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Comparative Analysis of Crystalline Silicon Solar Cell Characteristics in an Individual, Series, and Parallel Configuration and an Assessment of the Effect of Temperature on Efficiency †

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Abstract: Solar energy is gaining immense significance as a renewable energy source owing to its environmentally friendly nature and sustainable attributes. Crystalline silicon solar cells are the prevailing choice for harnessing solar power. However, the efficiency of these cells is greatly influenced by their configuration and temperature. This research aims to explore the current–voltage (I−V) characteristics of individual, series, and parallel configurations in crystalline silicon solar cells under varying temperatures. Additionally, the impact of different temperature conditions on the overall efficiency and Fill Factor of the solar cell was analyzed. With the aid of a solar simulator and required conditions, the I−V characteristics of each configuration—individual, series, and parallel—were obtained. The solar panel was subjected to various temperature settings, and I−V characteristics were obtained for each configuration to calculate the maximum power and Fill Factor for each case. In addition to this, the results showed that the parallel configuration has a larger power output, followed by the individual and series configurations. Additionally, the temperature of the solar panel had a significant effect on the output power of the solar cells. The maximum output power is also affected by temperature variation. The Fill Factor, on the other hand, was observed to be dependent on the configuration but had no significant variation with respect to the temperature. The effect of solar irradiance was also observed in a configuration with a definite temperature. This research offers valuable insights into the ideal configuration and optimal temperature for achieving maximum efficiency in crystalline silicon solar cells. Hence, a definite configuration with optimum temperature yields maximum power output and helps in attaining maximum efficiency.

Keywords: crystalline silicon solar cells; configurations; temperature; current—voltage characteristics; solar irradiance

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1. Introduction

Solar energy is one of the emerging renewable energy sources, with photovoltaic (PV) systems playing a pivotal role in harnessing this abundant and sustainable energy [1–4]. Among various PV technologies, crystalline silicon solar cells remain the dominant choice due to their high efficiency, reliability, and cost-effectiveness [5,6]. As the demand for solar energy continues to grow, optimizing the performance of solar cells becomes crucial to enhance their energy conversion efficiency [7–9]. The current–voltage (I−V) and power–voltage (P−V) characteristics of these cells are fundamental in understanding their behavior and performance. These characteristics represent the relationship between the output current and voltage at different operating conditions [10].

Over the years, various researchers have studied the performance of solar cells under different configurations and operating conditions to enhance their performance. Understanding the V-I characteristics of solar cells is vital for improving their design and overall efficiency. Several studies have explored the impact of different configurations of solar cells on their performance. Wang and Hsu (2011) investigated the characteristics of solar cells in series and parallel configurations and found that the parallel arrangement showed improved output power compared to the series configuration [11]. Temperature and configuration alter the open-circuit voltage (V_{oc}) and short-circuit current (I_{sc}).

Many researchers have examined the influence of temperature on I−V characteristics. Shaltout et al. (2000) analyzed the temperature-dependent behavior of solar cells and revealed that increasing temperature led to reduced efficiency due to increased carrier recombination [12]. In contrast, Kojima (2009) demonstrated that certain solar cell materials displayed enhanced performance at elevated temperatures, attributing this to reduced resistance [13]. However, there is still a lack of comprehensive research exploring the combined influence of configuration and temperature on crystalline silicon solar cells.

The proposed work aims to investigate and analyze the V-I characteristics of crystalline silicon solar cells in individual, series, and parallel configurations under different temperature conditions, and the effect of illumination. With the help of these observations, efficiency and Fill Factors for different configurations and temperatures are also tabulated. The findings from this research will contribute to the ongoing efforts to improve the performance and effectiveness of solar photovoltaic systems.

