



SNEC 11th International Photovoltaic Power Generation Conference & Exhibition, SNEC 2017 Scientific Conference, 17-20 April 2017, Shanghai, China

Experimental evaluation of a solar window incorporating rotationally asymmetrical compound parabolic concentrators (RACPC)

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Abstract

Building integrated photovoltaic (BIPV) systems have been proposed to make solar photovoltaic systems more attractive. These systems are not only capable of generating electricity, but can also contribute to minimise energy consumption in buildings by providing natural illumination, space and water heating, ventilation and shading. Despite these advantages, one of the issues that still prevents the widespread adoption of BIPV systems is their high capital cost. This paper discusses a novel type of non-imaging optical concentrator that can be used to reduce the capital cost of a BIPV system. This new concentrator, known as *rotationally asymmetrical compound parabolic concentrator* (RACPC), has a flat entrance aperture that facilitates integration within a double-glazing window and reduces fabrication costs. The RACPC, which has a geometrical concentration of 3.66x, also offers other advantages over conventional solar concentrators: suitability for fenestration, ease of integration with square PV cells, and passive tracking. Several experiments were carried out on a double-glazing solar window incorporating an array of 4x3 concentrator-PV cells. The experiments were carried out indoors under standard test conditions. The results show that the RACPC-PV window effectively increases the short-circuit current by a factor of over 3 at normal incidence when compared with a non-concentrated solar window. The solar window also shows an increase in maximum power generation by a factor of nearly 3.

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Peer-review under responsibility of the scientific committee of the SNEC 11th International Photovoltaic Power Generation Conference & Exhibition.

Keywords: solar; concentrator; photovoltaic; PV; BIPC; RACPC

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1. Introduction

Global warming and the destruction of the environment are two major problems related to the use and extraction of fossil fuels. Other issues include sustainability, economic, political and social problems. This has motivated the use of alternative sources of energy, as well as the search for techniques and technologies to make a more efficient use of it [1, 2].

From the renewable energy sources available, solar has great potential to contribute to satisfy the world's energy needs. This is particularly the case in countries that have high levels of insolation and several hours of sunlight per day. However, despite the reduction in prices of solar photovoltaic (PV) modules and the environmental benefits of using renewable energy sources, many people are still reluctant to adopt solar PV systems as their capital cost is still considered to be too high.

One of the technologies that have been developed to make solar PV systems more attractive is called building integrated photovoltaics (BIPV). A BIPV system involves the use of elements of a conventional PV system to replace parts of the structure of a building. The idea behind BIPV systems is that they not only generate electricity but also minimise energy consumption by providing natural illumination and water and space heating. They also can contribute to the ventilation of a building and provide shade. Despite these advantages, BIPV systems suffer from the same problem as building applied PV (BAPV) systems: their capital cost is perceived to be too high, which prevents their adoption.

One of the solutions that have been proposed to reduce the cost of conventional and BIPV systems involve the use of optical concentrators [3]. An optical concentrator is a reflector or a lens that redirects light from a large area to a smaller area, effectively increasing the irradiance at the PV cell. Several concentrators of different types have been proposed for solar applications in the past. These include refractive, reflective, tracking, non-tracking, 2-D, 3-D, and luminescent concentrators [4]. As the integration of an optical concentrator within a BIPV system has specific requirements, not all the concentrator types are equally suitable for building integrated concentrating photovoltaic (BICPV) applications. To satisfy the requirement of system integration, while providing passive tracking, optimum gain and minimum deterioration of performance, the optical concentrator should be of the non-imaging refractive-reflective 3-D type. This paper discusses a novel optical concentrator of these characteristics called *rotationally asymmetrical compound parabolic concentrator*, which has a geometrical gain of 3.66x.

