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Performance Measurement of Peltier Element Design using Solar Test Simulator Concerning Light and Temperature Parameters

Cholish[1,*], Muhammad Rusdi[1], Rahmawaty[2], Muhammad Anhar Pulungan[2], Abdul Azis[3], Abdullah[1], Malik Abdul Karim[4]

1 Department of Electrical Engineering, Politeknik Negeri Medan, Medan City, North Sumatra 20155, Indonesia
2 Department of Mechanical Engineering, Politeknik Negeri Medan, Medan City, North Sumatra 20155, Indonesia
3 Department of Electrical Engineering, Universitas Muhammadiyah Sumatera Utara, Kota Medan, North Sumatra 20238, Indonesia
4 Mechanical Engineering, Faculty of Engineering, Universiti Teknologi Petronas, Bandar Seri Iskandar, 32610 Seri Iskandar, Perak, Malaysia

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ABSTRACT

This study investigates the application of Peltier element technology for testing solar panels under varying environmental conditions, focusing on light intensity and temperature. A solar test simulator was used to design and implement the Peltier elements and the circuit was simplified by calculating the capacitor charging factor. This simplification aligns with the specific characteristics of the solar panels and offers a cost-effective approach to equipment development while delivering optimal results. The design, which incorporates surface temperature regulation via Peltier elements at adjustable distances, allows for the accurate simulation of varying light and temperature conditions on the surface of the tested solar panels. The voltage applied to the Peltier element directly influences the temperature it produces, measured in real-time during controlled temperature variation experiments. These measurements were conducted under three simulated sunlight conditions, allowing for detailed observation of the instantaneous voltage changes in the cooling element. The study created a Solar Test Simulator prototype designed for solar panel testing. The results demonstrate that the Peltier element-based system effectively controls temperature variations and accurately reflects the real-world performance of solar panels under diverse environmental conditions. The temperature measurements, taken across two solar panels with varying specifications, validate the effectiveness of this approach, making it a valuable tool for solar panel testing and optimization.

Keywords:
Solar panels; optimization; internet of things; reflector; cooling

1. Introduction

Solar panels are components of semiconductor materials that work as processors for converting sunlight or solar energy into electrical energy with the concept of photovoltaic [1,2]. When sunlight hits the solar cell's surface, photons will form, providing energy to the valence electrons of the semiconductor material so that the light is distributed spectrally. When the solar energy increases, a potential difference occurs, producing an electric [3,4]. For solar panels, the term Fill Factor (FF)

* *Corresponding author.*
E-mail address: cholish@polmed.ac.id

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parameter determines the efficiency value of the solar panel. Where to find the Fill Factor (FF) value can be calculated using the maximum panel current multiplied by the maximum panel voltage and then divided by the current under the short-circuit condition multiplied by voltage under the short-circuit condition [5,6]. The working principle of photovoltaic, often called solar cells, consists of a connection of semiconductor materials, classified as either p-type or the electron flow occurring in n-type (p-n junction) semiconductors exposed to sunlight, which can be described as electric current flow. The characteristics of solar cells consist of three, in general, characteristic power where this characteristic is the curve of the product of current (I) and voltage (V), generally called the V-I characteristic curve, which shows the output power that can be produced by solar cells at a maximum point called MPP (Maximum Power Point), characteristic current (I) and voltage (V) Irradiance is a characteristic curve that shows the relationship between current (I) and voltage (V) at a certain irradiance value and characteristic current (I) and voltage (V) temperature is a characteristic curve that shows the relationship between current (I) and voltage (V) at a certain temperature [7-9]. The application of solar panel testing using thermoelectric cooling systems is increasing with the simplification activities carried [10-13]. The implementation of solar panel testing apparatus utilizing many methodologies encompassing temperature fluctuations across an array of established illumination sources, including incandescent, LED and halogen lamps. They are conducted through the utilization of a device designated as a solar test [14-16]. The testing objective was to ascertain the performance of solar panels that match the installation needs according to the power capacity requirements and the thermodynamic state at the surface of the solar panel. The temperature reading indicates it serves as the basis for this calculation [17-19].