2. Materials and Methods

As seen in Figure 1, a crystalline silicon solar cell is an n-p junction diode [14]. In the absence of illumination, the current is expressed as,

$$I = I_0 \left[exp\left(\frac{qV}{kT}\right) - 1 \right] \quad (1)$$

where I is the current passing through the cell, q is the charge, V is the voltage across the cell, T is the temperature in degrees Kelvin, k is the Boltzmann constant, and I_0 is the reverse saturation current. The expression governing the I−V under illumination is:

$$I = I_0 \left[exp\left(\frac{qV}{kT}\right) - 1 \right] - I_{ph} \quad (2)$$

where I_{ph}, which is the light-induced current, is dependent on the level of illumination. We can observe that a short circuit current, $I_{sc} = I_{ph}$, travels through the solar cell's leads when the voltage is zero (V = 0). If the leads are left disconnected, the voltage across them is V_{OC}.

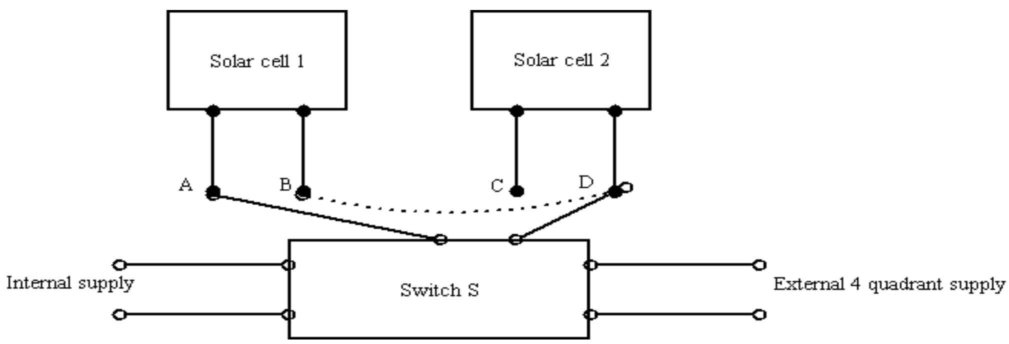

Figure 1. Single solar cell.

This section details the experimental setup, data collection, and analysis procedures that were followed to attain the research objectives.

2.1. Experimental Setup

The experimental setup, as shown in Figure 2, is capable of generating controlled conditions for measuring the IV (current–voltage) characteristics of crystalline silicon solar cells in different configurations (individual, series, and parallel). The key components of the experimental setup included:

- Solar Simulator: A solar simulator was employed to provide a stable and controlled light source that mimics sunlight. This simulator ensured consistent illumination conditions for all experiments, reducing external factors that could affect the measurements.
- Crystalline Silicon Solar Panel: A high-quality crystalline silicon solar panel was selected as the test specimen. This panel served as the basis for measuring the IV characteristics under various conditions.
- Temperature Control System: To examine the impact of temperature on solar cell performance, a temperature control system (calibrated with the help of a reference thermometer) was integrated into the setup. This system allowed for precise control of the solar panel's temperature within a specified range (5 °C to 50 °C).
- Load Resistor (R): This standardized the external electrical load across all configurations and temperature settings.

Figure 2. Experimental setup.

2.2. Data Collection

The project involved comprehensive data collection to assess the performance of the crystalline silicon solar panel. The primary data points gathered included:

- I−V Characteristics: For each configuration (individual, series, and parallel) and at various temperature points, the I−V characteristics were plotted. This involved sweeping the voltage across the solar cell while measuring the corresponding current output. These measurements were repeated multiple times to ensure accuracy and consistency.

- P−V Characteristics: For each configuration (individual, series, and parallel) and at various temperature points, the P−V characteristics were plotted, and the corresponding maximum power output was tabulated.
- Temperature variation: The solar panel was subjected to a range of temperatures (from 5 °C, up to 50 °C in steps of 5 °C) by tuning the temperature control system. Temperature readings were monitored and recorded throughout the experiments.
- Illumination: To assess the impact of illumination, the experiment was performed at a fixed temperature of 55 °C. The solar cell was exposed to varying illuminance to analyze its performance under different illumination levels.

