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Experimental Research on PV Power Generation System Using V-trough Concentration

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Abstract:

Four sets of photovoltaic power generation systems were built: monocrystalline V-trough concentration, polycrystalline V-trough concentration, monocrystalline flat-panel, and polycrystalline flat-panel photovoltaic power generation systems, and experimental tests were carried out. The results show that under the same meteorological conditions, whether using monocrystalline silicon solar cells or polycrystalline silicon solar cells, the maximum and average electrical power of the V-trough concentrated photovoltaic power generation systems are greater than those of the flat-panel photovoltaic power generation systems. Among them, the maximum and average electrical powers of the monocrystalline V-trough concentrated photovoltaic power generation system are greater than those of the polycrystalline V-trough concentrated photovoltaic power generation system. The maximum and average electrical efficiencies of the monocrystalline V-trough concentrated photovoltaic power generation system are 3.70% and 1.48% higher than those of the monocrystalline flat-panel photovoltaic power generation system, respectively. The maximum and average electrical efficiencies of the polycrystalline V-trough concentrated photovoltaic power generation system are 3.13% and 1.99% higher than those of the polycrystalline flat-panel photovoltaic power generation system, respectively. The maximum and average surface temperatures of the solar cell in the monocrystalline V-trough concentrated photovoltaic power generation system are 1.13°C and 3.27°C lower than those in the monocrystalline flat-panel photovoltaic power generation system, respectively. The maximum and average surface temperatures of the solar cell in the polycrystalline V-trough concentrated photovoltaic power generation system are 0.95°C and 3.61°C lower than those in the polycrystalline flat-panel photovoltaic power generation, respectively.

Keywords:

V-trough concentrator
Photovoltaic power generation system
Electrical power
Electrical efficiency

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1. Overview

As resource availability becomes increasingly constrained, the world faces various energy shortages, making the development of new and renewable energy sources an urgent priority and strategic goal for economic and social progress [1]. Solar power generation is a key method of utilizing renewable energy, valued for its broad applicability and mature technology [2].

Currently, primary methods of solar energy utilization include solar thermal applications and photovoltaic (PV) power generation. However, PV systems often face challenges such as low solar energy flow density and dispersed energy, which affect the output power of solar cells [3]. Concentrating sunlight can significantly enhance the output power per unit area of solar cells and mitigate the dispersive nature of solar radiation. Both domestic and international studies have extensively examined low-concentration collectors for conventional PV systems [4-8]. Low-concentration collectors include Compound Parabolic Concentrators (CPC) and V-trough concentrators; compared to CPCs, V-trough concentrators have a simpler structure and are easier to manufacture [9]. Fraidenraich [10] derived design formulas for V-trough concentrators, ensuring uniform radiation distribution on the solar cell surface, and also developed a formula to calculate the power generation cost for concentrated PV (CPV) systems based on these designs. Sangani *et al.* [11] developed a single V-trough concentrator with a theoretical geometric concentration ratio of 2.0, which improved system output power by 44% compared to PV flat-plate systems with passive cooling components. Using ray-tracing software OptisWorks, Al-Shohani *et al.* [12] simulated and optimized the maximum concentration ratio, minimum irradiance non-uniformity, and minimum tilt height of reflectors for V-trough concentrators. Their results indicated optimal groove angles of 30°, 30°, 22°, and 19° for concentration ratios of 1.5, 2.0, 2.5, and 3.0, respectively. Wu *et al.* [13] combined a V-trough concentrator with a non-cavity PV/T component, demonstrating through experiments that the photovoltaic-thermal efficiency of the V-trough low-concentration PV/T component was higher than that of both non-cavity and cavity PV/T components, suggesting substantial application potential. Wang *et al.* [14] concentrated sunlight on PV cells using a low-concentration collector, designing a dual V-trough low-concentration PV system. They used a solar tracking and data collection system to study characteristic parameters such as short-circuit current, open-circuit voltage, and maximum power of a conventional monocrystalline silicon solar cell module under various concentration conditions. Their results showed that the dual V-trough low-concentration increased cell power by 27%, short-circuit current by 25%, and cell surface temperature to 44.8°C. V-trough concentrator PV systems do not require high-precision solar tracking systems; using low-cost concentrator devices to gather solar radiation on the cell surface, these systems address issues of low solar energy flow density and dispersed energy, significantly boosting output power per unit area and effectively reducing PV system costs, thus contributing significantly to the advancement of solar PV generation.

