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Optimum Design of V-Trough Solar Concentrator for Photovoltaic Applications

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Abstract. This paper presents a novel design of V-trough Solar Concentrator (VSC) for low concentrator photovoltaic (CPV) applications. The conventional VSC design comprises of two flat reflectors slanted by an angle and attached to a PV module. The maximum reported concentration ratio (CR) and optical efficiency (OE) of this concentrator are 2x and 89.91%, respectively. This paper demonstrates the process of improving the VSC. The geometrical and optical performance of the conventional VSC were optimized by the theoretical image technique. The experimental CR and OE are increased by 43.50% and 4.32%, respectively. Then, a crossed V-trough design "Pyramid" is suggested to increase the concentrated radiation. Pyramid concentrator boosted the CR, but the OE is dropped. Eventually, a new VSC geometry is proposed and resulted in CR of 4.70x and OE of 91.83%. The new design demonstrates the possibility of obtaining the same CR using a smaller reflector area than conventional and pyramid V-trough configurations, leading to a reduction in production cost. The results show the potential to further improve this type of solar concentrator for photovoltaic applications.

INTRODUCTION

Solar concentrators can play an important role in providing concentrated solar irradiation for effective thermal and electrical energy conversion at affordable prices. A concentrator can increase the sunlight intensity by focusing the incoming light from a large area onto a small area, enabling generation of the same amount of power using less active area (such as solar cells). The concentrators can be categorized according to (i) the optical shape (parabolic dish or trough, etc.), (ii) concentration ratio (low, medium and high), (iii) the shape of concentration image (point focus, line focus, etc.), (iv) the type of end-use application (thermal, photovoltaic and hybrid) and (v) imaging and non-imaging concentrators [1].

The V-trough Solar Concentrator (VSC) and Compound Parabolic Concentrator (CPC) are non-imaging solar concentrators, which usually have a low CR. They can concentrate light by reflection or refraction. Reflective concentrators use mirrors and refractive concentrators use lenses [2, 3]. A VSC consists of two flat reflectors slanted by an angle to form a "V" shape, with the solar cells (or thermal absorber) positioned between the two reflectors near the focal point. The advantages of a VSC include: i) uniform concentration output, which is desirable for PV applications; ii) simple and easy fabrication due to its flat shape [4]. The choice of CPC or VSC depends on a specific application, which requires consideration of a number of parameters such as the acceptance angle, light reflections path, truncation, reflector to aperture ratio, reflector cost, etc. [5].

In the literature of VSC, several researchers concluded that VSC is limited to obtain a geometrical CR of 3x for a single reflection case [6, 7], this led researchers to develop and optimize CPC rather than VSC [8, 9]. In this paper, we report a new design of V-trough concentrators, which aims to approach the performance of CPC but keep the flat nature of reflectors and it will be shown that VSC is capable of achieving CR greater than 3x.

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V-TROUGH CONCENTRATOR: DESIGN AND CONSTRUCTION

The basic structure of VSC is consisting of two flat reflectors attached to an absorber. In this study, the absorber is a PV cell as the VSC will be used for photovoltaic applications. The symmetrical mirrors or "*reflectors*" are working to increase the incoming solar radiation that reaches the aperture of concentrator by reflecting the incident rays to a small-area PV cell placed between the reflectors. The reflectors slanted by an angle with the horizontal plane, this angle called *reflector tilt-angle*, φ. Where the angle of the V shape is the *vertex angle*, ψ which represents two times the *trough angle θ*, as shown in FIGURE 1.