2. Design and fabrication of a RACPC based window

The design of the RACPC has been discussed in detail by Abu-Bakar et alia [5]. The concentrator consists of three parts: a flat refractive entrance aperture, a totally internally reflecting profile, and a flat and square or rectangular exit aperture. The mathematical design model is based on a ray-tracing algorithm that is used to create several cross-sections of the lens around its axis of symmetry. For each cross-section, the totally internally reflective profile of the concentrator is defined point by point in such a way that rays impinging at the entrance of the concentrator at the maximum angle of incidence (defined by the acceptance angle of the concentrator) are refracted and subsequently directed to the concentrator profile where they barely satisfy the condition of total internal reflection to be redirected to the exit aperture. The mathematical algorithm is automated by coding the equations using a programming language. For this project, the algorithm was programmed using MATLAB[®]. The design programme creates a point cloud which can subsequently be exported to a Computer-Aided Design (CAD) software to create a volume of the lens. The input variables used in the design programme to create the concentrator are: the index of refraction of the material, the half-acceptance angle of the concentrator, the length of the PV cell, the width of the PV cell, the total height of the concentrator, the width of the entrance aperture, and the number of extreme rays. The design programme not only generates 3-D coordinates of the concentrator profile, but also provides some geometrical information such as the entrance aperture of the concentrator and its geometrical gain.

From the various manufacturing techniques available, Computer Numerical Control (CNC) Machining was selected to fabricate the concentrator as it produces the best quality and it is not expensive for a small number of samples. However, it must be noted that for mass production a different manufacturing technique (e.g. injection moulding) must be used in order to make the use of the concentrators cost effective. The material used to manufacture the RACPC was polymethyl methacrylate (PMMA). This material was selected due to its high trans-

mittance, long life span, high resistance to ultraviolet (UV) degradation, and because it is 100% recyclable [6]. The index of refraction of the PMMA used is 1.49, and its transmittance is 92%. Figure 1 shows several views of one of the RACPCs manufactured using CNC machining.



Fig. 1. RACPC manufactured using CNC machining.

The solar cells used for the fabrication of the solar window are laser grooved buried contact (LGBC) silicon cells specifically designed for concentrating photovoltaic (CPV) applications. These cells are intended for concentration ratios below 10x. The efficiency of these cells was experimentally determined to be 14.9% as reported by Freier et alia [7]. The 100-mm² solar cells used, which were purchased from Solar Capture Technologies Ltd., were tabbed with a flat lead wire of 0.1 mm thickness and 1 mm width.

Twelve of the tabbed PV cells were interconnected in series, forming a 4 x 3 array. This array was subsequently attached to a 200 mm x 200 mm x 4 mm glass plate provided by Strathclyde Insulating Glass Ltd. The spacing between the PV cells was set to be 10 mm, to minimise the spacing between the optical concentrators. An optical concentrator was mounted on top of each of the PV cells of the array by using an encapsulating material (Sylgard-184). This material, which is a silicon elastomer with an index of refraction of 1.44 and a transmittance of 94%, provides bonding between the concentrator and the PV cell. It also acts as an index-matching gel, which allows the transmission of light from the concentrator to the PV cell with minimum losses. Once the concentrator-PV array was satisfactorily attached to the glass as shown in Figure 2(a), the concentrating RACPC panel was sent to Strathclyde Insulating Glass Ltd. for assembly within a double-glazing unit (Figure 2(b)), and subsequently to Windows-Plus UK, for the addition of the window's PVC frame.

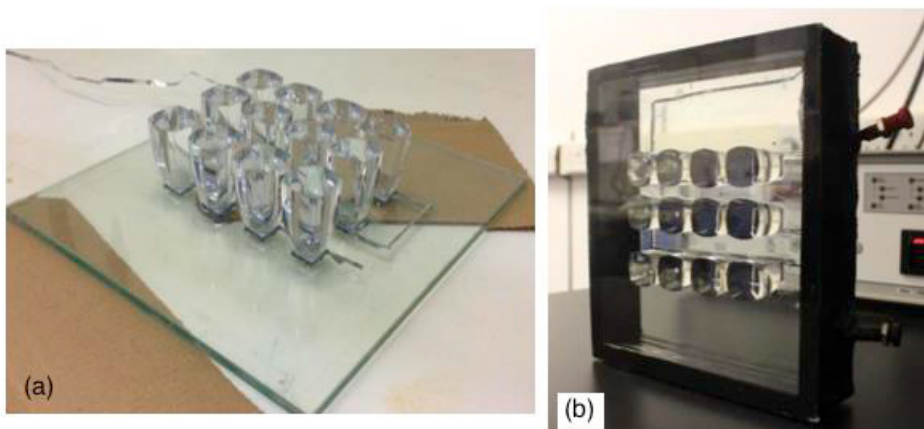


Fig. 2. (a) Concentrating RACPC glass panel; (b) RACPC double glazed unit.