In summary, numerous studies have investigated the performance of V-trough concentrators in PV systems, but few have provided comparative analyses of the power generation performance of concentrator PV systems and flat-panel PV systems under identical experimental conditions or examined how monocrystalline and polycrystalline silicon solar cells affect PV system performance. This paper sets up four PV systems for experimental testing: a monocrystalline V-trough concentrator PV system, a polycrystalline V-trough concentrator PV system, a monocrystalline flat-panel PV system, and a polycrystalline flat-panel PV system.

2. Design of the V-trough concentrator

The reflection path of vertically incident light within the V-trough concentrator is shown in **Figure 1**, where n represents the sequence of incident light rays. In **Figure 1**, the groove angle ψ is half the apex angle of the V-trough, d denotes the opening width of the V-trough, and the origin O of the coordinate system is set at the vertex of the V-trough. The edge vertical light ray "1" reflects first at n = 1, located at the upper left corner of the V-trough (distance Y_0 from the central axis O_z of the V-trough opening), then reflects again at n = 2 (distance Y_1 from the central axis O_z), and reflects a third time at n = 3 on the left side of the V-trough (distance Y_2 from the central axis O_z). To ensure the light ray undergoes only one reflection before reaching the solar cell surface, the solar cell can be placed on or above the horizontal plane at $n = 2$.

The physical V-trough concentrator used in this study is shown in **Figure 2**. It is made by bending a single aluminum mirror sheet with a thickness of 1 mm. The V-trough concentrator is designed for vertical incidence, with the base aligned with the $n = 2$ horizontal plane in **Figure 1**. This design ensures that light reflects only once within the concentrator, achieving a high concentration ratio and minimizing reflection losses.

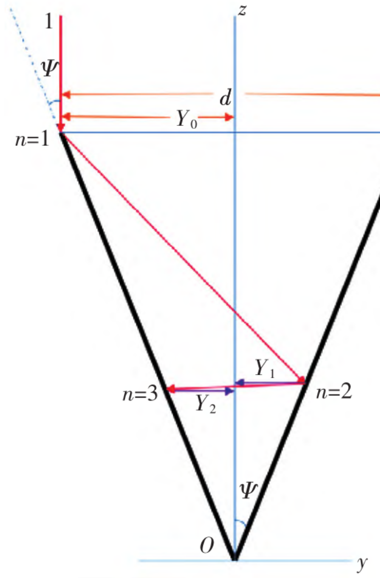

Figure 1. Reflection path of vertically incident light within the V-trough concentrator

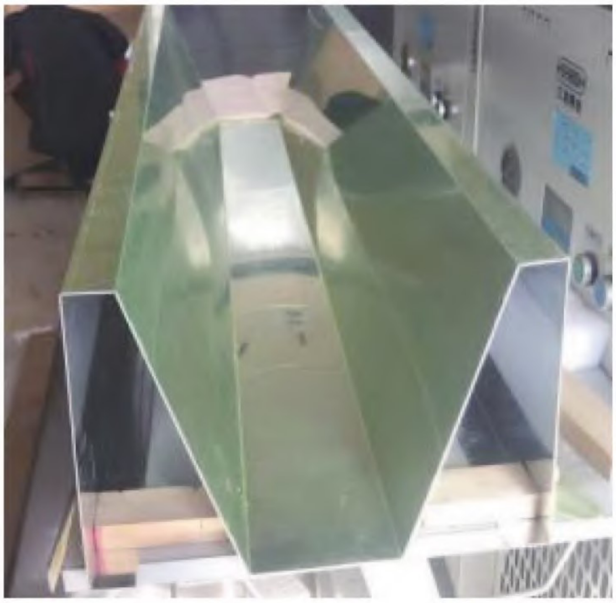

Figure 2. Physical V-trough concentrator

The theoretical concentration ratio of the V-trough concentrator is 2.5, with a groove angle of 20°, a base width of 10 cm, and a slant height of 21 cm. The aluminum mirror has a reflectivity of 0.85, and the solar cell panel dimensions are 1,000.0 mm × 100.0 mm × 3.5 mm. Structural parameters of the V-trough concentrator are shown in **Figure 3**, with all dimensions in centimeters.

