A comparison of performance of flat and bent photovoltaic luminescent solar concentrators

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Abstract

To employ new solar photovoltaic technologies in products and buildings, many systems need to be adapted. Inspired by the cylindrical shape, in this work we have evaluated the performance of luminescent solar concentrator photovoltaic (LSC-PV) elements with narrow PV cell strips that could be integrated in an outdoor lighting pole. Silicon photovoltaic (PV) cells were attached to the back of both flat and cylindrically bent PMMA lightguide sheets containing the dye Lumogen Red 305, and mirrors to non-covered edges of the light guides. The energy performance of these two elements was measured. The flat and bent LSC-PV elements were also simulated using optical modeling and the resulting performance parameters from simulations and experiments were compared. From simulations for a flat LSC-PV, the optical collection efficiency, concentration and electrical conversion efficiencies were found to be 18%, 1.8% and 2.8%, respectively, for a geometric gain of 10. For a bent LSC-PV shape, the respective values are 21%, 1.4% and 3.4% for a geometric gain of 6.7. Due to reduced sensitivity to the angular dependence of incoming irradiance it is expected that these bent LSC-PV elements would perform well on both sunny and cloudy days.

Keywords: Luminescent solar concentrators; Silicon PV; Product integrated PV; Solar-powered street lighting

1. Introduction

Solar energy harvesting using luminescent solar concentrator photovoltaic (LSC-PV) modules was originally proposed in the late 1970s (Goetzberger and Greubel, 1977; Weber and Lambe, 1976). In an LSC, sunlight penetrates the top surface of a lightguide made from inexpensive plastic or glass. The light is absorbed by luminescent materials, which are either embedded in the lightguide or applied in a separate layer on top and/or bottom of the lightguide. The luminescent materials can be organic fluorescent dyes, inorganic phosphors or quantum dots. The absorbed light is re-emitted at longer wavelengths, and a fraction of the re-emitted light is trapped in the higher refractive index lightguide by total internal reflection. The emitted light is guided to small PV cells attached to edges of the lightguide where it is converted into electricity. While the efficiency of

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the device compared with a bare solar cell array is modest, the LSC-PV is an attractive technology for use in consumer products or the built environment: the lightguide elements may be colorful and manufactured in a variety of sizes, the device performs well under both direct and indirect light, and could generally be employed anywhere plastic and are glass sheets are currently being used but now providing the element the additional function of electrical power generation (De Boer et al., 2012; Debije and Verbunt, 2012). In recent work on LSC-PVs, Philips Research has reported an efficiency of 4.2% for LSCs of 50 x 50 mm² which is considered to be a record for Si-based LSCs (Desmet et al., 2012).

Considerable experience exists in product integrated photovoltaics (PIPV) (Reinders, 2012). In general it is assumed that to be able to use solar PV technologies in products or buildings, the PV cells often need to be adapted to the application (Reinders et al., 2013). Experiences with LSC-PV in a product context are limited and design issues with this PV technology may be different than with conventional solar cells in PIPV (Apostolou and Reinders, 2014). In particular, geometric modifications and efficiency (Bose et al., 2009; Chatten et al., 2011; Corrado et al., 2013; Inman et al., 2011; McIntosh et al., 2007; Pravettoni et al., 2009) play a role with regards to product-integrated LSC-PV. To evaluate these aspects (Viswanathan et al., 2012), this paper explores the effect of integration on the energy performance of LSC-PV in a light pole for outdoor lighting, like the one shown in Fig. 1, using both experiments and modeling. Due to the pole’s cylindrical shape, we adjusted the conventional flat design of LSC-PV elements to a new structure.

Specifically, the PV cells have been moved from the edges to the back of a LSC-PV element (Corrado et al., 2013), which is a new location compared to conventional flat LSC-PV elements, mirrors have been placed on the non-covered edges, a diffuser reflective sheet made of micro cellular polyethylene terephthalate (MCPET) has been attached at the back of the LSC lightguide (in between the cells), and the shape has been altered from flat to a (half-)bent cylindrical LSC-PV. The device structure is illustrated by Fig. 2.