2.3. Efficiency and Fill Factor Calculation

Efficiency and Fill Factor are critical parameters for assessing the performance of solar cells. To calculate these values for each configuration and temperature point, the following steps were followed:

- Open Circuit Voltage (V_{oc}): The V_{oc} was measured by determining the potential across the solar cell when there was no current flowing (at maximum resistance position).
- Short Circuit Current (Isc): The I_{sc} was measured by setting minimum resistance, resulting in maximum current flow.
- Efficiency Calculation: The efficiency of each configuration and temperature condition was calculated using the formula:

$$\text{Efficiency}(\%) = \frac{P_{out}}{P_{in}} \times 100 \quad (3)$$

where P_{out} is the power output of the solar cell ($V_{oc} \times I_{sc}$), P_{in} is the input power from the solar simulator ($I_{sc} \times Area\ of\ the\ solar\ cell \times Solar\ irradiance$)

- Fill Factor Calculation: The Fill Factor (FF) can be calculated using the following formula:

$$Fill\ Factor = \frac{P_{out}}{V_{oc} \times I_{sc}} \quad (4)$$

2.4. Data Analysis

- The characteristics: The I−V characteristics, P−V characteristics, efficiency, and Fill Factor of individual, series, and parallel configurations were compared, in the specified range of temperatures, to identify the relationships.
- Temperature dependency: The effect of temperature on solar cell efficiency and Fill Factor was visualized using graphical representations.
- Impact of change in illumination: At a temperature of 55 °C, the impact of illuminance on the solar cell's behavior was assessed. This provided insights into the cell's response to varying levels of illumination.

2.5. Data Presentation

The behavior of the system was presented using graphical representations, such as I−V curves, P−V plots for efficiency, and tabulation of maximum power output data. The effect of illuminance was observed by plotting I−V and P−V characteristics for two values of illuminance conditions and maintaining a fixed temperature.

3. Results

By changing the resistance in the circuit (using a variable load resistor), the current and voltage for a particular temperature are recorded. Hence, I−V and P−V characteristics obtained for an individual cell can be plotted for different temperatures, as shown in Figures 3 and 4. The cells are placed in series to reveal the impact of temperature on their maximum power, and the respective characteristics are plotted in Figures 5 and 6. Similarly, I−V and P−V characteristics for the cells in parallel are depicted in Figures 7 and 8.

Figures 9 and 10 demonstrate the impact of illuminance on the I−V and P−V characteristics for an individual solar cell at a temperature of 55 °C.

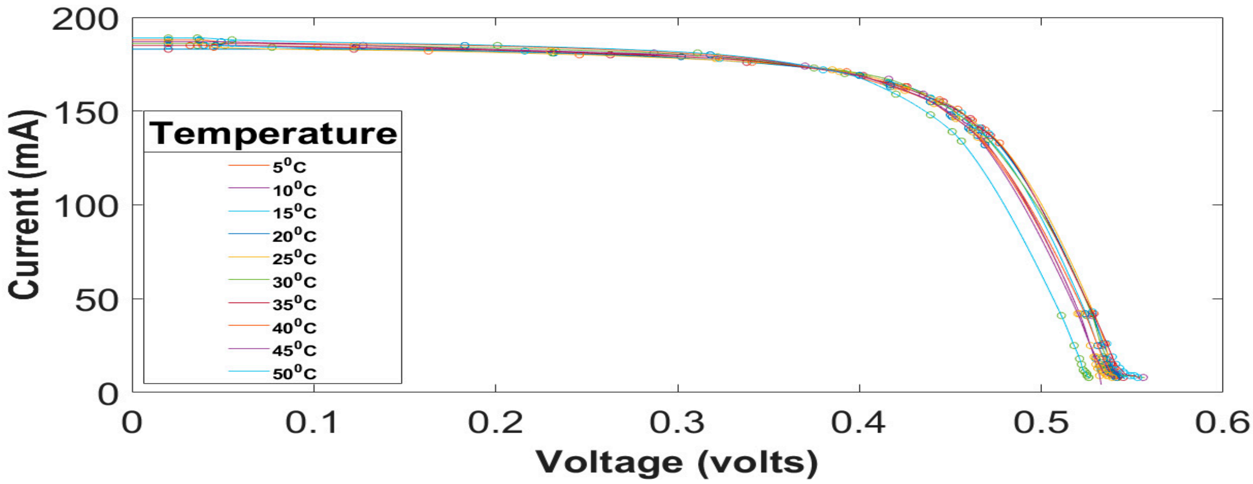

Figure 3. I−V characteristics of an individual solar cell.