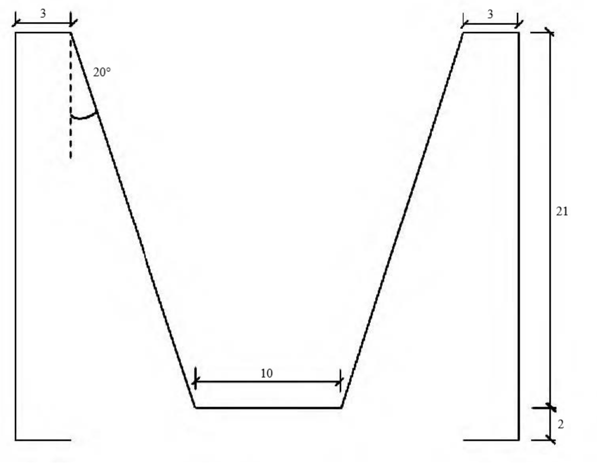

Figure 3. Structural parameters of the V-trough concentrator

3. Experimental system

3.1. Experimental system setup

The V-trough CPV power generation system primarily comprises the V-trough concentrator and solar cells. The PV power generation experimental system is shown in **Figure 4**. Both the V-trough concentrated photovoltaic system and the flat-plate photovoltaic system consist of a PV power generation system and a data collection system.

Key parameters measured in the experiment include solar irradiance, surface temperature of the solar cells, and the output current and voltage of the solar cells. A pyranometer is used to measure solar irradiance during the experiment, a temperature-humidity sensor measures environmental temperature and humidity, and a wind speed sensor measures ambient wind speed. The output current and voltage of the solar cells are measured using current/voltage sensors, and the surface temperature of the solar cells is measured using adhesive-type platinum resistance thermometers.

