5BV.1.38

SYSTEM ENGINEERING AND DESIGN OF LSC-PV FOR OUTDOOR LIGHTING APPLICATIONS

B. Viswanathan, A. Reinders, D.K.G. de Boer, A. Ras, H. Zahn & L. Desmet
Delft University of Technology & Philips Research, Eindhoven, Netherlands
Design for Sustainability, Faculty of Industrial Design Engineering, Delft University of Technology, Landbergstraat 15, 2628 CE Delft, The Netherlands
E-mail addresses for correspondence: B.Viswanathan@student.tudelft.nl; a.h.m.e.reinders@tudelft.nl; dick.deboer@philips.com

ABSTRACT: Solar photovoltaic outdoor lighting applications usually comprise flat plate PV modules mounted on top of a light pole. In our paper instead, it is thought of to design the light pole as a luminescent solar concentrator photovoltaic (LSC-PV) module with solar cell strips and hence reduce costs of silicon solar cells because concentration effects reduce the area and costs of PV cells when compared to conventional PV modules. In our project different types of LSC-PV systems were simulated, studied and analyzed. We evaluated the performance of LSC-PV elements in flat and cylindrical bent shapes, fit for applications in the pole. The modules were made using commercially available PMMA plastic and contained red lumogen dye throughout the bulk. An important parameter determining the functionality of LSC-PV modules is the optical collection efficiency and modules having values sufficiently above 1 are considered to be economically and optically viable for use in electricity generation. From experiments for a flat LSC-PV with PV cells ate the back and mirrors on non-covered edges, the optical collection efficiency, concentration and electrical conversion efficiency that we have obtained are 19%, 1.9 and 2.9% respectively for a gain of 10. Similarly for a similar arrangement of half-bent LSC-PV shape, optical collection efficiency, concentration and electrical conversion efficiency are 15%, 1 and 2.4% respectively for a gain of 6.7.The losses in bent LSC-PVs are higher than those in the flat (increase of 52.5%), however bent LSC-PVs systems are expected to perform well on both sunny and cloudy days. Critical design parameters affecting LSC-PV systems have been studied and the outcome is expected to result in an optimized design shown by illustrations in our paper
Keywords: luminescent solar concentrators, crystalline silicon, solar street-lighting, product-integrated PV, design

1 INTRODUCTION

A luminescent solar concentrator (LSC) [1] consists of a light guide containing luminescent material that converts incident short-wavelength light into longer-wavelength light, which is guided towards photovoltaic (PV) cells. LSCs are attractive, since they are inexpensive and thin and can be easily integrated in built environment [2] and other appliances. In the recent progress made in LSC materials, Philips Research has reported and a record efficiency of 4.2% for Si-based LSCs [3, 4]. We envisage the use of LSCs for outdoor lighting, in which the LSC could be incorporated as a bent part of e.g. a light pole. Here we compare the performance of flat and bent LSCs.

The purpose of the project is to design an optimally performing LSC-PV system which can be designed as a cylindrical light pole made to power LEDs for outdoor lighting applications, see Figure 1 This research work specifically focuses on the street-lighting application where it is possible to replace the solar panel and the light pole units of solar based street-lights by the designed LSC-PV cylindrical module. The system engineering of the entire outdoor lighting product that uses LSC-PV system comprising of the LSC-PV light pole for generating the energy, the batteries and charging controllers for storing the electricity for operation during times when sunlight is not available and a lighting unit on top with 4 LED modules, has been carried out. Additional value added features in the product, for an occupancy sensor or the usage of the lighting product for grid connected and stand alone applications might also be considered in the design.

The idea behind using the LSC-PV lighting system is that the concentration achieved through LSC-PVs are high and LSC-PVs split the function of the solar cells into two parts – absorption of photons is done by the dyes and the conversion to electrical energy happens in the strips of crystalline-silicon solar cells (c-Si) that are mounted in the LSC. This greatly reduces the amount of expensive Si that is otherwise used in solar panels in solar based outdoor lighting products.

In this paper we measure, model and optimize the performance of LSC PV modules with a flat and bent shape with the purpose to select appropriate LSC PV elements for integration in a street-lighting system.

Figure 1 shows the difference between LED street-lighting based on PV panels and the proposed LSC-PV poles for the electricity generation.

