V-Trough Optimization for a Multipurpose Integrated Solar Energy Project in Helwan of Egypt

Yasser A Abdel-Hadi1*, Mohamed Sabry1, Ahmed Ghitas1, Harjit Singh2 and David Redpath2

1 PV Unit, Solar and Space Research Department, National Research Institute of Astronomy and Geophysics (NRIAG), Cairo, Egypt.
2 College of Engineering, Design and Physical Sciences, Brunel University, London, UK

* E-mail: yasser_hadi@yahoo.com

Abstract. A solar concentrator of the type V-Trough is designed for a multipurpose integrated solar energy project in Helwan of Egypt. A suitable place in the NRIAG is selected. A concentration ratio matching the stability of the unconventional cooling technique for PV module 2.3 is chosen. A new cooling system with heat pipes for the module is manufactured. The optimum angles of setting the system for a maximum performance during the year are calculated using a ray tracing technique. The optimum dimensions of the PV module are 100 cm × 35 cm with an output voltage of 11.4 V and an output current of 4.29 A. The results show that establishing a solar thermal PV project with these conditions is promising for providing energy for off-grid local multipurpose integrated solar energy projects in that area.

Keywords: Solar Energy Concentration, Ray tracing, Electrical and Thermal PV module.

1. Introduction

An increased interest in the studies concerning hybrid Photovoltaic/Thermal (PV/T)solar energy systems for maximizing total output of the solar energy utilization [1], [2]. These studies revealed that such PV/T collectors have high overall efficiency than the traditional stand-alone PV and solar thermal systems operating separately. A solar concentrator can increase the collected solar intensity by directing the incoming light rays onto a small collector area, enabling to operate under higher input solar power, hence producing higher output. Solar concentrators can share effectively in increasing the collected solar energy by concentrating such irradiation for effective thermal, electrical or hybrid energy conversion at affordable prices [3]. Solar concentrators are classified according to their optical device used (parabolic dish or trough, etc.), by their concentration ratio (low, medium and high), or by the type of their formed image (point focus, line focus, etc.) [4].

To reduce total system cost, non-imaging solar concentrators can efficiently use commercial reflective surfaces such as mirrors or high reflection films designed to collect extreme angular rays of incident solar radiation compared to just the axial rays collected by imaging systems [5]. Although their low optical tolerances, the development of non-imaging optics[6]enabled the development of line axis solar energy concentrating systems that can asymptotically approach the maximum geometric
concentration of a light source for a particular angle of view. Non-imaging systems are more suited to Concentrating Solar Photovoltaic (CPV) systems as the distributed collected radiation across the collector provides a suitable uniformity of illumination required by solar cells to avoid shading, hence reduced performance[7].

V-trough solar concentrator is one of those non-imaging line axis optical systems, which offers an attractive option for integration to photovoltaic and thermal solar arrays. It is probably one of the least complex solar reflective concentrating systems to manufacture and operate with reasonable efficiency with zero or infrequent single axis adjustments, monthly or seasonal [8]. V-trough concentrators can also collect a reasonable amount of incident diffuse solar radiation at its aperture.

Many V-trough systems have been built up and tested all over the world with different concentration ratios depending on their chosen orientation and tracking strategy. Reported concentrations ratios of as high as 4X and as low as 2X, and their collection efficiency have been varied accordingly. It has been mentioned that [6] the collected percentage of diffuse radiation incident on the concentrator aperture is the reciprocal of the concentration ratio. Optimizing the V-trough concentration ratio is then subject to the weather conditions and the percentage of diffused radiation intensity to that of direct.

The V-trough system under investigation has a chosen geometrical concentration ratio of 2.3X and the collector is a PV/T novel hybrid system that maximizes its electrical output by cooling the PV using heat pipes and collect such thermal energy by means of active water-cooling sub-system. In this work, we only show the predicted V-trough optical performance in two different modes of orientations; yearly fixed and monthly tracking. Measured PV/T performance and the collection efficiency of the whole system will be published elsewhere.