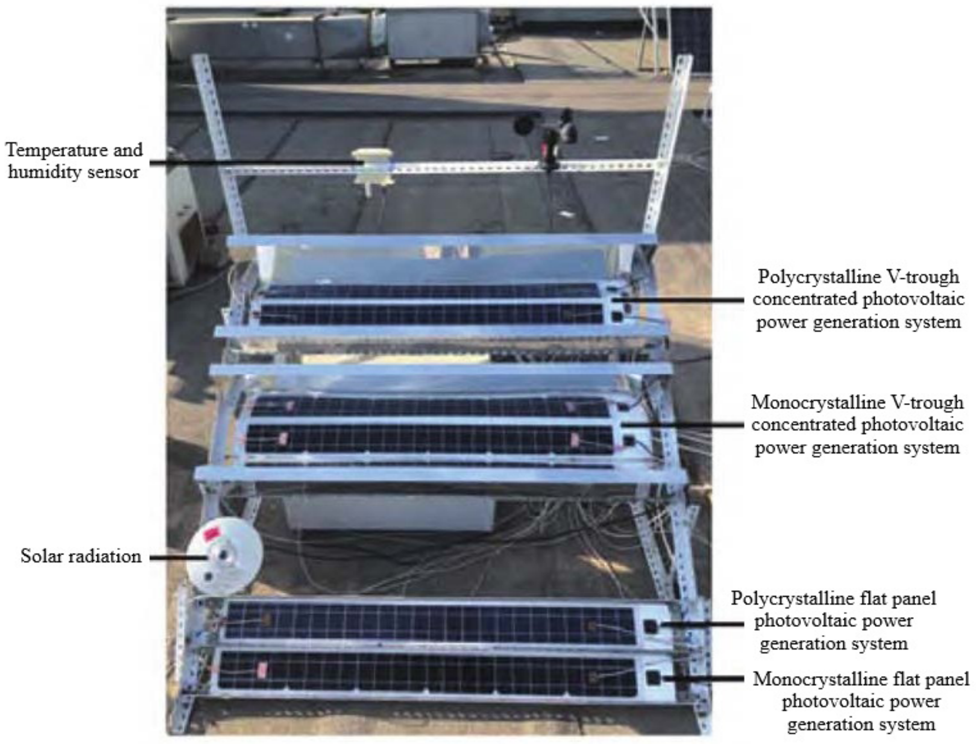

Figure 4. Photovoltaic power generation experimental system

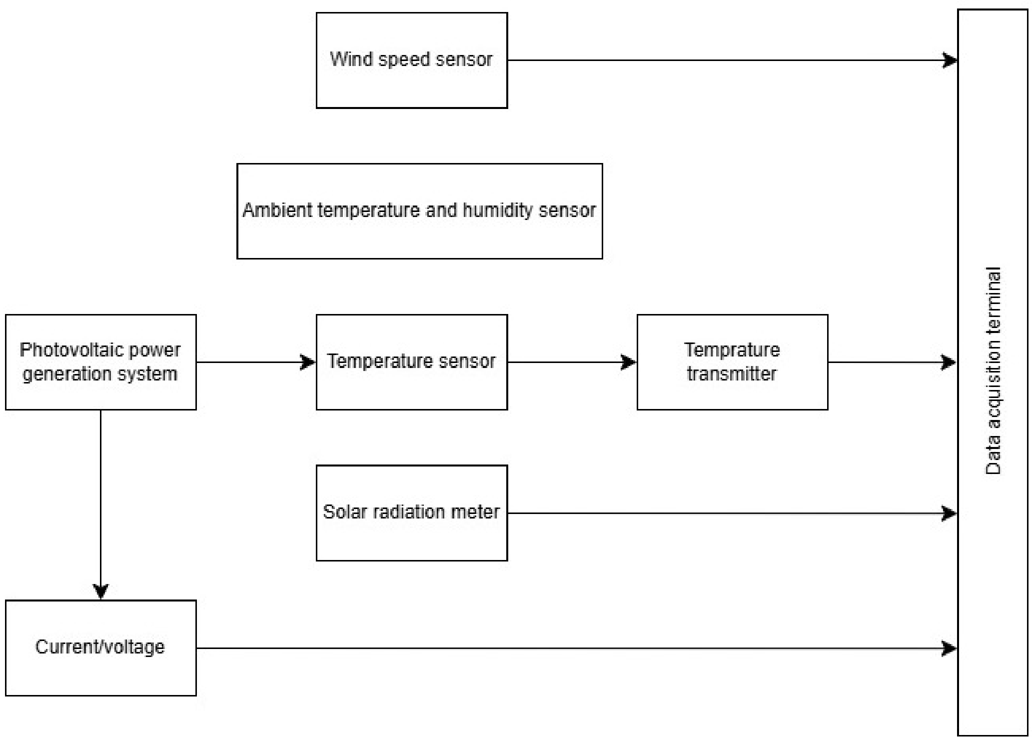

Figure 5. Data collection system

3.2. Data collection system

All measuring devices use RS485 communication lines and the Modbus communication protocol. After real-time data collection is completed, data is sent to the data acquisition terminal. The terminal processes real-time data from each device in a pre-set format and saves it to a database via a data network. The data collection system is shown in **Figure 5**.

3.3. Evaluation metrics

The electrical power P of the generation system is calculated using the formula:

$$P = UI$$

where P is the electric power (W), U is the solar cell output voltage (V), and I is the solar cell output current (A).

The electrical efficiency η of the generation system is calculated as:

$$\eta = \frac{P}{EA}$$

where η is the electrical efficiency, E is the solar irradiance (W/m^2), and A is the area of the solar cell (m^2).

4. Results and discussion

The experimental system was installed on the rooftop of a university building in Beijing, with the platform tilted at an angle of 37°. The experiment was conducted from May to June 2021, with data collection each day from 8:30 to 16:30. The operating conditions on May 30, 2021, were selected as a typical case for analysis.

