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Influence of partial shading on performance of a V-trough CPV system with various truncation levels

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Abstract

This study experimentally investigates the performance of a fixed concentrated photovoltaics system consisting of a photovoltaics module coupled with V-trough concentrators under partial shading conditions. V-troughs had the same trough angles, but different truncation levels (reflector lengths). Their geometric concentration ratios were 2.35 and 1.80. Research covers a wide range of operating parameters – generated power, electrical efficiency, module's average temperature, and characteristic curves – offering a unique multidimensional experimental comparison of concentrated photovoltaics performance with V-troughs of different truncation. The objective is to determine a relationship between the V-trough geometry, working conditions, and generated power. Findings reveal that the maximum power point and short-circuit current are strong functions of the truncation level and angle of incidence. For angles close to 0°, these parameters reach greater values at lower truncation. At higher angles, this trend reverses. While concentrator-integrated systems have a higher peak power than the bare module (by 23% and 18% for the longer and shorter concentrators, respectively), they experience greater temporal fluctuations in operational parameters due to shading. Their daily average power production was comparable to that of the bare module as shading cast by V-trough reflectors led to a loss in the instantaneous generated power of up to 45% compared to the system with no concentrator. Thus, among the tested concentrators, the shorter one is more cost-effective due to reduced material consumption. Additionally, the maximum power of concentrator-integrated systems was produced when the module temperature reached 70ºC, rather than when the solar irradiance was maximum.

Keywords: Concentrating photovoltaics; V-trough concentrator; Truncation; Experimental studies

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1. Introduction

The capacity of solar photovoltaics (PVs) is increasing worldwide, which gives impetus to the development of methods to generate more electric power per unit area of a photovoltaic (PV) module. These methods would allow reducing the number of modules required to achieve the desired power generation, and thus lowering the cost of a PV system installation.

One of the approaches to maximise the generated power involves using concentrated photovoltaics (CPV), where mirrors or lenses concentrate solar energy onto the surface of the module, thus increasing the solar irradiance that enters the module. Various CPV configurations are available. One of them is a V-trough consisting of two flat mirrors placed at a predetermined angle relative to the module's surface. It is an example of non-imaging optics, which offers low concentration of solar energy. Compared to high concentration optics, in V-trough based systems, using sun-tracking can be avoided [1], which reduces the cost of the installation. Moreover, their simple geometry translates into a lower production cost and allows more uniform

Nomenclature

a – receiver area, m^2
A – aperture area, m^2
A_{in} – area through which solar rays enter the system, m^2
C – geometric concentration ratio
G – solar irradiance on a tilted surface, W·m^{-2}
H – height of the concentrator, m
H_{init} – height of the concentrator without truncation, m
I_{mp} – maximum power current, A
I_{SC} – short-circuit current, A
L – aperture length, m
L_{PV} – length of the PV module, m
P_{in} – incoming solar power, W
P_{PV} – power produced by the PV module, W
$S_{U,CF}$ – standard deviation in voltage calculated using calibration function, V
$S_{U,DMM}$ – standard deviation in voltage measured with a multimeter, V
t_{ave} – average PV module temperature, °C
t_{bottom} – temperature of the PV module bottom part, °C
t_{mid} – temperature of the PV module middle part, °C
t_{top} – temperature of the PV module top part, °C
u – uncertainty
U_{mp} – maximum power voltage, V
U_{oc} – open-circuit voltage, V
w – receiver width, m
W – aperture width, m
W_{PV} – width of the PV module, m
Z – length of the reflectors, m

Greek symbols

β_{opt} – optimum tilt angle, deg
δ – acceptance angle, deg
δ_{max} – maximum acceptance angle, deg
Δ – decrease from maximum to minimum relative to maximum, %
η_e – electrical efficiency of the system
θ – trough angle, deg
φ – latitude, deg
Ψ – vertex angle, deg

Subscripts and Superscripts

ave – daily average value
instant – instantaneous value
max – maximum value

Abbreviations and Acronyms

AoI – angle of incidence, deg
CPC – compound parabolic concentrator
CPV – concentrated photovoltaics
GTI – global tilted irradiance, W·m^{-2}
MPP – maximum power point
MPPT – maximum power point tracking
PV – photovoltaic
PVs – solar photovoltaics
TL – truncation level

illumination of the PV module compared to the other popular CPV geometry – compound parabolic concentrator (CPC) [2]. However, when a V-trough with no sun-tracking is employed, uniform illumination cannot be assured throughout every day of its operation due to the change of the elevation angle of the sun [1]. The non-uniformity has an adverse effect on the PV module's open-circuit voltage, efficiency [3,4] and operational lifetime [5].

Ustaoglu et al. [4] numerically investigated the performance of a PV module coupled with chosen non-imaging concentrators, such as V-troughs and CPCs, and a cooling system. They demonstrated that with a V-trough concentrator, the heat flux in the central part of a photovoltaic module can be approximately eight times higher than at the edges, depending on the angle of incidence (AoI) of the sun rays. In a more recent paper, Ustaoglu et al. [6] performed another numerical analysis of the performance of a cooled PV module coupled with truncated V-troughs, CPCs, and compound hyperbolic concentrators. They showed that for the case with no truncation, the heat flux reaching the surface of a PV module with a V-trough varied from nearly 0 W/m^2 close to the edges to approximately 2000–4000 W/m^2 near the central part of the module, depending on the AoI. For angles of incidence greater than 0º, the PV module experienced a step-wise change in heat flux of approximately 1000 W/m^2 along its length. The authors did not provide the length-wise heat flux distribution for the truncated concentrators. However, they reported that for AoI of 0º, introducing a 55% truncation level reduced the maximum temperature of the PV module from 335 K to 330 K, and that for AoI < 30º higher truncation resulted in reduced power generation. Ustaoglu et al. [6] concluded that among all the analysed geometries V-troughs demonstrated the most beneficial performance.

In outdoor experiments, Singh et al. [5] measured illumination along the width of the V-trough's receiver using fourteen photodiodes. They reported that, depending on the angle of incidence, the relative intensity of illumination can vary between approximately 5 and 55 across the receiver. They used a V-trough with its focal line oriented in the east-west direction.

Hadavinia and Singh [7] simulated the performance of a PV module coupled with a V-trough having various trough angles. They analysed trough angles ranging from 0 to 45º and AoI varying from 0 to 45º. Their results indicate that for a 50-cm-high V-trough, the highest optical concentration ratio averaged over AoIs corresponding to the highest solar irradiance throughout the day was achieved for the trough angle of 22º.

In his PhD thesis, Hadavinia [8] presented more detailed results of his studies on a PV module with V-troughs having trough angles of 15º and 22º. His simulations showed that apart from AoI = 0º, where the energy flux distribution on the PV module surface was uniform, most of the other AoIs resulted in two areas on the module's surface, where the energy flux concentration differed by approximately 20 units. In his experimental studies using a V-trough with a trough angle of 19º, he observed that the current-voltage curves differed from the typical ones. Instead of the current plummeting after a certain voltage was exceeded, it decreased gradually over the full range of voltages. Hadavinia [8] attributed this behaviour to the partial shading of the PV module.

More papers address the influence of partial shading on a bare PV module. Under such conditions, the PV module's power-voltage characteristic curve can have multiple local maximum power points (MPPs) [9]. This can negatively affect a PV system coupled with an MPPT solar charge controller, as the controller cannot differentiate between local and global MPPs [9]. Zhang et al. [9] showed both analytically and experimentally that introducing different irradiance levels to one or two PV cell strings out of a three-string PV module with bypass diodes results in one or two additional MPPs in the characteristic curve, respectively. The lower the irradiance reaching the strings, the lower the power associated with those additional MPPs. Depending on the shading scenario, the minimum local MPP could be approximately half of the maximum. Similar results were obtained by Bharadwaj and John [10], who reported that introducing three areas of different irradiance on the surface of a PV module with bypass diodes resulted in three different voltages in the I-V curve for which the current started to drop significantly. In other words, the current decreased in a step-wise manner, remaining constant within a given voltage range and dropping with each subsequent interval of higher voltage. In their experiment, the maximum current within the three intervals was 7 A, while the minimum was approximately 4.7 times lower. Brecl et al. [11] simulated the performance of a PV module with bypass diodes under partial shading conditions caused by chimneys or a pole. They reported that for the shortest day of the year in Ljubljana, Slovenia, shading could result in a power loss of 26–78%, and that this loss is influenced by the orientation of the PV module (landscape or portrait).