2. Experimental

As luminescent light guides we use 3 mm thick polymethylmethacrylate (PMMA) plates purchased from Evonik (PLEXIGLAS Fluorescent Bright Red 3C02 GT) containing approximately 200 ppm of the dye Lumogen F Red 305 (BASF) with absorbance >99% at 575 nm (and

Fig. 1. Left: an existing solar street-lighting pole with conventional flat-plate PV modules, right: a street-lighting pole with integrated bent LSC-PV elements.
91% transmission outside the absorption band); see Fig. 3 for the absorption and emission spectra. The measured quantum efficiency of this dye is 0.95. We made a 100 × 100 mm² flat prototype (Desmet et al., 2012) and a 157 × 100 mm² bent prototype, the latter formed by shaping the material on a mould at ca. 110 °C. Silicon PV cells were mounted to the bottom of each lightguide, as shown in Fig. 4a and b. Note that in the case of the flat sheet, the PV cells alone without the PMMA plate would cover 10% of the area and hence the effective efficiency would be 1.6%. All edges of the light guides are covered with 3M Vikuiti Enhanced Specular Reflector (ESR) foil (>98% reflectance). At the bottom of the LSC we used a Furukawa Electric MCPET diffuse reflector with 99% reflectance separated by an air gap to recycle escaped light (De Boer et al., 2012).

The experimental set-up used for photovoltaic measurements is shown in Fig. 5. In this set-up, the electrical performance of the samples is measured while illuminated by a halogen lamp source with a color temperature of 3300 K and an irradiance of 520 W/m². Previously (De Boer et al., 2012) it was found that solar cell efficiencies measured in this experimental set-up can differ up to 10% relatively from those obtained with a solar simulator. Two types of spectral measurement experiments were carried out on different LSC-PV shapes. In the first, the light was incident at 0 degrees. In the second, a rotational stage was used to vary the incidence angle from −60 to +60 degrees. The latter experiment enables predictions about performance at diffuse illumination.

The experimental set-up yielded details such as the bare-cell efficiency of the PV cells, efficiency of the LSC-PV elements, optical collection efficiency and concentration of LSC-PV shapes. Efficiency (η) is defined as the electrical power obtained from the PV cells attached to the LSC as
a fraction of the incident irradiance on the LSC surface. *Bare-cell efficiency* \( (\eta_0) \) means the electrical power obtained from the directly illuminated PV cell before attachment to the light guide as a fraction of the incident irradiance. *Collection probability* or *optical collection efficiency* \( (P) \) means the ratio of photons reaching the surfaces of the PV cells to those incident on the (total) LSC surface. This is related to the above-defined efficiencies as: \( P = \eta/\eta_0 \). *Geometric gain* \( (G) \) means the ratio of the total (projected) illuminated lightguide surface area and the PV cell surface area present in the LSC. *Concentration* \( (C) \) means the ratio between outgoing and incoming optical irradiance of the concentrator: \( C = PG \). In general, LSC-PV modules having concentration values sufficiently above 1 are preferred for use in electricity generation. The relative error in the measurements is in the order of 10% due to spectrally distributed deviations between the irradiance at standard test conditions (at 1000 W/m\(^2\) and AM1.5) and irradiance during measurements of the efficiency \( \eta \) in the experimental set-up described above containing a halogen lamp. This error progresses in the simulations which we will describe in the following section.

3. Optical modeling by ray-tracing simulations

Optical modeling techniques are widely used to determine the optical collection of LSC-PV modules (Spencer and Murty, 1962). A three-dimensional model was built employing ray tracing to model the effect of several design parameters on the collection efficiency of the LSC-PV...
modules. In this way, one can optimize device properties, analyze results, compare with experiments and study parameters important for prototype improvement.

In this research, LightTools® ray-tracing software has been used for building the optical models. The models were built to mimic the experimental devices in terms of materials, sizes, shapes and concentration of dye. Sun’s rays were modeled with the AM1.5G spectrum taking into account both direct and diffuse irradiation.

The absorption spectrum of the Red 305 dye in the LSC-PV models is used to determine the probability of an absorption event of the ray (De Boer et al., 2012). The quantum yield of the fluorescent dye (i.e. the ratio of the number of photons emitted to the number of photons absorbed) provides the probability of the emission event (Zollers, 2011). When an emitted ray intersects a surface boundary, the Fresnel reflection and transmission coefficients are used to determine the reflection and transmission probabilities. In the LightTools models, \( \eta_0 \) was considered to be the experimentally measured value of 16% for the cells; this is, of course, a simplification as a real cell demonstrates variation in response with wavelength. The geometric gain \( G \) varied with the shape of the LSC-PV solar module. The simulations yield the collection probability \( P \), from which \( \eta \) and \( C \) can be derived. Three different types of LSC-PV systems were simulated, studied and analyzed as shown in Table 1: conventional flat LSC-PV modules with cells attached to the sides, flat LSC-PV modules with bottom-mounted solar cells and hollow half-bent and full-bent cylindrical LSC-PV modules with bottom-mounted cells.

