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Impact of shading on a flat CPV system for façade integration

L.A.A. Bunthof[a,*], F.P.M. Kreuwel[b], A. Kaldenhoven[a], S. Kin[b], W.H.M. Corbeek[a], G.J. Bauhuis[a], E. Vlieg[a], J.J. Schermer[a]

[a] Radboud University, Institute for Molecules and Materials, Applied Materials Science, Heyendaalseweg 135, 6525 AJ Nijmegen, The Netherlands
[b] Wellsun, Molengraafsingel 12, 2629 JD Delft, The Netherlands

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ABSTRACT

Recently adopted energy efficiency policies in the EU induce a movement towards energy-neutral buildings. Building integrated photovoltaics technology connects with this ambition, as aside from the generation of electrical energy, it allows additional benefits such as heat generation, or daylight regulation by transmission of diffuse sunlight through transparent parts of the system. In this study three Concentrator Photovoltaic (CPV) system configurations that allow for the construction of semi-transparent building façade elements are investigated outdoor. The systems are a Fresnel lens based concentrator, a novel flat planar optic concentrator, and a 4×4 panel of these flat optics. The flat optic has no air cavity to account for optical focal depth which is highly beneficial when incorporated in a window. In particular the energy production of the systems when partially shaded is investigated, as adjoining systems will move behind one another during sun tracking, because the optics spacing must be small to achieve good daylight regulation. The planar optic concentrator is found to display similar performance as a Fresnel lens based concentrator of similar concentration. For a multi-receiver panel, shading introduces a loss of performance ranging from 7% to 12% which is attributed to electrical interconnection as individual receivers do not suffer this loss.

1. Introduction

Forty per cent of the European energy consumption is attributed to buildings (Parliament, 2010). The European Union actively adopts energy efficiency policies to reduce this amount and has defined in the Directive on the Energy Performance of Buildings the "20-20-20" objectives: 20% decrease in greenhouse gas emissions, 20% share of renewable energy and 20% improvement in energy efficiency by 2020. Building-Integrated Photovoltaic (BIPV) systems address these goals perfectly. Among BIPV technologies, Building-Integrated Concentrating Photovoltaic (BICPV) systems possess additional features that make them particularly interesting for building integration, such as the possibility of heat generation (Gomes et al., 2014), or daylight regulation (Yamada et al., 2011). Also the replacement of expensive semi-conductor cell area by cheaper and more environmentally friendly concentrating optics can make for a more viable system in terms of both cost and environment (Chemisana, 2011). On the other hand it should be noted that the light-to-electricity efficiency is generally smaller for BICPV systems because of optical losses, uncollected diffuse irradiation, etc. However, in the particular case of window integrated CPV, this uncollected insolation can be transmitted inside, providing natural lighting while converting the blinding direct component into electricity. In recent years, there has been an increase in BICPV for integration in either the roof or the façade. Chen et al. designed a diffusive solar cell window which transfers solar radiation to solar cells at the edge of the window (Chen et al., 2012). Aste et al. show a new generation luminescent solar concentrator (LSC) for façade integration. They show a better energy performance ratio for the LSC compared with standard PV modules (Aste et al., 2015). Gomes et al. studied shading in asymmetric Photovoltaic Thermal (PVT) collectors caused by oblique solar angles and found that impact by shading can be reduced by transparent end gables, as well as by reducing the cell area (Gomes et al., 2014). Sharma and Mallick discuss a dielectric compound parabolic concentrator suited for building integration in higher latitude locations. Real time outdoor performance of the concentrator is compared to a non concentrating flat plate and the souperior output power of the concentrator is shown both for sunny and rainy days (Sarmah and Mallick, 2015). Zacharopoulos et al. have shown that at higher sun tilt angles, non-imaging dielectric linear concentrators for façade integration collects far more solar radiation than a flat plate PV of the same area (Zacharopoulos et al., 2000). Baig et al. discuss several low

* Corresponding author.
E-mail address: L.Bunthof@science.ru.nl (L.A.A. Bunthof).

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concentration systems for building integration. Emphasis is placed on non-uniformity in illumination and temperature across the PV as well as detailed modeling and performance analysis of the systems (Baig, 2015; Baig et al., 2014, 2015). Chemisana et al. designed a holographic concentrator for building integration that protects the solar cell from overheating as the infrared is not concentrated in this setup. They find that the use of the concentrator increases the efficiency of the PV cell by 3%. Also they designed a façade integrated PVT collector based on two reflecting strips and stationary PV. They show the increased performance of this system compared to reference (Chemisana et al., 2013, 2016). Voarino et al. introduce a CPVT system for roof integration that relies on a prism combined with a parabolic mirror that rotate separately to track the sun instead of using a heavy and bulky tracking system (Voarino et al., 2014). Many of these systems are designed to be stationary with low concentration, while others are designed for high concentration. Higher concentration systems have a low acceptance angle, thus are more restrictive towards the use of the diffuse part of the insolation and often require sun-tracking to function properly, yet they also offer the greatest reduction in cell area which allows for good cost-efficiency. Additionally, because the bright direct fraction of light is concentrated to the PV while diffusive light is not concentrated in high concentration setups (as detailed in Fig. 1), these offer the best opportunity to include a daylight regulation functionality, which will be the focus of the systems discussed in this work.