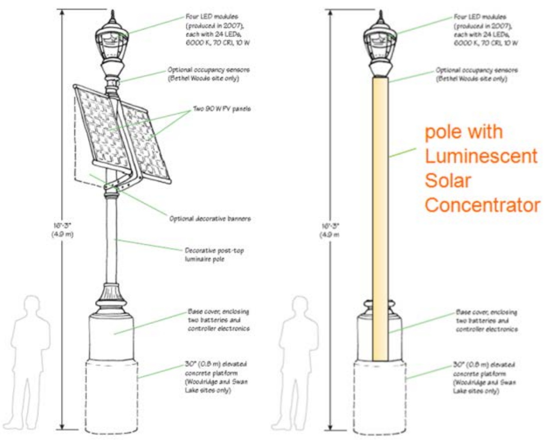


Figure 1: Left: an existing solar street-lighting pole, right: a street-lighting pole with integrated bent LSC-PV

elements

2 MATERIALS ANDEXPERIMENTAL SET-UP

As luminescent light guides we use 3 mm thick PMMA plates containing the dye Lumogen F Red 305 (BASF) with absorption of 99% at 575 nm, from Evonik [5]. We made a 100×100 mm^2 flat prototype and a 157×100 mm2 bent prototype (by shaping the material at ca. 100^{o}C) with bottom-mounted silicon PV cells, as shown in Figures 2(a) and (b).The c-Si PV cells (Narec [6]) have dimensions of 5×50×0.1 mm^3 and measured efficiency η_0 = 0.16. The 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 reflector (99% reflectance) separated by an air gap. Further we followed the same procedure as described in Ref. [3].

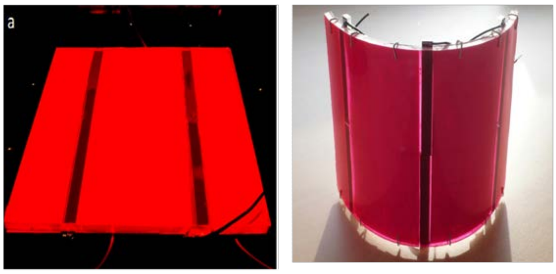


Figure 2 (a): Flat 100×100 mm^2 LSC prototype with four PV cells; **(b):** Bent 157×100 mm^2 LSC prototype with six PV cells

The solar simulator and measurement set-up to determine the efficiencies of the samples are described in Ref. [3] as well. Like in that paper, we define *efficiency* (η) as the electrical power obtained from the PV cells attached to the LSC, as a fraction of the incident optical power on the LSC surface. *Bare-cell efficiency* (η_0) means the electrical power obtained from the directly illuminated PV cell before attachment to the light guide as a fraction of the incident optical power. *Collection probability* (P) means the ratio of photons reaching the surfaces of the PV cells to that incident on the total LSC surface: $P = \eta / \eta_0$. Geometric *gain* (G) means the ratio of the total light-guide surface area and the PV cell surface area present in the LSC. *Concentration* (C) means the ratio between incoming and outgoing optical irradiance of the concentrator: $C = PG$. We used a rotational stage to vary the angle of incidence of the incident light.

Simulations were performed using LightTools [7] ray-tracing software as described in Ref. [2]. The simulations yield the collection probability P, from which η and C can be derived.

3 MEASUREMENTS AND SIMULATION

In this section the research approach for designing the street-lighting system is explained. Two different routes – experiments and optical modelling/simulations – were adopted in order to study the performance of different LSC-PV shapes.

The design modification was effected in conventional square planar LSC-PVs as a part of this research where the cells from the sides were moved to the back of the LSC-PV. Further to this design modification, the shape modification was effected where square planar LSC-PVs were changed to half-bent LSC-PVs. The different steps in design modification which was carried out as a part of the project is explained in Figure 3.

Three different types of LSC-PV systems were simulated, studied and analysed through experiments – flat LSC-PVs with cells attached to the sides, flat LSC-PVs with bottom mounted solar cell configuration and hollow half-bent cylindrical LSC-PVs with bottom mounted cell configurations. This is shown in Table 1. Double the number of cells were used as those modelled in the simulations for the sake of easier measurements and manufacture of the LSC-PV demos.