This study aims to gain insight into the mechanisms of hot gas. The analysis examines channel flow patterns and determines local heat transfer coefficients. By numerically resolving the two-dimensional heat conduction problem, the study elucidates the interrelationships between the thermal resistances of heat exchangers and their geometric parameters. The principal objective is to gain insight into how thermal resistances impact the cooling capacity and efficiency of the thermoelectric cooling system. The research also involves optimizing heat exchangers based on fin thickness and spacing between fins. Solar Test Simulators (STE) are instruments designed to simulate solar panels' static and dynamic characteristics. They are important in testing and validating photovoltaic systems, as they permit precise control of the conditions under which these systems are evaluated. In contrast to the inherent unpredictability of actual environmental conditions, an STE provides a controlled setting that facilitates the evaluation and implementation of photovoltaic (PV) subsystems [20]. The ST comprises two principal components: the reference PV model and the PV power electronics controller. Both have been designed to achieve simplicity of operation. The existence of sophisticated methodologies proposed in the literature for integrating the PV model into the STE system, these approaches frequently entail intricate iterative calculations associated with solar panel equations, rendering them less feasible in practice. To respond to this situation, it is proposed that a new STE be introduced to facilitate the integration and implementation of the PV model. The approach utilizes a straightforward, non-iterative method to reference the STE, employing a clear and direct solar panel model that circumvents the necessity for iterative calculations. In distinction to existing solutions, the proposed STE is distinguished by its simplicity and adaptability, eliminating the necessity for complex iterative calculations of implicit solar panel equations. The STE system uses a basic proportional-integral (PI) controller and a DC-DC buck power converter. A 200 W solar panel experiment, including the EN 50530 test, demonstrates the system's effectiveness. The experimental outcomes verify that the proposed STE can accurately simulate the solar panel’s static and dynamic behaviour [21]. Changes in the output value of the solar panel against the capacity of the use of energy sources can be shown through the characteristic curve displayed on the monitor [22,23] Knowledge of solar panel testing equipment that can provide comprehensive information is carried out to obtain an applied product in the form of a solar test simulator through a simple circuit with measurements of the capacitor charging factor. Calculating the current and voltage on the capacitor as the switching process occurs has provided excellent information and comprehensive results. The problem of expensive testing equipment must be answered through the design of the device to be [24,25]. The design of applied technology through the implementation of a switching system circuit with measurements on the capacitor charging system will contribute to the technology of implementing a data recording system through the calculation of the capacitor charging factor used [26].

2. Methodology

The implementation of this research begins with the solar test simulator. The device has been constructed in a manner that enables it to quantify the capacity of a solar panel and then determine the position of the lighting contained in the equipment to obtain the best results [27]. The surface temperature of the solar panel is managed by adjusting the voltage applied to the Peltier element used as shown in Figure 1. In the next step after temperature conditioning, measurements are taken to obtain results on the utilization of solar panels in detail using the method of calculating the capacitor charging factor to get a characteristic curve, which is then displayed on the monitor designed on the equipment [28] as shown in Figure 2 and Figure 3. The solar panels used in this study were 50 Wp monocrystalline panels selected for their high efficiency and reliability. Each panel was subjected to a series of tests to evaluate its performance under varying light intensities and temperature conditions. The panels were connected in series to observe the combined effect on voltage and current output. The experimental setup included a solar simulator capable of providing consistent and controllable light intensity. The simulator was calculated to ensure the light intensity matched the specified levels in the datasheet. A Peltier module was also used to maintain a stable temperature of 42.2°C, ensuring the temperature fluctuations did not affect the results. A high-precision digital multimeter was used to measure the electrical parameters accurately. The multimeter could measure voltage, current and resistance with minimal error. A pyranometer measured the incident light intensity in W/m², ensuring the light levels were consistent across all testing. The thermal parameters were quantified using a thermocouple attached to the posterior aspect of the solar panel, which was actuated by a mechanism. The thermocouple was connected to a data logger, which recorded temperature readings at regular intervals. This setup allowed continuous monitoring and ensured the temperature remained constant throughout the experiments.

