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Novel Optical Concentrator Technology for Building Integrated Photovoltaic Systems

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ABSTRACT

This paper describes a novel type of solar concentrator for use in Building Integrated Photovoltaic (BIPV) Systems. The new design called *rotationally asymmetrical compound parabolic concentrator (RACPC)* is based on a novel algorithm that caters for the variation of the position of the sun throughout the day and throughout the year. The RACPC is designed to tackle the following issues: (i) to increase the electrical output of a concentrating photovoltaic (CPV) system by providing sufficient concentration gain; (ii) to minimise the usage of the PV material with the corresponding reduction of CPV system cost, and (iii) to eliminate the requirement of mechanical tracking by providing a wide field-of-view. The experimental results presented here indicate that the RACPC increases the short circuit current by 3.01x when compared with a bare solar cell.

Keyword: Solar energy, solar concentrator, rotationally asymmetrical compound parabolic concentrator.

1. Introduction

The detrimental effects of extracting and using fossil fuels are motivating the development and adoption of renewable energy technologies. Greenhouse gasses (GHG) such as carbon dioxide, which are the results of burning fossil fuels, contribute to the greenhouse effect that is responsible for an increase in the average earth temperature of $0.85^{\circ}C$ since the pre-industrialisation period (Fischer & Knutti, 2015). To mitigate the GHG emissions while satisfying the world's energy needs, one of the options suggested by the Intergovernmental Panel on Climate Change is the deployment of renewable energy technologies such as solar photovoltaic (PV) (IPCC, 2011). At present, the world consumes approximately 150 PWh of energy. This is supplied by three main sources: fossil fuels (87%), renewable sources (9%) and nuclear (4%) (BP, 2015).

With regards to solar PV technologies, it is estimated that more than 72 GW of PV modules were produced in 2014, with the crystalline modules dominating 90% of the market (REN21, 2015). In terms of installation, it was reported that the cumulative PV installed capacity reached nearly 177 GW by the end of 2014, with approximately 49% of the PV modules installed in Europe (see Figure 1) (IEA-PVPS, 2015; REN21, 2015). In 2014 alone, approximately 40 GW were installed worldwide, an increase of 29% when compared with the previous year (IEA-PVPS, 2015; REN21, 2015).

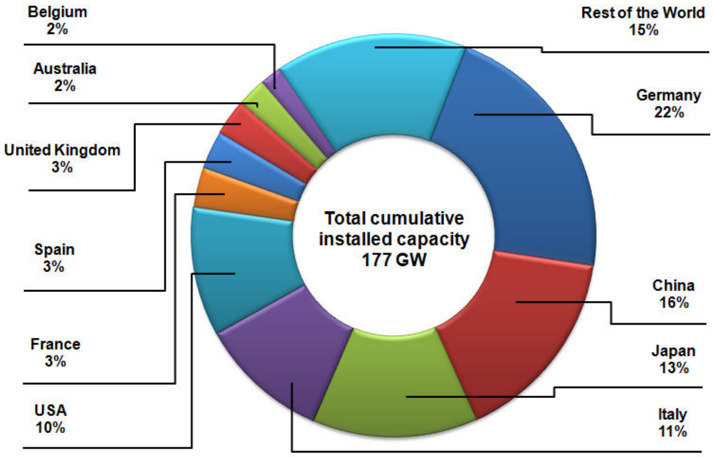

Figure 1: Cumulative PV installed capacity in 2014. Adapted from (IEA-PVPS, 2015; REN21, 2015).

In spite of an oversupply and declining prices of PV modules, the overall installation cost of a PV system in many countries is still considered very expensive. It is estimated that the PV material within a PV module contributes to 73% (Goodrich et al., 2013) of the module cost. This corresponds to 32.85% of the overall installation cost. To achieve a reduction in the cost of a PV module without compromising its performance, a number of researchers have suggested to incorporate a solar concentrator within the PV module design (Mallick, 2003; Muhammad-Sukki, 2013; Sarmah, 2012; Sellami, 2013; Zacharopoulos et al., 2000).