2. Methodology

According to the topography of the area of the National Research Institute of Astronomy and Geophysics (NRIAG) and the distribution of the already existing buildings, the best location for setting the system was in the locations of latitude $\phi = 29.863526^\circ$ N ($29^\circ$ 51ʹ 48.6936ʺ N) and longitude $\lambda = 31.342028^\circ$ E ($31^\circ$ 20ʹ 31.3008ʺ E). Figure 1 shows the sketch diagram of the location of the system beside the new building of the National Research Institute of Astronomy and Geophysics (NRIAG).

![Figure 1](image)

**Figure 1.** The sketch diagram of the location of the system besides the new building of the National Research Institute of Astronomy and Geophysics (NRIAG).

The system of V-Trough concentrator is supposed to be set at the position shown in figure 1 south-faced. There are two cases to optimize its performance; either to set it stationary with an optimum tilt angle or to track it seasonally or monthly according to the sun position during the year. For both cases, it is necessary to calculate the position of the sun during the year for the operation time of the system. Providing that the high operation hours of the system are during the day and especially...
around the noon time, we calculated the limits of the sun positions for the system location. It is obvious that the sun altitude reaches its higher value at noon. Table 1 shows the sun altitudes at noon for the cardinal days of the annual seasons.

| Date                  | Noon Time  | Sun Declination | Sun Altitude at Noon |
|-----------------------|------------|-----------------|----------------------|
| Winter Solstice (21st December) | 11:56:22  | -23.44º         | 36.48º               |
| Spring Equinox (21st March)    | 12:01:37  | 0.4º            | 60.31º               |
| Summer Solstice (21st June)    | 11:56:22  | 23.44º          | 83.34º               |
| Autumn Equinox (21st September) | 11:47:34  | 0.54º           | 60.45º               |

The limits of sun elevation angles in both winter and summer solstices are calculated to be 36.48º and 83.34º respectively. Therefore, the rays entering the V-Trough concentrator will be subtended between those angles. The optimum tilt angle for monthly variation has been statistically calculated by three specific anisotropic models (Tamps–Coulson, Perez and Bugler) at Helwan site [9]. Optimum tilt angle values measured from the zenith based on geometric factor are represented in Table 2. The experimental verification was presented based on weekly measurements obtained at a multi-position test facility[10].

| Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sep. | Oct. | Nov. | Dec. |
|------|------|------|------|------|------|------|------|------|------|------|------|
| Predicted | 55   | 45   | 30   | 15   | 5    | 5    | 5    | 15   | 25   | 40   | 50   | 55   |
| Experiment | 51   | 48   | 33   | 21   | 4    | 4    | 7    | 20   | 32   | 48   | 53   | 55   |

Figure 2 shows the Schematic diagram of the V-Trough concentrator which has to be analyzed to match the setting conditions at that location, where $W_a$ is the width of the aperture, $W_r$ is the width of the absorber and $L$ is the length of segment which is the reflector side of the V-Trough.
Figure 2. Schematic diagram of the V-Trough analysis.

If the acceptance angle is $\theta_a$, then from figure 2, we can derive the formulas from which we can calculate the dimensions of the V-Trough from the Equations (1 to 3).

\begin{align*}
W_a &= W_r + 2c \\
c &= \frac{(W_a - W_r)}{2} \\
tan\theta_a &= \frac{c}{H}
\end{align*}

Then, the height of the V-trough can be calculated from Equation (4).

\[ H = \frac{c}{tan\theta_a} = \frac{(W_a - W_r)}{2tan\theta_a} \]

Accordingly, the length of the trough segment can be calculated from Equation (5).

\[ L = \frac{H}{cos\theta_a} \]