Despite many works on partial shading of PV modules, little attention has been given to experimental investigations of PV modules coupled with V-troughs of various truncation levels. Discussed papers either examine single V-trough geometry or rely on numerical simulations, leaving systematic experimental data on the effect of truncation on PV module performance largely absent. This paper addresses this gap by experimentally assessing how the performance of a fixed PV module with V-trough concentrators of different reflector lengths (truncation levels) is affected by shading from the reflectors. The main goal is to determine the relationship between the V-trough geometry, operational conditions, and power generation. Lower truncation levels increase geometric concentration ratios and shading. The former leads to higher module temperatures and reduced electrical efficiency. Thus, to assure a comprehensive analysis, a multitude of operational parameters are studied: generated power, solar irradiance, the PV module electrical efficiency and average temperature, as well as the module current-voltage and power-voltage characteristic curves. By studying such a broad set of parameters, our paper provides a multidimensional experimental comparison of a PV module performance while coupled with V-troughs of various truncation levels, offering insights unavailable in prior works.

2. Experimental setup

The experimental setup is shown in Fig. 1. Its main component was a commercially available PV module (brand: Maxx, model: 10 W) that was connected to a maximum power point tracking (MPPT) solar charge controller (Lumiax MT1050EU). An ammeter (EXTECH EX470A multimeter) was used to measure the current from the PV module, while the MPPT controller monitored the produced voltage. Generated electricity powered a 10 W LED lamp, and any excess power was stored in three parallel-connected batteries (each having the capacity of 7.2 Ah). Three T- type thermocouples, placed at the top, bottom, and in the middle of the module's back surface, measured the module temperature. These thermocouples, together with a pyranometer (Kipp&Zonen SP Lite) for measuring solar irradiance, were connected to a data recorder (LUMEL KD7).

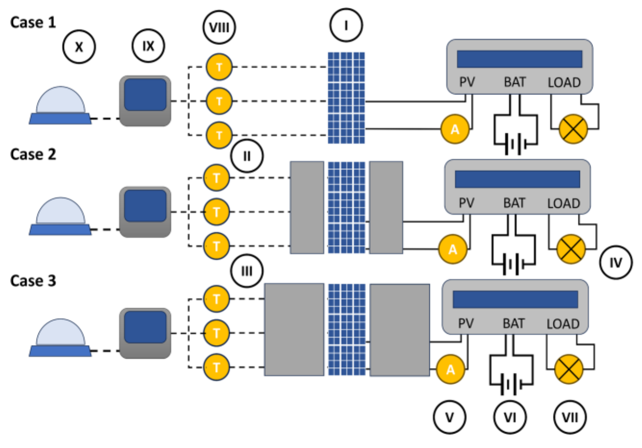

Fig. 1. Schematic of the experimental setup used in the study. I – PV module, II – PV module with the shorter concentrator, III – PV module with the longer concentrator, IV – MPPT solar charge controller, V – ammeter, VI – batteries, VII – LED lamp, VIII – thermocouples used to measure PV module temperature, IX – data recorder, X – pyranometer.

Three cases were studied: the PV module without a concentrator and the same PV module coupled with shorter and longer V-trough concentrators differing in truncation level (TL). These concentrators had the same trough angles but different lengths of their reflectors (Z). Detailed specifications of the PV module used are provided in Table 1.

Table 1. Specification of the PV module used in the experiments.

Power, W	U_{oc}, V	I_{sc}, A	U_{mp}, V	I_{mp}, A	Dimensions $L_{PV} \times W_{PV}$, m × m
10	22.64	0.58	18	0.54	0.43 x 0.19

2.1. V-trough concentrators

In the experiment, two types of non-imaging V-trough concentrators were used, the geometry of which is schematically presented in Fig. 2. Each comprises two flat reflectors positioned at a trough angle (θ) of 10° measured from the normal to the receiver plane. Constructed from stainless steel 304 with a BA finish, the concentrators vary in truncation level, defined as:

$$\mathrm{TL} = \frac{H_{init} - H}{H_{init}}, \tag{1}$$

where H represents the height of the truncated V-trough, and H_{init} denotes the height of the initial V-trough without truncation. For the concentrator with no truncation, the reflectors were 735 mm long, and H_{init} was 724 mm. For the truncated concentrator, the reflectors were 399 mm long, resulting in a height H of 393 mm and a truncation level of 46%. Varying heights of V-troughs led to differences in another crucial parameter characterising V-trough geometry – the geometric concentration ratio (C) expressed as:

$$C = \frac{A}{a} = \frac{W}{w}. \tag{2}$$

The values of C together with the geometric dimensions of both concentrators are detailed in Table 2.

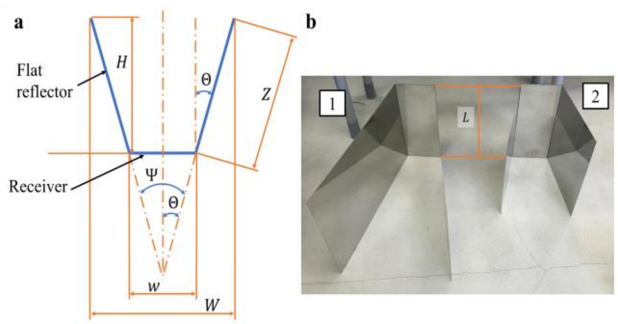

Fig. 2. V-trough concentrators used in the study. a - geometry, b - a photo showing both V-troughs: 1 – the longer one, 2 - the shorter one.

Table 2. Geometric dimensions of V-trough concentrators used in the study.

Concentrator	Truncation level (TL), %	Aperture length L, mm	Receiver width w, mm	Aperture width W, mm	Reflectors length Z, mm	Geometric concentration ratio C, -
Longer	0	450 ± 1	200 ± 1	470 ± 1	735 ± 1	2.35
Shorter	46	450 ± 1	200 ± 1	360 ± 1	399 ± 1	1.80

3. Experimental procedures

The experimental campaign took place outdoors on the campus of Wroclaw University of Science and Technology, Wroclaw, Poland (51°6'35.72"N and 17°3'28.13"E) in May and June 2023. Each geometry (the bare module and the module with the longer/shorter concentrator) was investigated individually on separate days from 10:00 to 14:00 (UTC+02:00). Throughout the experiments, the PV system was facing south with a slight tilt towards the east, resulting in an azimuth angle of approximately 30 degrees. The focal line of the V-trough was vertically oriented, and the experiments were carried out under clear sky conditions. During the experiments, voltage and current produced by the PV module, along with solar irradiance, were recorded at 15-minute intervals.

Performance of a PV module is significantly influenced by its tilt angle, the optimum value of which depends on, inter alia, the latitude of an installation site and cloud cover. Consequently, to determine the optimum tilt angle for a PV module installed in Wroclaw, with a latitude of approximately 51 degrees north, we employed the formula developed by Jacobson and Jadhav [12]. This formula incorporates meteorological data from locations investigated by the authors, and for the northern hemisphere is given by:

$$\beta_{opt} = 1.3793 +$$
$$+\varphi[1.2011 + \varphi(-0.014404 + 0.000080509\varphi)]. \tag{3}$$

For Wroclaw, Eq. (3) yields the optimum tilt angle equal to approximately 35º, and this value was used in our experiments.

In our experiments, we used vertically oriented V-troughs of fixed tilt and azimuth angles (see Fig. 3) so that we could study the influence of partial shading on PV module performance during experiments of relatively short duration. This allowed us to assess the power loss introduced by the shadow cast by the V-trough reflectors when no two-axis sun-tracking is employed.

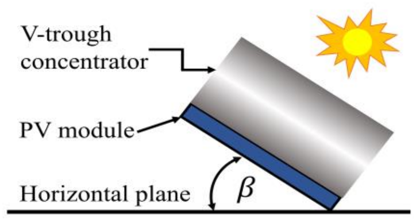

Fig. 3. Tilt angle used in the experimental campaign.

4. Data reduction and uncertainties

4.1. Electric performance of the system

As the experimental setup consisted of a PV module coupled with an MPPT solar charge controller, it was assumed that the module always worked at the maximum power point for given irradiance conditions. The electrical efficiency of the system in all studied cases was calculated as:

$$\eta_e = \frac{P_{PV}}{P_{in}}, \tag{4}$$

where:

$$P_{PV} = U_{mp} I_{mp},$$
$$P_{in} = A_{in} G. \tag{5}$$

A_{in} is the area through which solar rays enter the system. For the case with no concentrator, it equals the surface area of the PV module ($A_n = L_{PV} \times W_{PV}$), whereas for the cases with concentrators, it equals their aperture area ($A_{in} = L \times W$).