Type of module	**Dimensions**
Flat LSC-PV + 2 cells on sides+ mirrors on non-covered edges	LSC - 100X100X5 mm, PV cells – 100x5 mm
Flat LSC-PV + 4 cells (2 cells in simulations) attached at back + mirrors on non-covered edges	LSC - 100X100X3 mm, PV cells – 100x5 mm
Flat LSC-PVs + 6 cells (3 cells n simulations) in back	LSC – 100x157x3 mm, PV cells – 100X5 mm
Half-bent hollow + 3 cells (6 cells in simulations) in bottom	LSC – 100X157X3 mm, PV cells – 100X5 mm
Full-bent hollow + 6 cells at back in simulations	LSC – 100X157X3 mm, PV cells – 100X5 mm

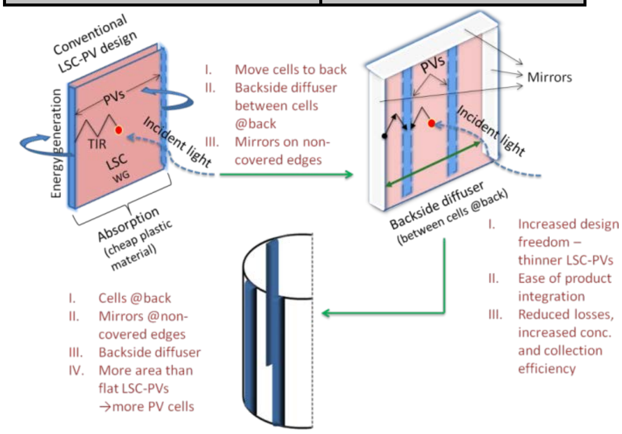


Figure 3: Design modification scheme – transition from flat conventional LSC-PVs to cylindrical LSC-PVs

Table 1: LSC-PV schemes studied using experiments/simulations

The general scheme of how both experiments and simulations are used to arrive at a conclusion for the suitability of LSC-PVs for street-lighting applications is shown in the Figure 4 below.

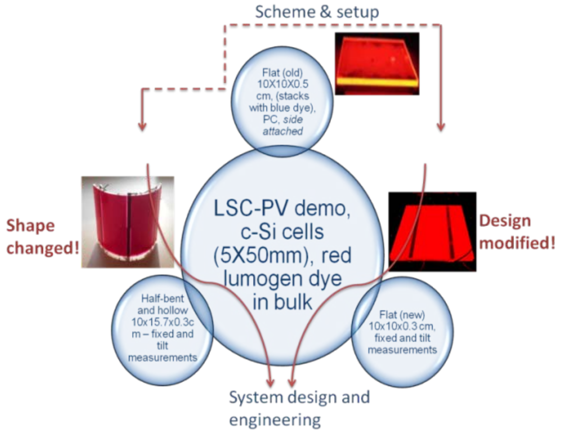


Figure 4: Scheme and setup of the study of the different LSC-PVs shapes in the research

3.1 MEASUREMENTS

The experimental set-up used for spectral measurements is shown in the Figure 5. In the setup the sample is placed and measured with a Halogen light source which provides light with the same spectrum of sun's rays (direct light – mostly incident during peak afternoon hours). Two types of spectral measurement experiments were carried out on the different LSC-PV shapes. In one type the light was made incident at 0 degrees and the other where the demo was adjusted (-60 through +60 degrees) to ensure that light is incident from directions.

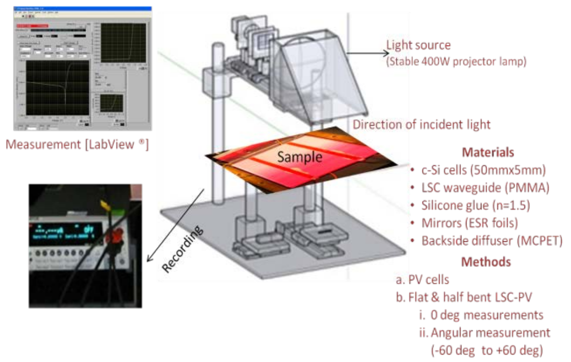


Figure 5: The experimental set-up for spectral measurements**.**

The experimental setup was used to test the performance of LSC-PV shapes for both direct/perpendicularly incident sunlight whereas the variation of the angles of incidence were able to study performance for diffuse/lambertian type of light.

The performance of LSC-PV shapes, sizes and designs were carried out and this was further tested and verified by building the demos as optical models.

3.2 OPTICAL MODELLING BY RAY TRACING SIMULATIONS

Optical modelling has been carried out using LightTools® (LT) software. LT has been used here for building the optical models which are built very similar to the demos used in experiments. The main purpose of the carrying out the optical modelling is that it can enable the following.

