influenced by their working temperature. To analyze the output of a selected PV panel model, it was initially simulated using PVsyst software under the weather conditions. However, one critical factor that homeowners should examine before investing in solar is the reliability and failure rates of solar panels. Estimating the cell temperature under service conditions is essential because the proportion of solar radiation that reaches a panel and is converted to electrical power is affected by the temperature of the PV cells. The "Plackett Burman Design" of trials is used to examine the relative importance of incident irradiance in hourly values (GlobInc) as a heat source on performance ratio (PR). Results generally indicates that higher temperatures reduce electrical efficiency, performance ratio (PR) has been employed as a measuring scale for the PV system performance. Panel temperature raises the risk for PV system efficiency and performance.

1. Introduction

The photovoltaic (PV) effect is the process by which solar panels convert sunlight into electricity. The more sunlight they receive, the more power they produce. However, overheating affects solar panel efficiency, lowering the percentage of sunshine that can be converted into electricity. Solar panel efficiency has increased dramatically overtime because of advances in materials, manufacturing techniques, and design innovation.

1.1. Photovoltaic panels faults

Determining the actual average failure rate of solar panels can be difficult due to differences in panel quality, installation techniques, and climatic factors. However, industry estimates indicate that the failure rate is rather low, ranging between 0.05% and 0.2% each year. The reliability of solar panels is heavily influenced by the manufacturing method and materials used. Panels from reputed manufacturers with strict quality control techniques tend to have lower failure rates according [1].

The information in [2]'study included the MTBF for the inverter's internal components as well as several significant DC side components such as the PV module, mounting structure, PV string cabling, and fuses. The most important failure modes were listed by [3], along with an indicator of the failure rate's order of magnitude. Failure rates of a few key system components; PV module, inverter, and mounting structure, were examined in a study by [4].

The failure rate of the inverter as a whole, as well as of its internal elements and the PV array's individual components such as; PV module, fuse, connector, string wire, etc., were disclosed by to Baschel et al. (2018) [5]. Although PV modules have a failure rate lower than inverters, the number of panels greatly outnumbers the number of inverters in any solar system. As a result, comparing failure rates normalized by the nominal power of the equipment is sensible. Technical Risks in PV projects development and operation by [6 and 7].

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*Mohamed F. Nasr, Mechanical Engineering Department, National Research Centre, Cairo, Egypt, +2 01223216615, mf_nasr@yahoo.com

1.2. Effect of temperature on PV efficiency and performance

Temperature-dependent changes in short-circuit current and open-circuit voltage result in a drop in output power and a rise in filling factor in [8]' research. Several researches discussed several factors that affect the performance of PV systems since PV modules often operate in a variety of; weather situations, environmental factors like temperature and solar radiation according to [9]; [10]; [11]; and [12]. It is evident that the temperature of the PV cell (Tc) is a crucial factor in estimating other parameters in outside settings. A PV module's cell temperature can be estimated using a variety of models. There are a range of models available, from basic ones that ignore wind speed and thermal dynamics to sophisticated ones that consider in [13]. While most traditional models indicate uncertainties of 2°C and greater, validation results of several temperature models of [14] are described in reveal that the uncertainty in the cell temperature calculation using an advanced model that accounts for dynamics and wind speed can be as low as 1°C.Today photovoltaic panels have an efficiency of 15% to 23%, while laboratory testing has produced even greater efficiency, topping 40% in some circumstances. A number of factors have an impact on PV panel performance and efficiency. Temperature, humidity, and solar panel efficiency are all interconnected aspects that influence the overall performance of a photovoltaic system. The effect of high temperatures and humidity on the PV-panel productivity and efficiency were also studied by [15] and [16].

The main effect of an increase in operating temperature is a drop in voltage. The impact of the operating temperature on annual energy production was found to depend on both module technology and site environmental conditions. [17] investigated the sensitivity of annual energy production to temperature coefficients; for various PV module technologies. The authors reported that it is in the range of -2% to -10%. The temperature of a photovoltaic panel's module has a significant impact on how efficiently power is produced by [18]. Since PV modules convert only 20% of solar energy into electricity and 80% into heat, electrical efficiency drops as module temperature rises are detailed in [19]' contributions. The band-gap energy of the PV cell material and module temperature is highly correlated. In general, band-gap energy decreases at high working temperatures [20]. The maximum power that the PV module can generate, which is dependent on the short-circuit current (Isc) and the open-circuit voltage (Voc) as given in [21]. The literature indicates that module temperature depends on a number of environmental variables, including solar irradiance, wind speed, ambient temperature, and some PV constructional parameters, including materials and glass transmittance as details in studies of [22]; [23]; [24]; [25] and [26]

According to published research, solar cell's efficiency rises to 12% at a temperature of 36°C before declining due to temperature rise as shown by [27]. The operating temperature of a single-crystal silicon solar cell has a major impact on its efficiency. Without cooling, the solar cell's efficiency drops by 3.13% at an operational temperature of 56°C under 1000 W/m^2 of radiation conferring the study of [28]. Additionally, studies reveal that at 64°C, efficiency decreases by 69% by [29]. Moreover, efficiency decreases to 5% as the module temperature rises from 43 to 47°C, demonstrating how wind speed affects the rate at which temperature rises as exposed in [30]'study. For each degree Celsius; that solar cells are heated, electrical efficiency falls by 0.03% to 0.05% in the absence of cooling, [31] and [32].

PV performance is influenced by encapsulation or cover materials' thermal dissipation and absorption characteristics. Currently, research is being conducted to improve PV power extraction through cooling approaches. Cooling methods are very specific. A single cooling method is insufficient to develop for large solar PV installations due to the rising cost and efficiency. On the other hand, when "phase change material" (PCM) and microchannel water cooling are utilized in tandem, heat transfer and overall efficiency would increase as focusing on [33]' investigation. The focus of the following study is how temperature sensitivity impacts solar cells (545 Wp Si-mono PV panels) in the same way that it does other semiconductor devices. Most of the properties of semiconductor materials are impacted by temperature rises.