4.2. Solar irradiance on a tilted surface

The pyranometer used to measure solar irradiance incident on the system was placed at the same angle as the PV module. Consequently, it measured global tilted irradiance (GTI), which is the sum of direct, diffuse and reflected radiation reaching the PV module or the aperture of the concentrators, depending on the case studied. Therefore, in this work, G in Eq. (5) equals GTI.

4.3. Uncertainties

Uncertainties of direct measurements (current, solar irradiance and module's back surface temperatures) were determined based on the accuracy of the measuring equipment. Voltage was measured using a built-in function of the MPPT controller (Lumiax MT1050EU). We calibrated the controller with a multimeter (UNI-T UT89XD) of known accuracy and applied a regression analysis to determine the calibration function. This function takes the following form: $y = bx + a$, where x is the actual value (taken from the multimeter), and y is the value measured with the controller. We calculated uncertainty in U_{mp} as a sum of standard deviation in the actual voltage determined using the calibration function $s_{U,CF}$ and standard deviation in the measurement taken with the multimeter $s_{U,DMM}$:

$$u(U_{mp}) = \sqrt{s_{U,CF}^2 + \frac{s_{U,DMM}^2}{3}}. \quad (6)$$

Uncertainties of the calculated parameters (incoming solar power, electrical efficiency and the average module's back surface temperature) were determined using the error propagation method. Specific values of measured and calculated parameters together with their uncertainties are listed in Table 3.

Table 3. Uncertainties of measured and calculated parameters.

Parameter	Measured/calculated range	Uncertainty
U_{mp}	14.72 – 19.66 V	0.10 – 0.13 V
I_{mp}	0.225 – 0.849 A	0.011 – 0.026 A
t_{top}	28.70 – 74.30 °C	0.5 °C
t_{mid}	28.80 – 88.40 °C	0.5 °C
t_{bottom}	28.70 – 88.30 °C	0.5 °C
t_{ave}	28.77 – 82.53 °C	0.3 °C
G	838 – 1089 W·m^{-2}	2.4%
P_{PV}	3.96 – 12.68 W	0.19 – 0.40 W
P_{in}	52.22 – 224.61 W	1.31 – 5.44 W
η_e	0.023 – 0.167	0.001 – 0.007

5. Results and discussion

In order to compare the performance of the PV module working with and without concentrators, it was necessary to verify that all the systems were investigated under similar irradiance conditions. Figure 4 presents temporal variations of solar irradiance for the PV module with and without concentrators. In all studied cases, changes in solar irradiance followed a similar pattern: first, it increased to reach its peak value at between 11:30 and 12:15 depending on the day of the experiment, and then it steadily declined until the end of the experiment. This behaviour is primarily due to the absence of sun-tracking in the experimental setup, resulting in decreased irradiance as the sun's position shifted over time. Generally, deviations from this pattern were minimal across all cases, except for an anomaly observed at 11:30 for the system with the shorter concentrator, attributed to transient cloud cover. However, this deviation did not substantially impact the average solar irradiance reaching the system, which was 984.53 W·m^{-2} for the PV module without a concentrator, 997.88 W·m^{-2} for the system with the shorter concentrator, and 990.35 W·m^{-2} for the longer concentrator. Thus, the overall irradiance levels in all the cases were comparable.

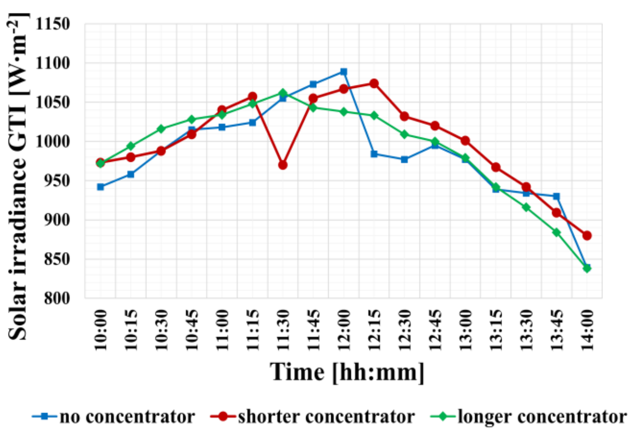

Fig. 4. Solar irradiance as a function of local time for all studied cases.

5.1. Power generation

Figure 5 shows the power output for each analysed system over time. Concerning instantaneous power generation, the system equipped with the longer concentrator demonstrated the highest performance, reaching a maximum power of 12.68 W. The system with the shorter concentrator achieved only slightly worse maximum power output of 12.19 W. In contrast, the system without a concentrator yielded a maximum power of 10.33 W. These results are a consequence of the amount of solar power reaching the PV module in each system, which was the highest when the longer concentrator with the highest geometric concentration ratio was used, and the lowest when there was no concentrator.

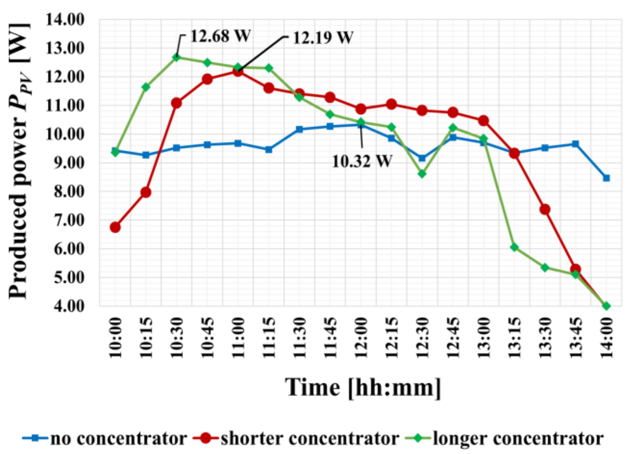

Fig. 5. Power produced by each studied system as a function of local time. Labels show the maximum values for each system.

When considering the time-averaged power generation, the system without a concentrator attained an average power output of 9.61 W with a standard deviation of 0.45 W. In comparison, the system with the shorter concentrator produced on average

9.66 W with a standard deviation of 2.47 W, while for the longer concentrator system, the average was 9.57 W with a standard deviation of 2.80 W. Thus, all the studied systems produced similar average power, however the fluctuations in generated power over time were greater for the systems with concentrators, as evidenced by their higher standard deviations. These fluctuations can be attributed to shading effects caused by the reflectors of the concentrators. As the sun's position shifted during the experiment, changes in the angle of incidence of the incoming radiation led to partial shading of the PV module. At 14:00, this translated into about a 45% loss in generated power compared to the bare module.

The data presented in Fig. 5 show that the optimum angle of incidence occurred at around 11:00 for the system with the shorter concentrator and approximately at 10:30 for the system with the longer concentrator. The more the time of a given measurement was away from the time corresponding to the maximum produced power, the greater the drop in power generation was observed. Both systems equipped with concentrators exhibited a maximum percentage drop in instantaneous power production of 68% compared to their maximum generated power, while for the PV module without a concentrator, this drop was only 18%. Such substantial losses in instantaneous power in the case of the systems with V-trough concentrators highlight that their performance is strongly affected by the angle of incidence of the incoming radiation, and the resulting partial-shading and illumination non-uniformity. Similar behaviour of the power generated by a bare PV module and a system with a V-trough concentrator was reported by Hadavinia and Singh [7]. In their experiments (conducted between 10 a.m. and 2 p.m.), the standard deviation of the power produced by the system with the concentrator was eight times higher than for the bare module, whereas in our study for the system with the shorter concentrator, it was 5.5 times higher than for the bare PV module. Furthermore, results of simulations performed by Parapudi et al. [13] show that in the summer months of June and July in London, UK, bare monocrystalline silicone PV modules and those coupled with a V-trough having a geometric concentration ratio of 1.40 and a trough angle $\theta = 20°$ yielded nearly the same monthly electrical energy production.

5.2. Optimum operating point

Comparing the data in Figs. 4 and 5 also shows that for the systems with concentrators, the time of peak power generation did not coincide with the time of the maximum solar irradiance. Instead, the peak power output occurred approximately an hour earlier than the peak solar irradiance was observed. This indicates that solar irradiance is not the only factor affecting generated power. One such parameter of interest is the temperature of a photovoltaic module. The temporal evolution of the module's temperature, together with changes in solar irradiance and generated power for all the examined cases, is illustrated in Fig. 6.

