Measured Efficiency of a Luminescent Solar Concentrator PV Module Called Leaf Roof

Angèle Reinders, *Senior Member, IEEE*, Michael G. Debije, and Alexander Rosemann

***Abstract*—A functional prototype of a luminescent solar concentrator photovoltaic (LSC PV) module, called Leaf Roof, aims at demonstrating the design features of LSC PV technologies such as coloring, transparency, and flexibility in physical shape. In this paper, the prototype is presented and the first measurements of its performance are shown. The geometrical gain of this new type of PV module is 3.6. For two types of Leaf Roof modules, *I–V* curves have been measured resulting in efficiencies of 5.8% for a red-colored PV module, and 5.5% for a green-colored PV module under similar conditions. These results demonstrate colorful, robust solar energy collectors which can be produced in a wide variety of shapes are viable, attractive devices for use in building integrated systems. Additionally, thanks to the use of poly(methyl methacrylate) (PMMA) as a cell encapsulant, the Leaf Roof modules are less susceptible to energy losses at elevated temperatures due to high irradiance and high ambient temperature conditions.**

***Index Terms*—Building integrated photovoltaic (PV), luminescent solar concentrator (LSC), PV module.**

I. Introduction

The functional principle of luminescent solar concentrator photovoltaics (LSC PV) was originally proposed in the late 1970s [6], [16]. An LSC is a technology for harvesting solar energy that is comprised of a transparent, thin, shaped plate acting as a lightguide with a large surface area. This lightguide consists of a transparent material with a refractive index higher than air, usually a polymer or glass, containing luminescent pigments, usually called a "dye." Photons originating from solar irradiance enter the LSC and are absorbed by dye molecules and subsequently re-emitted at longer wavelengths. A large fraction of the re-emitted radiation is trapped in the lightguide by total internal reflection (TIR) at the material's surfaces. TIR is interrupted at the interface between the lightguide and attached solar cells, where the photons are converted into electricity (see Fig. 1). To increase TIR, inwardly directed transparent reflectors are attached to the surfaces of the lightguide that are not covered by solar cells. Due to the use of a limited fraction of the total area of the lightguide (namely, the edges), the efficiency of LSC PV elements is at present significantly lower than other PV technologies. The world record efficiency for LSC PV in a lab setting is 7.1%, currently held by ECN in the Netherlands ([7]; Slooff *et al*. [13]), and the theoretically expected efficiency for LSC PV devices is in range of 10% [11], [12]. However, in real-life applications, the efficiency of LSCs is usually in the order of 3–4%, see Table I for a comparison of various LSC PV concepts. In this brief communication, a new type of LSC PV module, called Leaf Roof, is presented which resulted in a visually attractive design with a higher efficiency measured under standard test conditions (STC) than achieved so far for other real-life applications.

In general, LSC PV modules have other advantages apart from aspects related to energy performance, such as enhanced aesthetics via the possibility of customizing coloring, transparency, shape, and surface texture of the plastic LSC PV modules. These aspects will create interesting opportunities for building integration of PV technologies that will be appreciated

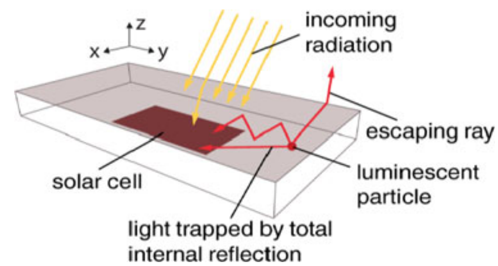

Fig. 1. Working principle of an LSC PV element.

TABLE I
Specifications of Selected LSC PV Devices Reported in the Literature

Author (date)	η_{STC} (%)	PV Cells	Location of cells	LSC size (cm)	Dye
Slooff *et al.* [13]	7.1	GaAs	Edges	$5 \times 5 \times 0.5$	Red305, CRS040
Atse (2015)	1.3	silicon	Edges	$50 \times 50 \times 6$	DTB, DPA
Desmet *et al.* [4]	4.2	silicon	Edges	$5 \times 5 \times 0.5$	Red 305, perylene perinone
Corrado *et al.* [2]	3.4	silicon	Back	63×163	Red 305
Corrado *et al.* [1]	6.2*	silicon	Back	31.5×5	Red305

*This efficiency has not been measured under STC.

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A. Reinders is with ARISE and the Department of Design, Production and Management, Faculty of Engineering Technology, University of Twente, Enschede 7522 NB, The Netherlands (e-mail: a.h.m.e.reinders@utwente.nl).

