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Mohammad Alnajideen ; Mazin Al-Shidhani; Marwan Naaman; Martin Eze; Fouad Suliman

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A Comparative Study of 3D Printed Non-Imaging Solar V-Trough and Compound Parabolic Concentrators for Low-Cost, High-Performance CPV Applications

Mohammad Alnajideen[1, 2, a)], Mazin Al-Shidhani[3)], Marwan Naaman[1], Martin Eze[1,4] and Fouad Suliman[1]

[1] *School of Engineering, Cardiff University, Cardiff CF24 3AA, Wales, UK*
[2] *Faculty of Engineering, Mutah University, Al-Karak 61710, Jordan*
[3] *Petroleum Development Oman, P.O Box:81, Postal Code 100, Muscat, Sultanate of Oman*
[4] *Department of Electronic Engineering, University of Nigeria, Nsukka, 410001, Enugu, Nigeria*

[a)] Corresponding author: AlnajideenMI@cardiff.ac.uk

Abstract. Non-imaging solar concentrators are capable of increasing power output and reducing the cost of photovoltaic (PV) cells. This paper discusses the performance of non-imaging concentrators with two distinct configurations: V-trough and compound parabolic. The concentrators were successfully designed, fabricated, tested and characterized as reported in our previous papers [1, 2]. Herein, we present a comprehensive comparison between those non-imaging concentrators in terms of concentration ratio, power output, conversion efficiency, optical efficiency, light uniformity, angular response and cost. The results demonstrate the advantages of using V-trough and compound parabolic concentrators, particularly beneficial to be employed as the secondary optical elements with a primary concentrator and high-cost III-V cells such as GaInP/GaAs/Ge.

INTRODUCTION

Concentrator Photovoltaic (CPV) uses optics materials to focus sunlight from a relatively large area aperture onto a small area PV receiver, enabling the generation of the same amount of electric power using a less active area of PV cells [1]. The research into CPV systems has taken place since the 1970s when US Sandia Labs developed the first Fresnel lens CPV system with 350kW capacity [3]. Afterwards, significant improvements have been achieved to develop cost-effective optics materials and highly efficient PV cells to reduce the cost of electricity generation [4]. Concentrating optics can be consisted of reflective or refractive materials and are categorized according to their optical shape of reflective/ refractive optics (i.e., parabolic, dish, lens), concentration ratio (low, medium, high and ultra-high), the shape of concentration image (point or line focus), type of end-use application (electrical, thermal or hybrid) and imaging and non-imaging concentrators [1, 5].

V-trough solar concentrator (VSC) and compound parabolic concentrator (CPC) are non-imaging concentrators, and both were employed as primary or secondary optical elements [6, 7]. In recent years, research work has focused on improving the geometrical aspect and optical performance of CPC rather than VSC [8-11]. This is back to the compactness of the CPC geometry and its capability for producing a relatively higher concentration ratio than the VSC [12, 13]. However, the advantages of VSC over CPC include (i) the uniform illumination on the receiver area that is desirable for PV applications, (ii) simplicity of the fabrication, as it is made of flat mirrors and does not require complex curved shapes, and (iii) low cost due to the ease of fabrication [14, 15]. To date, a few experiments on VSCs have been implemented and no experimental study has compared non-imaging VSCs and CPCs in detail. Consequently, this study aims to evaluate the optical and electrical performances of VSC and CPC. Several V-trough concentrators of different trough configurations and crossed compound parabolic concentrators were designed, constructed and tested as described by [1, 2, 5, 16].

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CONCENTRATORS

A number of non-imaging concentrators were designed and fabricated as shown in **FIGURE 1**. Four V-trough solar concentrators of each type of conventional and double-trough, which the latter is referred to as Onagraceae because its trough configuration is inspired by the Onagraceae flowers, were designed at different acceptance angles (θ). Similarly, five crossed compound parabolic concentrators were designed. The design parameters of concentrators are listed in **TABLE 1**. The design and fabrication processes, as well as the materials used to build the concentrators, can be found in refs [1, 2]. All concentrators fabricated have the same reflective material and the same receiver area (10mm x 10mm ±0.01mm), where a silicon PV cell is placed.