The data shown in the figure indicate that for the systems with concentrators, the maximum power was generated when the PV module's temperature was approximately 70ºC (Fig. 6b and Fig. 6c). This points to the existence of an optimum operating point for the CPV system in terms of the amount of incoming solar energy. It seems that this point should not be chosen solely based on the maximum value of solar irradiance, but also based on the PV module's temperature. As this temperature is a strong function of irradiance, its high value is an indicator of a large amount of solar energy reaching the PV module. However, its value should not exceed a certain limit (in our case 70ºC), because then the performance loss due to the temperature rise starts to be visible.

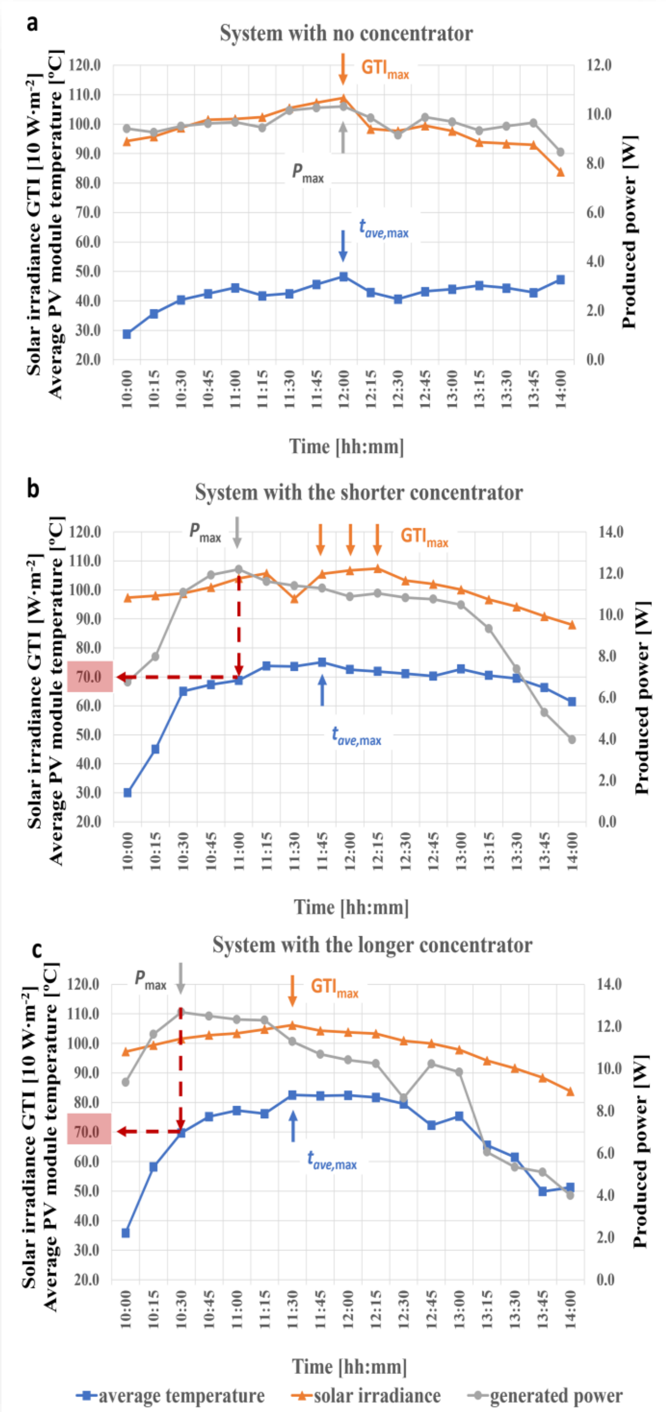

Fig. 6. PV module temperature, solar irradiance and generated power for each studied system as a function of local time.

Bahaidarah et al. [14] reported a similar 30-minute shift between the time of maximum irradiance and the time of maximum power generated by a PV module with a V-trough. In their simulations for a chosen day in September, the peak power production of the V-trough system occurred around 11:30 a.m., when the module temperature was approximately 61ºC (about 2ºC lower than the maximum temperature of the PV panel during that day), while the maximum irradiance occurred at 12 p.m. As in their work, the optimum temperature in terms of power production was 61ºC, and in our study, it is 70ºC, additional experiments need to be conducted to identify parameters which determine the optimum operating temperature. These parameters could be, e.g. V-trough geometry and material, PV module's model and type, day of the year, location, or weather conditions.

Interestingly, no time shift between the peak generated power and the peak solar irradiance was observed in the case of the system without a concentrator (Fig. 6a). This might be due to the fact that when no concentrator was used, the PV module's temperature did not exceed the limit of 70ºC, so it did not have a noticeable negative impact on the module performance.

5.3. Temperature of the photovoltaic module

Figure 7 shows a comparison of PV module temperature for all the studied systems. As expected, the highest panel temperature was observed for the system with the longer concentrator, i.e. with the highest geometric concentration ratio. The maximum recorded temperature for this system reached 82.5ºC. For the system with the shorter concentrator, the maximum temperature was 75ºC, and for the bare PV module, it was 48.3ºC. The higher the concentration ratio, the greater solar irradiance reaches the PV module's surface, resulting in higher module temperatures. Similar values of the maximum panel temperature were reported by Parapudi et al. [13]. In their simulations for a chosen day in June, the temperature of a bare PV module was ca. 47ºC, and for a panel coupled with a V-trough (C = 1.40), the temperature was about 79ºC.

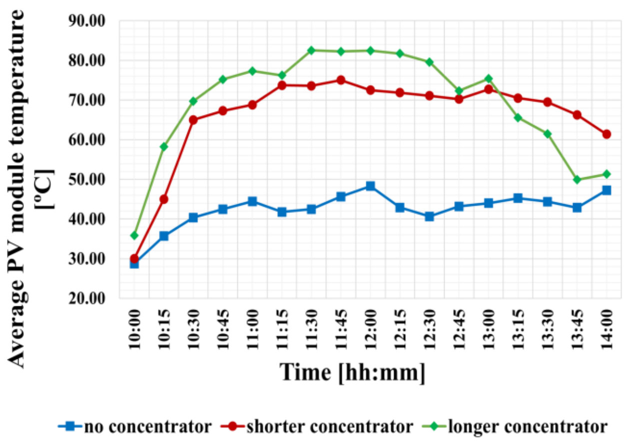

Fig. 7. Average temperature of the PV module as a function of local time for each studied system.

The most significant change in temperature over time occurred for the system with the longer concentrator. After 13:00, its temperature dropped below that of the system with the shorter concentrator. This can be attributed to the shading introduced by the reflectors of the concentrator. The longer the reflectors are, the greater the shading and its impact on the PV module temperature.

5.4. Electrical efficiency

Time evolution of electrical efficiency for all the studied systems is presented in Fig. 8. The highest efficiency on average of 15.70% was achieved by the system with no concentrator. The systems with the shorter and longer concentrators demonstrated significantly lower average efficiencies of 5.92% and 4.51%, respectively. Employing concentrators increased solar power entering the system, however, it did not translate onto a proportional rise in generated power, which is reflected in lower efficiencies.

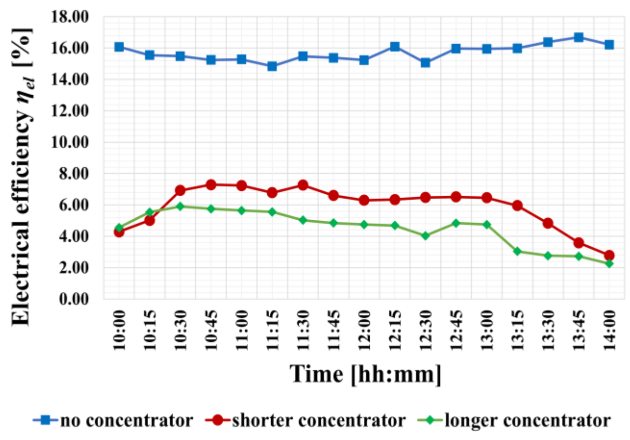

Fig. 8. Electrical efficiency as a function of local time for each studied system.

For example, in the system incorporating the shorter concentrator, the incoming power was 1.8 times higher compared to the system without a concentrator, as determined by the geometric concentration ratio. However, the maximum generated power only increased by a factor of 1.18. Similarly, in the system with the longer concentrator, the incoming power was 2.35 times higher, yet the maximum generated power increased by a factor of only 1.23. The differences between the relative increases in the incoming and generated power can be attributed to the optical losses of the CPV system.