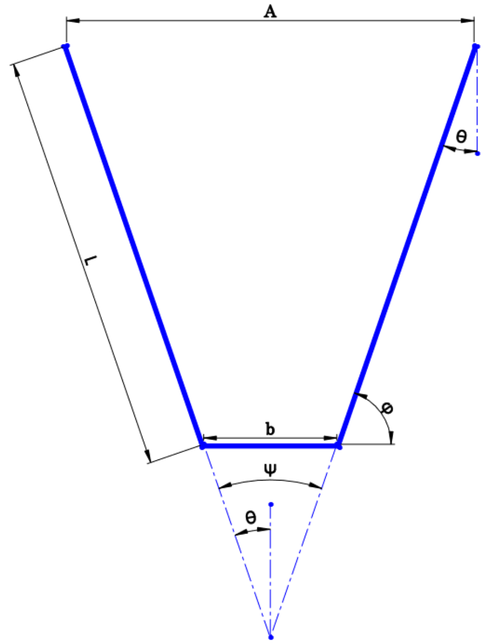

FIGURE 1. Design Structure of V-trough Concentrator.

To design VSC, the trough angle must be less than 45°, otherwise, all incident rays fall on the area of the reflector will be rejected. The concentrator design depends on three key parameters: (i) the reflector tilt-angle, φ, (or vertex angle, ψ), (ii) the dimensionless ratio of reflector-length to PV width (*L/b*), and (iii) the geometrical CR. The geometrical and effective CR can be expressed by [10]:

$$C_{geo} = \frac{A}{b} = 1 + 2\cos\Psi \tag{1}$$

$$C_{eff} \geq 1 + 2\rho\cos\Psi = \rho C_{geo} \tag{2}$$

Where *A* and *b* are the aperture and absorber area, ρ is the reflectance of the mirror (or *reflector*) and *L* is the reflector length. In the literature, the first V-trough concentrator was proposed by Hollands[11]. The maximum theoretical concentration ratio for a single internal reflection is 3x, while the maximum reported experimental concentration ratio and optical efficiency are 2x and 89.91%, respectively [4].

In this study, it will be proved that VSC can achieve CR greater than 3x, an attempt to develop a crossed VSC "Pyramid", and a new VSC geometry is proposed, designed, simulated, constructed and tested. The improvement process started with theoretical approaches, ray-tracing simulation and experimental validations. The proposed V-trough geometry is formed by adding two additional reflectors to Hollands "or conventional" concentrator [11], resulting in four symmetrical reflectors surrounded the PV cell referred to as *Double V-trough Solar Concentrator* (DVSC). The addition of two more reflectors is anticipated to further increase the CR compared with a conventional VSC. This design resulted from an attempt in overcoming the drawback of the "pyramid" concentrator as shown in FIGURE 2(b). For comparison, a conventional VSC and a DVSC are shown in FIGURES 2(a) and 2(c), respectively.

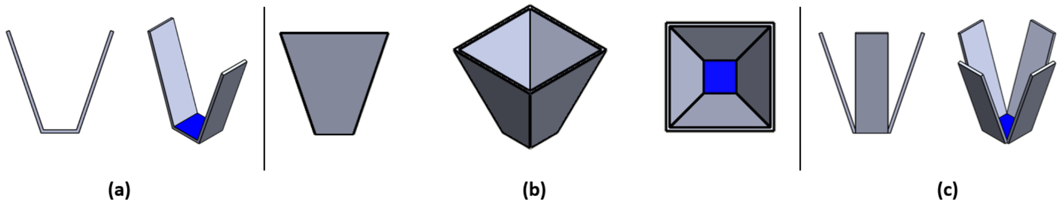

FIGURE 2. V-trough Concentrators (a) Conventional (b) Pyramid and (c) Proposed DVSC.

The development methodology of this work was accomplished through three logical steps:

- The geometry of VSCs is calculated based on the theoretical approaches that derived by Hollands [11].
- Convey the idea of designing and truncating CPC to design a crossed VSC as a Pyramid shape.
- Eventually, a new VSC geometry was induced based on the result of the second step. This new concentrator is able to offer CR greater than 3x.

Four concentrators of each type of conventional VSC, Pyramid and DVSC were designed at different reflector tilt-angles of 60°, 65°, 68° and 71° as listed in Table 1. The geometry was calculated using the theoretical framework by Hollands [11] and then the concentrators were simulated and constructed. The frames of the concentrators were designed by *SOLIDWORKS©,* afterwards, were printed using a 3D printer (*ULTIMAKER Extended 2+©*) and the reflective surfaces were formed by manually gluing the highly reflective aluminium thin films (spectral reflectivity of 95%, *Alanod GmbH*) on the inner surfaces of the concentrators. The constructed concentrators formed the optical part of the VSC-PV system (FIGURE 3a).