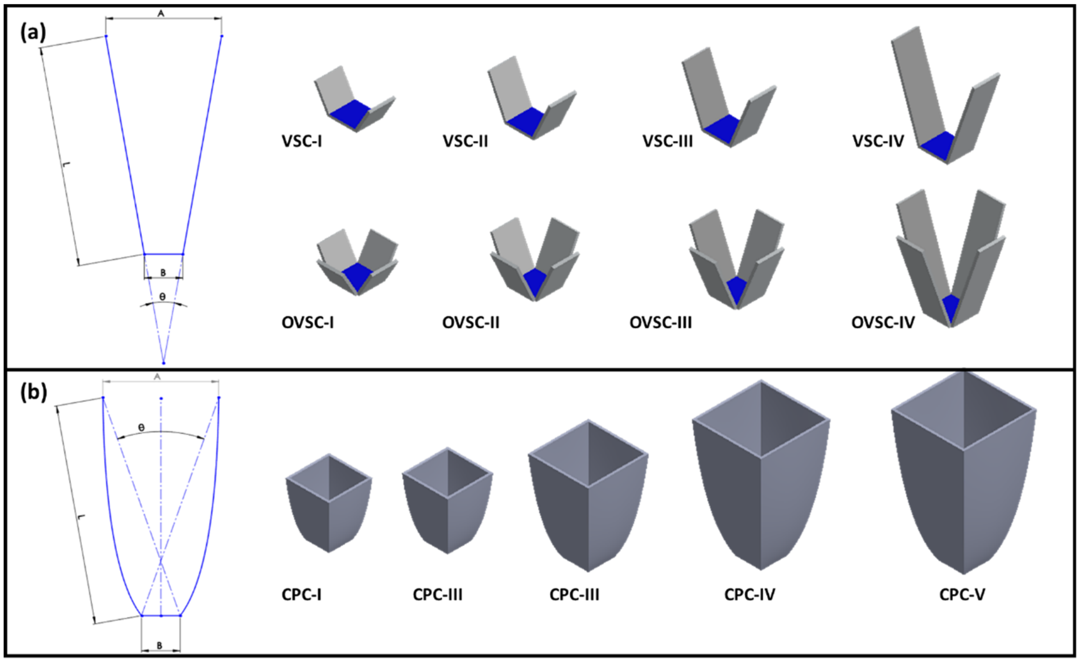

FIGURE 1. Schematic diagram of non-imaging Concentrator Photovoltaic (a) V-trough Solar Concentrators and (b) Compound Parabolic Concentrators (CPC). VSC and OVSC represent conventional and Onagraceae V-trough solar concentrators respectively. $\boldsymbol{A}$, $\boldsymbol{B}$, $\boldsymbol{L}$ and $\boldsymbol{\theta}$ are aperture width, receiver width, reflector length and acceptance angle, respectively.

TABLE 1. Design Parameters of VSCs, OVSCs and CPCs. $\boldsymbol{\theta}$, $\boldsymbol{A_{ap}}$, $(\boldsymbol{L/W_{ap}})$ and $\boldsymbol{CR_{geo}}$ are the acceptance angle, aperture area, aspect ratio (reflector length to PV receive width) and geometrical concentration ratio, respectively [5, 16].

Type of Concentrator		θ	A_{ap} (mm^2)	(L/W_{ap})	Reflector area (mm^2)	CR_{geo}	Cost ($) *
VSC	I	30.0°	200.0	1.0	200.0	2.00	2.39
	II	25.0°	228.6	1.5	304.0	2.29	2.90
	III	22.0°	250.8	2.0	403.0	2.51	5.77
	IV	19.0°	306.0	3.1	633.0	3.06	6.97
OVSC	I	30.0°	300.0	1.0	400.0	3.00	4.79
	II	25.0°	357.2	1.5	608.0	3.57	5.80
	III	22.0°	401.6	2.0	806.0	4.02	11.53
	IV	19.0°	512.0	3.2	1266.0	5.12	13.92
CPC	I	36.0°	289.0	1.9	812.0	2.89	10.03
	II	30.0°	400.0	2.6	1100.0	4.00	10.33
	III	24.0°	600.3	3.9	1600.0	6.00	11.47
	IV	20.6°	806.6	5.1	2094.0	8.30	12.54
	V	19.5°	900.0	5.6	2294.0	9.00	13.10

* the cost of a single prototype concentrator, more details are available in [5, 16].