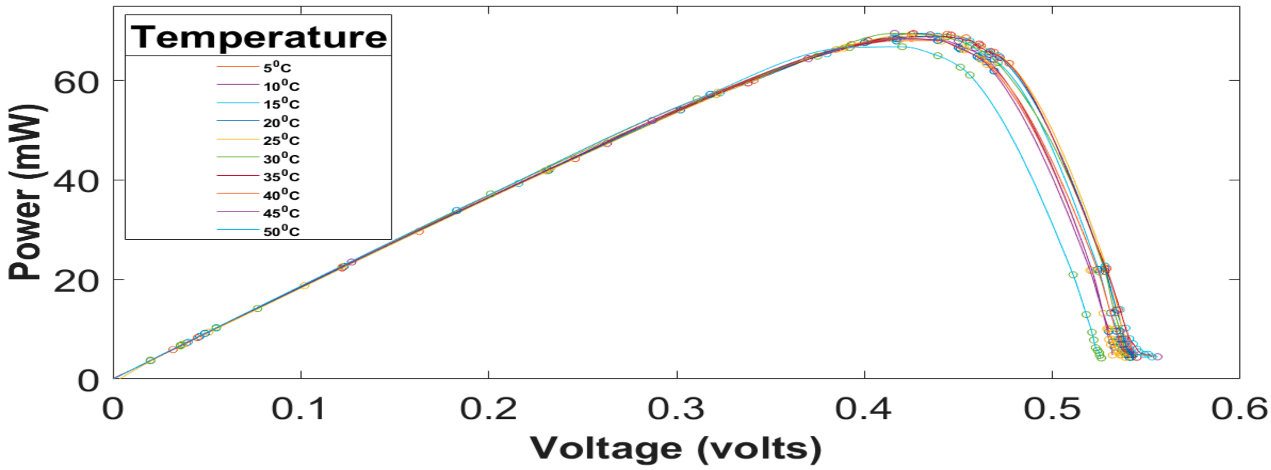

Figure 4. P−V characteristics of an individual solar cell.

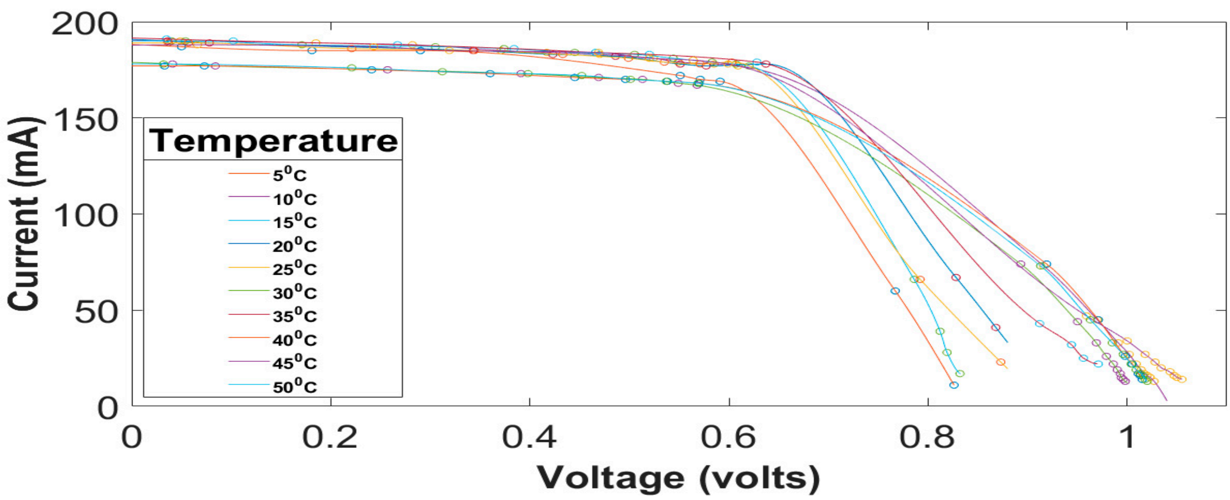

Figure 5. I−V characteristics of two solar cells connected in series.