A concentrator is an optical element that works by focusing solar radiation incident on a large area, into a smaller area to which a solar PV cell is attached (Muhammad-Sukki et al., 2010). The corresponding increase in irradiance can be used to offset the displacement of expensive PV material while maintaining the desired level of electrical output, as the concentrator can be fabricated using inexpensive materials such as plastic (Muhammad-Sukki et al., 2010). In the specific case of building integration, concentrating PV (CPV) technologies incorporating low gain concentrators (gains < 10x) in the design are desirable since they have a wider half-acceptance angle to maximise the collection of sunlight throughout the day as well as to cater for variations of sun path throughout the year. This eliminates the need for electro-mechanical sun-tracking. Low gain concentrators use in CPV systems are known as *low-concentration photovoltaics (LCPV)* systems.

This paper proposes a new type of compound parabolic concentrator (CPC) design for use in BIPV systems. This concentrator is known as a rotationally asymmetrical compound parabolic concentrator (RACPC).

2. Design and fabrication of an RACPC

The RACPC is a new variation of the CPC. The design algorithm was developed by modifying the algorithm proposed by Ning et al. in 1987 for the dielectric totally internally reflecting concentrator (DTIRC). This is possible due to the fact that the CPC is a particular case of the DTIRC family of concentrators, in which the entrance aperture of the optical element is flat. The novel algorithm to create the RACPC was coded in MATLAB® to automate the design process according to a number of design parameters. The input variables are: the total height of the concentrator (*HTot*), the half-acceptance angle (θ_a), the length of the PV cell (L_{PV}), the width of the PV cell (W_{PV}), the trial width of the entrance aperture (d_1), the index of refraction of the material (n); and the number of extreme rays (N). The detailed algorithm to produce the design has been presented in Abu-Bakar et al., (2014). Figure 2 helps to explain the process of designing the RACPC. Based on the input parameters, the MATLAB® programme produces a sequence of 2-D cross sections that correspond to an angular increment on the x-z plane. The first 2D-symmetrical design is plotted as ‘Position 1’ in Figure 2. Three subsequent cross-sections, are indicated by cross-sections 2, 3 and 4 respectively. The process stops when a 180° rotation around the y-axis is completed. The program then generates a point cloud corresponding to the 3-D coordinates of the RACPC, and obtains some important parameters of the design: the geometrical concentration gain, the half-acceptance angle and the maximum width of the entrance aperture of the concentrator.

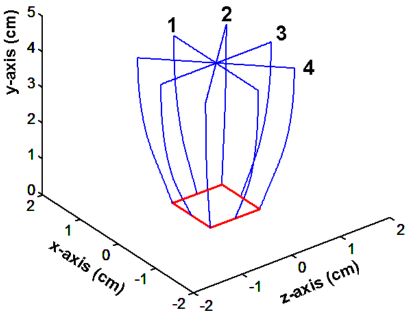

Figure 2: Cross-sections used in the generation of a RACPC by using an angular incremental approach.

Once the point cloud is obtained, the Cartesian coordinates are transferred to a Computer-Aided Design (CAD) software for the analysis of the 3-D design. The software used in this project to produce the CAD file was GeoMagic®. The CAD file was then sent to an industrial partner (UK Optical Plastics Limited, United Kingdom - (Messiou, 2014)) for the fabrication of a prototype using a single-point diamond turning process. Photographs of the prototype of the concentrator are presented in Figure 3.

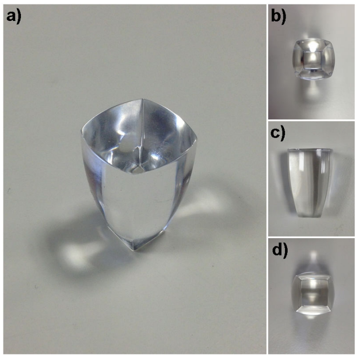

Figure 3: The RACPC prototype fabricated for experimental purposes, where (a) is the isometric view; (b) is the top view; (c) is the side view, and (d) the bottom view of the concentrator.