2. Material and Method

2.1 PVsyst Cell Temperature Model

First, the PV panel output performance was simulated using the PVsyst software. This software allows the study of fundamental data of a PV panel (545 Wp Si-mono PV panels). All data were obtained under standard test condition (STC); 25 °C and 1000 W/m^2. Aside from that, the capability of the PV panel performance can be evaluated since the efficiency of the panel area is offered. The simulation's goal is to see how different operation temperatures affect PV panel output performance. Figure:1 illustrates the energy balance of the PV module:

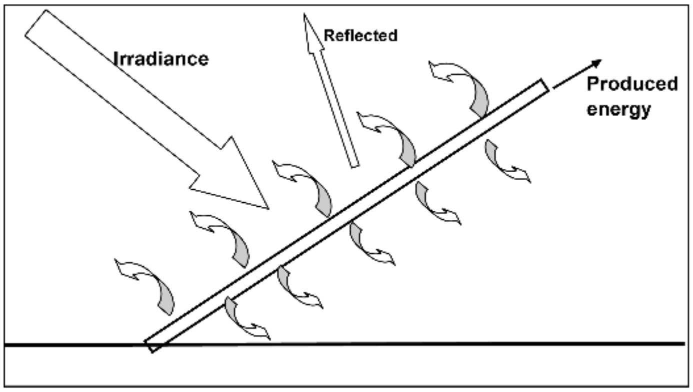


Figure 1: Energy balance, accounting for all incoming and outcoming energy fluxes in the array (PVsyst 7.4 Help 2024)

The goal of the "Module temperature according to irradiance" option is to display the behavior of the module in "realistic" situations. The (I/V) graph is often displayed at various irradiances for the same temperature. Assessing the temperature of the array (or cell) during the simulation is the goal. Cell temperature is a basic input parameter. This is analyzed using an energy balance as demined in equation (1), which takes into account all incoming and outgoing energy fluxes in the array. At thermal equilibrium, the energy flows should be balanced by the array cooling thermal loss, which is primarily convective, as seen in figure (1) [PVsyst 7.4 Help 2024].

$$\text{Ginc} \cdot \text{Alpha} \cdot (1 - \text{Effic}) = U \cdot (\text{Tcell} - \text{Tamb}) \quad (1)$$

The equation's left side lists the various energy fluxes, and its right side specifies the heat transfer that is required to maintain thermal equilibrium. Cell temperature is determined using equation (2) [PVsyst 7.4 2024]:

$$\text{Tcell} = \text{Tamb} + 1 / U \cdot (\text{Alpha} \cdot \text{Ginc} \cdot (1 - \text{Effic})) \quad (2)$$

The primary input parameter utilized in the simulation is the heat loss factor. However, this parameter may fluctuate with wind speed. As a result, this parameter can be divided into a constant component (Uc) and a factor proportional to wind velocity (Uv):

$$U = \text{Uc} + \text{Uv} \cdot \text{WindVel} \quad (3)$$

2.2 PV PR (Performance Ratio) Estimation

The performance ratio is the ratio of energy effectively produced (used) to energy that would be produced if the system operated continuously at its nominal STC efficiency. The PR is defined in IEC EN 61724. In most grid-connected systems, the available energy is denoted as E_Grid “Energy injected into the grid”. In stand-alone systems, PV energy is effectively delivered to the user. The potential energy produced under STC conditions is indeed equal to GlobInc× PnomPV, where PnomPV is the STC installed power. At STC (1000 W/m², 25°C), 1 kWh of incident irradiation generates 1 kWh of electricity.

Therefore, for a grid-connected system:

$$\text{PR} = \frac{\text{E\_Grid}}{(\text{GlobInc} \times \text{PnomPV})} \quad (4)$$

The efficiency of the PV modules has no effect on the PR. The performance ratio (PR) indicates the availability of solar energy for final use. As a result, when a portion of the energy is used internally (E_Solar), it should be clearly reflected in the PR evaluation. When a system includes storage, the storing losses (battery charge and discharge inefficiencies, DC-AC and AC-DC conversion devices) should also be considered in the PR.

Therefore, in the following formula, the E_Grid should be changed to E_Grid + E_Solar, [PVsyst 7.4 2024].

$$\text{PR} = \frac{(\text{E\_Grid} + \text{E\_Solar})}{(\text{GlobInc} \times \text{PnomPV})} \quad (5)$$

The performance ratio (PR) is a significant metric in the PV sector; it is frequently used as a contractual condition, as well as to verify annual yield. This is not an easy operation because the PR varies over the year. "Weather-corrected Performance Ratio”. This technique fails to adjust for other weather contributionssuchas irradiance level, wind velocity, variable soiling, and so on. The concept is to determine an average array temperature that is weighted by GlobInc's incident irradiance and averaged throughout the course of the year's working hours. Then for a specified period, the PR (corr) is defined by the following equations (6 and 7) [PVsyst 7.4 2024]:

$$\text{PR (corr)} = \text{E\_Grid} / (\text{PNomPV} \times \Sigma \text{ hours} (\text{GlobInc} / \text{GRef} \times (1 + \text{muPmpp} \times (\text{Tarray} - \text{TArrayAver}))) \quad (6)$$

Where:

$$\text{TArrayAver} = \Sigma \text{ hours} (\text{GlobInc} \times \text{TArray}) / \Sigma \text{ hours} (\text{GlobInc}) \quad (7)$$

The yearly PR (corr) number should mathematically equal the yearly PR if the $\text{TArray}_{\text{Aver}}$ is computed using the same data. The results, however, are not as compelling because other contributions in the majority of PV systems vary depending on the season. Applying this PR adjustment appears to overcorrect the seasonal PR behavior with shed systems. The mutual shadings, which are more noticeable in the winter, are to blame for this. With tracking systems, this correction is virtually useless because the temperature effect is being largely overtaken by seasonal fluctuations brought about by tracking.