Another issue is that not only electrical efficiencies of the systems with concentrators are at least 50% lower than for the PV module with no concentrator, but they also display greater temporal variability. Again, this can be attributed to shading – as the sun changes position, reflectors of concentrators start to cast shadow on the PV module, which reduces the performance of the module with time. These effects have been documented in the existing literature. Figure 9 shows a comparison between the electrical efficiencies of the bare PV module and the system with the shorter concentrator determined in this work and those reported by Parapudi et al. [13] as a function of the angle of incidence (AoI). AoI was calculated according to the procedure described in [13]. We chose the system with the shorter concentrator for comparison as it bears more resemblance to the V-trough studied in [13] than the system with the longer concentrator (C = 1.80, trough angle θ = 10° and receiver width w = 200 mm vs. C = 1.40, trough angle θ = 20° and receiver width w = 33 mm in [13]).

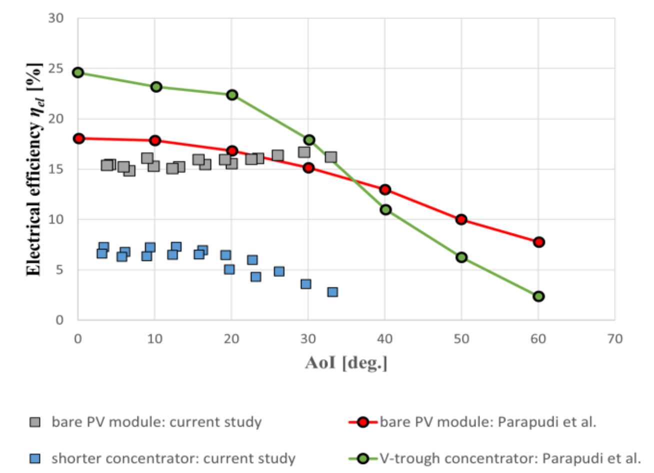

Fig. 9. Comparison between electrical efficiencies obtained in this study and those of Parapudi et al. [13].

In the case of the bare PV module and AoI < 33°, similar electrical efficiencies to those of Parapudi et al. [13] were obtained. We did not study AoI > 33° due to the limited duration of the experiment, which restricted studied solar positions. For the system with the concentrator, the dependence of electrical efficiency on AoI in our work had a similar shape to that reported in [13]. Up to AoI ≈ 20°, the electrical efficiency in our study was nearly constant, whereas in [13], it decreased slightly. When AoI was > 20°, electrical efficiency started to fall at a higher rate in both our investigation and the paper by Parapudi et al. [13]. This behaviour was attributed to partial shading of the PV module.

The shape of η_{el}(AoI) in our study closely follows the theoretical angular acceptance function, which can be found, for example in [15]. This function describes the dependence of the fraction of sun rays reaching the receiver of a V-trough to those reaching the aperture on the angle of incidence. For AoI below the acceptance angle δ, all incoming rays reach the receiver.

For δ < AoI < $\delta + 2\theta$, the acceptance starts to fall gradually to the value of 0 at the maximum acceptance angle $\delta_{max} = \delta + 2\theta$ where no sun rays reach the PV module. Analysing Fig. 9 indicates that for both the V-trough used in our study and the one in Parapudi et al. [13] research, $\delta \approx 20°$. This value is further confirmed by calculating the acceptance angle using the rearranged formula that can be found in [16]:

$$\delta = \operatorname{asin}(C) - \theta. \tag{7}$$

For the shorter concentrator, the resulting acceptance angle is ca. 24º, and for the concentrator in the work of Parapudi et al. [13], $\delta \approx 26°$. However, for the system with the concentrator, the efficiencies obtained in our study are much lower than those reported in [13]. This is probably due to the lower reflectance of the stainless steel that our concentrator was made of, compared to the one employed in [13]. Reflectivity has a direct impact on the fraction of sun rays falling on the aperture surface that reaches the PV module. The higher the reflectivity of the concentrator surface, the more light flux is incident on the PV module. Parapudi et al. [13] used MICRO-SILVER 4200 AG, whose total reflectivity is 0.98, while Ustaoglu et al. [17] reported that for their polished stainless steel concentrator, the measured reflectivity varied between 0.383 and 0.653 for wavelengths of light ranging from 200 to 1200 nm. Similar to Ustaoglu et al. [17], we used a stainless-steel V-trough. Its lower reflectivity could translate into lower power production and, consequently, lower electrical efficiency compared to the system studied by Parapudi et al. [13].

Taking instantaneous and average daily power production as well as electrical efficiency into account, the system equipped with the shorter concentrator is a preferable choice for non-sun-tracking configurations. It achieves comparable power generation to the system with the longer concentrator, but at a reduced cost owing to lower material consumption; the total reflectors area calculated as $2{\cdot}Z{\cdot}L$ is 0.36 m^2 for the shorter concentrator and 0.66 m^2 for the longer one.

5.5. Manual sun-tracking

For every studied system after finishing the experiments for its fixed position, we changed its position (azimuth) manually so that it directly faced the sun. Then, we took the final measurement at about 14:10 to assess the impact of manual sun-tracking on generated power. The results presented in Fig. 10 show that the concentrator systems experienced an increase of more than 200% in instantaneous generated power when their position was adjusted. This is a strong indicator that choosing the fixed position of a CPV system with a V-trough may cause a significant loss in generated power due to partial shading of the PV module. Consequently, in terms of power maximisation, some form of sun-tracking is recommended for such systems. For example, in the systems with the focal line oriented in the east-west direction, seasonal adjustment of their tilt angle should be employed.

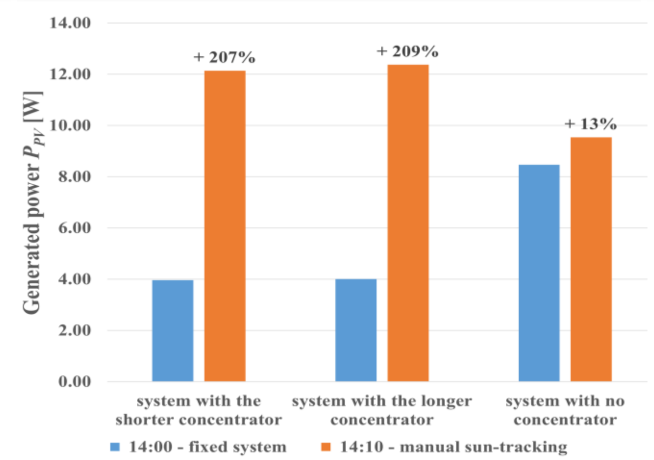

Fig. 10. Comparison between the generated power for the systems with a fixed position and position facing the sun for all studied cases.

In the case of the system with no concentrator, and thus no partial shading, the gain in produced power was only 13%, indicating lower sensitivity to the change of the angle of incidence.

Comparisons between the performances of V-trough CPV systems with and without sun-tracking are rather scarce in the literature. The available papers mostly deal with comparative analyses of the power produced by a bare PV module with and without tracking, and the power of a CPV system with dual-axis tracking [18,19]. In this study, the use of manual sun-tracking in the system without a concentrator resulted in a 13% power gain. Hussein et al. [19] reported a similar increase of 24% in generated power for a bare photovoltaic module with a vertical single axis tracker, tracking diurnal movement of the sun in the W-E direction, compared to a module without tracking.

Concepcion et al. [20] analysed the performance of a V-trough CPV system with and without a two-axis tracker. In their study, the energy produced by the former system was more than 20% higher than that of the latter, which is a significantly lower gain compared to our results. This might be due to the fact that the V-trough in [20] had a trough angle of 30º instead of 10º used in the current study. Reflectors placed at an angle of 30º cast less shadow than those at an angle of 10º. Consequently, limiting shading with tracking had a less profound impact on the performance of the V-trough system with a higher trough angle. However, Concepcion et al. [20] did not provide information on the V-trough height, so a conclusive comparison between the shadow cast by their and our reflectors cannot be carried out.

5.6. Current-voltage and power-voltage characteristic curves

The data for current-voltage and power-voltage characteristic curves for each system were collected in July 2024 at the same location, using the same module and concentrators with the same tilt angle as described in Sections 2. Experimental setup and 3. Experimental procedures. The tested systems faced south. In these tests, the module was connected to four sliding rheostats having a total resistance of 200 Ω instead of a solar charge controller. For each system, the experiments started at 11:30 and ended at 15:30 (UTC+02:00). Every 30 minutes, the values of voltage and current produced by the module were collected for resistances varying from 0 to 200 Ω using two UNI-T UT890D+ multimeters. Additionally, global tilted irradiance (GTI) was measured with a Hukseflux SR05-D2A2 pyranometer. For the system with no concentrator, the average GTI was 991.44 $W \cdot m^{-2}$, for the system with the shorter concentrator, it was 970.78 $W \cdot m^{-2}$, and for the longer concentrator 1032.44 $W \cdot m^{-2}$. Thus, GTI can be considered similar for all the studied systems. The temporal evolution of solar irradiance for each system is presented in Fig. 11.