The experiment began by setting up the solar simulator to provide a light intensity of 100 W/m². The Peltier module was activated to maintain the panel temperature at 42.2°C. Once the system reached a stable state, the light intensity was gradually increased in steps of 10 W/m², up to a maximum of 120 W/m². At each step, the voltage and current output of the solar panels were recorded. Each measurement was taken three times to ensure accuracy and repeatability. The average of these measurements was used in the analysis to minimize any potential errors. The results were then tabulated and analysed to determine the relationship between light intensity, temperature, voltage and current. The collected data were analysed using statistical methods to identify trends and correlations. A linear regression analysis was conducted to ascertain the correlation between light intensity and electrical output. The slope and interception of the regression line provided insights into the efficiency of the solar panels under different conditions. Additionally, a detailed comparative analysis was conducted between the empirical findings obtained from the experimental procedure and the technical specifications provided in the datasheet for the solar panel in question. This comparison helped validate the measurements' accuracy and the experimental setup's reliability.

This research was conducted in the form of designing solar panel testing equipment. Some modifications are made, such as adjusting the distance of the Peltier element and the slope of the solar panel board location, which will provide several conditions following the overall light utilization [29-33]. Additional tests were conducted using different angles of incidence for the light source to validate the findings further. The angles ranged from 0° to 180°, with measurements taken at regular intervals. This allowed for evaluating the panel's performance under varying light conditions, simulating real-world scenarios where the angle of sunlight changes throughout the day. Each angle test involved adjusting the solar simulator to the desired angle and repeating the measurement procedure. The outcomes of the experiments were contrasted with the outcomes of the preliminary assessments to evaluate the impact of the incident angle on the performance characteristics of the panel. All experiments were conducted in a controlled environment to minimize external influences. The laboratory was outfitted with sophisticated temperature and humidity control apparatus to ensure stable conditions. All potential sources of interference, including reflective surfaces and external light sources, were duly eliminated to ensure that the solar simulator solely influenced the measurements. By following these detailed materials and methods, we ensured the reliability and validity of our study. The results provide significant insights into the performance of solar panels under varying light intensities and temperatures, contributing to the understanding of solar energy systems. The experimental results are analysed to describe the relationship of the obtained data. The relationship of each data is analysed using the regression method and Pearson correlation, referring to Eq. (1) and Eq. (2).

$$\dot{y} = a + bx \tag{1}$$

$$r = \frac{\sum_{i=1}^{n}(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum_{i=1}^{n}(X_i - \overline{X})^2 \sum_{i=1}^{n}(Y_i - \overline{Y})^2}} \tag{2}$$

Where:
$\dot{y}$ = the Regretion
b = Slope
ɑ = Intercept, the value of y when x = 0
r = Pearson Correlation
x = Value of the explanatory variable
$\bar{Y}$ = the average (mean) of all values Yi
$\bar{X}$ = the average (mean) of all values Xi