2.3 PV energy yield estimates

To evaluate a site's potential for photovoltaic (PV) energy generation by running models with the best available data and techniques. The near P50 estimate, or the "best estimate," is the anticipated outcome of the modeling. P50 is simply a statistical degree of confidence that indicates there is a 50% chance that the anticipated solar resource/energy yield will be exceeded. This implies that the expectation might not be met with the same likelihood. It is anticipated that the P90 value, which is lower, will be exceeded in 90% of cases. A probabilistic method for interpreting the simulation results across a number of years is the P50 - P90 evaluation.

2.4 Plackett-Burman designs to evaluate significant energy parameters that affect PV performance ratio (PR):

Plackett-Burman designs are created using the ReliaSoft's DOE++. The PV performance ratio (PR) results are entered for further analysis. The "Performance Ratio" includes the design matrix as well as reaction statistics. Such designs are commonly used to investigate a large number of factors that have a considerable impact on the response. Finding the significant parameters that affect PV performance ratio (PR) and estimating the levels of those factors that will enhance the results are the test's goals. According to equation (5), there are three components being investigated: E_Grid (kWh), E_Solar kWh, and GlobInc kWh/m². As an alternative, a 12-run Plackett-Burman experiment will be carried out. Highly fractional Plackett-Burman designs let you take into account a subset of combinations of up to three elements at two levels each detail in: (https://help.reliasoft.com/reference/experiment_design_and_analysis/doe/highly_fractional_factorial_designs.html, 2024). Contrary to fractional factorial designs with two levels. According to Table 1, the data are estimated from PVsyst Software as follows:

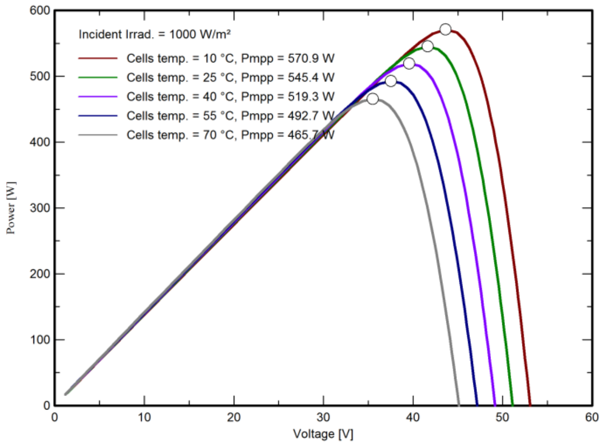
Table 1: Energy and heat parameters & PV performance ratio (PR)

Month	E_Grid (kWh)	E_Solar kWh	GlobInc kWh/m²	PR(ratio)
January	56840	208.5	148.9	0.913
February	53958	196.4	143.3	0.9
March	65447	206.8	176.8	0.885
April	69205	201.9	191.6	0.863
May	71066	220.7	198.1	0.858
June	69046	291.5	194.2	0.851
July	69704	300.7	197.9	0.843
August	69645	289.3	197.6	0.843
September	66855	199.9	186.4	0.857
October	61065	198.5	166.4	0.877
November	52476	188.7	139.8	0.898
December	49069	206.5	128.6	0.913

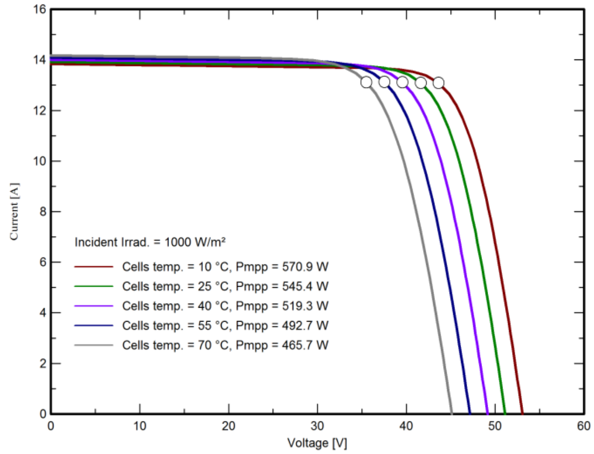
kWh	kilowatt-hour is a composite unit of energy
kWh/m²	kilowatt hour per square meter unit of GlobInc

3. Results and Discussion

The characteristics of output power of a photovoltaic panel; with a distribution of PV panel temperatures under constant solar irradiation is estimated from PVsyst Software and displayed as follows in figures (2 a & b).



(2.a) P-V curve



(2.b) I-V curve

Figure 2: The characteristics of a photovoltaic panel at varying temperatures under constant 1000 Wm-² solar irradiance

The features of the power-voltage (P-V) is shown in figure (2.a) and current-voltage (I-V) curves figure is depicted in (2.b) based on different PV panel temperatures are displayed in these figures. According to an analysis of the two numbers, a rise in the temperature of the PV panel would result in a progressive drop in the output voltage. Nevertheless, the PV panel's output current only marginally varies when the temperature rises. These above figures show that an increase in temperature of 15 °C results in a 25.5 W decrease in output power. Analyzing these numbers, it was determined that the PV panel's minimum output power at 70 °C was 465.7 W. In the meantime, when the PV panel's temperature was lowered to 10°C, the maximum output power reached 570.9 W.

The efficient output power of a PV panel is the primary factor that determines the payback time of an integrated PV system. This is because the photovoltaic panel was thought to be the most important part in the system. The impact of PV panel temperature on output performance at varying solar irradiation intensities is shown in figure: 3.