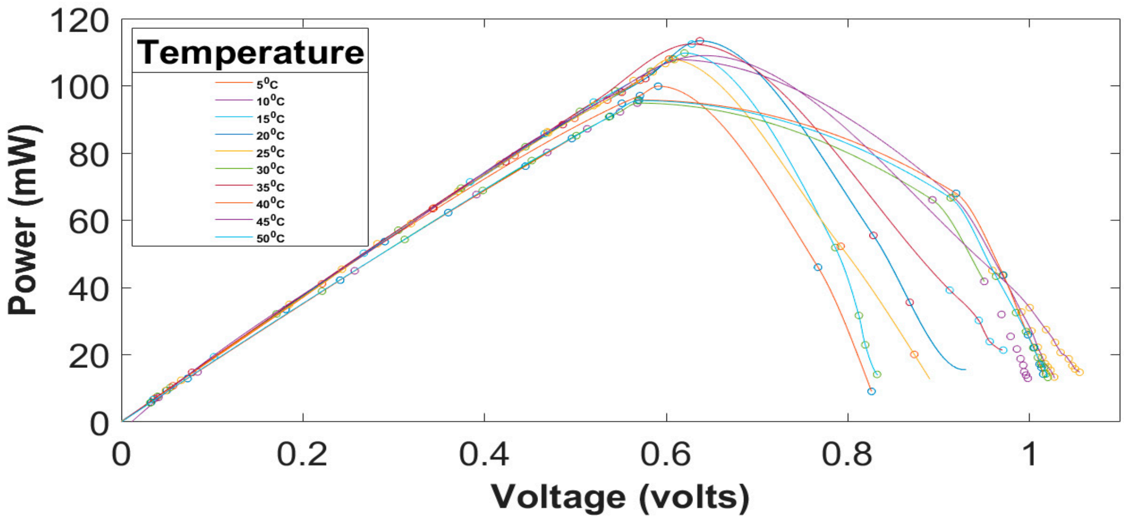

Figure 6. P−V characteristics of two solar cells connected in series.

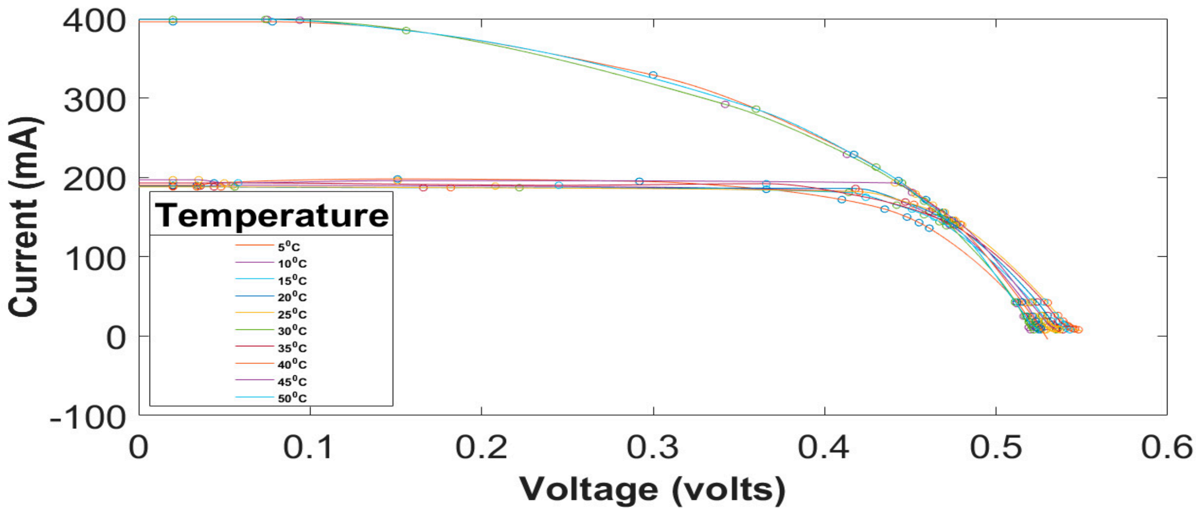

Figure 7. I−V characteristics of two solar cells connected in parallel.