In this paper we study the concept of incorporating CPV into a building façade to act primarily as a window with an incorporated daylight regulation functionality, as well as a source of energy. This concept entails the removal of the harsh direct illumination by the system to be converted into energy, while allowing natural lighting of the building interior, as diffuse light passes through transparent parts of the system. Three model CPV systems are considered in this context. Firstly a common Fresnel based system with a triple junction (TJ) cell having a geometric concentration factor of 100. Secondly, a novel planar optic based high concentration receiver which relies on internal reflections to guide direct sunlight to an integrated TJ cell (Morgan et al., 2014–2015). The prime benefit of this receiver for BICPV is that it is flat and does not feature an air cavity to account for optical focal depth, as opposed to a Fresnel lens based system. The receiver has a high geometrical concentration factor of 920; we will show that in practice, the actual concentration factor typically exceeds 600. Therefore this system has the potential for much higher electrical output than existing BIPV systems that typically do not exceed concentration factors of 50, whilst also providing daylight regulation functionality. Finally a 4×4 panel of these receivers is considered. As for all high concentration PV applications, precise tracking of the sun is required (Andreev and Luque, 2007; Luque-Heredia et al., 2012), as the optic of these systems is designed to transfer direct illumination to a small high-efficiency TJ III/V solar cell. Such cells are currently mainly used for spacecraft applications but with the development of the Epitaxial Lift-Off process, the high purity semiconductor wafers that are required to produce these cells can be reused after separation of a single or even multiple cell structures (Bauhuis et al., 2010; Voncken et al., 2004; Yoon et al., 2010). This allows for a significant cost reduction, increasing the utilization potential of these cells in other application areas such as CPV systems or high-end consumer products.

In ground-based CPV, systems are usually spaced far apart to avoid overlap (Rodrigo et al., 2013a, 2015). However, when daylight regulation functionality is wanted, all harsh sunlight should be filtered at any time of the day. Thus individual CPV receivers must be in close proximity to each other. In this case adjoining panels will partially slide behind one another during tracking as further detailed in Fig. 5, so each panel casts a shadow on the one behind it. Therefore in this work, the electrical power generation of the three above mentioned CPV systems is studied in detail using outdoor measurements, while partial shading of the systems is applied. Furthermore, a parallel and series interconnection scheme of a multi-receiver system may have implications for the system tracking (Morgan et al., 2014–2015). For that reason we propagate the shading along the x and y axis across the surface of the systems, to deconvolute any non identical effects on the systems electrical performance this entails.

2. Experimental

2.1. Device description

The first device under test, shown in Fig. 2 features a $10\,\text{cm} \times 10\,\text{cm}$ Fresnel lens made of PMMA as a concentrating optic, which has a focal depth of 10 cm. A $10\,\text{mm} \times 10\,\text{mm}$ TJ cell mounted on a ceramic printed circuit board (PCB) and equipped with a bypass diode is placed in the lens' focal point, giving the system a geometric concentration factor of 100.

Secondly a planar optic receiver is investigated, which consists of a $4\,\text{cm} \times 4\,\text{cm}$ planar focusing optic, a $1.3\,\text{mm} \times 1.3\,\text{mm}$ TJ III/V cell, a bypass diode, a copper heat sink and integrated wiring (Morgan et al., 2014–2015). The benefit of using this type of receiver compared to more regular optics is that the optical system does not have an air cavity to account for the focal distance of the optics and thus is flat. This significantly enlarges its potential for utilization in building-integrated systems. The receiver has been described elsewhere (Morgan et al., 2014–2015) and will not be further detailed here. The receiver has a high geometrical concentration factor of 920.

Finally a 16 receiver panel of these planar optics is investigated, which is shown in Fig. 3. It consists of a 4×4 array of planar optic receivers with integrated solar cell assembly, which are interconnected in 4 parallel strings that are in turn connected in series. In application, multiple panels will be enclosed in a transparent glass enclosure. Fig. 5 shows a schematic representation of such a setup consisting of nine panels with w and h the width and height of a panel respectively, and d_{hor} and d_{vert} the horizontal and vertical heart-to-heart distance between panels.[1] The system layout is optimized primarily with daylight regulation in mind, in such a way that apparent full coverage of the façade is achieved at any time during the day as a function of the sun position. Thus, if sunlight is incident perpendicular to the façade, the individual panels are located side by side, fully covering the façade without covering each other (thus $d_{hor} = w$ and $d_{vert} = h$). The system tracks the sun by tilting and rotating the individual panels. As can be seen from Fig. 5b-d, during tracking a panel may be shadowed by the building (black) or another panel (gray). The shadowing by the building around the semi-transparent system is highly dependent on the way it is incorporated in the façade and becomes less important as the system becomes increasingly larger. However, shading by adjacent panels is an intrinsic phenomenon in the above described concept. Therefore its influence on the electrical output of the system will be evaluated in detail in this study.

2.2. Measuring procedure

In order to determine the electrical energy production of the three systems, outdoor current-voltage (IV) measurements have been performed to closely approximate actual operating conditions. Aside from investigating the electrical performance of the

[1] From the figure can also be noted that in application, the system needs a space in front of the window to enable mechanical tracking.