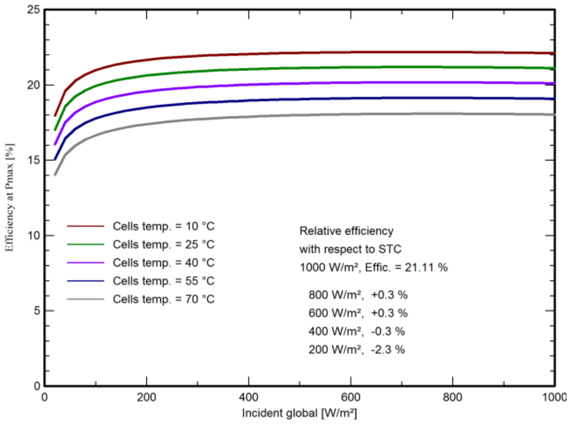


Figure 3: Power output efficiency with different solar irradiation and PV panel temperatures

In figure: 3 it could be seen that when high solar irradiation and low temperatures are combined, the PV panel produces its maximum output power. The highest efficient power output of the PV panel was 21.11% when the panel temperature was 25 °C at 1000 Wm^{-2}. All of these values were similar to the PV panel's standard test condition (STC). Unfortunately, the efficiency of the PV panel reduced when subjected to high PV panel temperatures. The lowest obtained efficiency was when the PV panel temperature was 70 °C. Meanwhile, efficiency decreased when PV panel temperatures reached 55 °C, 40 °C, and 25 °C, respectively.One crucial factor in a solar panel is its cell temperature. Temperature affects efficiency, which in turn affects output power. The panel's rated power is provided for STC "Standard Test Conditions" (1000 W/m^2 and 25^o C). Cell temperatures can range from 50°C to 75°C which are varied with ambient temperatures. For this reason, estimating the cell temperature under service circumstances is crucial. Figure:4 exhibits the relation between cell temperature and ambient temperature, while figure:5 presents the relation between PV cell output and PV cell temperature.

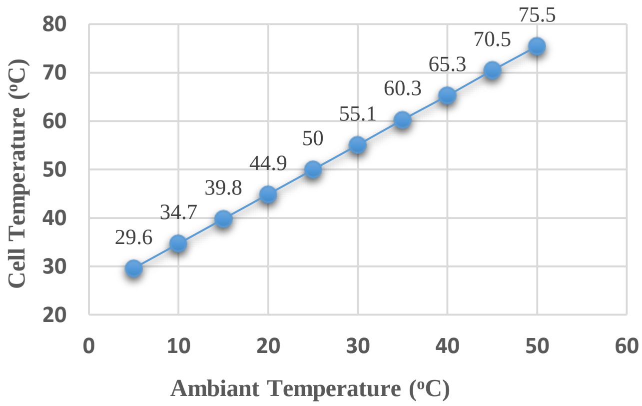


Figure 4: Cell temperature depends on the ambient temperature.

From figure: 4, it could be seen that Cell Temperatures are increasing with increased ambient temperature. The Model validated that efficiency is the percentage of solar energy that falls on a panel and is turned into electricity.

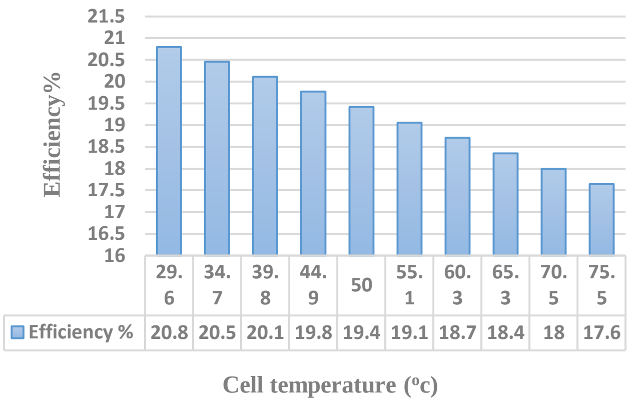


Figure5: Efficiency of PV cell output varies with PV cell temperature.

Figure: 5 showed how higher temperatures cause the efficiency of the output electricity generated by PV panels to steadily decline. It clearly indicates that peak solar irradiation does not always result in an effective PV panel operation. High solar irradiation may boost output power; however, this effect is offset by the influence of the PV panel temperature, which reduces efficiency. As a result, PV panel temperature might be regarded as an important factor for forecasting energy production. Temperature and solar panel efficiency are two interrelated parameters that influence the overall performance of a photovoltaic system. Figure: 6 presents the effect of (monthly average ambient temperature) on PV performance ratio.

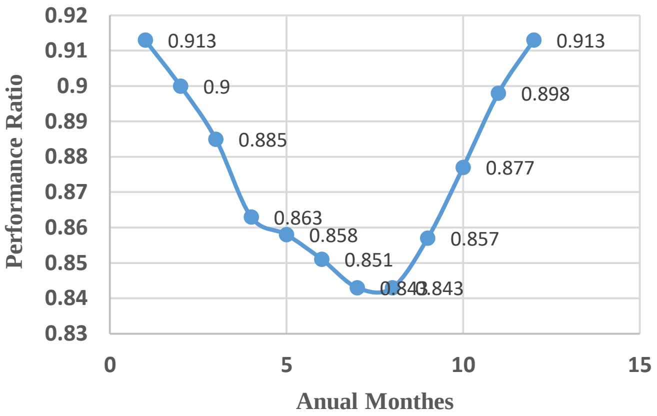


Figure 6: Effect of (monthly average ambient temperature) on PV performance ratio.

As can be seen from figure (6), performance in high-temperature months caused declination of the performance ratio. The system's performance appears to have declined more swiftly in July and August than in previous months. In addition to system features like panel efficiency, system design, inverter efficiency, cell mismatch, wiring, etc., the PR is also heavily influenced by a variety of meteorological factors, including high temperatures for PV modules, sunlight reflection from panel surfaces, etc. Weather-related characteristics are important for the plant's day-to-day operations.The PR is influenced not only by system features (panel efficiency, system design, inverter efficiency, cell mismatch, wiring, etc.), but also by a variety of weather parameters such as elevated PV module temperatures, sunlight reflection from panel surfaces, etc. Weather-related elements are critical to the plant's daily operations.Figure:7 illustrates simulated uncorrected Performance Ratio (calculated using equation 5), and corrected (calculated using equation 6) where the corrected are the PR values that are modified to become weather-corrected.