- Virtual prototyping of 3D models
- How much further could simulation results go?
- Optimize model properties
- Analyse results
- Compare results with expt.
- Study other parameters important for demo improvement

The models were built in LT very similar to experimental demos in terms of materials, sizes, shapes and concentration of dye. Further the sun's rays were modelled and then ray-tracing simulations were carried out. Beer-Lambert law [7] and the absorption spectrum of the luminescent species in the LSC-PV models are used to determine the probability of an absorption event of the ray happening with the luminescent species during ray tracing [8]. The quantum yield of the luminescent species further provides the probability of the emission event (calculated as the ratio of the number of photons emitted to the number of photons absorbed). Randomly generated numbers are usually tested against the calculated probabilities to determine whether the event occurs or not in the case of both absorption and emission. When an emitted ray intersects a surface boundary Fresnel equations [9] are used to determine whether it is transmitted or reflected and with a random number that is generated ray tracing simulations can determine whether reflection or transmission happens.

The LSC-PV models of different shapes were constructed using different LT commands and options to fix the position, size and dimensions in the software. The following steps were followed to have the demos constructed in LT and for running optical simulations.

1. LSC WG (waveguide) geometry was first defined by fixing dimensions, positions and sizes. The material used for constructing the WG was defined by inputting the refractive index (n) in the software
2. Defining the luminescent material, in this case the phosphor or organic dye, in the LSC WG with inputs of concentration, absorption and emission profiles of the material
3. Creation of the solar cell geometry – by defining shape, dimensions and positions. The material used for solar cells in this case is c-Si
4. Defining the glue with appropriate geometry and material properties (n) in order to virtually attach the c-Si cells to the LSC WG geometry constructed of different shapes. The glue is a very important part of the whole LSC-PV setup in the sense that it provides the most essential optical contact between the LSC WG and the PV cells. This is very important for the transmitted luminescent photons to reach the cell and be available for conversion to electrical conversion.
5. The space between the glued PV cells was covered with backside diffuser material (MCPET) and the edges of the LSC WG which are not covered by cells were made mirrors. The MCPET acted like a mirror at the back offering about 95% reflection and recycled the luminescent photons which would otherwise escape the WG. The mirrors on the non-covered edges provided an arrangement which made the LSC-PV demo repeat itself infinite times and prevented the escape of photons from the sides. Both these scavenging techniques help in better photon wave-guiding and collection on PV cells.

The above steps when carried out for each of the optical demos resulted in the different shapes and a snapshot of the renderings from simulations is shown in Figure 6.

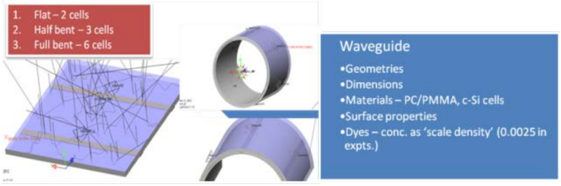


Figure 6: Different LSC-PV geometrical primitives built in LT for simulation

Defining the glue forms a very crucial part of the LSC-PV models. It has been done differently for both flat and bent shapes.
For flat shape it is more of a straight forward approach where both the LSC WG and the solar cells are flat and the parallel region between the two needs to be filled with glue of 'n' matched with the LSC-WG. For bent LSC-PVs, the LSC WG is bent whereas the solar cells would have to be attached flat and unbent. In that case the area between the bent LSC WG and the cell were calculated carefully using Pythagoras relation as is shown in Figure 7.

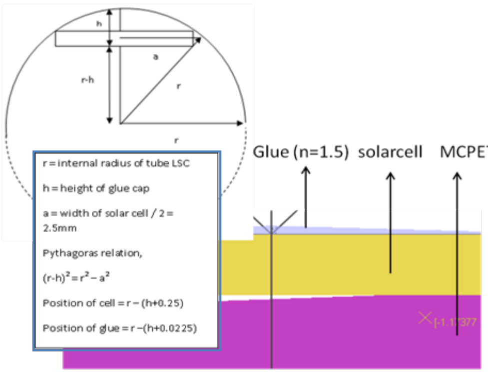


Figure 7: Virtual representation of modelling of thin layers of glue in half bent LSC-PV

In order for simulations of designs or models that use phosphors to be accurate, appropriate and careful modelling of phosphors is essential in LightTools. The interaction of light with phosphor is a complicated physical and optical process. LightTools has several input functions which allow the modelling of a wide variety of fluorescent materials. The input variables are

1. Adding a new user material for modelling phosphor
2. Adding a phosphor particle to the user material
3. Specifying the properties of the phosphor particles

In addition to the complex input model for phosphors LightTools also requires a set of (measured) data which are mentioned below.