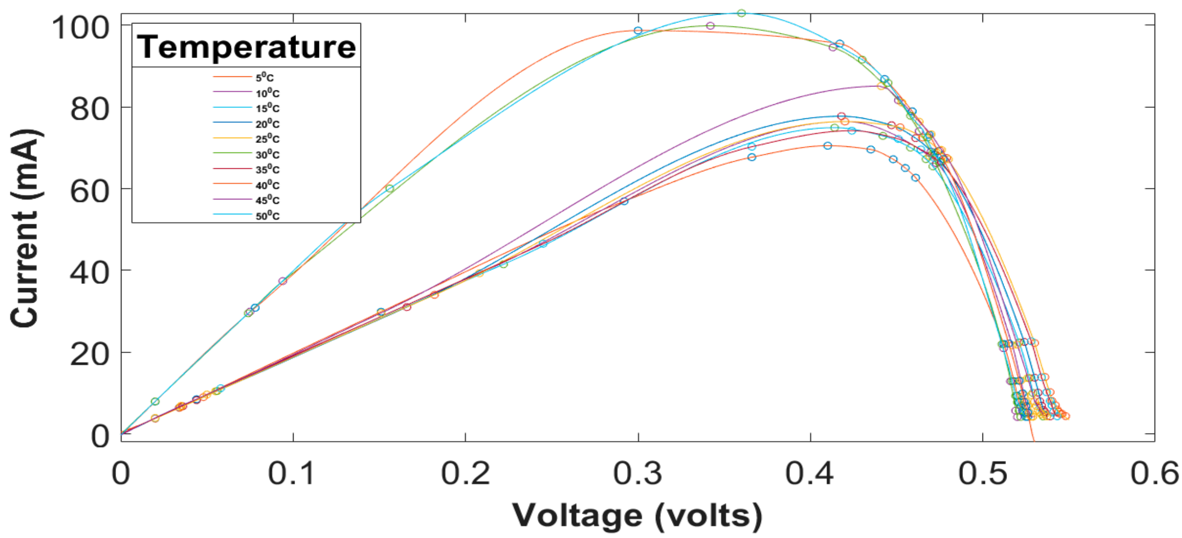

Figure 8. P−V characteristics of two solar cells connected in parallel.

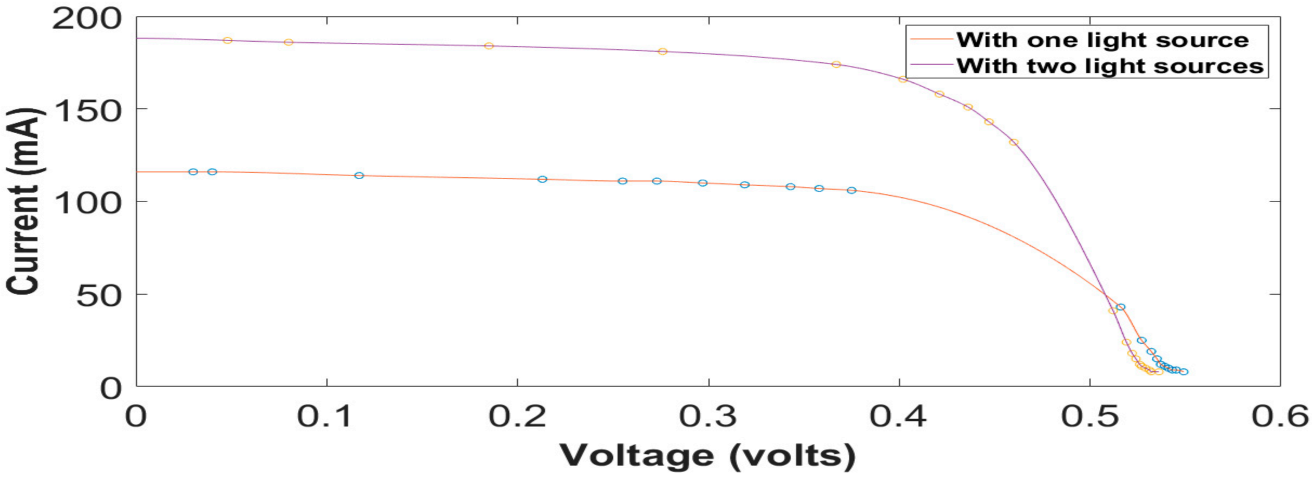

Figure 9. Effect of illuminance on the I−V characteristics.