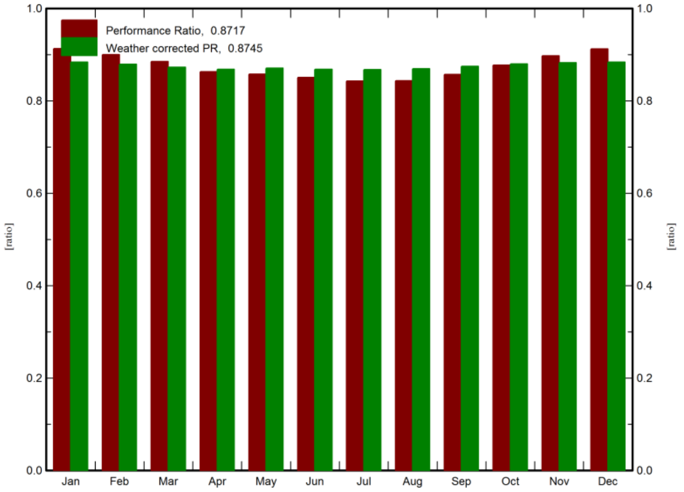


Figure 7: Corrected and uncorrected Performance Ratio (PR)

Figure :7 shows the PR determined for every month in a year-long simulation. Utilizing Equation (5), the PR values are shown by the red bars. The corrected PR for the same time, as calculated by Equation (6), is displayed by the green bars. Due to this bias, there will be falsely low numbers in the summer (posing a danger for the PV installation) and falsely high values in the winter (posing a risk for the PV customer as a poorly performing plant may pass the test during this time). This metric's instability serves as the incentive for a revised PR. PR is not constant throughout the year without the weather adjustment.

The PVsyst software computes the power loss ratio owing to increased module temperature by taking into account the location's temperature profile as stored in the meta database. Because the site is near Cairo, Egypt, a desert region with substantial temperature losses has been calculated to reflect the high temperature profile. PV module properties are determined at 25°C (STC temperature).

Figure 8 illustrates the relation between module temperature and losses ratio.

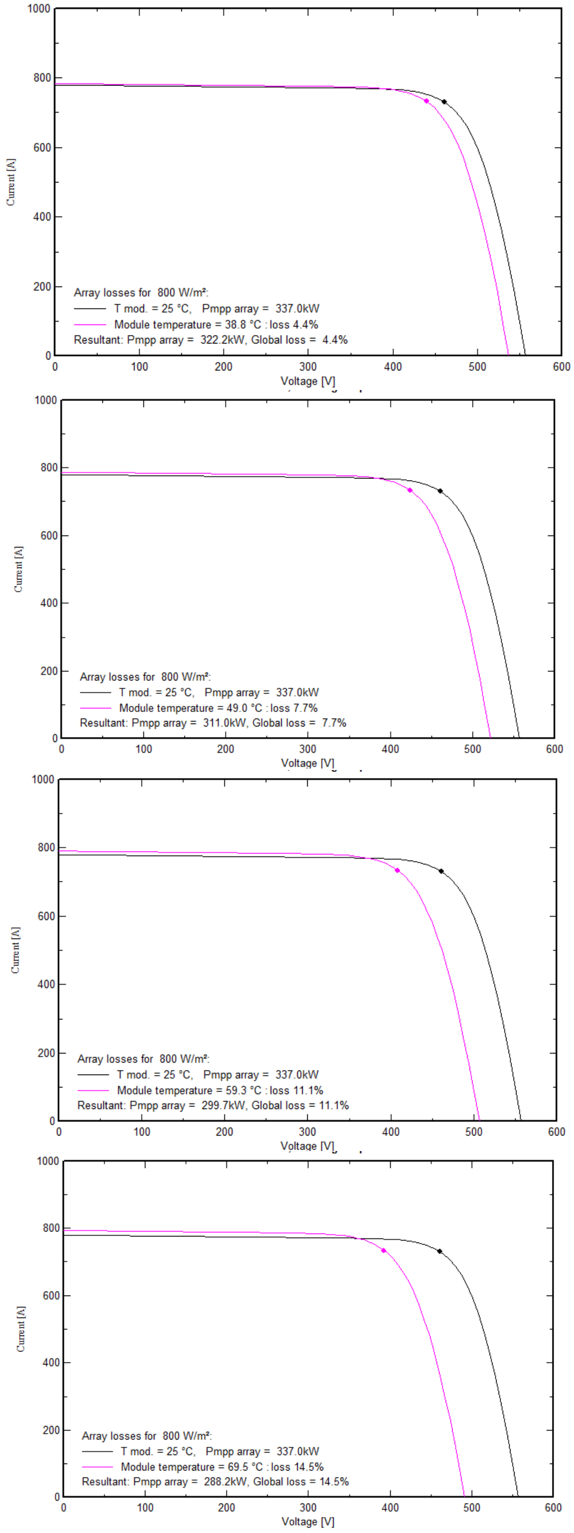


Figure 8: Relation between module temperature and losses ratio

Considering the temperature coefficient of the 545 Wp Si-mono, the losses are around 3.40% for every 10 ºC increase in module temperature, as illustrated in figure:8. When installing a PV array on a tilted roof with an air duct between the roof and the modules, the air circulation is driven by the temperature difference between the entering (ambient) and outgoing air, resulting in a relatively weak motor (low air speed). Because the thermal capacity of the air is limited, the air will be heated when passing under the first modules, resulting in no substantial heat exchange in the top modules, which will be "fully insulated." In this case, determining the array temperature is quite challenging, as it may be highly inhomogeneous.