1. The absorption spectrum of the phosphor
2. The quantum yield
3. The mean free path (often inferred from the absorption spectrum)
4. The emission spectrum
5. The refractive index of the phosphor [10]

Using ray-tracing simulations, about six different parameters were studied using LT simulations. Figure 8 shows the different parameters which have been studied as function of P (optical collection efficiency).

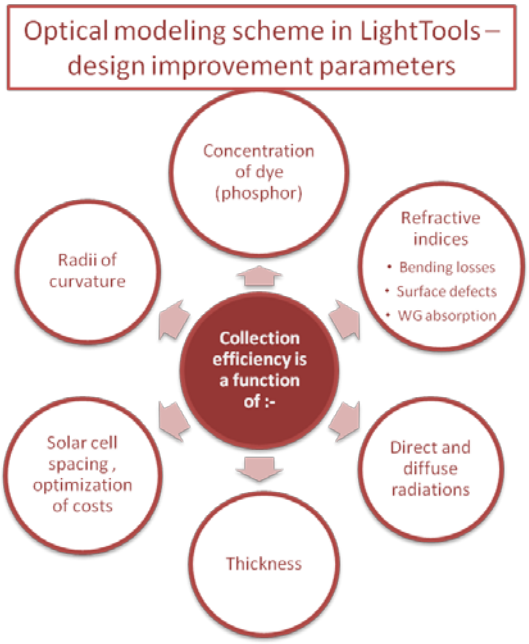


Figure 8: Optical modelling in LT-design improvement

4 RESULTS AND DISCUSSIONS

The obtained experimental and simulated values for the above-mentioned parameters are shown in Table 2. Note that the performance for the flat 100×100 mm^2 LSC is better than that of a similar one with side-attached LSCs [4], which has η = 2.4% (with an MCPET back reflector).

Table 2: Experimental and simulated performance parameters of flat LSC with four PV cells and bent LSC with six PV cells

	η (%)	*P (%)*	*G*	*C*
flat, measured	**2.9**	**19**	**10**	**1.9**
flat, simulated	2.8	18	10	1.8
bent, measured	**2.4**	**15**	**6.7**	**1.0**
bent, simulated	3.4	21	6.7	1.4

The comparison between experimental and simulation results for both flat and half-bent LSC-PVs are shown in the Figure 9a, b below. Both the figures suggest that there is very good correlation between results from experiments and simulations.

The simulations yield a higher efficiency value for the bent sample than for the flat one, since the latter contains less PV cells. The reason that the simulated concentration value is less for the bent LSC is that more rays can escape the bent light guide.

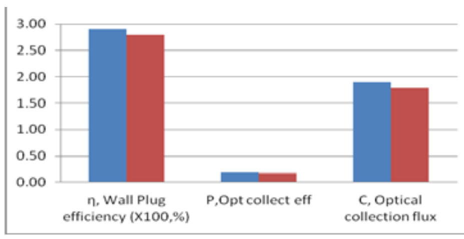


Figure 9 (a): Comparison between experimental and simulation parameters for flat LSC-PVs - in blue, experimental results, in red, simulated results, for concentration of dye = 0.0025

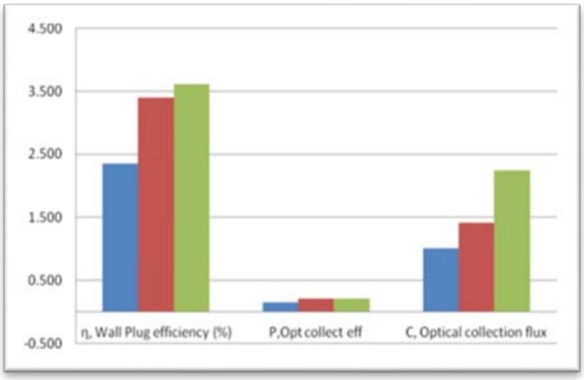


Figure 9 (b): Comparison between experimental and simulation parameters for half bent LSC-PVs. In blue, experimental results , in red, simulated values for perpendicular light, in green, simulated values for lambertain light, all for concentration of dye = 0.0025.