As shown in FIGURE 3(b), the second part consists of a Laser Grooved Buried Contact (LGBC) monocrystalline silicon cell 10mm x 10mm mounted on a direct copper-bonded (DCB) alumina ceramic plate and the assembly is then placed on an aluminium water-cooled stage to maintain the temperature of the PV cell at 25°C during test. A thermocouple (K-type) was placed in a groove between the ceramic plate and the water-cooled stage. All gaps at interfaces are filled with thermal grease (thermal conductivity of 2.9 $W.m^{-1}. K^{-1)}$ to ensure good thermal contact.

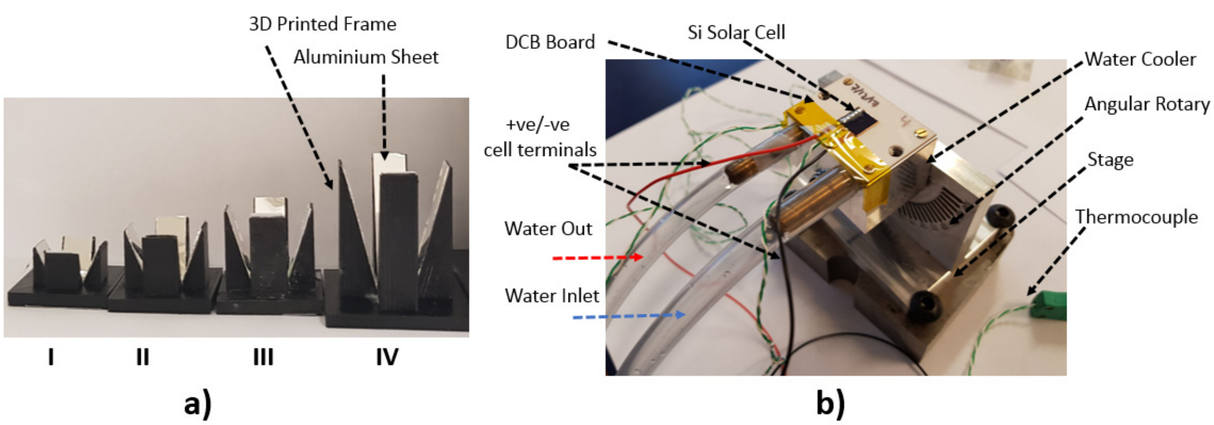

FIGURE 3. VSC- PV System(a) the Concentrators and (b) the PV Assembly Mounted on Water-Cooled Stage.

TABLE 1. The Design Parameters of the Conventional VSC, Pyramid and DVSC Concentrators.

VSC	φ	(*L/b*)	Geometrical Concentration Ratio		
			Conventional VSC	Pyramid	DVSC
VSC-I	60°	1.000	2.00x	4.00x	3.00x
VSC-II	65°	1.521	2.29x	5.22x	3.57x
VSC-III	68°	2.013	2.51x	6.29x	4.02x
VSC-IV	71°	3.164	3.06x	9.36x	5.12x

SIMULATION AND EXPERIMENTAL SETUP

The optical simulation was performed using *TracePro*© software [12]. This simulation combines Monte-Carlo tracing and 3D-CAD Models to analyze and evaluate the optical behaviour of optical systems. Ray-tracing is used widely to design, simulate and optimize different types of optical systems. In this study, *TracePro*© is used to optically evaluate the V-trough design. As discussed early, the design of V-trough concentrator is mainly depending on (*L/b*), the φ value and the geometrical CR. Obviously, the effective CR is always less than the geometrical CR due to the reflectance of the used reflective material as shown in Equation 2.