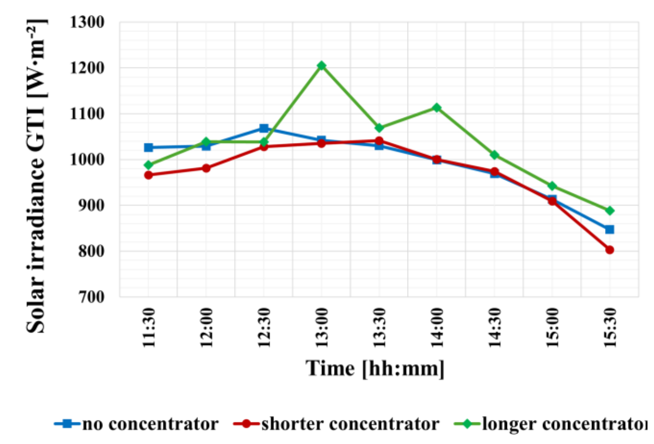

Fig. 11. Solar irradiance as a function of local time for all studied cases measured during the experiments on PV module characteristic curves.

Figures 12a and 12b depict the current-voltage and power-voltage characteristic curves for all the studied systems at the time when AoI of the sun rays was approaching 0°.

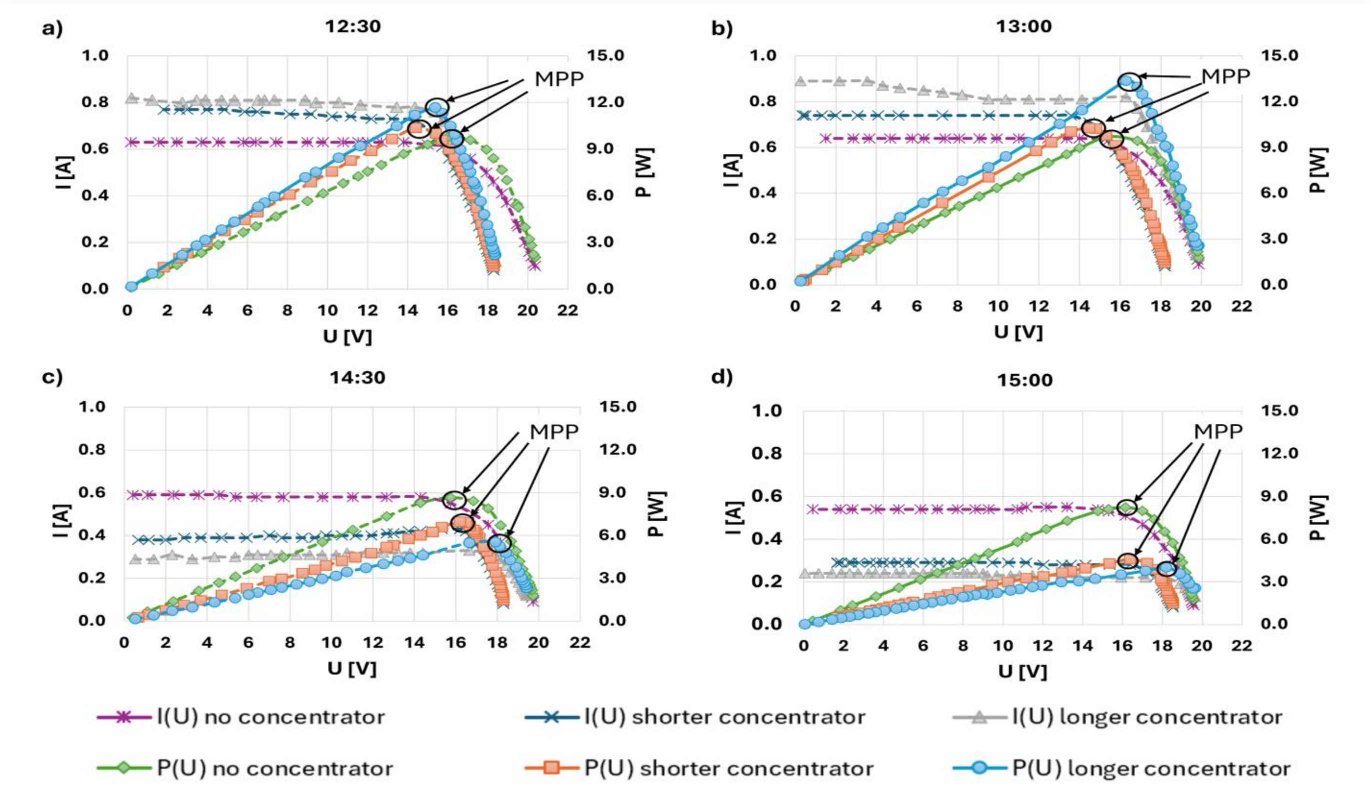

Fig. 12. Characteristic curves for all studied systems at selected times.

As expected, the longer the concentrator, the greater were the short-circuit current I_{sc} and the maximum generated power (MPP). However, as the position of the sun changed, the shadow cast by the concentrator reflectors caused performance deterioration, which can be observed in Figs. 12c and 12d for the local time of 14:30 and 15:00. At 15:00, the short-circuit current for the system with the longer concentrator was by 17% and 56% lower compared to the systems with the shorter concentrator and no concentrator. As for MPP, the system with the longer concentrator produced 13% and 51% less power than the systems with the shorter concentrator and no concentrator. This highlights the extent to which shading influences PV module performance.

Table 4 presents the comparison between I_{sc} and MPP at 13:00 and 15:00 for all the studied systems. The data indicate that the lower the TL of the system, the greater is the relative percentage drop in I_{sc} and MPP it experiences as the position of the sun changes. Thus, low truncation levels (associated in our work with higher geometric concentration ratios) are not advisable when no sun-tracking is employed.

Table 4. Comparison of I_{sc} and MPP between the studied systems at 13:00 and 15:00.

Concentrator in the system	Time: 13:00		Time: 15:00		Percentage drop relative to 13:00	
	I_{sc}, A	MPP, W	I_{sc}, A	MPP, W	in I_{sc}, A	in MPP, W
None (TL = 100%)	0.64	9.7	0.55	8.2	14.1%	15.2%
Shorter (TL = 46%)	0.74	10.3	0.29	4.6	60.8%	55.4%
Longer (TL = 0%)	0.89	13.4	0.24	4.0	73.0%	70.1%

Multiple MPPs in the power-voltage curves were not observed. This is because the PV module used in the experiment was probably not equipped with by-pass diodes. By-pass diodes would weaken the negative effect of shadow on the PV module performance. Thus, they are recommended in fixed systems with concentrators where no sun-tracking is used.

6. Summary

Table 5 presents a summary of the papers dealing with the impact of shading on V-trough PV systems, including the results of the present study. It covers PV module and V-trough characteristics, generated power, PV module temperature, electrical efficiency and characteristic curves. If information of interest was not directly given in the original paper but could be estimated from the figures included, it was denoted by approximately equals sign (≈). If the analysed paper included both a simulation and an experiment, the data from the experiment were given.

Analysis of the summary indicates that most of the experimental studies focus on either smaller or bigger PV modules ($A_{PV} < 0.064$ m^2 or $A_{PV} \leq 1.24$ m^2) than the one used in our paper. The experiments featured V-troughs with higher trough angles $20° \leq \theta \leq 30°$ than in our work, but similar geometric concentration ratios varying between 2 and 2.6, which entails a lower height of the concentrator reflectors. The instantaneous power loss in the experimental studies ranged from 40% to 98%, which further confirms that shading can substantially deteriorate the PV module performance.

It is worth noting that apart from our work and the paper of Ustaoglu et al. [6], no authors provided the data on V-troughs with various truncation levels, and Ustaoglu et al. [6] based their analysis on numerical calculations. Nonetheless, the results of both our experiment and Ustaoglu et al.[6] simulations indicate that truncating V-troughs reduces the maximum PV module temperature. All studies show that introducing concentrators generally lowers the average electrical efficiency and leads to a more pronounced instantaneous power loss compared to the systems with bare PV modules.