The optical performance and concentration flux of flat LSC module with solar cells attached in the sides was found to be better than similar sized solar panel modules. Further there was an observed improvement in concentration flux over both solar panel modules and flat LSC-PVs with cells attached to the sides, when flat LSC-PVs with solar cells attached to the bottom were tested and studied through experiments and simulations. The flat LSC-PVs with bottom mounted cell configurations were made to have mirrors in the sides in order to have the effect of multiple units and a backside diffuser to reflect the light escaping from the PMMA LSC WG back to the LSC. The additional contribution to the increase in concentration flux can be attributed to the effect from the mirrors in the sides which actually made the single LSC-PV module act as repeated such a unit infinite times and also the effect of the backside diffuser.

Improved light trapping and prevention in the escape of the absorbed photons was the result such as mirrors on the sides; backside diffuser further improved this effect of increase in concentration flux and optical efficiency – effect of both led to improvement of concentration in the newer designs by 23% and conversion efficiency by 20%. Experiments and simulations of bent LSC-PV hollow and half cylinder module was also hence made with edges as mirrors and back side diffuser. Spectral measurement experiments were carried out and the efficiencies of the LSC-PV system and concentration flux were calculated, studied and compared with flat LSC-PVs. It was observed that the concentration flux of the hollow half-cylinder was slightly lesser than that for flat LSC-PVs but was more than ‘1’ which makes them useful optically and mechanically for being used as the light pole itself.

Bent LSC-PVs are expected to perform better than flat ones because of the increase in optical path. They improve the ease with which light poles are designed and also reduce complications in wiring. Further bent hollow LSC-PV tubes allow the inclusion of stacked design possibilities and that is both a mechanical and an engineering advantage for product/system formation as against that of flat LSC-PVs (even stacked flat LSC-PVs).

The sensitivity of the optical collection efficiency of the both flat and bent hollow cylindrical LSC-PVs was studied using experiments and simulations. The results show that the efficiency of the bent LSC-PV is 20% lesser than the flat LSC-PVs. But interestingly the sensitivity to angular dependence for the incoming incident radiation was flatter and lesser in the case of bent LSC-PVs than flat LSC-PVs which showed huge variations. The flat sample showed a cosine behaviour with conversion efficiency of slightly above 2.5% whereas bent sample showed cosine behaviour only from top cell (conversion efficiency=2%). Further cells at the sides of bent sample showed higher efficiency at 60 degrees (conversion efficiency 1.2% for cells on the left and right sides). The resulting total efficiency (only 2% compared to 2% for flat) was found less angular dependant than for flat. Thus the impression is that for fully bent LSC-PVs even the very less angular dependence for tilt measurements is expected to vanish with symmetry. This provides insights into the usefulness of the hollow and half-cylinder LSC-PVs for use in both cloudy and sunny days effectively over that of flat LSC-PV configuration in terms of variation in optical efficiency with varying angle of incident radiation from the sun. However bent LSC-PVs suffered from additional losses contributed by external reflections, host absorption and self-absorption and escape cone losses when compared to flat LSC-PVs. Hence various mechanisms to trap light, to reduce external reflections and self absorption are studied and suggested so that the efficiency of the bent and hollow LSC-PV tubes can be made higher or similar to flat LSC-PVs. The radii of LSC-PV hollow cylindrical tubes can also be made very big so that they could perform close to that of flat designs and can make use of the flatness for reduced losses and can also use the mechanical and engineering advantage of the hollow and half-cylinder bent configurations. But with the increase in radii the number of cells correspondingly increase and a trade off with increase in Si costs needs to be achieved. The bent cylindrical LSC-PV tube design is optimized for thickness of the tube, concentration of the dye and radius of curvature for varying angles of incident radiation and types of illuminations – lambertian and perpendicular light using simulations. The effects were studied and verified through experiments.