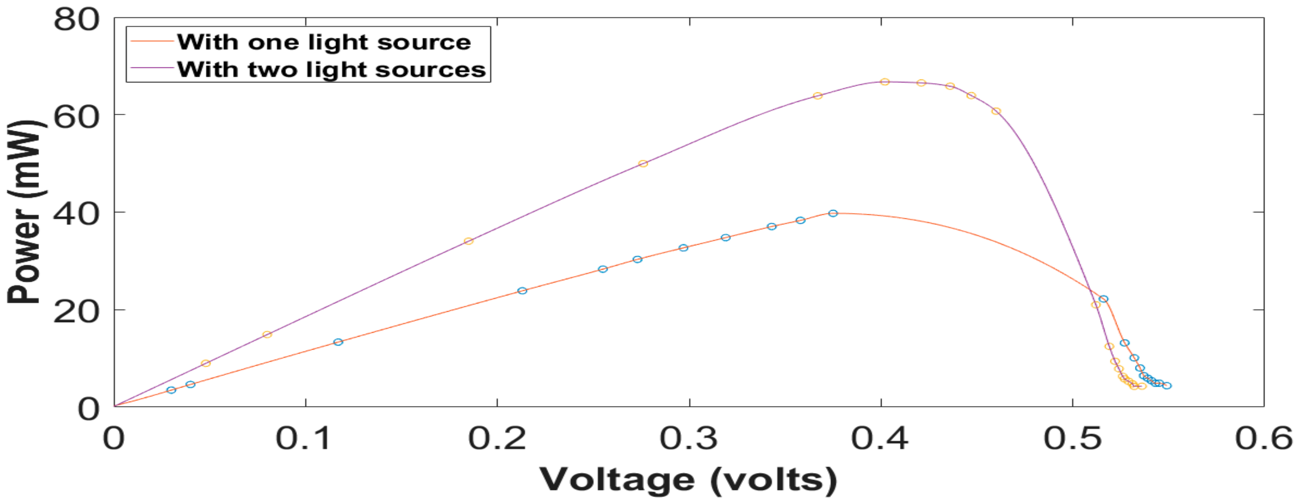

Figure 10. Effect of illuminance on the P−V characteristics.

The variation in maximum power with respect to the temperature from 0 °C to 50 °C in steps of 5 °C is given in Table 1. Tables 2 and 3 compare the efficiency and Fill Factor values for different temperatures and configurations.

Table 1. Maximum power output variation with temperature.

Temperature (°C)	Pmax_Individual (mW)	Pmax_Series (mW)	Pmax_Parallel (mW)
5	68.045	99.879	70.52
10	68.297	107.793	76.44
15	68.82	109.74	74.934
20	69.438	113.386	80.23
25	69.275	107.937	76.44
30	69.472	94.856	99.864
35	68.923	112.412	74.86
40	68.388	95.76	98.7
45	68.425	106.622	94.833
50	66.78	95.592	102.96

Table 2. Efficiency at different temperatures in various configurations.

Temperature (°C)	Individual Cell	Series	Parallel
5	14.96%	13.51%	15.51%
10	15.02%	14.58%	16.81%
15	15.13%	14.85%	16.48%
20	15.27%	15.34%	17.64%
25	15.23%	14.61%	16.81%
30	15.27%	12.83%	21.96%
35	15.15%	15.24%	16.46%
40	15.04%	12.96%	21.7%
45	15.04%	14.43%	20.85%
50	14.68%	12.93%	22.64%

Table 3. Fill Factor values at different temperatures in various configuration.