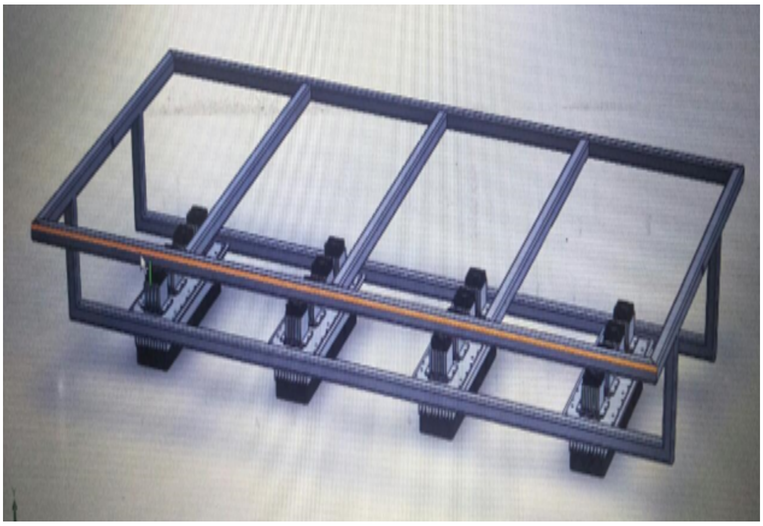

Fig. 1. Peltier element system design

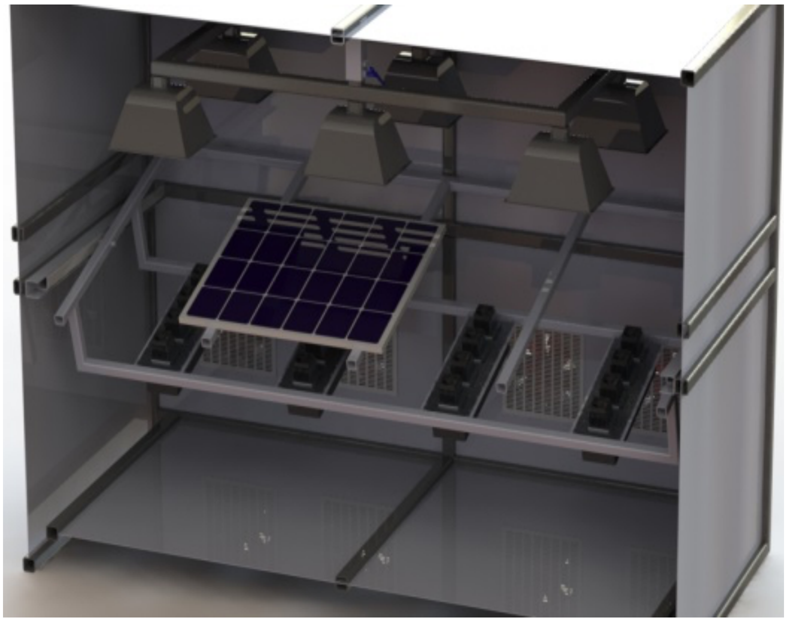

Fig. 2. 3D design layout in front view

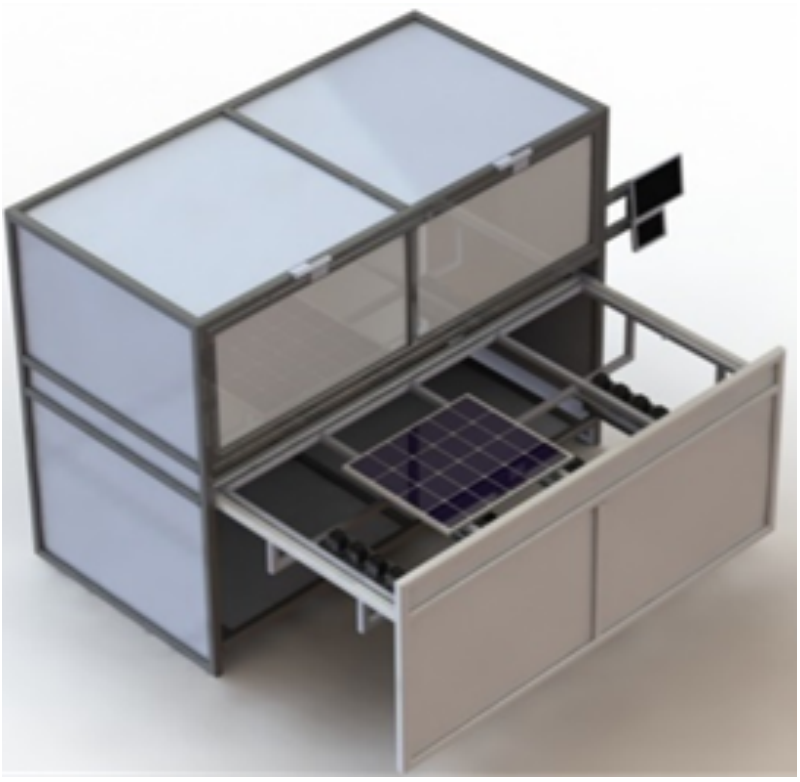

Fig. 3. 3D design layout in top view

3. Results

Table 1 shows the performance measurement results, which explains the parameter that the Peltier can stably hold the room temperature at 42.2°C. This affects the current and voltage values released by the 50 Wp solar panel. The current value increases along with the value of increased light intensity. Meanwhile, the voltage value is directly proportional to the current, exceeding the max V value of 20V. This concludes that the Peltier can maintain temperature stability so that the utilization of voltage and current values on solar panels can be maintained properly. In each measurement, the light intensity received by the solar panel (Light Reff) varied from 5 W/m² to 120 W/m², while the emitted light intensity (Light) remained constant at 100 W/m². The temperature was also kept stable at 42.2°C. As the intensity of reflected light increased, the voltage and current generated by the solar panel also increased. The voltage increased from 18.64 V at 5 W/m² reflected light intensity to 20 V at 80 W/m² reflected light intensity and remained stable at 20 V at higher intensities. The current also increases proportionally, starting from 0.17 A at 5 W/m² reflected light intensity to reach 0.65 A at 120 W/m² reflected light intensity.

Table 1
The performance of the test simulator solar panel

Intensities		50 Wp Solar Panel			
No.	Light Reff (W/m^2)	Light (W/m^2)	Temperature (°C)	Voltage (V)	Current (I)
1.	5	100	42,2	18,64	0,17
2.	10	100	42,2	18,74	0,19
3.	20	100	42,2	18,94	0,23
4.	30	100	42,2	19,9	0,29
5.	40	100	42,2	19,9	0,30
6.	50	100	42,2	19,9	0,36
7.	60	100	42,2	19,93	0,43
8.	70	100	42,2	19.98	0,47
9.	80	100	42,2	20	0,52
10.	90	100	42,2	20	0,55