In the literature of VSC, it observed that most of the researchers who experimentally built and examined the V-trough concentrators, their concentrators were not designed according to the fundamental theories that developed for this type of solar concentrator. This might demonstrate the reason behind the improper design, which will produce unpredictable results. Here, two examples explain this argument. Assume a VSC has two symmetrical flat reflectors titled by 57° from the horizontal plane (or trough angle 33°), the reflector area is [30m (L) x 10m (W)], the PV area is [10m x 10m] as shown in FIGURE 4(a). At first glance, this design will create an aperture area of [42.68m x 10.00m] (see Equation 1), the geometrical CR is 4.27x. This concept is true in theory not necessary on reality. In case of using 95% reflective material, it should offer approximately 4.06x excluding the involved optical and misalignment loss.

Theoretically, (*L/b*) should be 0.747 according to the image technique described by Hollands [11], this means *L* must be 7.47m not 30m. The extra length 22.53m will not contribute to the concentrator because it will reject all the incident light as shown by ray-tracing simulation in FIGURE 4(c). This case is described as *VSC before truncation*. Truncated VSC takes the effective reflector length and here it is 7.47m, making the geometrical CR of the VSC about 1.81x. Figure 4 (c) and 4 (d) show the ray-tracing simulation of this example before and after truncation, and Table 2 shows the difference in the required reflective material, geometrical CR and OE between both cases. It is obvious the truncation process is a key factor as it saves the cost of reflective material and refines the optical performance.

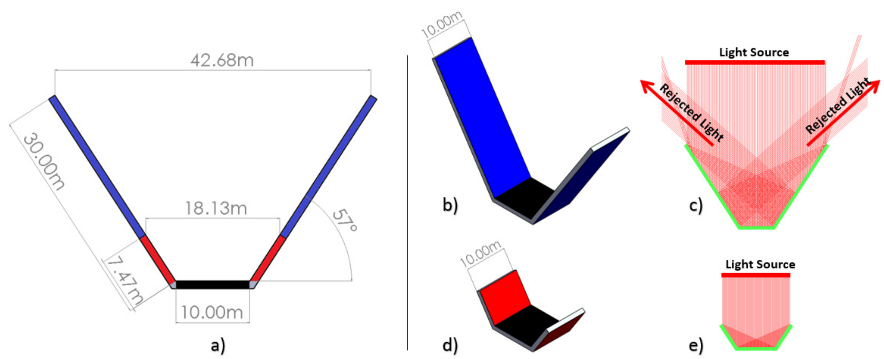

FIGURE 4. (a) Example of a VSC design before (blue and red) and after truncation (red), (b) Non-truncated VSC, (c) Ray-tracing of non-truncated VSC, (d) Truncated VSC and (d) Ray-tracing of truncated VSC.

TABLE 2. VSC Design: Before and After Truncation.

Parameter (s)	VSC (before truncation)	VSC (after truncation)
PV area	10m x 10m	10m x 10m
Reflector area	30m (L) x 10m (W)	7.47m (L) x 10m (W)
(L/b)	3.000	0.747
Geometrical CR	4.27x	1.81x
Effective CR (ρ=0.95)	1.72x	1.72x
Optical Efficiency	40.28%	95.00%
Area of reflectors	600m^2	149.40m^2

Using the same example above. If the reflector width is 30mm, only 10m will contribute to the concentrator that matches the length of PV. This clearly explains the purpose of using the theoretical image technique that already involved in the optical ray-tracing simulation. In this research, all VSCs were designed properly and optically simulated before fabricating them.

The pyramid concentrators were first designed, simulated and constructed. To avoid repetition, a single example presents the pyramid concentrator (VSC-IV) as listed in Table 1. The simulated results show that part of the incident light is reflected out of the concentrator, rather than concentrated to the absorber area. A detailed inspection of the simulation results reveals that the corner areas in this structure do not contribute to light concentration. It can be seen from FIGURE 5(a) that the light falling on to the corner areas are reflected out and the experimental work using light shutters confirms that these areas are inactive as shown in FIGURE 5(b). This observation explains a significant discrepancy between the calculated geometrical CR (9.36x) and measured CR (4.70x) for pyramid concentrators. The corner areas do not only contribute to the CR, but it is also reduced the OE and consumed more reflective materials. Double VSC is created based on this observation, simulation and experimental works to figure out this conclusion. The purple colour in FIGURE 5(b) plus the cell area (yellow) shows the borders of the DVSC.