Meteorological conditions on the typical operating day are shown in **Figure 6**. Solar irradiance first increased and then decreased, reaching a peak around 11:30, with a maximum irradiance of 925 W/m^2 and an average irradiance of 708 W/m^2. Outdoor temperatures showed an overall upward trend, reaching a peak of 32.8°C at around 16:00, with an average outdoor temperature of 28.0°C.

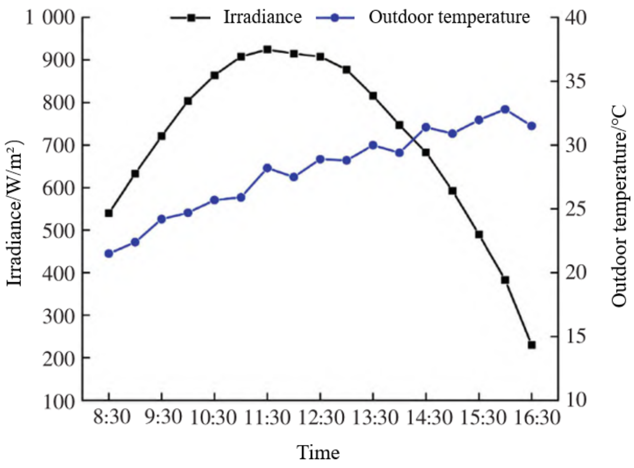

Figure 6. Meteorological conditions on a typical operating day

4.1. Electric power output

The power output trends for the monocrystalline V-trough CPV power generation system and the monocrystalline flat-panel PV power generation system are shown in Figure 7. Both systems exhibited a similar trend, with power output initially rising and then declining, reaching their peak power around 12:00. The maximum power output for the monocrystalline flat-panel PV system was 7.63 W, with an average power output of 5.75 W. In comparison, the monocrystalline V-trough CPV system achieved a maximum power output of 13.20 W and an average power output of 8.26 W, representing an increase of 73.00% in maximum power and 43.65% in average power compared to the flat-panel system.

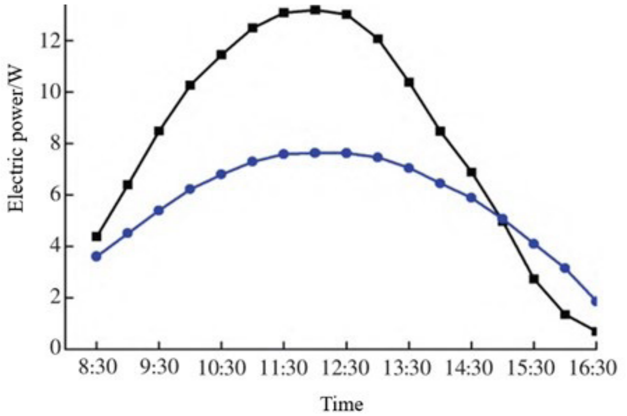

Figure 7. Power output trends for monocrystalline V-trough CPV power generation system and monocrystalline flat-panel PV power generation system

The power output trends for the polycrystalline V-trough CPV system and the polycrystalline flat-panel PV system are shown in **Figure 8**. Both systems showed similar trends, with power output initially rising and then declining, peaking around 11:30. The maximum power output for the polycrystalline flat-panel PV system was 7.58 W, with an average power output of 5.71 W. In comparison, the polycrystalline V-trough CPV system achieved a maximum power output of 12.83 W and an average power output of 7.86 W, representing an increase of 69.26% in maximum power and 37.65% in average power compared to the flat-panel system.

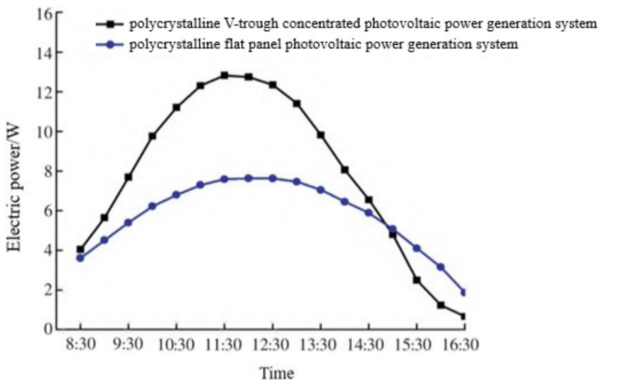

Figure 8. Power output trends for polycrystalline V-trough CPV power generation system and polycrystalline flat-panel PV power generation system

Regardless of whether monocrystalline or polycrystalline solar cells were used, the V-trough CPV system demonstrated higher maximum and average power output than the flat-panel PV system. Under the same meteorological conditions, the monocrystalline V-trough CPV system outperformed the polycrystalline V-trough CPV system in terms of both maximum and average power output.