11.	100	100	42,2	20	0,58
12.	110	100	42,2	20	0,63
13.	120	100	42,2	20	0,65

Table 1 describes the performance measurement results of the 50 Wp solar panel at various reflected light intensities. Each row in the table shows a different measurement, from very low to very high reflected light intensity. Further analysis shows that as the light intensity increases. There is a noticeable rise in the current output, which can be attributed to the increased photon energy conversion. The voltage output also shows a similar upward trend, stabilizing around 20V at higher light intensities. Despite varying light conditions, this consistency in voltage output highlights the reliability and efficiency of the Peltier element in maintaining optimal operational temperatures for the solar panels. Additionally, the stability of the temperature maintained by the Peltier element ensures that the efficiency of the solar panels is not compromised. This is particularly important in practical applications where temperature fluctuations can significantly impact the performance and longevity of solar panels. Maintaining a stable temperature allows for consistent energy output, which is critical for applications that require reliable power sources.

Based on Figure 4, temperature comparison, the Solar Panel is a component of the Solar Test Simulator and the angle of incidence of light varies from 0° to 180°. For a given incident angle, the light and temperature distribution slope are defined as the ratio of light intensity at a point to the intensity at an infinitesimal point source. The lowest slope is 0.20, corresponding to the angle of incidence of 0°. The highest slope is 32.2, corresponding to an incidence angle of 180°. The average temperature in the solar panel is 42.2 degrees Celsius. The amount of Peltier temperature will affect the high and low temperatures produced by the solar panel.