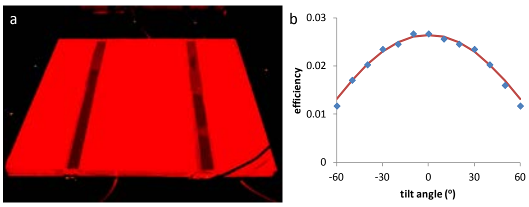


Figure 10 (a): Flat 100×100 mm^2 LSC prototype with four PV cells. **(b)** Measured efficiency *vs.* tilt angle. The solid line indicates a cosine fit – blue dots – measured values, red line cosine behaviour

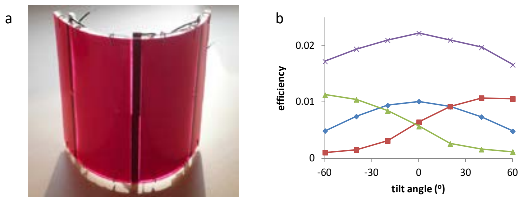


Figure 11 (a) Bent 157×100 mm^2 LSC prototype with six PV cells. **(b)** Measured efficiency *vs.* tilt angle showing the contributions due to the PV cells in the centre and at the right and left side, as well as the total efficiency – purple – total, blue – cells at centre, green – cells at left, red – cells at right

Figures 10 and 11, shows the measured tilt-angle variation of the efficiencies for the two samples. The flat sample shows cosine behaviour, expected based on the angular variation of irradiation. The bent sample shows cosine behaviour for the centre PV cells, but the cells at the sides show highest efficiency when they are horizontal (at ca. ±60^o). The resulting total efficiency is less angular dependent than for the flat LSC. For a fully bent cylinder with equally spaced PV cells, the tilt variation would vanish at all.

When half and full bent LSC-PVs were compared and their benefits studied through simulations, we observed that half-bent LSC-PVs would be a strategic decision as far as use in northern hemisphere (where sun faces the south and doesn't illuminate one complete half of PV cells on the other half).This is depicted in Figure 12.

Figure 12: Sun light's only south façade in northern hemisphere.

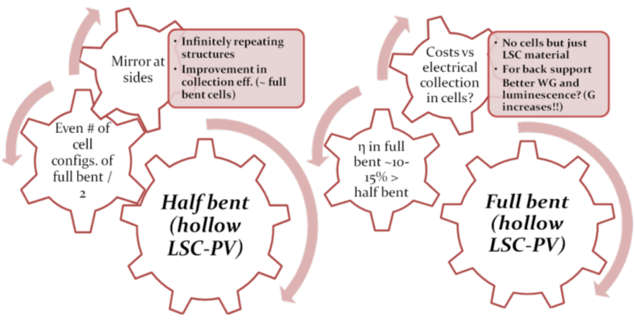
Half bent hollow better choice than full bent hollow!
Design option 1: Half-bent hollow - mirror on sides and plastic material as back support, solar cells south facing
Design option 2: Half bent hollow with LSC material as back support, solar cells south facing

- Better for integration in light-poles
- More area of LSC needed in comparison to cells – meeting energy requirements
- **Better for diffuse conditions –better choice for winter!**

5 DISCUSSION AND CONCLUSIONS

The new design of LSC-PV where cells where moved from side edges to back of the WG along with the adopted schemes for scavenging losses (in this case the mirrors on non-covered edges and MCPET backside diffuser) led to an increase of concentration by 23% and conversion efficiency by 20%. When the same design of moving cells to back was employed for other shapes (in this case half-bent LSC-PVs), the concentration and conversion efficiency were were similar to that of the conventional LSC-PV design with cells mounted on edges. While modifying the shape it should also be noted that with increase in area of WG, the number of cells also has to be increased correspondingly. This leads in turn to increase in conversion efficiency. The concentration of half bent concentrators from experiments was just 1 and in simulations it was found to reach 1.4.
The sensitivity of the optical collection efficiency of the both flat and bent hollow cylindrical LSC-PVs was studied using experiments and simulations. The results show that the efficiency of the bent LSC-PV is 20% lesser than the flat LSC-PVs. But interestingly the sensitivity to angular dependence for the incoming incident radiation was flatter and lesser in the case of bent LSC-PVs than flat LSC-PVs which showed huge variations. The flat sample showed a cosine behaviour with conversion efficiency of slightly above 2.5% whereas bent sample showed cosine behaviour only from top cell (conversion efficiency=2%). Further cells at the sides of bent sample showed higher efficiency at 60 degrees (conversion efficiency 1.2% for cells on the left and right sides). The resulting total efficiency (only 2% compared to 2% for flat) was found less angular dependant than for flat. Thus the impression is that for fully bent LSC-PVs even the very less angular dependence for tilt measurements is expected to vanish with symmetry. Thus bent LSC-PVs can perform better for cloudy days.