RESULTS AND DISCUSSION

The PV cell was illuminated using a solar simulator under standard test conditions [17] to characterize its electrical performance as the reference for studying its performance when illuminated using solar concentrators. The I-V curves of the cell were acquired using AUTOLAB I-V tracer, before and after using the concentrators presented in **FIGURE 1**. The detailed experimental setup and procedure are described in [1, 2, 5].

FIGURE 2 presents the I-V and P-V characteristic curves of the PV cell measured using the conventional VSCs, OVSCs and CPCs. The photocurrent, voltage and power output of the PV cell are increased under the light concentration using the corresponding concentrators compared to the values obtained using the bare cell (i.e., without concentrators). The level of increase varies depending on the concentrator employed with the PV cell. This is due to the variations in the light intensities produced by concentrators with a variety of optical performances. In general, the power output from the PV cell using CPCs is higher than that obtained from VSCs and OVSCs. This is due to the crossed, coherent and parabolic shape of the CPC, which is an advantage over V-trough concentrators. The power output of the PV cell using the VSC, OVSC and CPC is (1.8 – 3.1), (2.6 – 5.2) and (2.9 – 10.3) times as large as the power output from the bare cell. The conversion efficiency of the PV cell (12.6%) tested under one sun (without concentration, 1kW/m^2) is increased by (4.4% - 7.3%) and (6.8% - 10.8%) using the conventional VSCs and OVSCs, respectively. Using the CPCs, the efficiency of the cell (9.5%) is increased by 18.6 - 34.6%, demonstrating the advantage of the concentrator PV. All experiments were repeated in sets of three and the standard deviation of the data sets is less than 3%.