7. Conclusions

In this work, three different PV systems were experimentally tested in outdoor conditions in May/June 2023 and July 2024 in Poland using a commercially available PV module: without a concentrator, and with two distinct stainless-steel V-shaped concentrators of different truncation levels. The position of all systems was fixed – they all faced either south or south with a slight tilt towards east, and the focal line of the concentrators was vertically oriented. The primary objective was to determine the dependence between the V-trough geometry, working conditions and power output, taking into account the influence of shading introduced by V-trough reflectors. Here are the main findings:

- The highest instantaneous power of 12.68 W was generated by the system with the longer concentrator; the system with the shorter concentrator ranked second with 12.19 W; the bare PV module reached 10.32 W. Thus, both systems with concentrators demonstrated similar performance in terms of the maximum instantaneous power production.
- Due to shading, the systems with concentrators were subject to greater changes in generated power over time than the system with no concentrator. The instantaneous power loss reached up to 45% compared to the bare PV module. Consequently, all the systems produced a similar average power of 9.57–9.66 W.
- The system with the longer concentrator reached the highest instantaneous PV module temperature (82.5ºC) and the lowest average electrical efficiency (4.51%). Due to shading, these parameters exhibited the greatest variation in time among all the studied systems. The bare PV module reached the lowest instantaneous surface temperature and the highest average electrical efficiency with their maxima of 48.3ºC, and 15.70%, respectively. It also demonstrated the lowest variation of these parameters.
- The V-trough with the higher truncation level allowed limiting the adverse effect of shading. It offered similar average power output to the system with the longer concentrator at a lower price due to a reduction in material consumption. Based on that, the system with the shorter concentrator is the preferred option. However, its geometric concentration ratio cannot be equated with the optimum value yielding the maximum possible power. Determining this optimum ratio requires further studies.

- The highest instantaneous power output was observed for the bare PV module when the solar irradiance was maximum, and for the systems with V-troughs when the PV module temperature was 70°C. This indicates that the employed strategy for maximizing power output should depend on module temperature. Below its certain (limit) value, the position of the system (tilt and azimuth angles) should ensure the maximum irradiance incident on the PV module. Above the limit, the position should prevent any additional temperature rise. Further experiments are required to determine parameters that can influence this limiting temperature (V-trough design, PV module model, weather conditions, etc.).
- MPP and short-circuit current are strong functions of truncation level and AoI. For AoI close to 0°, the MPP and I_{sc} reach greater values at lower truncation levels. At higher AoIs, lower truncation leads to an increased percentage drop in both these parameters relative to their values at AoI ≈ 0°. For the system with the longer concentrator, the drop reached more than 70% between 13:00 and 15:00. This shows the profound influence that partial shading can have on the CPV system performance.

Manual adjustment of the CPV system azimuth angle may translate onto an above 200% higher instantaneous power production. This shows that the CPV system design should reduce shading to the greatest extent possible. The results of our study show that for fixed V-trough systems, partial shading of PV modules causes substantial variation in operational parameters, and that in general, this variation is more pronounced in low truncation level systems. Designing and optimizing a fixed V-trough system requires performance assessment based on, e.g. the daily/monthly averages of operational parameters, instead of their instantaneous maxima.

Table 5. Summary of the data on V-trough systems including our research.

Paper	Study type	PV module characteristics	V-trough characteristics	Generated power	PV module temperature	Electrical efficiency	Characteristic curves
Current study	Experiment Wroclaw, Poland May/June 2023 (10:00 – 14:00), July 2024 (11:30 – 15:30) $\beta = 35°$ Changing parameter AoI and TL.	$A_{PV} = 0.08\ \mathrm{m}^2$ $P_{PV} = 10$ W $U_{oc} = 22.64$ V $I_{sc} = 0.58$ A $U_{mp} = 18$ V $I_{mp} = 0.54$ A	Stainless Steel 304 BA Finish $\theta = 10°$ $H_{init} = 724$ mm TL = 0/46% $C = 2.35/1.80$	For bare/TL = 46%/TL = 0%: $P_{PV}^{max} = 10.33/12.19/12.68$ W $P_{PV}^{ave} = 9.61/9.66/9.57$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} = 18/68/68\%$	For bare/TL = 46%/ TL = 0%: $t_{ave}^{max} = 48.3/75.0/82.5$°C $\Delta t_{ave}^{max} = 40/60/57\%$	For bare/TL = 46%/ TL = 0%: $\eta_{el}^{ave} = 15.70/5.92/4.51$ $\Delta\eta_{el}^{instan} = 11/62/62\%$	For bare/TL = 46%/TL = 0%: At 13:00: $I_{sc} = 0.64/0.74/0.89$ A MPP = 9.7/10.3/13.4 W At 15:00: $I_{sc} = 0.55/0.29/0.24$ A MPP = 8.2/4.6/4.0 W $\Delta I_{sc} = 14/61/73\%$ ΔMPP = 15/55/70%
Bahaidarah, Tanweer, Gandhidasan, & Rehman, 2015 [14]	Simulation& Experiment Dhahran, Saudi Arabia June 2012 (8:00 – 16:00) $\beta = 45°$ Changing parameter AoI.	$A_{PV} = 1.24\ \mathrm{m}^2$ $P_{PV} = 230$ W $U_{oc} = 48.7$ V $I_{sc} = 5.99$ A $U_{mp} = 41$ V $I_{mp} = 5.61$ A	Glass mirror Reflectivity 79% $\theta = 30°$ $H = 789.4$ mm TL = 0% $C = 2.15$	$P_{PV}^{max} \approx 200$ W $P_{PV}^{ave} \approx 147$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} \approx 88\%$	$t_{ave}^{max} \approx 58$ °C $\Delta t_{ave}^{instan} \approx 31\%$	No experimental data	No experimental data
Concepcion, Villanueva, Dalumpines, Magwili, & Pacis, 2020 [20]	Experiment Philippines May 2019 (7:00 – 17:00) $\beta = 60°$ Changing parameter AoI.	No info	Aluminum Reflectivity 85% $\theta = 30°$ $C = 2$	For bare PV module/module + concentrator: $P_{PV}^{max} \approx 31/41$ W $P_{PV}^{ave} = 24/31$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} \approx 68/71\%$	No experimental data	No experimental data	No experimental data. The data on charging parameters: For bare PV module /module + concentrator: At 12:30: $I \approx 2.5/3.1$ A $P \approx 30/40$ W At 17:00: $I \approx 1/1$ A $P \approx 10/12$ W $\Delta I \approx 60/68\%$ ΔP ≈ 67/70%
Hadavinia & Singh, 2019 [7]	Simulation& Experiment London, UK September 2017 (10:00 – 14:00) Changing parameter AoI.	$A_{PV} = 0.006\ \mathrm{m}^2$ + cooling	Alanod Miro-Silver 2 4200AG Reflectivity >98% $\theta = 22°$ $H = 50$ mm $C = 2.6$	For bare PV module/module + concentrator: $P_{PV}^{max} \approx 0.83/2.25$ W $P_{PV}^{ave} \approx 0.68/1.32$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} \approx 98/98\%$	No experimental data	For bare PV module/module + concentrator: $\eta_{el}^{ave} \approx 13.88/10.44\ \%$ $\Delta\eta_{el}^{instan} \approx 25/56\%$	No experimental data

Table 5. Summary of the data on V-trough systems including our research (continued).