4.2. Electrical efficiency

The trend in electrical efficiency for the monocrystalline V-trough CPV system and the monocrystalline flat-panel PV system is shown in **Figure 9**. Both systems displayed a similar trend of rising efficiency followed by a decline, with efficiency reaching a peak around 14:00. The monocrystalline flat-panel PV system achieved a maximum efficiency of 8.64% and an average efficiency of 8.09%. In comparison, the monocrystalline V-trough CPV system reached a maximum efficiency of 8.96% and an average efficiency of 8.21%.

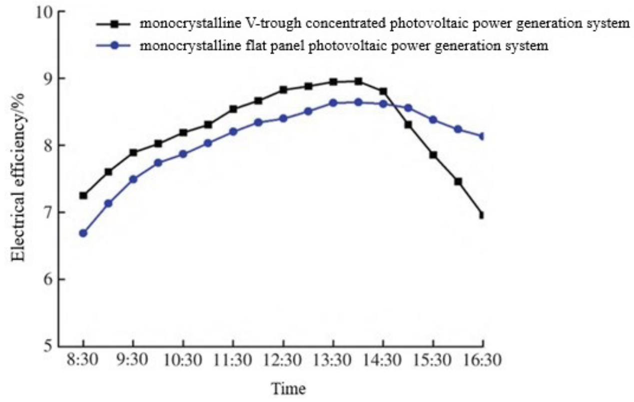

Figure 9. Electrical efficiency trends for monocrystalline V-trough CPV system and monocrystalline flat-panel PV system

The electrical efficiency trend for the polycrystalline V-trough CPV system and the polycrystalline flat-panel PV system is shown in **Figure 10**. Both systems showed a similar pattern, with efficiency increasing and then decreasing, peaking around 14:00. The polycrystalline flat-panel PV system achieved a maximum efficiency of 8.62% and an average efficiency of 8.03%, while the polycrystalline V-trough CPV system reached a maximum efficiency of 8.89% and an average efficiency of 8.19%.

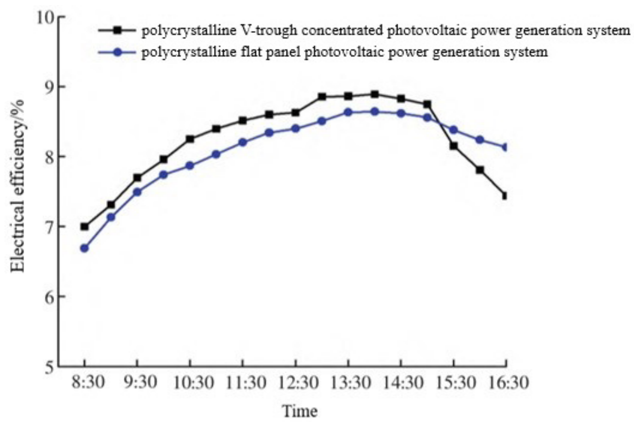

Figure 10. Electrical efficiency trends for polycrystalline V-trough CPV system and polycrystalline flat-panel PV system

The maximum and average electrical efficiency of the monocrystalline V-trough CPV system increased by 3.70% and 1.48%, respectively, compared to the monocrystalline flat-panel PV system. For the polycrystalline systems, the maximum and average efficiencies of the V-trough CPV system were 3.13% and 1.99% higher, respectively, than those of the flat-panel PV system.