Figure (9) represents a Gaussian probability distribution for a number of years,

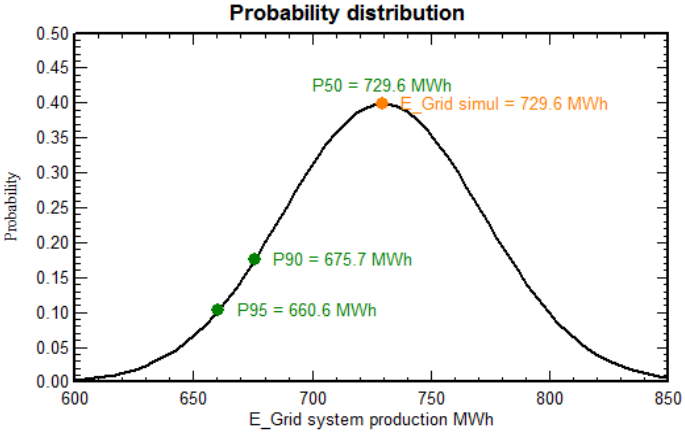


Figure 9: Gaussian probability distribution for a number of years (P50 - P90 evaluations)

Estimates of how much electricity a solar power plant will generate in the future are required to assess a project's financial risk. P50 and P90 exceedance probabilities based on many years of historical weather data are useful for this calculation. Simulations based on datasets showing solar resources over a multi-year period may overestimate the P50 value over the same period. For places with enough data, simulation has been used to compare meteorological file forecasts between P50 or P90 values computed from multi-year data sets.

From figure: 9 it could be seen that the value near P45 (E_Grid = 729.6 Mwh) is the highest value. It would have the same effect if the climate evolved positively. It's interesting to note that the projected production distribution may change around the simulation result depending on how the simulation result is interpreted the value “energy injected into the grid” and weather data.

The effect probability plot is a linear representation of probability vs. standardized effect (the likelihood that any (E_Grid, E_Solar, and GlobInc) have a standardized effect is less than the given value). The points on this plot show the values for each term, indicating that all terms have a significant impact on the performance ratio (PR). If there is no error in the design, figure: 10 depicts the probability versus the effect of components, with the points representing the values for each term in the effect.

The "Plackett Burman Design" of trials was used to examine the relative importance of the variables influencing the performance ratio (PR) of PV systems such as E_Grid, E_Solar, and GlobInc. Figure :10 shows the applied Plackett-Burman designs to evaluate the effect probability of energy and thermal factors on performance ratio (PR)

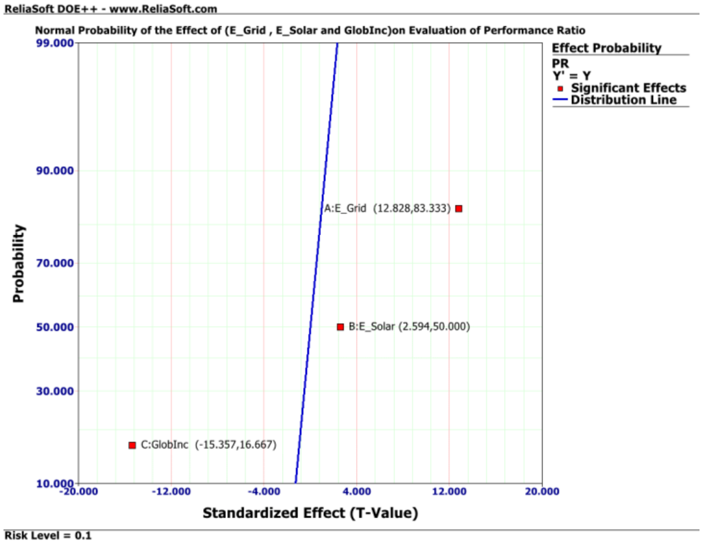


Figure 10: Plackett-Burman designs to evaluate the effect probability of energy and thermal factors on performance ratio (PR).

The regression equations display the coefficients for the performance ratio (PR). The first equation represents a model with coded values for the factors as equation (8):

$$PR = 0.9014 + 0.2649\, E_{Grid} + 0.0052\, E_{Solar} - 0.1999\, GlobInc \qquad (8)$$

The second equation displays the coefficients for a model with actual factor values as expressed in equation (9):

$$PR = 0.8913 + 1.3245E\text{-}05\ E\_Grid + 5.7480E\text{-}05\ E\_Solar - 0.0050\ GlobInc \qquad (9)$$

Figure 10 and the previous regression equations demonstrate that GlobInc, as a heating source has a variable effect on the performance ratio (PR).

Solar cells, like all other semiconductor devices, are temperature-sensitive. Temperature increases diminish a semiconductor's bandgap, affecting the majority of its material properties. As the temperature of a semiconductor increases, the band gap decreases, indicating that the energy of the electrons in the material increases. Lower energy is thus required to break the connection. In the bond model of a semiconductor bandgap, a decrease in bond energy reduces the bandgap. Thus, increasing the temperature reduces the bandgap.

4. Conclusions

When a PV array is installed on a tilted roof with an air duct between the roof and the modules, the air circulation is driven by the temperature difference between the entering (ambient) and exiting air. Because the thermal capacity of the air is restricted, it will be heated as it passes. The study focuses on how solar cells are affected by thermal sensitivity. As a result of the study, it is concluded that, the temperature of the PV panel increases, the output voltage decreases. After evaluating the data, it was found that the PV panel's minimum output power at 70°C was 465.7 W. Meanwhile, when the PV panel's temperature was reduced to 10 degrees Celsius, its maximum output was 570.9 watts. Exposure to elevated temperatures of the PV panel resulted in a decrease in its efficiency. Temperatures within cells can vary from 50°C to 75°C, depending on the ambient temperature. Estimating the cell temperature under service conditions is essential because the proportion of solar radiation that reaches a panel and is converted to electrical power is affected by the temperature of the PV cells. Two connected factors that affect a photovoltaic system's overall effectiveness are temperature and solar panel efficiency. Results generally indicate that higher temperatures reduce electrical efficiency. PR has been employed as a metric, utilizing both the jointly determined weather file and the weather-corrected computation. This removes the possibility that meteorological conditions could lead to observations that are too high or low. Without adjusting for the weather, PR is not consistent throughout the year. Gaussian probability distribution for a number of years, indicated that the value near P45 (E_Grid = 729.6 Mwh) is the greatest according weather data. The results of "Plackett Burman Design" show that all terms (E_Grid, E_Solar, and GlobInc.) significantly affect the performance ratio (PR). As a heating source, GlobInc has a varying effect on the performance ratio (PR).