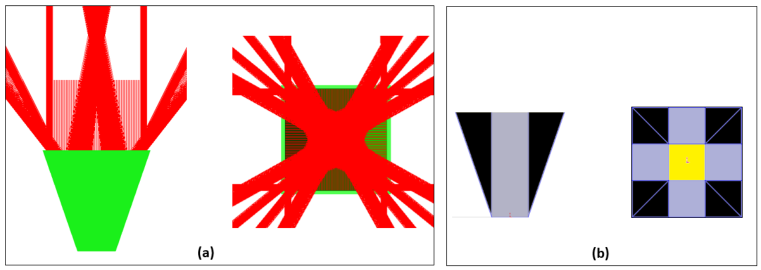

FIGURE 5. Pyramid Concentrator (a) Ray-tracing of Pyramid VSC-IV, (b) Inactive area (black) in Pyramid VSC-IV.

The experimental setup for the evaluation of the constructed concentrators is shown schematically in FIGURE 6. The testings were carried out in-house environment under a uniform illumination provided by a class ABB solar simulator (Oriel LCS-100 Newport Instrument) and a reference silicon solar cell was used to adjust and ensure the irradiance maintained at one sun (1000 W/m^2). The whole setup was secured inside a Faraday-cage and the I-V characteristics of the PV cell under illumination was acquired using AUTOLAB I-V tracer (PGSTAT302N). The temperatures of the PV cell and ambient were automatically monitored and recorded using thermocouples connected via a PICO data logger to a computer. The entire setup was measured at standard test condition, STC, (1kW/m^2 AM1.5G, 25°C). The uncertainties of the experimental apparatus used; AUTOLAB is ±0.2%, the solar simulator is less 6° collimation angle and the standard deviation of overall experimental measurements is less 2%. Because of the large divergence collimation angle of the light source (<6°), the incident beam over the illumination area is a bit away from the vertical axis. This difference introduces error in CPV applications that require uniform and small angle of collimation over its aperture areas before being concentrated. Moreover, this angle increases the non-uniformity of the illumination area.

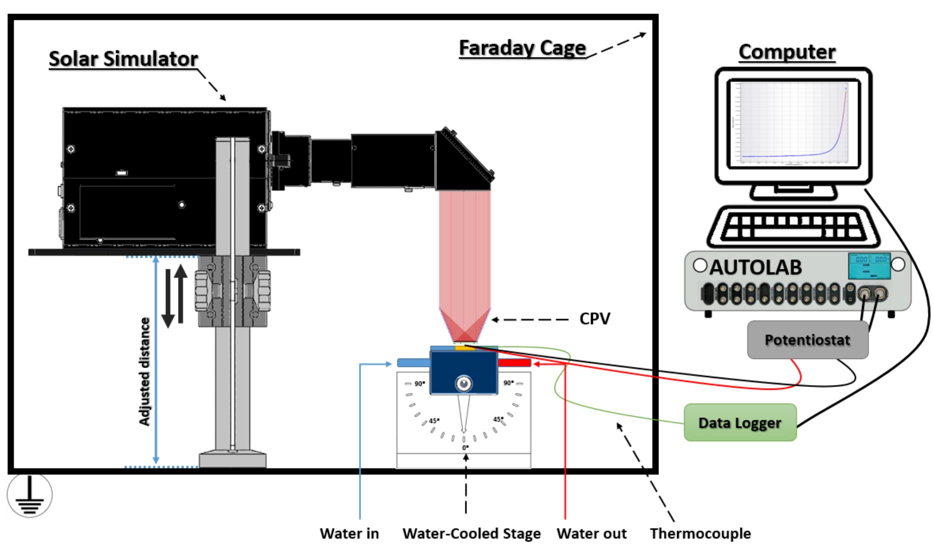

FIGURE 6. Schematic Diagram of the Measurement Setup.