Results from simulations showed that it would be advantageous to make a final choice on the design and shape as the half-bent LSC-PVs than the full bent LSC-PVs. This is because of the advantage and ease of engineering of mirrors on sides in half bent LSC-PV than in full bent designs. Additionally there is the advantage of not putting solar cells in the area of the full bent LSC-PV that does not receive sunlight. Although half-bent LSC-PVs would mean lesser cells than full bent ones and there could be a difference of 10-15% loss in conversion efficiency, it would make strategic sense to focus on the costs incurred by putting the additional cells. A comparison between half and full-bent LSC-PV shapes is shown in the schematic below Figure 13.



When the LSC-PV street-lighting system was designed by making an energy balance we find that 4% efficient LSC-PVs are still not able to catch up with solar panels with 16% efficiency. For such LSC-PV street-lighting system to come to existence either efficiency improvement of LSC-PVs has to happen (reaching at least ~10%) or the luminous efficacy of LED lamps becomes more. However the installation costs of the LSC-PVs are expected to be lower than that of PV panels especially since they are easily integrated in the products and do not need additional and costly sun-tracking systems due to their ability to handle diffuse radiations from sun better. Appropriate applications for LSC-PVs could be the low power applications such as use in mp3s charging, consumer products and so on.

Efficiency improvements could be achieved with using stacked designs, i.e. layers of LSCs with different dyes and spectrally matched solar cells. There are a great number of improvements that can and need to be made on the LSC to make it a more viable option for use in the urban environment .One aspect we find particularly intriguing is to provide an opportunity for the use of organic-based photovoltaics (OPV). One of the greatest challenges for OPV has been the inability of utilizing the ultraviolet portion of the UV spectrum, as well as survives the high energies of the UV light which causes premature degradation of the OPVs through destruction of the dye materials. However, the LSC does not illuminate the attached solar cell with a solar spectrum, but a much more narrow-band of light, generally in the near infrared, the range of wavelengths where OPVs perform their best. Coupled with the lack of exposure to UV light, this could provide the OPV with the first real niche application where they could excel.

LSC could best be used as a complement to silicon PV rather than a competitor, positioning itself in areas not normally accessible, such as areas with increased fractions of diffuse light. The LSC is to be brought directly into public view, not ‘hidden away’ as most silicon PV panels. Applications could include sound barriers, telephone poles, and bus stop roofing. As such the suggested design for a street-lighting pole shown in Figure 1 seems realistic.

6 ACKNOWLEDGEMENTS

We acknowledge the suppliers of the solar cells (Narec), the suppliers for the dye (BASF dye from Evonik), and the suppliers of backside diffuser (3M) for being able to construct the demos and test it. We acknowledge Prof. Michael Debije from Technical University, Eindhoven to have been enthusiastically involved with this research and provide better insights. We also acknowledge Mr. Kumar Narasimhan for insightful discussions regarding possibilities of employing LSC-PVs in street-lights in India.

8 REFERENCES

[1] W.H. Weber, and J. Lambe, “Luminescent greenhouse collector for solar-radiation,” Appl. Optics **15**, 2299-2300 (1976); A. Goetzberger, and W. Greubel, “Solar-energy conversion with fluorescent collectors,” Appl. Phys. 14, 123-139 (1977).

[2] M.G. Debije, P.P.C. Verbunt, “Thirty Years of Luminescent Solar Concentrator Research: Solar Energy for the Built Environment,” Adv. Energy Materials 2, 12-35 (2012).

[3] D.K.G. de Boer et al.,“Progress in phosphors and filters for luminescent solar concentrators,” Opt. Express 20. A395-A405 (2012).

[4] L. Desmet, A.J.M. Ras, D.K.G. de Boer, and M.G. Debije,“Monocrystalline silicon photovoltaic luminescent solar concentrator with 4.2% power conversion efficiency,” Opt. Lett. 37 (2012).

[5] PLEXIGLAS® Fluorescent Bright Red 3C02 GT, www.plexiglas-shop.com

[6] Narec Solar, http://narecsolar.com

[7]http://en.wikipedia.org/wiki/Beer%E2%80%93Lambert_law

[8]M Kennedy, A J Chatten, D J Farrell, R Bose “Luminescent Solar Concentrators: A Comparison of Thermodynamic Modelling and Ray-Trace Modelling Predictions”

[9] http://en.wikipedia.org/wiki/Fresnel_equations

[10] Michael Zollers, "Phosphor Modeling in LightTools", Synopsys Inc, 2011