4.3. Analysis of solar cell surface temperature

The temperature variation of the solar cell surface in the monocrystalline V-trough CPV system and the monocrystalline flat-panel PV system is shown in **Figure 11**. Both systems demonstrated a trend where the surface temperature of the solar cell initially rose and then fell, with the temperature reaching its highest point around 12:30. The maximum surface temperature for the solar cell in the monocrystalline V-trough CPV system was 54.32°C, with an average temperature of 45.13°C. In comparison, the monocrystalline flat-panel PV system reached a maximum surface temperature of 55.45°C and an average temperature of 48.40°C.

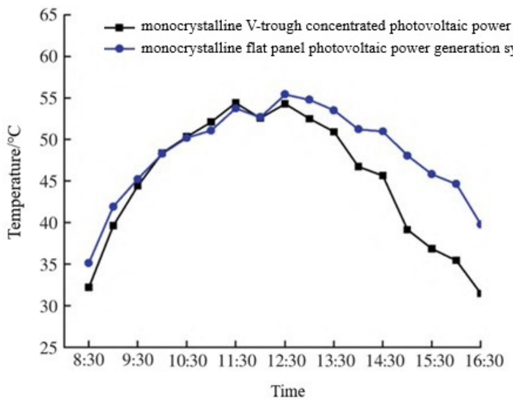

Figure 11. Solar cell surface temperature trends for monocrystalline V-trough CPV system and monocrystalline flat-panel PV system

The temperature variation of the solar cell surface in the polycrystalline V-trough CPV system and the polycrystalline flat-panel PV system is shown in **Figure 12**. Both systems exhibited similar trends, with temperatures rising and then falling, and the peak temperature occurring around 12:30. The polycrystalline V-trough CPV system's solar cell surface reached a maximum temperature of 57.94°C and an average temperature of 47.30°C, while the polycrystalline flat-panel PV system's maximum and average surface temperatures were 58.89°C and 50.91°C, respectively.

Compared to the monocrystalline flat-panel PV system, the monocrystalline V-trough CPV system reduced the maximum and average surface temperatures by 1.13°C and 3.27°C, respectively. Similarly, the polycrystalline V-trough CPV system reduced the maximum and average surface temperatures by 0.95°C and 3.61°C, respectively, compared to the polycrystalline flat-panel PV system.

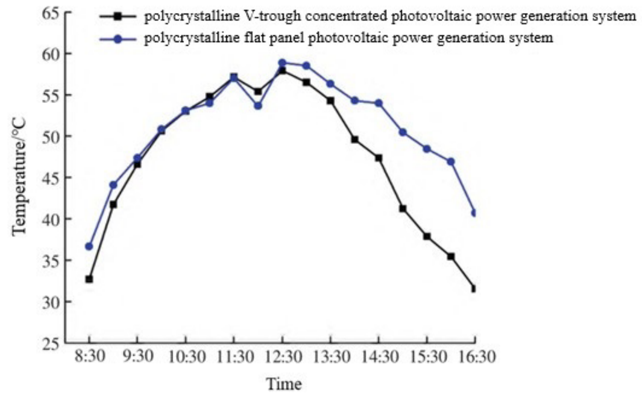

Figure 12. Solar cell surface temperature trends for polycrystalline V-trough CPV system and polycrystalline flat-panel PV system

5. Conclusion

(1) Under identical weather conditions, regardless of using monocrystalline or polycrystalline solar cells, the V-trough CPV system demonstrated higher maximum and average power outputs than the flat-panel PV system. Additionally, the monocrystalline V-trough CPV system achieved higher maximum and average power outputs than the polycrystalline V-trough CPV system.

(2) The maximum and average electrical efficiencies of the monocrystalline V-trough CPV system were improved by 3.70% and 1.48%, respectively, compared to the monocrystalline flat-panel PV system. For polycrystalline cells, the V-trough CPV system showed efficiency increases of 3.13% and 1.99% over the polycrystalline flat-panel PV system.

(3) The monocrystalline V-trough CPV system reduced the maximum and average solar cell surface temperatures by 1.13°C and 3.27°C, respectively, compared to the monocrystalline flat-panel PV system. Similarly, the polycrystalline V-trough CPV system reduced these temperatures by 0.95°C and 3.61°C compared to the polycrystalline flat-panel PV system.

Disclosure statement

The authors declare no conflict of interest.

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