This design shown in Figure 3 has a geometrical concentration ratio of 3.67, a total height of 3 cm, an exit aperture of 1 cm by 1 cm and an entrance aperture width of 2.0598 cm along both the x and z-axis. The material used in the fabrication of the prototype was Altuglas® V825T, a variation of the polymethyl methacrylate acrylic (PMMA) resin, which has a refractive index of 1.49 (ARKEMA GROUP, 2014). PMMA is a widely used material for optical concentrators due to its high transmittance (92%) and good resistance to photo degradation (Sarmah, 2012).

The RACPC has unique features and advantages when compared with conventional CPC designs. These include (Abu-Bakar et al., 2014):

1. It has a flat entrance aperture with four axis of symmetry (see Figure 3(b)), unlike the 3-D rotationally symmetry CPC or the CCPC which has a circular and square/rectangular shape respectively. By having a flat entrance aperture, an array of these concentrators can be moulded together with a thin layer of material (the same material that produces the concentrators) joining them. This facilitates the assembly process (Sarmah et al., 2012) and potentially reduce the assembly cost of the system.
2. It has a square exit aperture (Figure 3(d)), which matches a square solar cell. A square or rectangular cell is the most popular shape of PV cell due to its ease of manufacture (Mammo et al., 2013). The rotationally symmetry CPC, on the other hand, has a circular exit aperture which, if matched to a square PV cell would create losses.
3. It is a 3D concentrator is the sense that it provides gain on both planes perpendicular to the propagation of light along the concentrator axis, with a corresponding higher geometrical concentration gain than the 2D linear CPC design.

Figure 4 shows a prototype of the RACPC-PV fabricated for evaluation purposes. This prototype was tested indoors and compared to a non-concentrating PV cell.

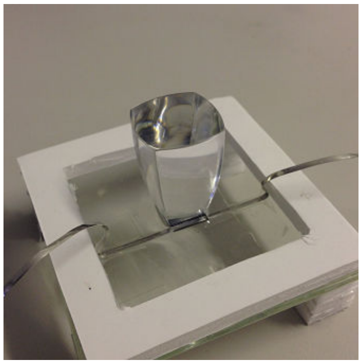

Figure 4: The prototype of RACPC-PV structure.

3. Indoor Experiments

The indoor experimental setup used to evaluate the characteristic of the RACPC is shown in Figure 5. A Class AAA solar simulator (Oriel® Sol3A Model 94083A) from Newport Corporation equipped with an AM 1.5G filter, was used to reproduce the spectral emission of the sun at the earth surface. This provides uniform illumination with a marginal error of ±2%. A variable slope base was placed approximately 38 cm beneath the solar simulator's lamp and within the uniform illumination area (20 cm x 20 cm) of the lamp. The variable slope base was used together with a digital tilt meter to accurately measure the tilt angle of the base. A Keithley source meter (Model 2440) with 4-wire connections was used to act as a high accuracy loading circuit (Muhammad-Sukki, 2013; Muhammad-Sukki et al., 2013). The source meter was connected to a computer which contained the Lab Tracer software from National Instruments®. This software was used to measure the electrical output from the PV cells. The RACPC-PV structure was first placed on the variable slope at 0º inclination. Under standard test conditions (STC), the solar simulator was configured to produce an irradiance of 1,000 W/m^2 and the room temperature was maintained at 25°C. The door and windows of the room were closed to avoid unwanted air flow and minimise temperature variations. The room windows had blinds to prevent unwanted light from entering the room. In order to obtain the current-voltage and power voltage curves of the concentrated-PV cell (and of the bare cell), and from these characterise the angular variation of the optoelectronic gain of the concentrator, the sample (RACPC-PV or the non-concentrating cell) was exposed to the solar simulator light for short periods of time (approximately 5s) using a shutter. This was done to minimise the increase in the solar cell's temperature which would have affected the readings of the open circuit voltage and the fill factor.