5. Conflict of Interest

The authors declare no conflict of interest.

6. References

[1] Rahman, Tuhibur, Ahmed Al Mansur, Molla Shahadat Hossain Lipu, Md. Siddikur Rahman, Ratil H. Ashique, Mohamad Abou Houran, Rajvikram Madurai Elavarasan, and Eklas Hossain. 2023. "Investigation of Degradation of Solar Photovoltaics: A Review of Aging Factors, Impacts, and Future Directions toward Sustainable Energy Management" *Energies* 16, no. 9: 3706. https://doi.org/10.3390/en16093706

[2] Gallardo-Saavedra, Sara, Luis Hernández-Callejo, and Oscar Duque-Pérez. 2019. “Quantitative Failure Rates and Modes Analysis in Photovoltaic Plants.” *Energy* 183:825–36. https://doi.org/10.1016/j.energy.2019.06.185.

[3] Villarini, Mauro, Vittorio Cesarotti, Lucrezia Alfonsi, and Vito Introna. 2017. “Optimization of Photovoltaic Maintenance Plan by Means of a FMEA Approach Based on Real Data.” *Energy Conversion and Management* 152:1–12. https://doi.org/10.1016/j.enconman.2017.08.090.

[4] Oozeki, T., Yamada, T., Kato, K., Yamamoto, T. (2008). An Analysis of Reliability for Photovoltaic Systems on the Field Test Project for Photovoltaic in Japan. In: Goswami, D.Y., Zhao, Y. (eds) Proceedings of ISES World Congress 2007 (Vol. I – Vol. V). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-75997-3_334

[5] Baschel, Stefan, Elena Koubli, Jyotirmoy Roy, and Ralph Gottschalg. 2018. "Impact of Component Reliability on Large Scale Photovoltaic Systems’ Performance" *Energies* 11, no. 6: 1579. https://doi.org/10.3390/en11061579

[6] D. Moser. 2016 “Technical Risks in PV Projects, Report on Technical Risks in PV Project Development and PV Plant Operation,” p. 139.

[7] Golnas, Anastasios. 2012. “PV System Reliability: An Operator’s Perspective.” *2012 IEEE 38th Photovoltaic Specialists Conference (PVSC) PART 2*, 1–6. doi: 10.1109/PVSC-Vol2.2012.6656744.

[8] Cangi H, Adak S, Yılmaz AS, 2021. Effect of Temperature on The I-V and P-V Curves of The Photovoltaic Cell. Journal of the Institute of Science and Technology, 11(4): 2682-2694. DOI: 10.21597/jist.978148

[9] Jordehi, A. Rezaee. 2016. “Parameter Estimation of Solar Photovoltaic (PV) Cells: A Review.” *Renewable and Sustainable Energy Reviews* 61:354–71. https://doi.org/10.1016/j.rser.2016.03.049.

[10] Tossa, Alain K., Y. M. Soro, Y. Azoumah, and D. Yamegueu. 2014. “A New Approach to Estimate the Performance and Energy Productivity of Photovoltaic Modules in Real Operating Conditions.” *Solar Energy* 110:543–60. https://doi.org/10.1016/j.solener.2014.09.043.

[11] Rekioua, D. and Matagne, E. , 2012. Optimization of Photovoltaic Power Systems, Monetization, Simulation and Control. Springer& Business Media. http://dx.doi.org/10.1007/978-1-4471-2403-0

[12] Kumar, Manish, and Arun Kumar. 2017. “An Efficient Parameters Extraction Technique of Photovoltaic Models for Performance Assessment.” *Solar Energy* 158:192–206. https://doi.org/10.1016/j.solener.2017.09.046.

[13] Maturi, L., Belluardo, G., Moser, D., Del Buono, M., 2014. BiPV System Performance and Efficiency Drops: Overview on PV Module Temperature Conditions of Different Module Types. Energy Procedia, Proceedings of the 2nd International Conference on Solar Heating and Cooling for Buildings and Industry (SHC 2013) 48, 1311–1319. doi:10.1016/j.egypro.2014.02.148

[14] Richter, M, E., Schmidt, T., Kalisch, J., Woyte, A., de Brabandere, K., Lorenz, E, M., 2015. Uncertainties in PV

Modelling and Monitoring. 31st Eur. Photovolt. Sol. Energy Conf. Exhib. 1683–1691. doi:10.4229/EUPVSEC20152015-5BO.12.5

[15] Martín-Chivelet, Nuria, Jesús Polo, Carlos Sanz-Saiz, Lucy Tamara Núñez Benítez, Miguel Alonso-Abella, and José Cuenca. 2022. "Assessment of PV Module Temperature Models for Building-Integrated Photovoltaics (BIPV)" *Sustainability* 14, no. 3: 1500. https://doi.org/10.3390/su14031500

[16] Dewi, Tresna, Pola Risma, and YurniOktarina. 2019. “A Review of Factors Affecting the Efficiency and Output of a PV System Applied in Tropical Climate.” *IOP Conference Series: Earth and Environmental Science* 258 (1): 012039. https://doi.org/10.1088/1755-1315/258/1/012039.

[17] King, D.L., Boyson, W.E., Kratochvil, J., others, 2002. Analysis of factors influencing the annual energy production of photovoltaic systems, in: Photovoltaic Specialists Conference, 2002. Conference Record of the Twenty-Ninth IEEE. IEEE, pp. 1356–1361.