The goal is to use the ray tracing technique to find out the optimum design to redirect the solar rays within this angular range into the absorber. The tilting of the V-Trough concentrator (the direction of the normal of the absorber) is chosen to be the mean angle between 36.48° and 83.34°, which is 56.38°. The absorber is a solar module of dimensions 100 cm × 35 cm shown in figure 3. So, the width of the absorber is 35 cm. One of the aims of this experiment is to gain thermal energy besides electrical energy. Thus, the PV module is designed in a way to reduce solar cells temperature and collect such waste thermal energy to maximize total output. The photovoltaic module is consisting of five strings. Each string contains four monocrystalline silicon solar cells. The solar cells are fitted on top of an aluminum sheet for good thermal connection with a thin foil of EVA material for electrical isolation. The back aluminum sheets are grooved for fixing copper heat pipes, which are used for fast thermal dissipation. The top of the sheet strings is directly connected internally with an aluminum bulk copper tubes embedded for water flow. This new cooling technique is used for actively cooling the PV module when it is used under high concentration system.
According to the calculations of the whole system, the needed value of the concentration ration was taken to be 2.3. The reflectivity of the two segments of the concentrator is chosen to be 0.7 representing the normal low-cost commercial mirror. The half-acceptance angle of the trough $\theta_a$ will be $25.77^\circ$ to match the needed concentration ratio. Accordingly, the width of the trough entrance (upper aperture) will be 80.5 cm, its height $H$ will be 47.1 cm, while sidereal length of each one of its segments $L$ will be 52.3 cm.

![Monocrystalline silicon PV module connected with active cooler](image)

**Figure 3.** Monocrystalline silicon PV module connected with active cooler; (a) front and (b) back sides.

The trough is assumed to be set stationary with south facing tilted position with an angle equals to the mean altitude of the sun over the year at Helwan which is calculated to be $56.38^\circ$. The Trace Pro© software was used to simulate the distribution of the concentrated rays inside the trough. The incident solar irradiance of 750 W/m$^2$, which is supposed to be an average solar irradiance for a sunny day, was simulated for the V-Trough of the mentioned dimensions. Figure 4 shows a schematic diagram of the reflections that the rays undergo inside the trough until they hit the absorber which is the PV-module.
Figure 4. A schematic diagram of the reflections that the rays undergo inside the trough until they hit the absorber which is the PV-module.

Also, it is important to simulate the distribution of the rays inside the trough after entering its upper aperture and undergoing their reflections to imagine their final distribution after the incidence on the PV-module. Figures 5-8 show a simulation for the detected rays distributed on the PV module according to different angles of incidence representing the possible apparent positions of the sun in the sky. It is important to notice that the chosen stationary angle (56.38°) is the reference angle, to which the incident ray coming from the sun has an angle of 0°.

Figure 5. The distribution of the incident rays (W/m²) on the PV module in the case of incident radiation of the same angle like the stationary facing angle of the V-trough (the difference in angles is 0°).

Figure 6. The distribution of the incident rays (W/m²) on the PV module in the case of incident radiation 10° smaller than the stationary facing angle of the V-trough (the difference in angles is 5°).
It is important to calculate the solar radiation intensity delivered to the PV module by the V-Trough concentrator. Figure 9 shows these values against the differences between the tilting angle of the V-trough and the angle of the incidences of the solar radiation. Accordingly, we can calculate the intensity concentration ratio resulted by the concentrator against the tilting angle. Its values are represented in Figure 10. Figure 11 shows the angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tilted to the angle of 56° to the south during the operation time between 9:00 and 15:00. Accordingly, the concentration ratio of the V-Trough during the same operation according to the angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tilted to the angle of 56° to the south is shown in Figure 12. Hence, the concentrated solar radiation intensity by the V-Trough delivered to the PV module during the operation time between 9:00 and 15:00 according to the angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tilted by angle of 56° is shown in Figure 13.

Figure 7. The distribution of the incident rays (W/m²) on the PV module in the case of incident radiation 20° smaller than the stationary facing angle of the V-trough (the difference in angles is 10°).