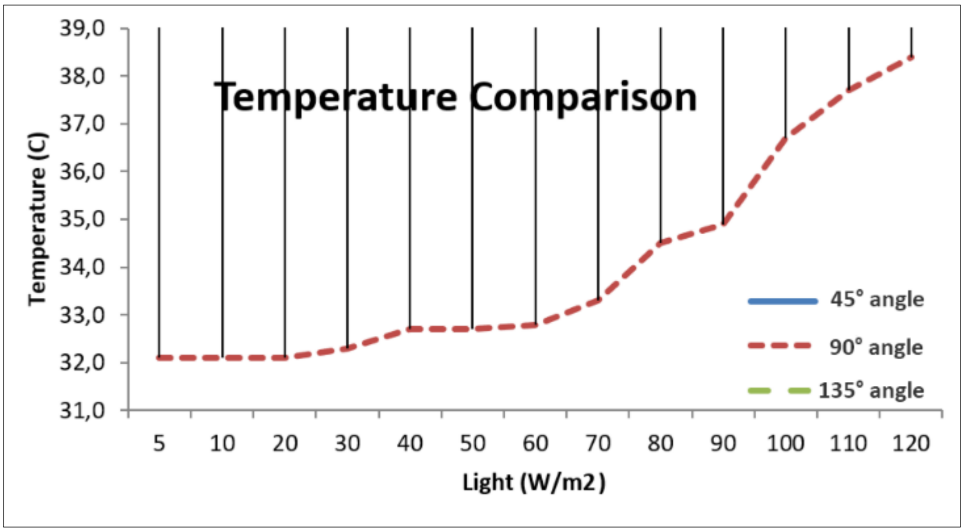

Fig. 4. Temperature comparison of solar test simulator solar panel

Based on Figure 5, a comparison of light that occurs in testing the angle of the solar panels was adjusted to 24° using the solar simulator, 90° and 180°. These angles were selected to evaluate the effects of light and temperature on the output voltage. The lowest voltage, 18V, was observed under these angles. Meanwhile, the highest voltage, 20V, was recorded with the angle at 24° and the average voltage was determined to be 19V. The quantity of light received will influence the production of high and low voltages.

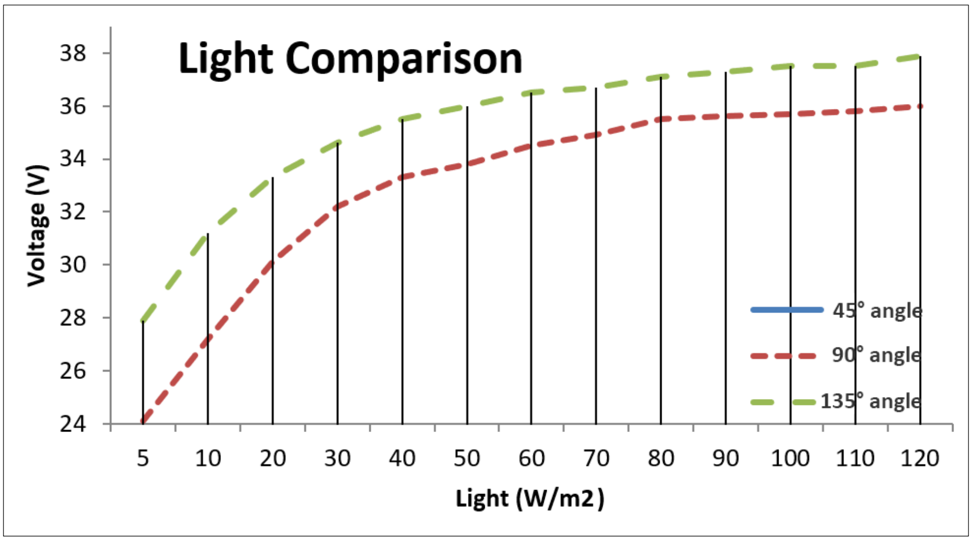

Fig. 5. Light comparison of solar test simulator solar panel

Based on Figure 6, a comparison of temperature and light, the phenomenon occurs in solar test simulators with solar panels oriented at 0° to 100°. At an angle of 180°, the lowest voltage observed was 18V, while the highest voltage reached 20V, resulting in an average voltage of 19V. The amount of light given will affect the high and low voltage produced and vice versa.