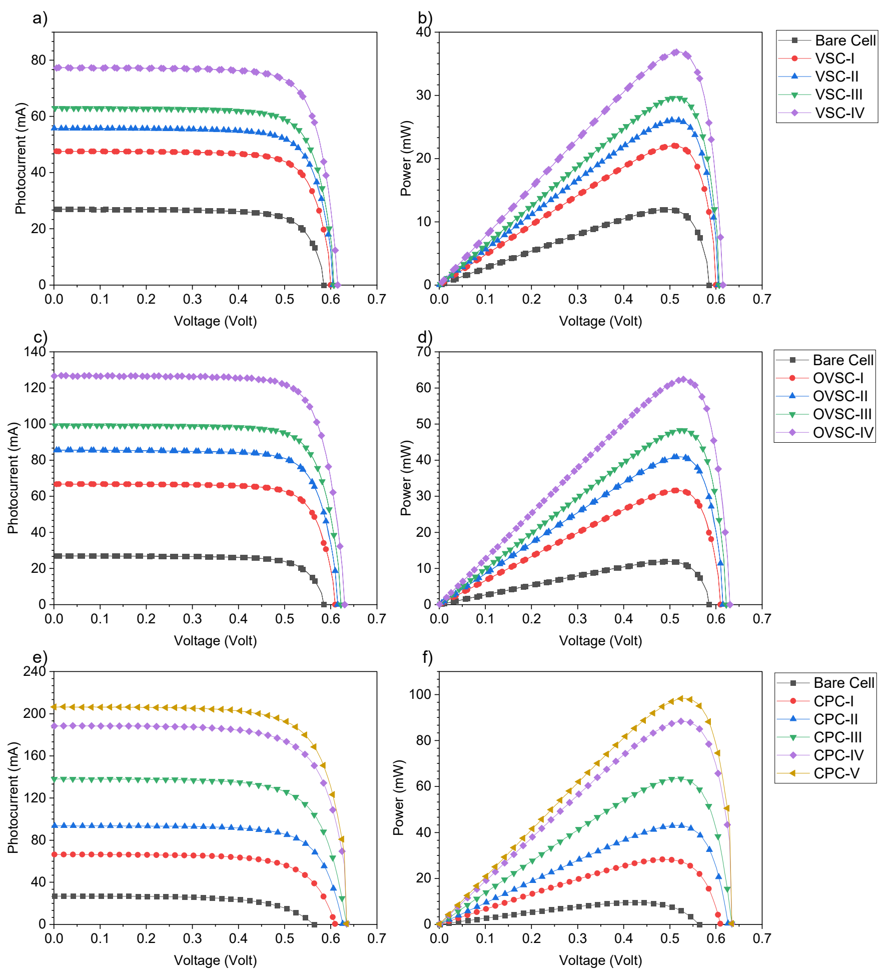

FIGURE 2. The I-V and P-V curves of the PV cell using (a-b) conventional V-trough Solar Concentrators (VSC), (c-d) Onagraceae V-trough Solar Concentrators (OVSC) and (e-f) Compound Parabolic Concentrators (CPC), respectively. A bare cell indicates the PV cell tested under one sun irradiance without a concentrator. Reprinted with permission from AIP Conference Proceedings 2012, 020001 (2018) and AIP Conference Proceedings 2149, 030001 (2019).

FIGURE 3 presents the concentration ratio, optical efficiency, and light uniformity of concentrators. The geometrical concentration ratio is calculated from the geometrical aspect of concentrators, the experimental (or the effective) concentration ratio is determined from the I-V measurement of the PV cell and the optical efficiency is then calculated from the geometrical and effective concentration ratios as given by [1, 2]. The uniformity of light distribution across the receiver/cell area is determined by direct measurement of light irradiance on the receiver area using the spectroradiometer. The receiver area is divided into 9 equally sized areas of 1.5 mm^2 each, and the spectroradiometer's detector is positioned on each sub-area respectively to measure the light irradiances. The uniformity indicates the standard deviation of light irradiances across the entire receive area as given by [1, 2]. It can be seen that for a specific type of concentrator, the optical efficiency increases with increasing the concentration ratio of the concentrator. The optical efficiency of the V-trough concentrators is slightly higher than that of CPCs of the same acceptance angle. Likewise, the light irradiance on the receiver plane of VSCs and OVSCs is slightly more uniform than that of the corresponding CPCs.

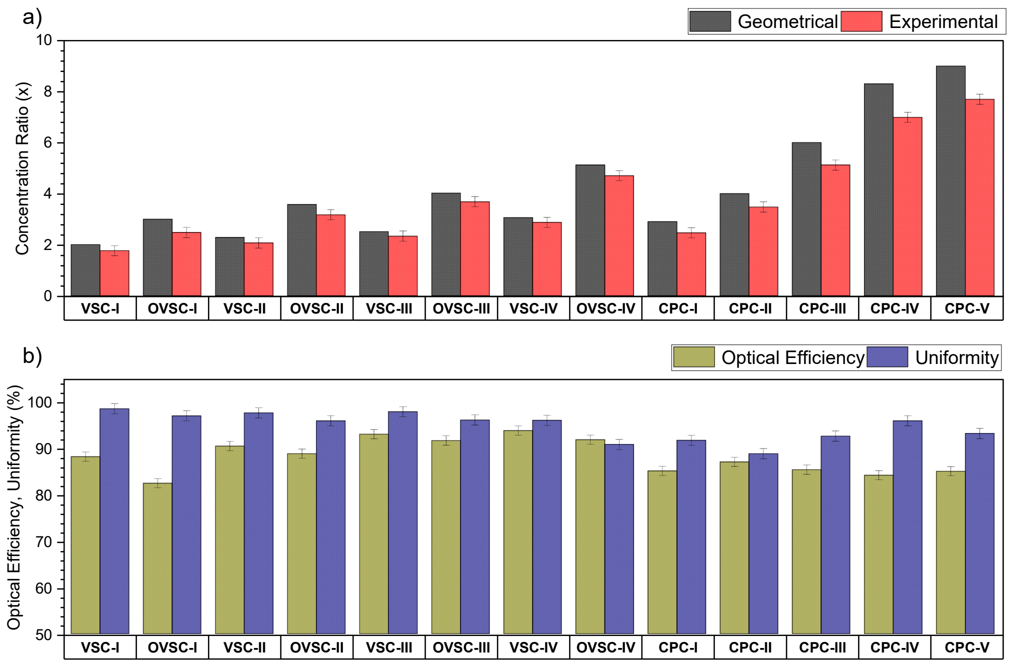

FIGURE 3. (a) The geometrical and experimental concentration ratio and (b) optical efficiency and uniformity of concentrators.