M. G. Debije is with Functional Organic Materials and Devices, Department of Chemical Engineering & Chemistry, Eindhoven University of Technology, Eindhoven 5612 AZ, The Netherlands (e-mail: m.g.debije@tue.nl).

A. Rosemann is with Building Physics and Services, Department of the Built Environment, Eindhoven University of Technology, Eindhoven 5612 AZ, The Netherlands (e-mail: a.l.p.rosemann@tue.nl).

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by architects. Particularly in the framework of building integrated PV, architects have a large impact on what does and does not go on the building envelope. With this in mind, with the Leaf Roof module, we try to link the technical possibilities of LSC PV modules to their market applicability.

Furthermore, there are practical considerations. Namely, in situations where maximum electrical efficiency in a minimum area are desired, silicon (or other technologies) PV modules are most appropriate. However, in locations where it is inappropriate or outright impossible to deploy standard solar panels, the usage of LSC PV modules could be actually preferred to silicon PV modules. Such locations include, but are not limited to, shady locations, North walls of buildings, and noise barriers [8], [9] where complete transparency is desired, street-level installations where appearance and robustness are required, or where space is not at a priority. Their relative insensitivity to solar conditions [3] could make LSC PV modules ideal for integration into locations such as bus stop shelters, sound barrier walls, park benches, and other urban applications.

II. LSC PV Module Leaf Roof

Traditionally, the LSC is a flat, rectangular sheet through which dye-emitted light is guided to small strips of PV cells attached to edges of the lightguide. Recently, however, new approaches [2], [10], [15] are being explored in which PV cells are attached to the back side of the lightguide, see Fig. 1, instead of to the edges. By this approach, the conversion efficiency of PV cells can be effective for a larger area than that of the edges only, as well as reduce the path length that emitted light must travel to reach a cell, thus reducing reabsorption losses. Additional steps are taken to modify the contour of flat sheet lightguides and to shape the sheet material by bending it [14], [15] to increase the design freedom and hence stimulate the applicability of LSC PV elements in product surfaces and for use in building added—or integrated—PV systems.

For the design of the LSC PV module called Leaf Roof, the primary goal is creating an attractive solar collection surface which creates a visually appealing interplay between colorful downshifting LSC surface area and front facing, direct sun processing PV cells. With an eye on performance, various cell configurations have been evaluated with regard to their efficiency by numerical simulations [5], [10] using various concentrations of dyes from the Lumogen series by BASF and different contours and thicknesses for the PMMA lightguide. These results will enable the application of LSC PV modules in a number of shapes and colors and therefore provide design freedom to architects. The final design consists of a rhombic tile configuration, see Fig. 2, comprised of six PV cells with a customized size of 52 cm^2 [resulting from cutting complete C60 PV cells (GEN C BIN J) from Sunpower with a 22.5% efficiency under STC in three slices]. The total area covered by PV cells is, therefore, 0.0304 m^2. Table II shows the effect of cutting these cells in three slices based on information from the datasheets of the manufacturer.

The present prototypes of the LSC PV Leaf Roof module consist of a 5 mm thick LSC PMMA lightguide containing 80 ppm of either Lumogen F red 305 dye or green 850 dye. To complete the module, a metallic back reflector made from copper is applied. The total area of the front surface of the Leaf Roof element is 0.11 m^2, leading to a geometrical gain of 3.6 or (an LSC coverage of 72%). Based on information shown in Table I, the theoretical efficiency will be 6.2% with I_{mpp} of 1.97 A and V_{mpp} of 3.49 V, without encapsulation combined with a PMMA lightguide.

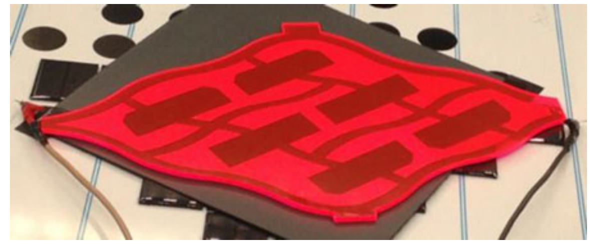

Fig. 2. Prototype of a recently developed new design for LSC PV elements, entitled Leaf Roof [10].