Figure 8. The distribution of the incident rays (W/m²) on the PV module in the case of incident radiation 30° smaller than the stationary facing angle of the V-trough (the difference in angles is 20°).
Figure 9. The concentrated solar radiation intensity received by the PV module against the differences between the tilting angle of the V-trough and the angle of the incidences of the solar radiation.

Figure 10. The concentration ratio of the V-Trough concentrator against the differences between the tilting angle of the V-trough and the angle of the incidences of the solar radiation.
Figure 11. The angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tilted to the angle of 56° to the south during the operation time between 9:00 and 15:00.

Figure 12. The concentration ratio of the V-Trough during the operation time between 9:00 and 15:00 according to the angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tilted to the angle of 56° to the south.
To increase the performance of the system, sometimes it is needed to apply the tracking mode. For such a two-dimensional system of concentrator, the optimum tracking mode is the seasonal tracking for the system which is set east-west facing the south. This means that the facing angle will be changed seasonally in order to collect the maximum possible solar radiation and to minimize the loss in the case of fixing the facing angle during the year. This will enhance the concentration ratio of the V-Trough to reach the upper limit of its geometrical value. Figure 14 shows the concentration ratio of the V-Trough during the operation time between 9:00 and 15:00 according to the angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tracked monthly. According to these values of concentration ratios, intensities of concentrated solar radiation shown in figure 15 can be attained.
3. Predicted PV Output

The output field measurements of the PV module and separate strings are shown in figure 16. The measurements were carried out around the noon-time on March 15, 2021 at the project location. The intensity of the incident global solar radiation recorded at that time was 909 W/m². The tool used for the electrical measurements was PV-data logger. The total output module voltage and current in series connection are 11.4 V and 4.3 A respectively. Accordingly, the maximum output power attained by the module is 49.02 W. Hence, we can report the maximum efficiency of the module as
15%. Then, the output power gained by the module can be plotted against the tilting angle as shown in figure 17.

Figure 16. Field measurements of the PV module.

Figure 17. The output power of the system against the differences between the tilting angle of the V-trough and the angle of the incidences of the solar radiation.

From figure 17, we can find that the power gained from the module during a spring day in the effective hours of the sun from 9:00 AM to 3:00 PM ranges between 40 and 80 W. The predicted output power obtained by the system in both cases (stationary tilted angle of 56° and monthly tracking by an optimum angle) can be represented in figures 18 and 19 respectively.
Figure 18. The predicted output power of the system during the operation time between 9:00 and 15:00 according to the angle of the incidence of the solar radiation on the cardinal days of the year seasons on the system tilted to the angle of 56° to the south.

Figure 19. The predicted output power of the system during the operation time between 9:00 and 15:00 according to the angle of the incidence of the solar radiation on the cardinal days of the year seasons for the monthly tracked system.

4. Conclusions
In this work, we reported an evaluation and optimization of using a simply concentrated solar radiation for increasing the output power gained from a solar PV module in an arid location in Helwan (35 km south of Cairo, Egypt). Using position calculations and ray tracing technique, we optimized a simple PV module system receiving a concentrated solar radiation by a simple solar concentrator of a V-trough shape. By this system, we got more than twice the value of the incident global solar radiation concentrated on the PV module of an efficiency of about 15%. The system was chosen to be fixed on
a tilting angle calculated according to the location latitude and longitude. The distribution of the rays received by the module is ray-traced and accordingly calculated according to the difference between the sun’s altitude and the fixed tilt angle. The maximum solar radiation power received by module was about 540 W which can be converted to about 83 W of electrical power. The power gained from the module in such a system during a spring day in the effective hours of the sun from 9:00 AM to 3:00 PM ranges between 40 and 80 W. The output power is slightly dropped for the sun’s altitude of 10° smaller or bigger than the fixed tilted angle of the system, while it drops dramatically (about the half of its maximum value) for the sun’s altitude more than 20° smaller or bigger than that angle. Such power range can readily increase on the summer days on which the received global solar radiation has higher values.

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