3. Experimental performance analysis

To evaluate the performance of the solar window incorporating the RACPC array, an Oriel Sol3A™ Class AAA solar simulator (model 94083A) from Newport Corporation was used to illuminate the concentrator-PV cell array with an irradiance of 1000 W/m². A 2440 5A source meter from Keithley Instruments was connected to a computer containing the software package LabTracer 2.0. These were used to obtain the I-V curves that characterise the concentrator-PV cell array. Several I-V curves were obtained by running tests on the solar window illuminated at angles of incidence ranging from 0° to 60° by using a variable slope base and a tilt meter. The angular increment for the tilts was 5°. The room temperature was kept at an average value of around 25 °C throughout the experiments.

Some of the most important parameters obtained from the I-V and P-V curves are the short-circuit current I_{sc} , the open-circuit voltage V_{oc} and the maximum power P_{max} . From the short-circuit current, the optoelectronic gain of the concentrator can be calculated. This is defined as the ratio of the short-circuit current produced by the PV cell with the concentrator on top, to that of the PV cell without the concentrator. Therefore, in order to obtain the optoelectronic gain of the concentrating window, a non-concentrating window incorporating an array of PV cells (without the concentrators) was used as a reference. A comparison of the I-V and the P-V curves of the concentrating and non-concentrating windows is shown in Fig. 3.

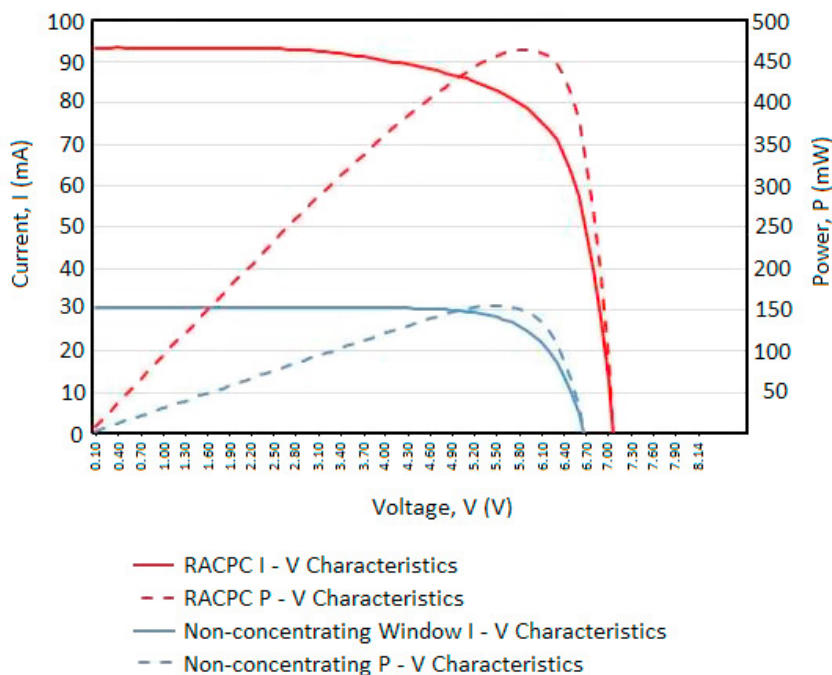


Fig. 3. I-V and P-V characteristics of the RACPC and the non-concentrating windows at normal incidence.

As it can be observed in Fig. 3, the short-circuit current of the PV cells incorporating the concentrators is 93.4 mA, whilst the short-circuit current of the window containing the bare PV cells is 30.51 mA only. This means that the use of the concentrators increases the current by a factor of 3.06 at normal incidence. Moreover, the open-circuit voltage of the PV cells also increases when incorporating optical concentrators, from 6.7 to 7.10 V, which consequently leads to an increase in power. Whilst the maximum power of the bare PV cell array is 155 mW, the maximum power of the concentrator-PV cell array is 464 mW. This corresponds to a power gain of 2.99x.

The optoelectronic gain at various angles of incidence is shown in Fig. 4. What can be observed from this figure is that the maximum optoelectronic gain is obtained at normal incidence and it gradually decreases as the angle of incidence increases. This behaviour is typical of optical concentrators [8]. The RACPC-PV window reaches 90% of its maximum value at $\pm 30^\circ$. The gain reduces to half the maximum value at $\pm 45^\circ$ and continues to decrease until a

value of almost 0 A is reached at $\pm 60^\circ$. This correlates well with previous experiments performed on a single RACPC-PV cell as reported by Abu-Bakar et alia [9], where the optoelectronic gain at normal incidence was 3.01x.