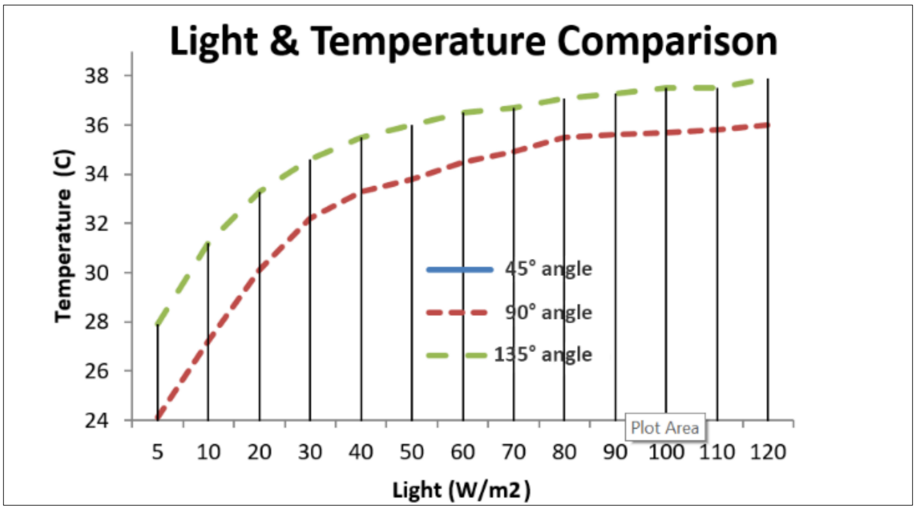

Fig. 6. Comparison of temperature and light of solar panel testing device

The findings also suggest that the Peltier element system's design and implementation effectively maintain solar panels' operational stability under varying environmental conditions. This has significant implications for developing solar energy systems, particularly in regions with fluctuating weather patterns. Maintaining stable performance under such conditions can enhance the viability and adoption of solar energy solutions. Overall, the results of this study demonstrate the effectiveness of the Peltier element in maintaining temperature stability and ensuring consistent performance of solar panels. The findings provide valuable insights for designing and optimizing solar energy systems, particularly in enhancing their reliability and efficiency under varying environmental conditions. A study using regression and Pearson coefficient was conducted. This aims to see the relationship between independent and dependent variables from experimental results. Each relationship between variables is observed based on the coefficient and R-sq from the analysis results with an error value of 5% (0.05). Furthermore, the regression analysis results are shown in Table 2.

Table 2
Regression analysis data

Coefficients Voltage Model	0.0107276
Coefficients Current Model	0.00418638
R-sq Voltage model	0.77
R-sq Current model	0.99

The regression analysis results show that voltage and current are closely related to the reference, with a coefficient percentage of 0.01 to 0.004. The error threshold limits this value and each closeness between data is 77% to 99%. Furthermore, the results of the person coefficient also illustrate a good relationship with each data. This is shown by the per cent (r) with a percentage value of 0.84 to 1 for each piece of data. The results of the Pearson correlation analysis are shown in Figure 7.

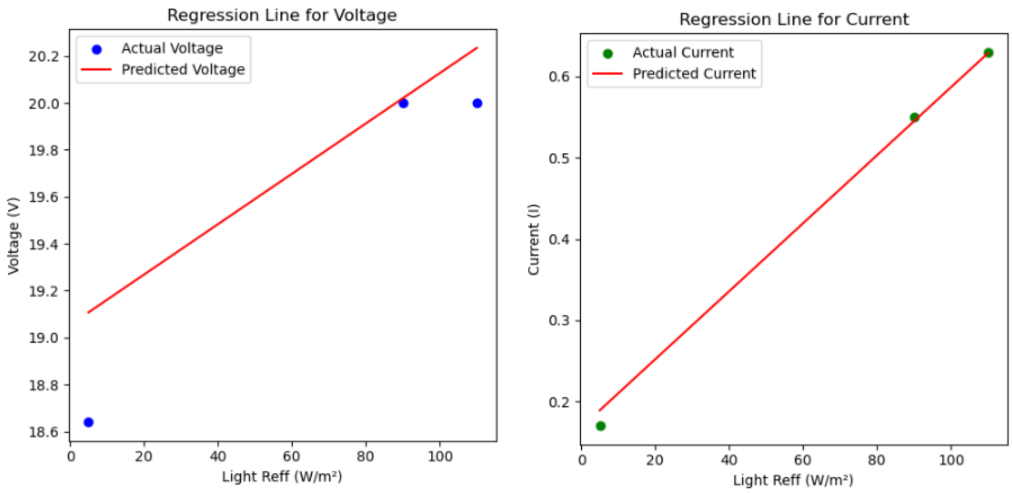

Fig. 7. Regression plot of analysis results

The data is re-analysed to observe the relationship between each data variable. The Pearson correlation (r) is represented from -1 to 1 in Figure 8.