FIGURE 4 shows the concentration ratio of concentrators as a function of angle of light incidence (AOI). The concentration ratio obtained from CPCs of the same acceptance angle of V-trough concentrators is found significantly higher than the latter at low AOIs. In order to compare the angular response of concentrators validly, the results of the concentration ratio are normalized to the maximum value of concentration ratio (i.e., at AOI=0º). Although CPCs offer a higher concentration ratio, the angular response of VSCs and OVSCs of low acceptance angles is better than those CPCs.

The comparison between concentrators is also made based on the same aperture area, effective concentration ratio and reflector area as shown in **FIGURE 5**. The angular response of OVSC-III is slightly poorer than CPC-II over only low AOIs (**FIGURE 5-a**) while the comparison between concentrators of the same effective concentration ratio shows CPCs I and II have higher concentration ratios than OVSCs I, II and III over low AOIs (**FIGURE 5-b-c**). OVCS-IV appears better than CPC-III (**FIGURE 5-d**). The rate of reduction of the concentration ratio of OVSCs over low AOIs is reversed when the AOI is above 22.5 º, 25.0 º and 22.5 º for OVSCs I, II and III, respectively.

Although OVSC-III and CPC-I have approximately the same reflector area, the OVSC-III can offer a higher angular response than the CPC-I as presented in **FIGURE 6**. This could be attributed to the large aperture area of OVSC-III (400 mm^2) compared to CPC-I (290 mm^2). The normalized data show CPC-I is more responsive to the light than OVSC-III when the AOI <30º.

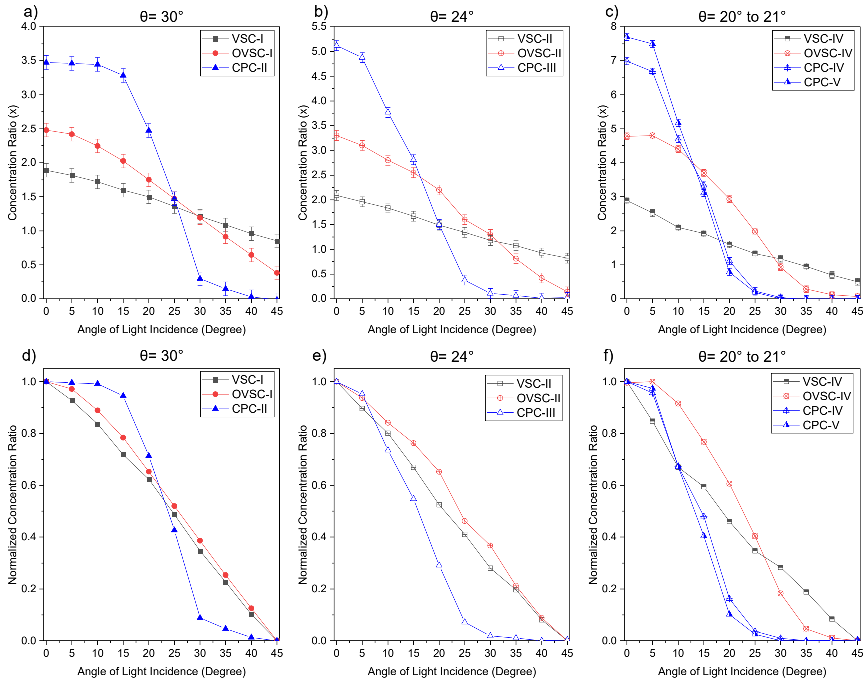

FIGURE 4. The angular response of VSCs, OVSCs and CPCs based on the acceptance angle.

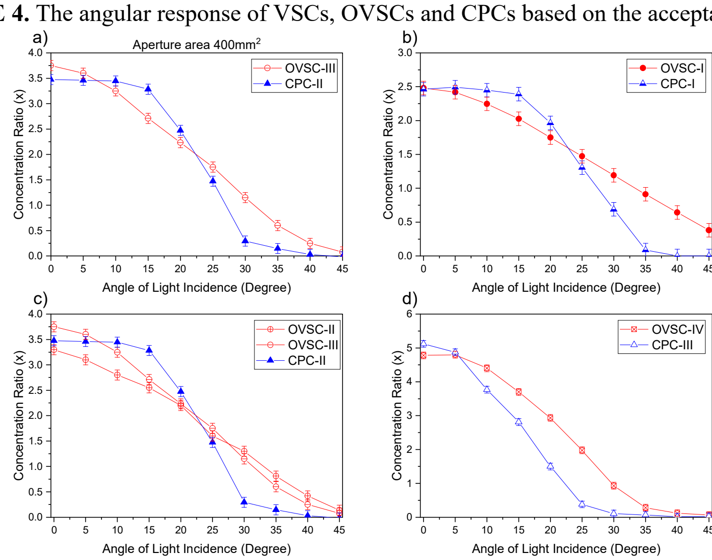

FIGURE 5. The angular response of OVSCs and CPCs based on (a) aperture area and (b-d) effective concentration ratio.