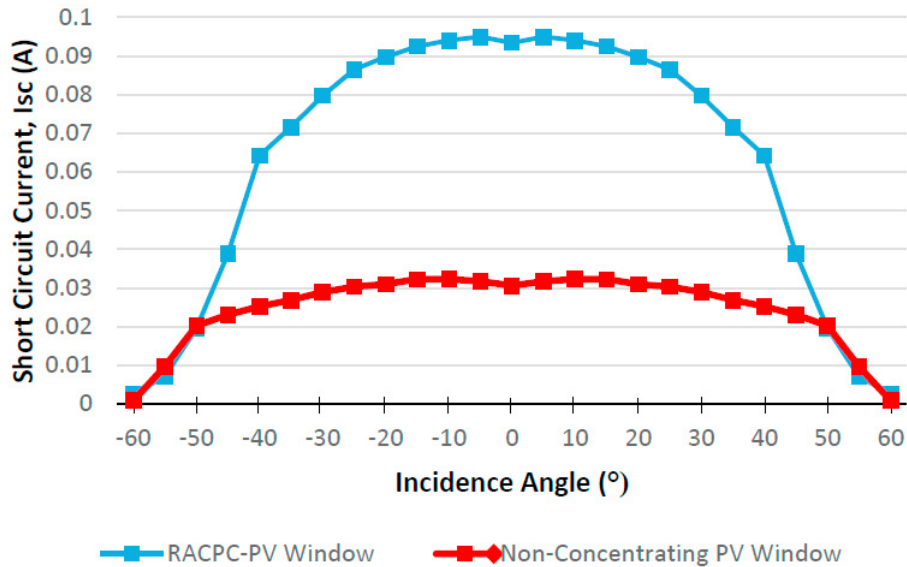


Fig. 4. Optoelectronic gain of the RACPC-PV cell array at various angles of incidence.

4. Conclusions and future work

What can be concluded from this work is that the RACPC effectively increases the electrical output of a PV cell. In the case of the 4 x 3 concentrator-PV cell array integrated within a double-glazing window, the optoelectronic gain is 3.06 at normal incidence, and the maximum power increases by a factor of 2.99. As shown in Section 3, the gain of the RACPC varies with the angle of incidence. Therefore, the angular characteristics of the concentrator-PV cell array must be considered when installing a solar window. A possibility could be to align the concentrator to the elevation of the sun that corresponds to the equinox for a particular geographical location in such a way that the angular range of the concentrator allows for light to be collected throughout the year (with the maximum variation given by the elevation of the sun at the solstices). This would also be the case when the RACPC-PV cell array is incorporated into skylights and double-skin façades. The wide field-of-view (FOV) on the perpendicular plane of the concentrator caters for variations of the sun position throughout the day.

Whilst the optoelectronic gain of the RACPC could be made higher by changing the design, this is not necessarily desirable as an increase in irradiance increases the temperature of the PV cell, which reduces its efficiency. Moreover, an increase in optoelectronic gain would have to be achieved at the expense of the acceptance angle, which would reduce the number of hours over which the concentrator can provide gain. In any case, the ideal optoelectronic gain value would have to be defined for a particular geographical location, and the specific FOV of the concentrator could be fine-tuned. The design algorithm of the RACPC is flexible and allows the design of other geometries (e.g. geometries that correspond to acceptance angles different to the ones used for the concentrator presented here) by selecting other input variables.

The RACPC geometry gives the possibility to injection mould concentrator arrays with the entrance aperture forming part of the first layer of a double glazing window. This reduces fabrication costs as incorporating individual concentrators within a solar window is a labour intensive process. The specific cost reduction in the fabrication process from reduction in labour time depends on the place of fabrication and the size of the concentrator array manufactured from a single tool.

Acknowledgements

This project is funded by Glasgow Caledonian University (GCU), the Energy Technology Partnership (ETP) and Majlis Amanah Rakyat (MARA). Thanks are due to Robert Tierney from Windows Plus Ltd. and to Martin Blore from Strathclyde Insulation Glass for contributing to integrate the solar windows. Thanks are due to Bole Solutions for the manufacturing of the concentrators. Thanks are also due to the technicians of the School of Engineering and Built Environment of GCU in particular to Colin Russel for helping with the integration of the optical concentrators and the solar PV cells on the glass substrate.

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