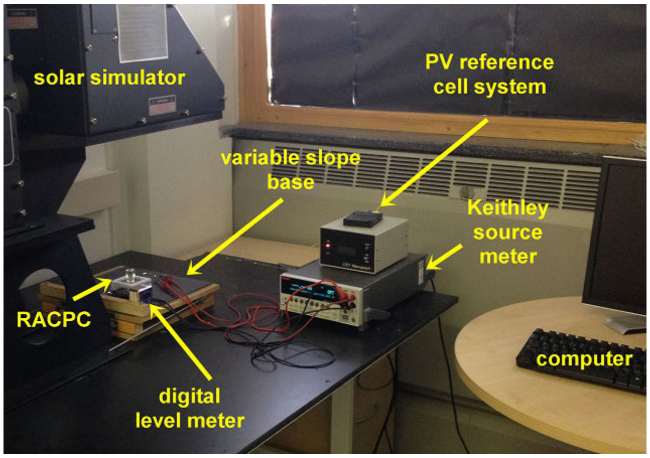

Figure 5: Indoor experimental setup.

3.1 Characteristics of the RACPC under STC at 0º inclination

Figure 6 shows the current-voltage (I-V) characteristics and the power-voltage (P-V) characteristics of the RACPC under STC. From Figure 6, the short circuit current of the bare cell was recorded as 35.5 mA. The introduction of the RACPC in the design increased the short circuit current by a factor of 3.01 when compared with the bare cell, generating 107.0 mA. The open circuit voltage was also increased from 0.560 V to 0.565 V when the RACPC was compared with a non-concentrating cell. The maximum power on the other hand was increased from 0.015 W to 0.050 W when the RACPC was compared with the bare cell, giving a maximum power ratio of 3.33. The experiment showed that the RACPC increased the fill factor from 77% to 79%.

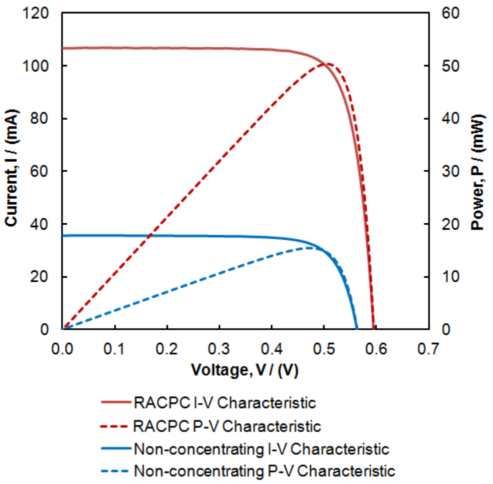

Figure 6: (I-V) and (P-V) characteristics of the RACPC and the bare cell under standard test conditions.

3.2 Angular response of the RACPC under STC

The next part of the experiment was the characterization of the angular response of the RACPC. This experiment evaluated the electrical performance that the system would have based on the variation of the sun position throughout the day. Instead of tilting the source, the variable slope base was tilted from 0° to 60° at increments of 5°. Each tilt was measured using the digital level meter.

Figure 7 compares the short circuit current generated by PV cell incorporating the RACPC to the one generated by the bare cell for angles of incidence within the ±60º range. In general, the short circuit current showed a decreasing trend when the angle of incidence increased. In Figure 7, at normal incidence, the concentrated structure generated the maximum value of short circuit current, 107.0 mA, which was 3.01x higher than the 35.5 mA short circuit current generated by the non-concentrating cell. The short circuit current from the RACPC-cell decreased to 50% of its peak value when the angle of incidence reached ±43º, and continued to drop when the angle of incidence increased. However, it was observed that the short circuit current generated from the RACPC-cell was always higher than the one generated from the bare cell when the angle of incidence was within ±50º. As for the bare cell, although the short circuit current value reduced when the angle of incidence increased, it showed a gradual drop from its peak value. It achieved 50% of its maximum short circuit current value when the angle of incidence was approximately ±60º. This reduction was mainly due to the cosine effect (Sarmah et al., 2014; Stine & Geyer, 2014).