RESULTS AND DISCUSSION

All constructed concentrators listed in Table 1 were characterized using the above-described setup except for the pyramids configurations that showed the same results as the DVCSs. FIGURE 7 presents the I-V (left-side) and P-V (right-side) curves of the conventional VSCs and the proposed DVSCs using the same PV cell. Table 3 illustrates the comparison of the performance of the PV cell using conventional VSCs and the DVSCs, respectively.

For VSC-I that designed at reflector tilt-angle of 60°, the short-circuit current increased from 26.98 mA without concentration to 47.59 mA, whereas it increased to 66.75 mA by DVSC. The PV power output also has increased from 11.98 mW as a bare cell to 22.05 mW and 31.62 mW by conventional VSC and DVSC, respectively. The experimental CR and OE can be calculated from the measured short-circuit currents output of the PV cell with and without solar concentration under the same condition using the following Equations:

$$CR_{exp} = \frac{I_{sc}\,(with\ concentration)}{I_{sc}(without\ concentration)} \tag{3}$$

$$OE = CR_{exp}/C_{geo} \tag{4}$$

The CR of conventional VSC-III and VSC-IV are 2.33x and 2.87x, respectively, which are 16.50% and 43.50% higher than these reported by Singh et al. [4]. The enhancement caused due to taking into account the design parameters and the image technique of Hollands [11]. The CR of the corresponding DVSCs are 3.68x and 4.70x, respectively, showing clear evidence that the CR of the V-trough can be greater than 3x.

TABLE 3. The Performance and Electrical Characteristics of the conventional VSCs and DVSCs.

	Mode	V_{oc} (Volt)	I_{sc} (mA)	P_{max} (mW)	Eff (%)	FF (%)	CR (x)	OE (%)
Bare Cell*	-	0.585	26.98	11.98	12.61	75.86	-	-
VSC-I	VSC	0.600	47.59	22.05	13.16	77.24	1.76	88.18
	DVSC	0.610	66.75	31.62	13.46	77.67	2.47	82.46
VSC-II	VSC	0.605	55.78	26.12	13.30	77.43	2.07	90.44
	DVSC	0.615	85.58	40.92	13.58	77.76	3.17	88.81
VSC-III	VSC	0.607	62.97	29.65	13.37	77.59	2.33	93.02
	DVSC	0.623	99.34	48.31	13.81	78.06	3.68	91.65
VSC-IV	VSC	0.610	77.44	36.88	13.53	78.08	2.87	93.79
	DVSC	0.629	126.86	62.39	13.97	78.19	4.70	91.83

* Bare cell it is the solar cell tested under one sun irradiance (without concentration).

It can be clearly seen from FIGURE 7 and Table 3 that compared to system without concentration the power of the same PV cell has increased more than three times by using the conventional VSC-IV, and more than 5 times by using the DVSC-IV. The fill factor and PV efficiency also show improvement with increasing the concentration ratio. However, the optical efficiency of the conventional VSCs is higher than the proposed DVSCs. The optical efficiency of the DVSCs is approximately 2% lower than that of conventional VSCs. This is because the added reflectors that are employed to increase the concentration also have optical loss, contributing to an increase in total losses.

FIGURE 8 shows the comparison of the concentration ratios obtained by theoretical calculation, simulation and experiment. A good agreement among the theory, simulation and experiment are evident. It is to be noted that for the same CR of 3x, the φ value for the conventional VSC-IV and proposed DVSC-I is 71° and 60°, respectively. This leads to a corresponding (*L/b*) value of 3.16 and 1.00, respectively. For a PV cell 10mm x 10mm, this requires 633 mm^2 of reflective material to construct the conventional VSC-IV, whereas only 400 mm^2 is required for construction of the DVSC-I. This offers 36.81% saving in the reflective material and hence a reduction in cost. FIGURE 9 shows the predicted cost of aluminium reflector required by construction of VSCs and DVSCs for achieving the same CR using a PV cell 10mm x 10mm.