TABLE II
Specifications of PV Cells in Leaf Roof PV Elements Based on Spec Sheets of Sunpower C60 Cells

Sort of PV cell	P_{mpp} (W)	η_{STC} (%)	V_{mpp} (V)	I_{mpp} (A)	V_{oc} (V)	I_{sc} (A)
Complete cell	3.42	22.5	0.582	5.93	0.687	6.28
Cut in 3 by laser cutting	1.14	22.5	0.582	1.97	0.687	2.03

Fig. 3. Leaf Roof configuration showing various color panels: photograph taken at the Dutch Design Week in 2015.

III. Measurements

I–V curves of the Leaf Roof modules were measured in October 2016 by Spire using a Spi-Sun Simulator 3500 SLP at standard test conditions of 1000 W/ m^2, a module temperature of 25 °C, and an AM1.5 spectrum. The resulting curves for a Leaf Roof module with either a red or a green Lumogen dye (each with a concentration of 80 ppm) are shown in Fig. 4. P_{mpp} of the red and green modules are, respectively, 6.37 and 6.08 W, resulting in efficiencies of, respectively, 5.8% and 5.5%. These values are high compared to the existing record of 3.8% by Corrado *et al.*, see also Table I.

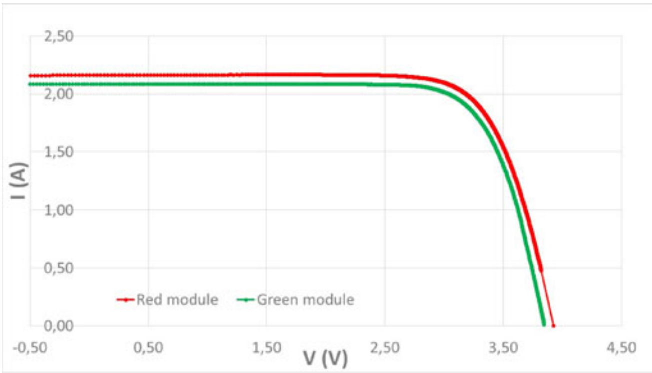

Fig. 4. *I–V* curves of a red and green LSC PV Leaf Roof modules.

TABLE III
SPECIFICATIONS OF MEASUREMENT EQUIPMENT

Variable	Equipment
Spectral distribution of global irradiance, 30° in plane	Grating Spectroradiometer, vis–NIR MS700, EKO Instruments
Horizontal global irradiance	Pyranometer CMP 11, Kipp&Zonen
30° in plane global irradiance	Pyranometer CMP 11, Kipp&Zonen
30° in plane irradiance	Reference cell, Mencke and Tegtmeyer
Wind speed	Anemometer, Theodor Friedrichs
Ambient temperature	Temperature sensor with Pt 100 element, Theodor Friedrichs
Short-circuit current	Shunt resistance
Open-circuit voltage	Shunt resistance
Module temperature	Two thermocouples per module

For the red module, I_{mpp} is 3% higher than bare PV cells that do not have a cover by a PMMA lightguide (see Table I), resulting in I_{mpp} of 2.03 A.

This result deviates from the expected increase currently predicted by simulations with the optical raytracing software LightTools. Namely, under an AM1.5 spectrum with 70% direct beam irradiance and 30% diffuse irradiance, the expected net incident solar irradiance on PV cells covered with a 5 mm thick PMMA sheet with 80 ppm of Lumogen F red 305 dye would be 17% higher than irradiance received by bare PV cells under similar conditions. The difference between 17% and 3% could be explained by, among others, the effect of laser cutting of the solar cells. According to the simulations, in the case of uncolored PMMA sheets, these cells would receive 5% more irradiance. Also, V_{mpp} of 3.14 V is 10% lower than expected. For the green module, V_{oc} has a value 3.85 V and for the red module, the extrapolated V_{oc} has a value of 3.93 V. This could be due to an increased series resistance caused by interconnects between the PV cells in this prototype. With this in mind, in future prototype development, it will be very important to consider appropriate designs for the reduction of series resistance

The red LSC PV module was also tested outdoors in a test bench for six PV modules at the University of Twente for a short period of time. The measurement setup comprises data acquisition equipment for one-minute recording of meteorological variables, module current, and voltage and module temperatures by a datalogger CR1000. Table III shows the specifications of the measurement equipment.