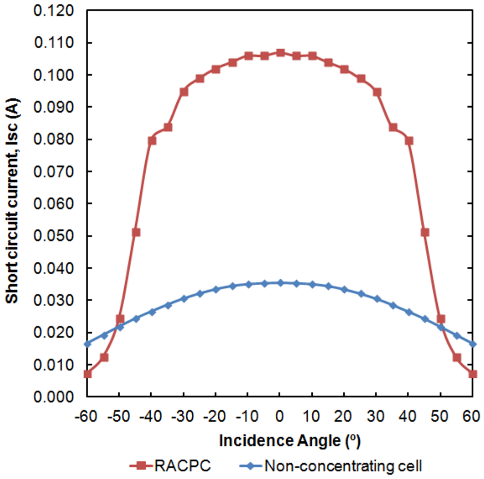

Figure 7: Short circuit current variation of the cell incorporating the RACPC and the bare cell at various angles of incidence.

Another important parameter that was quantified was the opto-electronic gain of the RACPC. The opto-electronic gain indicates the ratio of short circuit current produced from an concentrating-PV device to the one generated from a non-concentrating cell (Muhammad-Sukki et al., 2013; Ning et al., 1987; Sarmah et al., 2014). A higher opto-electronic gain is desirable since it translates into a higher short circuit current. The opto-electronic gain of the RACPC is presented in Figures 8. As it can be observed in Figure 8, the opto-electronic gain value remains fairly constant (at approximately 3) when the angle of incidence increases from 0 to ±40º. It drops to 90% of its peak value when the angle of incidence reaches ±43º. Beyond this angle, the opto-electronic gain suffers a sudden drop to almost 0.

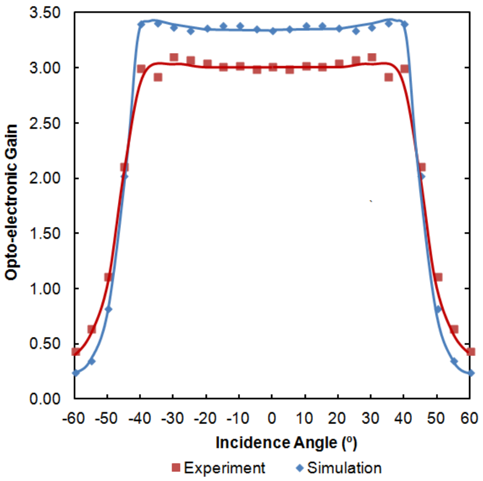

Figure 8: Opto-electronic gain of the RACPC at various angles of incidence.

According to Sarmah et al., (2014), the short circuit current of a concentrator drops when the angle of incidence is getting closer to (and higher than) the value of half-acceptance angle of the concentrator because of rays escaping from the side profile of the concentrator as well as at the concentrator-encapsulation interface. It can also be observed in Figure 8 that some of the instantaneous opto-electronic gain readings within the acceptance angle are higher than the ones recorded at normal incidence. This is due to trays impinging on the side profile of the concentrator arrived at the solar cell. When comparing the opto-electronic gain variation to the gain variation of the simulations obtained by Abu-Bakar et al., (2014) it can be observed that they present a similar trend.

4. Conclusion

A novel type of concentrator known as the RACPC has been proposed as a way to reduce the capital cost of a solar PV system. A specific design was fabricated and successfully tested indoors. This prototype underwent a series of indoor experiments and the results were compared with those of a non-concentrating PV cell. It was found that the RACPC increased the maximum power ratio of the system by up to 3.33x when compared with the non-concentrating cell. Within the half-acceptance angle of the RACPC, the electrical output was always higher than the one obtained from a non-concentrating cell, with a value of 3.01x. The opto-electronic gain was also compared with the simulation results and the results from the experiment showed good agreement with the ZEMAX® simulation analysis. It can be concluded that the RACPC has the potential to increase the electrical output from a solar PV system. This gain can be used to offset the reduction of the electrical output of a conventional PV cell of a smaller area and of a lower cost, contributing in this way to reduce the overall cost of a solar PV system.

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