The LSC lightguide geometry was first defined by fixing dimensions, positions and sizes. The material used for constructing the lightguide is defined by the refractive index \( n \). Two different shapes (flat and half bent hollow cylindrical) were used for forming the LSC lightguide using PMMA as the host material. The PV cell geometry was defined by the shape, dimension and positions of the solar cells, and the cells were taken as silicon (c-Si cells). The bare edges of the lightguide were defined as mirrors, whereas the backside diffusers were modeled as 95% reflecting surfaces. Defining the glue for attaching the PV cells forms a crucial part of the LSC-PV models. For all different LSC-PV modules, the space between the flat or bent LSC lightguide and the flat cell was filled with index-matching glue \( (n = 1.5) \).

LightTools requires a set of (measured) data such as absorption and emission spectra, mean free path (inferred from the absorption spectrum) and quantum yield of the dye as input (Zollers, 2011). The initial concentration of the Lumogen Red 305 (BASF) is the same as that used in the experimental setup using a high dye concentration. In LightTools this value of concentration of dye, 0.0025, was input as a relative value called the scale density factor. This value translates into a concentration of Lumogen Red 305 dye material of approximately 200 ppm. The emission spectrum of the dye is shown in Fig. 3.

Two different types of light sources have been modeled: a perpendicularly directed light source, i.e. direct irradiance, and a Lambertian source, i.e. diffuse irradiance. The incident light on the LSC was assumed to be an AM1.5G sun spectrum. The incident AM1.5G spectrum undergoes wavelength conversion by the Red 305 in the bulk before it reaches the PV cells. For the most efficient Lumogen concentration, almost all light with wavelengths within the absorption range of the dye (ca. 420–600 nm) is converted. The spectrum incident on the cells is similar to the emission spectrum of the Red 305 dye except that it is slightly shifted towards longer wavelengths because of re-absorption events; see Fig. 6. The type of light illumination incident on the LSC-PV demos has an effect on their optical collection efficiencies and also on the optimized dye concentrations.

The perpendicularly directed light source has been modeled in such a way that the source is an emitting surface at a certain distance from the LSC-PV combination. The Lambertian source has been modeled as a (cylindrical) surface emitting light in a half space towards the lightguide. This source resembles that of a cloudy day, whereas the perpendicularly directed source resembles that of the direct sunlight incident during peak afternoon hours.

Ray-tracing simulations were carried out in flat and bent LightTools models yielding \( P, \eta \) and \( C \), and the results were compared with experiments. The collection efficiency was

![Fig. 6. Simulated edge emission spectrum of light incident on solar cells.](image)

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Designs and shapes of LSC-PV demos LightTools.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of module</td>
<td>Dimensions</td>
</tr>
<tr>
<td>Flat LSC-PV + 2 cells attached at back + mirrors on non-covered edges</td>
<td>LSC – 100 × 100 × 3 mm, PV cells – 100 × 5 mm</td>
</tr>
<tr>
<td>Flat LSC-PV + 3 cells at back</td>
<td>100 × 157 × 3 mm, PV cells – 100 × 5 mm</td>
</tr>
<tr>
<td>Half-bent hollow + 3 cells at back</td>
<td>LSC – 100 × 157 × 3 mm, PV cells – 100 × 5 mm</td>
</tr>
<tr>
<td>Full-bent hollow + 6 cells at back</td>
<td>LSC – 100 × 157 × 3 mm, PV cells – 100 × 5 mm</td>
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</table>
studied as a function of dye concentration, solar cell pitch and lightguide thickness and the dye concentration has been optimized. Errors in the simulations are expected to be of the same order as the input characteristics from experiments, that is, \( \sim 10\% \).