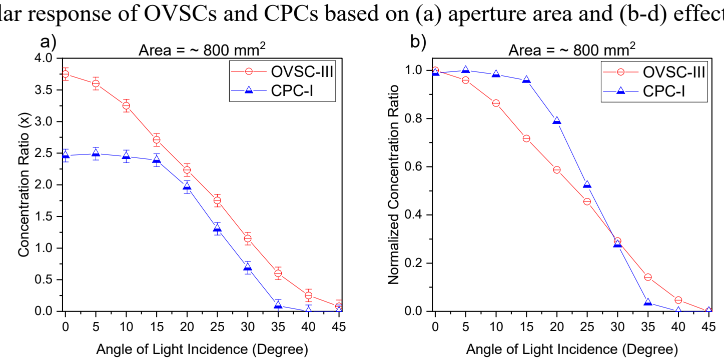

FIGURE 6. Comparison between CPC and OVSC of the same surface area of reflector.

In general, although CPCs offer a higher concentration ratio compared with conventional VSCs and OVSCs as illustrated in **FIGURE 3**, they exhibit a low optical efficiency and light uniformity that are considered performance challenges facing the development of CPV systems. The production cost of a laboratory-scale CPV prototype system is listed in **TABLE 1**. The cost per maximum power output of the concentrators is presented in **FIGURE 7**. It can be clearly seen that the fabrication cost of CPCs is sharply decreasing with the increase of the maximum power output (or concentration ratio) while it is contrary in the case of V-trough concentrators.

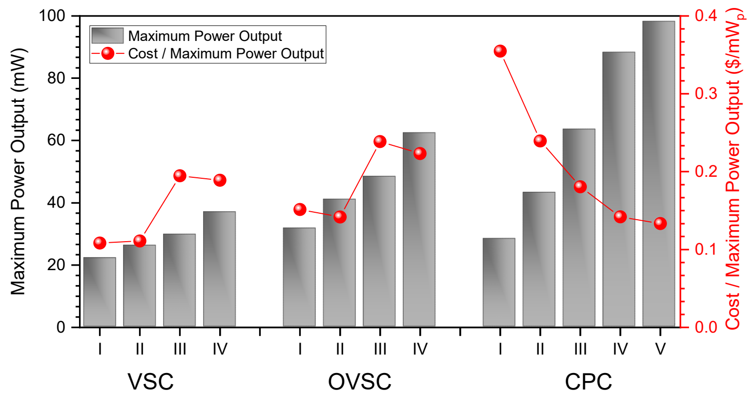

FIGURE 7. The maximum power output and the fabrication cost /maximum power output of concentrators.

CONCLUSION

A comparison between the performance of non-imaging solar concentrators was performed. The comparison of concentrators of the same acceptance angles shows CPCs exhibited a higher angular response than V-trough concentrators at low angle of incidence while the latter outperformed CPCs at high angles of incidence. The angular response of OVSCs and CPCs of the same aperture area and effective concentration ratio is found to be relatively similar, except for the case of OVSC-IV. Although CPCs can offer a higher concentration ratio, their optical efficiency and uniformity are lower than conventional VSCs by (4.60% to 7.2%) and (5.4% to 7.5%) respectively, and they are 4% lower than OVSCs. The cost of fabrication of a single CPV prototype shows the feasibility of using the concentrators. However, outdoor experimental work is required to determine the energy yield and feasibility more representatively to 'real-life' applications. More importantly, V-trough configurations are the only available design options for simultaneous beamsplitting and light concentrations using commercial dichroic mirrors that are required to facilitate the development of a novel hybrid Photovoltaic- Thermoelectric (PV-TE) system [18].

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