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Performance analysis of a dielectric based 3D building integrated concentrating photovoltaic system

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Abstract

The use of concentrating photovoltaic systems (CPV) in building integration has spurred towards the development of newer products, which have the potential to offer the convenience of pleasing architecture and day lighting along with simultaneous production of clean energy. This paper addresses the energy transformations and the expected energy output of a low concentrating photovoltaic system designed to have a geometric concentration of 3.6×. The optical element used is a three dimensional Cross Compound Concentrator (3DCCPC) made from clear polyurethane material. Small sized silicon solar cells based on the Laser Grooved Buried Contact (LGBC) technology having an absorber area of 1 cm^2 are utilised in the system. Both experimental and numerical analyses are performed confirming the optical, electrical and thermal performance of the system. While performing the optical analysis the concentrator was found to have a maximum optical efficiency of 73.4%. A maximum power ratio of 2.67 was observed when comparing the electrical output of the concentrator unit with a non-concentrating counterpart. The effects of non-uniformity caused by the use of the concentrator are analysed. The non-uniformity of flux distribution showed an average drop of 2.2% in the I_{sc} values which is again reflected in the overall power output. Manufacturing defects like the cell and concentrator misalignments are addressed and their impact on the overall performance are verified by numerical simulations. The operating temperature of the solar cells was found to have a parasitic effect on the overall performance of the system. A maximum temperature of 332 K was observed in the solar cell at 0° incidence and a incoming radiation of 1000 W/m^2 which brings down the overall power production by 14.6%. Finally, the expected system output over a given time period is presented showing the strengths and weakness while employing such a system.

Keywords: 3DCCPC; Non-uniform; CPV; BiCPV; CPC

1. Introduction

The rising energy prices and climate change have spurred the renewable energy revolution across the globe, driving us towards self-sustaining energy resources and the technology to harness it. Solar energy has proven to be one such potential alternative energy resource, which can be used for meeting our energy demands. The energy from the sun can be directly converted into electricity by the use of photovoltaic (PV) technology. According to a report by the International Energy Agency (Lausten, 2008) buildings consume more than 40% of world's energy. The adoption of PV technology in residential applications has seen an increasing trend for its application in the last few years. Starting with simple PV panels the industry is now moving towards Building integrated photovoltaics

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(BIPV) systems. These systems are designed to integrate PV systems seamlessly into structural elements of the buildings, making them a functional part of the building architecture. Such systems include semi transparent facades (Park et al., 2010), glass ceilings (Hughes, 2009), clay solar tiles (Magazine, 2010), thin films (Yoon et al., 2011) and Sphelar® cells (Biancardo et al., 2007). A review of some of the notable solutions are presented under (Petter Jelle et al., 2012) addressing their satisfactory appearance and high efficiencies with good weather stability. These systems however have huge costs associated with them making them less feasible for general applications.

Concentrating sunlight and focusing it on smaller sized cells can be sought as a viable solution in reducing the use of expensive solar cell materials for niche application as building fenestrations. Further, integrating these systems in our existing building structural elements could prosper the technology and increase its usage. Such applications can be categorised as Building integrated concentrating photovoltaic (BICPV) systems, which can prove to be the right solution towards sustainable modern buildings. These applications will help in having an optimised day lighting and simultaneous energy production, bringing efficient buildings closer to reality. Using the principle of concentrating sunlight reduces the amount of solar cell material required and makes it more cost effective. Integrating the structural elements like windows, facades, sky lighting, cladding, curtain wall, etc. with concentrating photovoltaic technology further adds prospects of an entirely new market in its own. Only a few of such applications have been developed across the world over the last decade (Zacharopoulos et al., 2000) (Nilsson et al., 2007; Tripanagnostopoulos et al., 2007), some of the recent developments have been reviewed (Chemisana, 2011). Few other developments very recently undertaken by our research group can be found under (Baig et al., 2012a,b; Sarmah et al., 2011; Mammo et al., 2013; Sellami et al., 2012; Sellami et al., 2011a,b,c; Baig et al., 2013). A new concept of integrating concentrating photovoltaics has been recently demonstrated by (Mammo et al., 2013), where a reflective type three dimensional compound parabolic concentrator (3D CCPC PV) was used as the optical concentrating element. The system maximum power output was found to be three times that of the similar kind of non-concentrator system with maximum electrical conversion efficiency of 14%. A 3D static concentrator called the square elliptical hyperboloid (SEH) with 4× was presented recently (Sellami et al., 2011a,b,c), this system was built using dielectric material and worked on the concept of total internal reflection. The system was found to have an optical efficiency of 40% with a wider acceptance angle equalling 120° thus enabling the sunlight capture all day from both direct and diffuse radiations. A similar system but with variable heights is presented under (Sellami and Mallick, 2012) recently. A two dimensional linear asymmetric CPC system based on dielectric concentrator was analysed by (Sarmah et al., 2011; Baig et al., 2013) the system has a concentration ratio of 2.8 capable of having maximum power ratios of 2.27. A system based on see-through prism CPV module for window integrated photovoltaics was analysed by (Yamada et al., 2011). This system generates approximately 1.15 times more electricity than a conventional module while operating with 63% less solar cell area. Other systems based on CPV/T concepts having a CR > 2.5× were addressed by (Tripanagnostopoulos et al., 2009) in which the thermal and PV module work together or separately with and without tracking mechanisms.

The current study brings forward a dielectric based three dimensional cross compound CPC (3DCCPC) with square entry and exit aperture. Earlier work on a reflecting type 3DCCPC may be found under (Mammo et al., 2013). This work introduces a refractive system using similar design features. The three dimensional shape is attained by sweeping the 2DCPC over a square profile. In this work, a refractive based prototype of the system is designed, manufactured and analysed both experimentally and numerically. Use of ray trace method is made to carry out the optical analysis of the concentrating element and finite element methods are applied to carry out the electrical and thermal analysis of the system. Results obtained are validated experimentally and the gaps highlighted.

2. System description

The system under study essentially consists of a concentrator element, an encapsulation material and a solar cell essentially placed between two glass sheets.

2.1. Concentrator

The concept of the compound parabolic concentrator (CPC) has been utilised in numerous solar energy applications including both thermal and photovoltaics. The concentrator element used in our study is a dielectric material based Three Dimensional Cross Compound Parabolic Concentrator (3DCCPC). The three dimensional design allows light to be concentrated in all the directions via total internal reflection. The concentrator geometry was designed by simply sweeping a segment of parabola about a square cross section as shown in Fig. 1. The details on the equations of the parabolic segment of the CPC can be found under (Sellami and Mallick, 2013) and (O'Gallagher, 2008). The refraction on its front air and dielectric interface allows having better external acceptance angle. The system is desired to have a concentration ratio (C) of 4×, using the following equation:

$$C = \left[\frac{n_R}{\mathrm{Sin}(\theta_a)}\right]^2 \tag{1}$$

The system half acceptance angle (θ_a) is found to be 48.5° for a refractive index (n_R) of 1.5, entry side of 20 mm and a height of 25.9 mm. However this is truncated by almost 37.6% to get a truncated height of 16.16 mm and