Temperature (°C)	Individual Cell	Series	Parallel
5	0.68	0.6466	0.7056
10	0.693	0.5524	0.7645
15	0.686	0.5966	0.741
20	0.696	0.581	0.7875
25	0.69	0.5705	0.7419
30	0.671	0.5339	0.4831
35	0.6737	0.568	0.6998
40	0.6724	0.533	0.4738
45	0.6788	0.5319	0.8964
50	0.6717	0.5265	0.4943

4. Discussion and Conclusions

The comprehensive analysis conducted in this project on crystalline silicon solar cell characteristics in individual, series, and parallel configurations, along with an assessment of the effects of temperature and illumination, provides valuable insights into the potential for a large-scale deployment of photovoltaic systems. One of the primary objectives of this project was to determine the optimal temperature and configuration settings for crystalline silicon solar cells. The maximum power output for individual cell configuration was observed at 30 °C, reaching 69.472 mW. This suggests that, under moderate temperature conditions, individual cells can achieve optimal performance. In contrast, the series configuration demonstrated its peak power output at 20 °C, delivering 113.386 mW. This finding implies that, in cooler climates, connecting cells in series may be the most efficient choice. The parallel configuration exhibited its maximum power output at 50 °C, with 102.96 mW. This indicates that, under high-temperature conditions, connecting cells in parallel can be advantageous.

Efficiency is a critical parameter in solar cell performance, and this project has shed light on the following results. The highest efficiency for individual cells was achieved at 20 °C and 30 °C, reaching 15.27%. This suggests that moderate temperatures are conducive to achieving optimal individual cell efficiency. Series-connected cells demonstrated their maximum efficiency at 20 °C, with an efficiency of 15.34%. This result highlights the importance of temperature control in optimizing series cell performance. In contrast, the parallel configuration showed its peak efficiency at 50 °C, reaching an impressive 22.64%. This finding suggests that under high-temperature conditions, parallel cell arrangements can deliver a good efficiency.

The Fill Factor is another critical parameter that affects solar cell performance [15].

Fill Factor in the individual cell: The highest Fill Factor value for the individual configuration was observed at 45 °C, with a value of 0.6788. This indicates the importance of temperature management to optimize the Fill Factor in individual cells. For the series configuration, the maximum Fill Factor value occurred at 5 °C, measuring 0.6466. This underscores the influence of low temperatures on the Fill Factor in series-connected cells. The parallel configuration demonstrated its peak Fill Factor value at 45 °C, registering an impressive 0.8964. This highlights the potential advantages of parallel cell arrangements under high-temperature conditions.

Furthermore, this work explored the impact of illumination on solar cell performance. Under conditions with a temperature of 55 °C, the effect of varying illumination levels was examined. With the temperature being held constant, the experiment demonstrated that increasing the illuminance led to a nearly twofold increase in power generation. Specifically, when two lamps were used, the maximum power generated was almost double that achieved with a single lamp.

The findings of this project not only contribute to our understanding of solar cell behavior but also pave the way for future research and development, which includes investigating and incorporating advanced materials into solar cell technology that could further increase efficiency and durability, making them even more viable for large-scale applications [16,17], implementing machine learning algorithms for real-time monitoring and control of solar panel configurations could optimize energy harvesting and improve system efficiency [18,19], and integrating efficient energy storage solutions will be vital for addressing intermittency issues, ensuring a stable energy supply, and supporting grid integration. Solar cell efficiency trends in different configurations and temperatures arise from semiconductor physics [20]. Moderate temperatures boost efficiency due to enhanced electron mobility. High temperatures reduce efficiency due to increased intrinsic carrier concentration, particularly in series and individual cells.

In conclusion, this project's findings have significant implications for optimizing the performance of crystalline silicon solar cells in various configurations and under different environmental conditions. The most recommended configuration is the solar cells in parallel, for optimum values of maximum power output, maximum efficiency, and Fill Factor. Key takeaways include temperature's impact on configuration efficiency, with moderate temperatures favoring individual cells, and high temperatures benefiting parallel setups.

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