Paper	Study type	PV module characteristics	V-trough characteristics	Generated power	PV module temperature	Electrical efficiency	Characteristic curves
Parupudi, Singh, & Kolokotroni, 2020 [13]	Simulation& Indoor experiment Changing parameter AoI (0-60°)	Monocrystalline PV module $A_{PV} = 0.003$ m^2 $P_{PV} = 0.54\ W$ $U_{oc} = 0.65$ V $I_{sc} = 1.13$ A	MIRO-SILVER 4200 AG Reflectivity 98% $\theta = 20°$ $C = 1.40$	No experimental data	No experimental data	For bare PV moule/module + concentrator: $\eta_{el}^{ave} \approx 16.85/15.37\,\%$ $\Delta\eta_{el}^{instan} \approx 59/90\%$	For bare PV moule/module + concentrator: For AoI = 0°: $I_{sc} \approx 1.1/1.5$ A For AoI = 30°: $I_{sc} \approx 0.93/1.1$ A $\Delta I_{sc} \approx 15/27\%$
Singh, Sabry, & Redpath, 2016 [5]	Simulation& Experiment London, UK July 2015 (10:30 – 14:30) β = 0° Changing parameter AoI.	4 x in series $A_{PV} = 0.016$ m^2 $P_{PV} = 2.85$ W $U_{oc} = 0.63$ V $I_{sc} = 5.7$ A $U_{mp} = 0.525$ V $I_{mp} = 5.43$ A	Alanod Miro-Silver $\theta = 25.95°$ $H = 152.86$ mm $C = 2.2$	$P_{PV}^{max} \approx 25$ W $P_{PV}^{ave} \approx 22$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} \approx 40\%$	$t^{max} = 110.3$ °C $\Delta t^{max} \approx 59\%$	No experimental data	No experimental data. The data on generated power: At 13:00: $I \approx 2.4$ A $P \approx 22.5$ W At 14:30: $I \approx 2.3$ A $P \approx 25$ W $\Delta P \approx 10\%$ $\Delta I \approx 4\%$
Ustaoglu, Ozbey, & Torlaklı, 2020 [4]	Simulation Changing parameter AoI.	$W_{PV} = 0.1$ m + cooling	Reflectivity 90% $\theta = 10°$ $H = 266$ mm$C = 1.94$	$P_{PV}^{max} \approx 210$ W $P_{PV}^{ave} \approx 151$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} \approx 96\%$	$t_{ave}^{max} \approx 31.25$°C $\Delta t_{ave}^{max} \approx 22\%$	$\eta_{el}^{max} \approx 19\%$ $\Delta\eta_{el}^{max} \approx 3\%$	For AoI = 0°: $I_{sc} \approx 5$ A MPP ≈ 4.1 W For AoI = 30°: $I_{sc} \approx 2.2$ A MPP ≈ 1.8 W $\Delta I_{sc} = 56\%$ ΔMPP = 57%
Ustaoglu, Akgül, & Okajima, 2023 [6]	Simulation Changing parameter AoI and reflector size α.	$A_{PV} = 0.2$ m^2 + cooling	Reflectivity 90% $\theta = 10°$ $H_{init} = 266$ mm Reflector size α $\alpha = 1/0.72/0.55/0.42$ $C = 1.94/1.68/1.52/1.40$	For $\alpha = 1/\,0.42$ $P_{PV}^{max} \approx 39/29.5$ W $P_{PV}^{ave} \approx 33.5/29.0$ W Drop in P_{PV} due to change of AoI: $\Delta P_{PV}^{instan} \approx 46/3\%$	For $\alpha = 1/\,0.42$ $t_{loc}^{max} \approx 62/55$°C $\Delta t_{loc}^{max} \approx 21/0\%$	For $\alpha = 1/\,0.42$ $\eta_{el}^{max} \approx 13.2/12.7\%$ $\Delta\eta_{el}^{max} \approx 8/2\%$	For $\alpha = 1/\,0.42$ For AoI = 0°: $P \approx 39/29.5$ W For AoI = 30°: $P \approx 21/28.5$ W $\Delta P \approx 46/3\%$

References

[1] Sangani, C.S., & Solanki, C.S. (2007). Experimental evaluation of V-trough (2 suns) PV concentrator system using commercial PV modules. *Solar Energy Materials & Solar Cells*, 91, 453–459. doi: 10.1016/j.solmat.2006.10.012

[2] Alnajideen, M., & Gao, M. (2022). A new configuration of V-trough concentrator for achieving improved concentration ratio of >3.0x. *Solar Energy Materials & Solar Cells*, 245, 111877. doi: 10.1016/j.solmat.2022.111877

[3] Franklin, E., & Coventry, J. (2002). Effects of Highly Non-uniform Illumination Distribution on Electrical Performance of Solar Cells. *40th Annual Conference for the Australian New Zealand Solar Energy Society*, 27−30 November, Newcastle, Australia.

[4] Ustaoglu, A., Ozbey, U., & Torlaklı, H. (2020). Numerical investigation of concentrating photovoltaic/thermal (CPV/T) system using compound hyperbolic - trumpet, V-trough and compound parabolic concentrators. *Renewable Energy*, 152, 1192–1208. doi: 10.1016/j.renene.2020.01.094

[5] Singh, H., Sabry, M., & Redpath, D. (2016). Experimental investigations into low concentrating line axis solar concentrators for CPV applications. *Solar Energy*, 136, 421–427. doi: 10.1016/j.solener.2016.07.029

[6] Ustaoglu, A., Akgül, V., & Okajima, J. (2023). Performance investigation of truncated low concentrating photovoltaic-thermal systems with V-trough, compound hyperbolic and compound parabolic concentrators. *Applied Thermal Engineering*, 232, 121028. doi: 10.1016/j.applthermaleng.2023.121028

[7] Hadavinia, H., & Singh, H. (2019). Modelling and experimental analysis of low concentrating solar panels for use in building integrated and applied photovoltaic (BIPV/BAPV) systems. *Renewable Energy*, 139, 815–829. doi: 10.1016/j.renene.2019.02.121

[8] Hadavinia, H. (2018). *Modelling and Experimental Analysis of Low Concentrating Photovoltaic for Use in Building Integrated and Attached Photovoltaic (BIPV/BAPV) Systems*. College of Engineering, Design and Physical Sciences, Brunel University London.

[9] Zhang, Y., Su, J., Zhang, C., Lang, Z., Yang, M., & Tingkun, G. (2021). Performance estimation of photovoltaic module under partial shading based on explicit analytical model. *Solar Energy*, 224, 327–340. doi: 10.1016/j.solener.2021.06.019

[10] Bharadwaj, P., & John, V. (2019). Subcell modeling of partially shaded photovoltaic modules. *IEEE Transactions on Industry Applications*, 55(3), 3046–3054. doi: 10.1109/TIA.2019.2899813

[11] Brecl, K., Bokalic, M., & Topic, M. (2021). Annual energy losses due to partial shading in PV modules with cut wafer-based Si solar cells. *Renewable Energy*, 168, 195–203. doi: 10.1016/j.renene.2020.12.059

[12] Jacobson, M.Z., & Jadhav, V. (2018). World estimates of PV optimal tilt angles and ratios of sunlight incident upon tilted and tracked PV panels relative to horizontal panels. *Solar Energy*, 169, 55–66. doi: 10.1016/j.solener.2018.04.030

[13] Parupudi, R.V., Singh, H., & Kolokotroni, M. (2020). Low Concentrating Photovoltaics (LCPV) for buildings and their performance analyses. *Applied Energy*, 279, 115839. doi: 10.1016/j.apenergy.2020.115839

[14] Bahaidarah, H.M., Tanweer, B., Gandhidasan, P., & Rehman, S. (2015). A combined optical, thermal and electrical performance study of a V-trough PV system—Experimental and analytical investigations. *Energies*, 8, 2803–2827. doi: 0.3390/en8042803

[15] Rabl, A. (1976). Comparison of solar concentrators. *Solar Energy*, 18, 93–111. doi: /10.1016/0038-092X(76)90043-8

[16] Madala, S., & Boehm, R.F. (2017). A review of nonimaging solar concentrators for stationary and passive tracking applications. *Renewable and Sustainable Energy Reviews*, 71, 309–323. doi: 10.1016/j.rser.2016.12.058

[17] Ustaoglu, A., Kandilli, C., Cakmak, M., & Torlaklı, H. (2020). Experimental and economical performance investigation of V-trough concentrator with different reflectance characteristic in photovoltaic applications. *Journal of Cleaner Production*, 272, 123072. doi: 10.1016/j.applthermaleng.2023.121028

[18] Gómez-Gil, F.J., Wang, X., & Barnett, A. (2012). Energy production of photovoltaic systems: Fixed, tracking, and concentrating. *Renewable and Sustainable Energy Reviews*, 16, 306–313. doi: 10.1016/j.rser.2011.07.156

[19] Hussein, L.A., Ayadi, O., & Fathi, M. (2021). Performance comparison for sun-tracking mechanism photovoltaic (PV) and concentrated photovoltaic (CPV) solar panels with fixed system PV panels in Jordan. *12th International Renewable Engineering Conference (IREC)* (pp. 1–8). Amman, Jordan. doi:10.1109/IREC51415.2021.9427808

[20] Concepcion, N.D.G., Villanueva, A.R., Dalumpines, A.K., Magwili, G., & Pacis, M.C. (2020). Design of an Azimuth-Altitude Dual Axis Tracking System (AADAT) for energy solar harvesting using photovoltaic V-trough concentrator. *11th IEEE Control and System Graduate Research Colloquium (ICSGRC)* (pp. 144−149). Shah Alam, Malaysia. doi: 10.1109/ICSGRC49013.2020.9232608