[18] Coskun, Can, Ugurtan Toygar, Ozgur Sarpdag, and Zuhal Oktay. 2017. “Sensitivity Analysis of Implicit Correlations for Photovoltaic Module Temperature: A Review.” *Journal of Cleaner Production* 164:1474–85. https://doi.org/10.1016/j.jclepro.2017.07.080.

[19] Rahman, Mohammad Mafizur, Md Hasanuzzaman, and Nasrudin Abd Rahim. 2017. “Effects of Operational Conditions on the Energy Efficiency of Photovoltaic Modules Operating in Malaysia.” *Journal of Cleaner Production* 143:912–24. https://doi.org/10.1016/j.jclepro.2016.12.029.

[20] Meyer, E.L., and E.E. van Dyk. 2004. “Assessing the Reliability and Degradation of Photovoltaic Module Performance Parameters.” *IEEE Transactions on Reliability* 53 (1): 83–92. https://doi.org/10.1109/TR.2004.824831

[21] Dubey, Swapnil, Jatin NarotamSarvaiya, and Bharath Seshadri. 2013. “Temperature Dependent Photovoltaic (PV) Efficiency and Its Effect on PV Production in the World – A Review.” *Energy Procedia* 33:311–21. https://doi.org/10.1016/j.egypro.2013.05.072.

[22] Olczak, P., Matuszewska, D., Lishchenko, A., Zhydyk, I., Koval, V., Iermakova, O. (2022). The economic efficiency of photovoltaic energy for energy prosumers. PolitykaEnergetyczna – Energy Policy Journal, 25(4), 95-114. https://doi.org/10.33223/epj/155095

[23] Kazanecka, E., Olczak, P. (2023). A specific yield comparison of 2 photovoltaic installations – Polish case study. PolitykaEnergetyczna – Energy Policy Journal, 26(4), 129-148. https://doi.org/10.33223/epj/171857

[24] Abiola-Ogedengbe, Ayodeji, Horia Hangan, and Kamran Siddiqui. 2015. “Experimental Investigation of Wind Effects on a Standalone Photovoltaic (PV) Module.” *Renewable Energy* 78:657–65. https://doi.org/10.1016/j.renene.2015.01.037.

[25] Said, Syed A. M., Ghassan Hassan, Husam M. Walwil, and N. Al-Aqeeli. 2018. “The Effect of Environmental Factors and Dust Accumulation on Photovoltaic Modules and Dust-Accumulation Mitigation Strategies.” *Renewable and Sustainable Energy Reviews* 82:743–60. https://doi.org/10.1016/j.rser.2017.09.042.

[26] Rajput, Pramod, O. S. Sastry, and G. N. Tiwari. 2017. “Effect of Irradiance, TemperatureExposure and an Arrhenius Approach to Estimating Weathering Acceleration Factor of Glass, EVA and Tedlar in a Composite Climate of India.” *Solar Energy* 144:267–77. https://doi.org/10.1016/j.solener.2017.01.027.

[27] Sher, Anis Ahmad, Naseem Ahmad, Mariyam Sattar, Usman Ghafoor, and Umer Hameed Shah. 2023. "Effect of Various Dusts and Humidity on the Performance of Renewable Energy Modules" *Energies* 16, no. 13: 4857. https://doi.org/10.3390/en16134857

[28] Sen, Ecem, and Melih Soner Celiktas. 2024. “Performance Evaluation and Thermal Stabilization of Photovoltaic Panels Using Phase-Change Materials.” *Energy* 302:131840. https://doi.org/10.1016/j.energy.2024.131840.

[29] Starowicz, A., Rusanowska, P., Zieliński, M., 2023. Photovoltaic cell – the history of invention – review. PolitykaEnergetyczna – Energy Policy Journal, 26(1), 169-180. https://doi.org/10.33223/epj/161290

[30] Adinoyi, Muhammed J., and Syed A. M. Said. 2013. “Effect of Dust Accumulation on the Power Outputs of Solar Photovoltaic Modules.” *Renewable Energy* 60:633–36. https://doi.org/10.1016/j.renene.2013.06.014.

[31] Nižetić, S., D. Čoko, A. Yadav, and F. Grubišić-Čabo. 2016. “Water Spray Cooling Technique Applied on a Photovoltaic Panel: The Performance Response.” *Energy Conversion and Management* 108:287–96. https://doi.org/10.1016/j.enconman.2015.10.079.

[32] Odeh, S., & Behnia, M. ,2009 “Improving Photovoltaic Module Efficiency Using Water Cooling”. *Heat Transfer Engineering*, *30*(6), 499–505. https://doi.org/10.1080/01457630802529214

[33] Verma, Shrey, Subhashree Mohapatra, Subhankar Chowdhury, and Gaurav Dwivedi. 2021. “Cooling Techniques of the PV Module: A Review.” *Materials Today: Proceedings* 38:253–58. https://doi.org/10.1016/j.matpr.2020.07.130.

Abbreviation and symbol

Alpha	Absorption coefficient of solar irradiance.
E_Grid	Energy injected into the grid
E_Solar	Energy supplied to the user from solar
Effic	PV efficiency
Ginc	Incoming irradiance at the module or PV array.
GlobInc	Incident irradiance in hourly values
GRef	1000 W/m^2
Isc	Short-circuit current
MTBF	Mean time between failure
muPmpp	Pmpp temperature coefficient of the PV module
PCM	Phase change material
PnomPV	STC installed power (manufacturer nameplate value)
PR	Performance ratio
PR (corr)	Weather-corrected Performance ratio
PV	Photovoltaic
STC	Standard test circumstances
Tamb	Ambient temperature, giving from the meteo data.
TArray	Array (cell) temperature of this hour
TArray$_{\text{Aver}}$	Array temperature average over the whole year, weighted by GlobInc
Tc	Temperature of the PV cell
U	heat loss factor
Uc	Constant component
Uv	Factor proportional to wind velocity
WindVel	Wind velocity