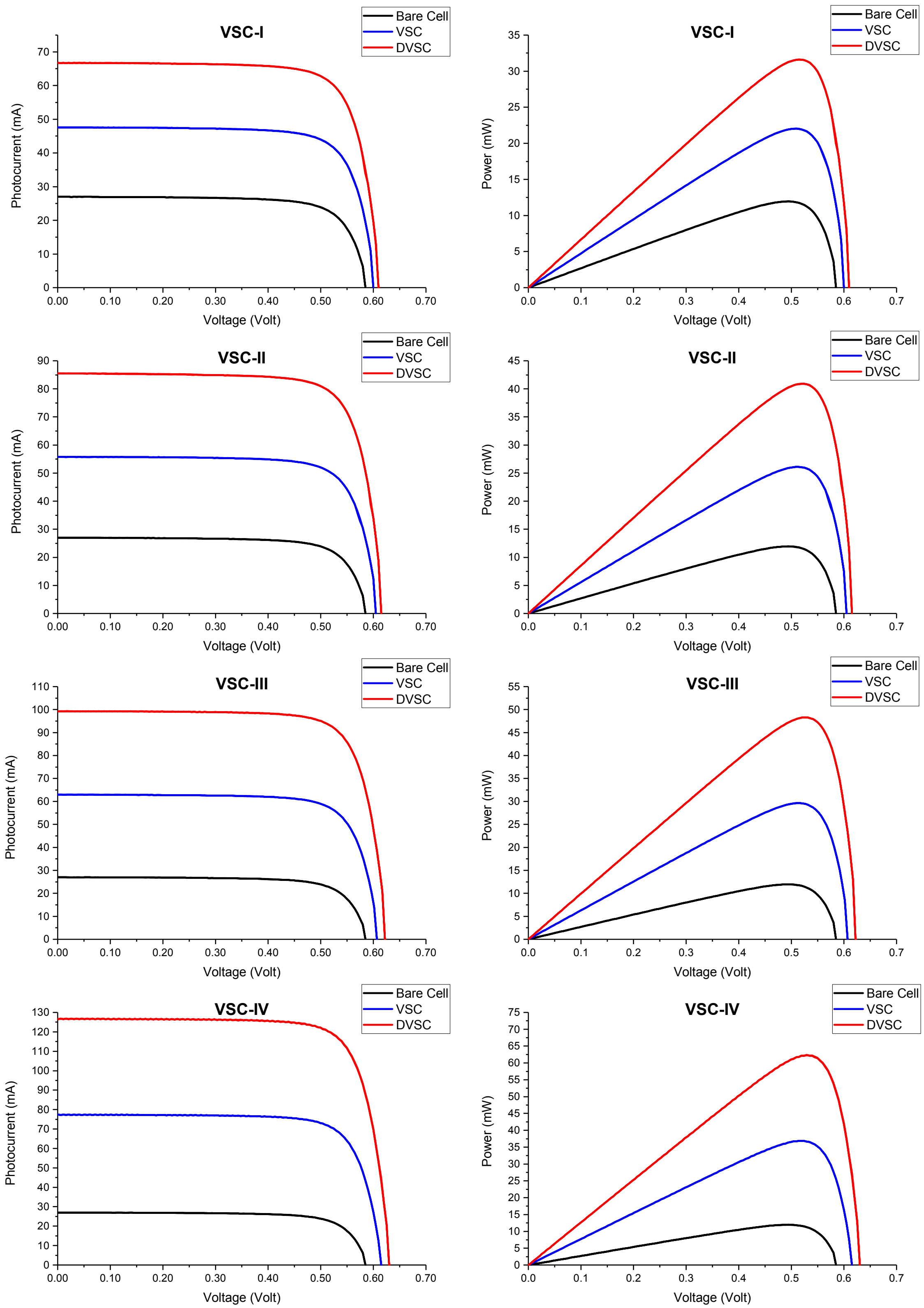

FIGURE 7. I-V (left) and P-V (right) Characterizations of the Conventional VSCs and Proposed DVSCs.