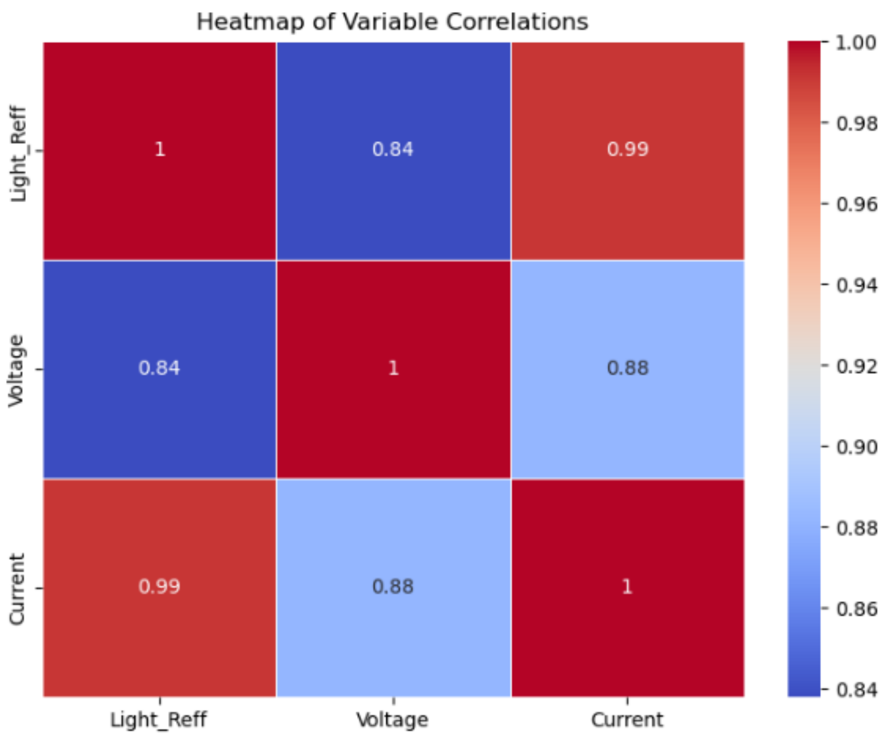

Fig. 8. Heat map data correlation

4. Conclusions

This research demonstrates the advantages of implementing an optimized system design for solar panels compared to standard, static setups. Solar panels with the system design allow automatic and manual control, providing flexibility and rapid fault correction. This feature is precious in ensuring continuous, efficient operation, as system malfunctions can be addressed immediately, minimizing downtime. The system also incorporates various functionalities, including adjustments for four solar reflector angle values, monitoring of solar panel temperature, manual control of the solar reflector drive motor, real-time weather data and voltage, current and power output measurements.

The testing confirms that the proposed system functions effectively as an Internet of Things (IoT)-integrated solar panel optimization solution. The variation in solar reflector angle, adjusted based on input from light and tilt sensors, has been proven to enhance solar panel performance significantly. The results show that the optimized system increases solar panel output power by 34.24% compared to static panels. Furthermore, when comparing the system to a setup with a solar reflector angle adjustment system and passive cooling, the optimized design achieved a remarkable 51.65% increase in output power. These improvements underscore the system’s capability to maximize sunlight absorption and maintain optimal operating conditions, resulting in greater energy production and system efficiency.

The research of IoT-based real-time remote monitoring further strengthens the system's reliability. It allows for continuous tracking of key parameters and enables proactive adjustments to maintain optimal performance. This feature is particularly advantageous in regions with variable weather conditions, where solar panel efficiency can fluctuate due to environmental factors.

Looking ahead, there are several promising avenues for future research and development. One potential direction is incorporating active cooling techniques, which could further enhance the thermal regulation of solar panels, particularly in high-temperature environments. Additionally, integrating advanced predictive algorithms that forecast weather patterns and adjust the solar reflector angles in anticipation of changes could lead to even more precise optimization. Such advancements would improve the overall efficiency of solar panel systems and ensure their adaptability to varying environmental conditions.

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