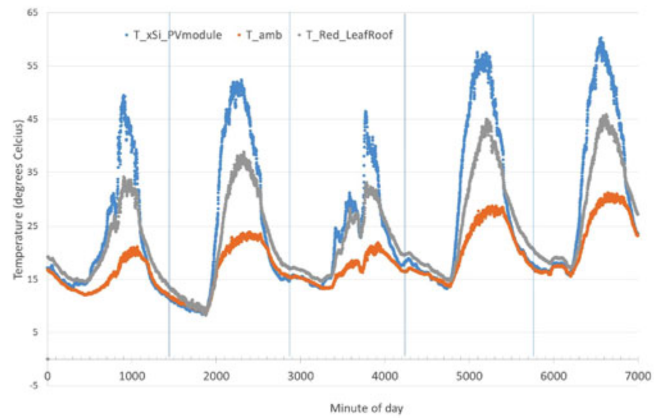

Fig. 5. Temperatures measured from September 9 to 13, 2016, at the PV test bench at the University of Twente, The Netherlands, blue: temperature of crystalline glass-sheet based PV module, gray: temperature of red LSC PV module, and orange: ambient temperature.

The results of temperature measurements which took place on the backside of the Leaf Roof modules in a relatively hot and sunny period in September 2016 are presented in Fig. 5. The results show a large difference between the temperature of a reference PV module, containing crystalline solar cells in a conventional glass-sheet PV module design, and the LSC PV module. Where a conventional PV module reaches a maximum temperature between 48 °C and 60 °C during a day, the temperature of an LSC PV module stays below 45 °C. With a temperature coefficient for crystalline solar cells for their power of −0.4% per °C, this temperature difference of 15 °C can result in a 6% higher yield for LSC PV modules compared to the conventional PV modules under the same high irradiance conditions of 880 $\mathrm{W/m^2}$ and an ambient temperature of 30 °C at a very low wind speed of 0.9 m/s. Basically, this different temperature behavior can be explained by two aspects. On the one hand, the properties of the dye that downshift the irradiance that is absorbed by the PV cells to energy levels close to the band gap will lead to less "waste" energy, in the form of heat, originating from the generation of electron hole pairs. On the other hand, PMMA is a material that absorbs and releases heat at a slower rate than glass, due to the difference between thermal conductivity of glass (typically ranging from 0.8 to 1.0 W/mK) and the thermal conductivity of PMMA, which is between 0.17 and 0.20 W/mK. These results support previous work [17] which studied the effect of cell positioning on polymer lightguides.

IV. CONCLUSION

We have demonstrated that large-scale LSCs of interesting physical shape and pleasant colors can be produced that maintain a reasonable geometrical gain and a high efficiency while simultaneously providing aesthetic design advantages. Moreover, temperature measurements indicate that LSC PV modules maintain lower temperatures than the conventional glass-sheet-based PV modules containing crystalline solar cells under similar irradiance and ambient temperatures. This will be favorable to the electricity production of crystalline solar cells under high irradiance and high ambient temperatures. As such, thermal properties of PMMA covered PV modules would be an interesting topic for extensive future research. Further performance improvements can be realized by reducing the series resistance between cell interconnects and optimizing the lightguides, both in shape as well as dye concentrations and cell positioning. This will be done in subsequent research and development of Leaf Roof LSC PV modules.

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Angèle Reinders (SM'17) studied physics and received the Ph.D. degree in chemistry from Utrecht University, Utrecht, The Netherlands, in 1999.

She is an Associate Professor in ARISE, Faculty of Engineering Technology, University of Twente, Enschede, The Netherlands, and a Visiting Professor in energy-efficient design with Delft University of Technology, Delft, The Netherlands. She did research in the USA, Canada, Indonesia, Italy, and Germany on PV systems and smart grids. She has published more than 100 papers and edited two books. Her current design-driven research focuses on applications of solar technologies in products, buildings, and local infrastructures.

Michael G. Debije received the degree in biophysics from the University of Rochester, Rochester, NY, USA, in 2000.

He is an Assistant Professor in the Group Functional Organic Materials and Devices, Department of Chemical Engineering and Chemistry, Eindhoven University of Technology, Eindhoven, The Netherlands. He has been an active worker and promoter of the luminescent solar concentrator devices for more than a decade. His current main topic of research is light control in the built environment.

Alexander Rosemann studied electrical engineering and received the Doctorate and Habilitation degrees from the Technical University of Berlin, Berlin, Germany, in 2001 and 2007, respectively.

He is a Full Professor and chairholder of Building Lighting in the Department of the Built Environment, Eindhoven University of Technology, Eindhoven, The Netherlands. Before his appointment as a Professor, he worked for an electrical utility in North America where his responsibilities included the advancement of energy efficiency policies, codes, and standards on municipal, provincial, and federal level.

Dr. Rosemann is currently a board member of de Nederlandse Stichting voor de Verlichtingskunde and contributes to work groups of several lighting associations (CIE, IES, and LiTG).