4. Results and discussions

4.1. Comparison between experiments and simulations

The values for characterizing performance of bent and flat LSC-PV modules are compared in Table 2 below. There is good correlation between experimental and simulation results. Light concentration is less for the bent LSC because more rays can escape the surface of the bent light guide. The measured efficiency for the bent LSC is lower than that simulated, probably due to imperfections introduced by the bending process. The efficiency of the flat 100 \( \times \) 100 mm\(^2\) LSC with bottom-mounted cells is 2.9%, better than that of a similar lightguide employing standard edge-mounted LSCs, which has \( \eta = 2.4\% \) (in conjunction with an MCPET back reflector). The concentration and conversion efficiency of the bent LSC was similar to that of the conventional LSC-PV design (that is, a flat LSC lightguide with cells mounted on edges). When modifying the shape of a LSC lightguide it should also be noted that with increase in area the number of cells also must be correspondingly increased to maintain similar efficiencies. The measured concentration of half-bent concentrators was just 1, whereas in simulations it was found to reach 1.4. This value is slightly less than that for flat LSC-PV modules, but since concentration is still more than 1, this makes the bent LSCs potentially useful as part of the light pole, or eventually as an element to be integrated in buildings or other products.

Figs. 7 and 8 show the measured tilt-angle variation of the efficiencies for the two samples. Note that all efficiencies relate to the incident power on the LSC. The flat sample shows a cosine response, which is expected based on the angular variation of irradiation. The bent sample shows cosine-like behaviour for the central PV cells, but the cells at the sides show highest efficiency when they are horizontal (at ca. \( \pm 60^\circ \)). The flat sample’s conversion efficiency is 2.5\%. In bent samples, conversion efficiencies of the cells on top and sides (both left and right) are 1.0\% and 1.2\% respectively. The resulting total efficiency for bent is 20\% less than for flat lightguide (slightly over 2\% compared to

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Table 2

<table>
<thead>
<tr>
<th>Type of module</th>
<th>( \eta ) (%)</th>
<th>( P ) (%)</th>
<th>( G )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flat measured</td>
<td>2.9</td>
<td>19</td>
<td>10</td>
<td>1.9</td>
</tr>
<tr>
<td>Flat simulated</td>
<td>2.8</td>
<td>18</td>
<td>10</td>
<td>1.8</td>
</tr>
<tr>
<td>Bent measured</td>
<td>2.4</td>
<td>15</td>
<td>6.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Bent simulated</td>
<td>3.4</td>
<td>21</td>
<td>6.7</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Fig. 7. (a) Flat 100 \( \times \) 100 mm\(^2\) LSC prototype with four PV cells. The prototype is transparent and has a red color. (b) Measured efficiency vs. tilt angle – blue dots: measured values, red line: cosine behaviour. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 8. (a) Bent 157 \( \times \) 100 mm\(^2\) LSC prototype with six PV cells. The prototype is transparent and has a red color. (b) Measured efficiency vs. tilt angle showing the contributions due to the PV cells in the centre and at the right and left side, as well as the total efficiency – purple crosses: total, blue diamonds: cells at centre, green triangles: cells at left, red squares: cells at right. Lines between data points have been added to assist the eye. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
2.5% for flat). However, the sensitivity to angular dependence for bent LSC-PVs for incoming incident radiation is less than for flat. For a fully bent cylinder with equally spaced PV cells, the tilt variation would vanish completely. This would make bent LSC-PV appropriate for applications in climates with variable irradiance conditions with a large share of diffuse irradiance, such as in Western Europe.

4.2. Optimization of dye concentration

The concentration of the Lumogen Red 305 dye was varied in the simulations. Lower dye concentrations led to insufficient absorption of the light. Higher dye concentration leads to increased reabsorption losses and hence decreases in the optical collection efficiency. The optimized dye concentration for different LSC-PV shapes and types of illumination is given in Table 3. The collection efficiency with very little dye is about 10% and increases slowly with dye concentration to reach a maximum of about 20%. Further increasing the dye concentration reduced collection efficiency due to excessive reabsorption events, and possible generation of non-emissive dye clusters within the lightguide.