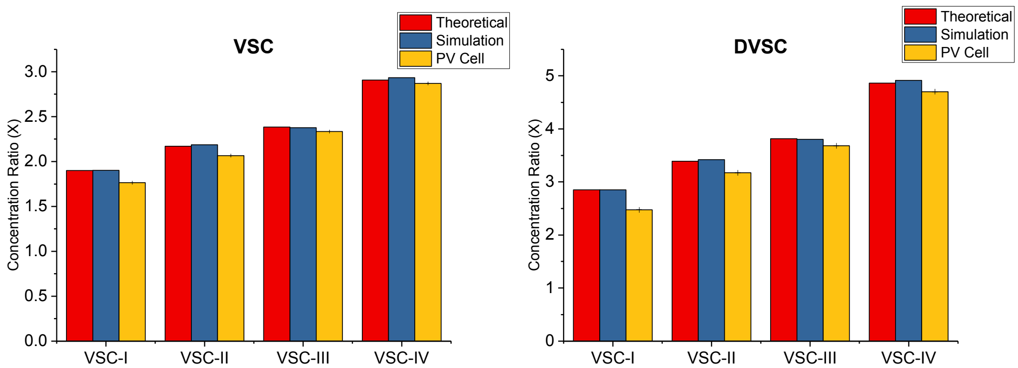

FIGURE 8. The Theoretical, Simulated and Experimental CR of the Conventional VSCs (left) and proposed DVSCs (right).

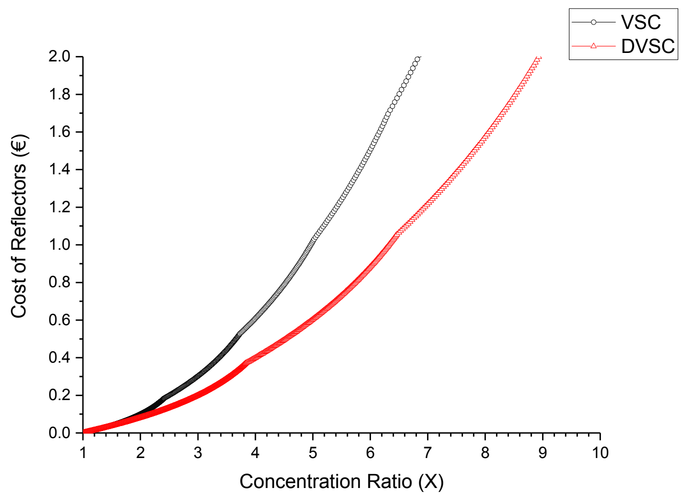

FIGURE 9. The Cost Potential of Reflective Material in Conventional VSCs and DVSCs at the Same CR.

CONCLUSIONS AND FUTURE WORKS

A novel V-trough solar concentrator was designed, simulated, constructed and experimentally evaluated at different reflector tilt-angles of 60°, 65°, 68° and 71°. The results from this investigation demonstrate that this new type of concentrators can achieve similar concentration ratio as the pyramid concentrators but exhibit a significantly improved optical efficiency due to elimination of inactive areas existing in the pyramid concentrators. Compared with conventional V-trough concentrators, this new design enables achieving the same concentration ratio using less reflector materials than conventional V-trough concentrator, leading to reduction in production cost. In addition, higher concentration ratio can be more readily achieved using this new design than using conventional V-trough, making it a promising alternative for low cost and low concentration applications of the future.

A comparative study of conventional VSC and DVSC involves several parameters will be considered in the future such as the angular tracking effects, the uniformity of absorbers, the total cost of the system, etc. The developed DVSC will be integrated in a full concentrator system as primary or secondary concentrator system. As presented in this study, VSC has the potential for further developments and is recommended for rooftop and low CPV applications.

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