From Table 3, we see that at the optimized dye concentration of 230 ppm for perpendicular illumination of a flat LSC-PV the maximum collection efficiency is about 18%. Since in this case the entire surface of the LSC-PV demo is illuminated \((G = 10)\), this leads to \(C = 1.8\). For the fully bent case, direct perpendicular illumination means a smaller fraction of the surface area is illuminated as compared to that for Lambertian emission where the entire surface is illuminated. The \(G\) values for perpendicular and Lambertian emissions are 3.3 and 10.5 respectively and the corresponding \(C\) values are 0.8 and 2.4. For fully bent LSC-PV modules, a higher concentration of dye can lead to higher collection efficiencies for both perpendicular and Lambertian types of emission (21%). \(\eta\) obtained from the optical modeling can be as high as 4% when the dye concentration is 680 ppm. It is evident that Lambertian emission from all sides results in a higher concentration flux for bent collectors than perpendicular emission from one side.

4.3. Effect of materials and changing solar cell spacing

The distance between the solar cells (pitch) was varied and the resulting effect on collection efficiencies has been simulated. In the experimental device discussed previously, spacing was maintained at 50 mm with 5 mm cell widths: here, the cell width is kept constant as 5 mm whereas the distance between the cells has been varied. The light concentration is reported as the fraction of light collected multiplied with the pitch/cell width.

For a dye concentration of 200 ppm (scale density 0.0025), the collection efficiency is calculated to be between 10% and 20% for the pitch/cell width equaling 10, and the fraction of light collected decreases with increasing pitch/ cell width. The impact of re-absorption losses seems to be limited. Light that has been converted and re-emitted at proper angles for total internal reflection can travel long distances through the lightguide. The light concentration factor, that is the intensity \((\text{W/m}^2)\) falling onto the solar cells divided by the intensity of the light incident on the lightguide, is shown in Fig. 9. For the pitch/cell width = 10 used in experiments the light concentration is between 1.5 and 2.

4.4. Optimization of costs with respect to cell spacing

Not only are collection efficiencies and light concentration important quantities for solar concentrator modules but the overall costs should be optimized as well. For an estimation of potential cost of a luminescent solar concentrator it is assumed that the costs for one unit area of Lumogen/dye lightguide material are 1/10 of the costs of the same unit area of solar cell material.

In Fig. 10, costs are given in relative units of costs per collected Watt of light: ‘1’ means the configuration with

<table>
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<th>Table 3</th>
<th>Calculated values of (p, c) and optimized phosphor concentration.</th>
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<tbody>
<tr>
<td>Configuration</td>
<td>Type of illumination</td>
</tr>
<tr>
<td>Flat LSC-PV (2 cells)</td>
<td>Perpendicular</td>
</tr>
<tr>
<td>Full bent (6 cells)</td>
<td>Perpendicular</td>
</tr>
<tr>
<td>Full bent (6 cells)</td>
<td>Lambertian</td>
</tr>
<tr>
<td>Half bent (3 cells)</td>
<td>Perpendicular</td>
</tr>
<tr>
<td>Half bent (3 cells)</td>
<td>Lambertian</td>
</tr>
</tbody>
</table>

Fig. 9. Light concentration as function of cell spacing and dye density (scale density of \(2.5 \times 10^{-3}\) corresponds to 200 ppm).
The curved devices could find application in areas with highly diffuse light conditions or as replacement architectural or structural elements where aesthetic advantages are important and the additional functionality of electrical generation is desirable.

Fig. 10. Relative costs of LSC setup as function of cell spacing and dye density (scale density of $2.5 \times 10^{-3}$ corresponds to 200 ppm).

5. Conclusions and recommendations

The simulations with LightTools provide good understanding of the fundamental design parameters that impact the collection efficiency of LSC-PV elements with various shapes. The experimental results compare favorably to the simulations. The surface losses in bent LSC-PV modules are higher than those in flat demos. On the other hand, bent LSC-PV modules show diminished impact to changing incident sunlight angles. For the investigated cases, the overall collection efficiencies are slightly above 20% for optimized dye concentration. However, the absorption spectrum of the luminescent material Red 305 covers only about 30% of the relevant part of the solar spectrum (400–600 nm), so the maximum obtainable collection efficiency is approximately 30%. In that wavelength region, approximately 70% of the available solar spectrum is used in the presented concept. To achieve higher efficiencies of LSC-PV, luminescent materials should be developed in the near future that are capable of efficiently absorbing light in the wavelength range between 300 and 800 nm and emitting in the near infrared regions (Debije and Verbunt, 2012).

The curved devices could find application in areas with highly diffuse light conditions or as replacement architectural or structural elements where aesthetic advantages are important and the additional functionality of electrical generation is desirable.

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