Direct versus indirect illumination of a prototype luminescent solar concentrator

Citation for published version (APA):

Debije, M. G., & Rajkumar, V. A. (2015). Direct versus indirect illumination of a prototype luminescent solar concentrator. *Solar Energy*, 122, 334-340. <https://doi.org/10.1016/j.solener.2015.08.036>

Document license:

TAVERNE

DOI:

[10.1016/j.solener.2015.08.036](https://doi.org/10.1016/j.solener.2015.08.036)

Document status and date:

Published: 01/12/2015

Document Version:

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

[Link to publication](#)

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy

If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Direct versus indirect illumination of a prototype luminescent solar concentrator

Michael G. Debije^{a,*}, Vikram A. Rajkumar^b

^a Dept. Chemical Engineering & Chemistry, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

^b Dept. Mechanical Engineering, Eindhoven University of Technology, 5600 MB Eindhoven, The Netherlands

Received 23 April 2015; received in revised form 27 July 2015; accepted 3 August 2015

Communicated by: Associate Editor J.-L. Scartezzini

Abstract

The luminescent solar concentrator could find application as an alternative way of generating electricity from sunlight in urban settings by virtue of its aesthetic and performance qualities. In particular, it has long been stated that the device functions equally well in direct and diffuse light, especially useful in the built environment but with little verification of this statement. In this work, we demonstrate the validity of this claim by comparing the performance of the luminescent solar concentrator in outdoor conditions ranging from clear to cloudy. We offer the explanation of an altered illumination spectrum to account for the increased efficiency of the device in overcast conditions. We also show the effect of gluing cells to the lightguide edge and conjecture on the differing impact the gluing has under direct and indirect sunlight.

© 2015 Elsevier Ltd. All rights reserved.

Keywords: Luminescent solar concentrator; Indirect light; Photovoltaic; Fluorescence

1. Introduction

The luminescent solar concentrator (or LSC) is a device intended for use as an electricity generator from sunlight to be used in the built environment (Debije and Verbunt, 2012). Normally, an LSC is a plastic plate filled or topped by luminescent molecules. The luminophores absorb incident sunlight and re-emit this light at longer wavelengths. A significant fraction of the re-emitted light remains trapped within the plastic lightguide by total internal reflection. The main exit for this trapped light is from the edges of the device, where one can mount thin, long photovoltaic (PV) cells for converting the emission light into electricity. The LSC is intended for use in urban settings since it may

be produced in many different colors, can be cut to essentially any desired shape, and is relatively robust. Another positive feature is the capability of absorbing sunlight from both front and rear sides and the potential to function in diffuse light conditions.

While the LSC is not a new concept, the device first being mentioned in the late 1970s (Weber and Lambe, 1976), there have been relatively few tests of the devices in real situations (Bakr et al., 1999; El-Shahawy and Mansour, 1996; Mansour et al., 2002; Pravettoni et al., 2009; Salem et al., 2000), almost exclusively having been confined to the laboratory settings and direct illumination from solar simulators. While there are statements that the LSC device performs well under diffuse illumination (Hernandez-Noyola et al., 2012; Reda, 2008; Vishwanathan et al., 2015), there are limited research efforts to verify this assertion (Aste et al., 2015; Desmet

* Corresponding author.

E-mail address: m.g.debije@tue.nl (M.G. Debije).

et al., 2012; Mansour, 1998; Mansour et al., 2002). Therefore, we have undertaken a series of experiments to attempt to ascertain whether this claim is true: does the LSC perform well under environmental diffuse light conditions, and, if so, to what extent?

2. Experimental

A prototype LSC was assembled by Airbus Defence and Space Netherlands from a $60 \times 40 \times 2 \text{ cm}^3$ cast Plexiglas® plate (Evonik) doped with Lumogen F 305 dye (BASF). The plate is held vertically by means of a handling frame made of aluminum as shown in Fig. 1. Only the top edge of the Plexiglas® plate is polished smooth while the other edges are unpolished and remain as-cut. A total of eighteen $6 \times 4 \text{ cm}^2$ multi-crystalline silicon PV cells (Angewandte Solarenergie-ASE GMBH, nominal efficiency $>14\%$ at 25°C) were attached to the top and the bottom edges of the aluminum frame and pressed tightly to the Plexiglas® plate (9 cells per edge). Some cells were later adhered to the lightguide edge by a silicone-based glue. Black tape covers the protruding parts of the PV cells which extend beyond the edges of the waveguide so the exposed surface area of each cell to the edge of the LSC plate is 11.6 cm^2 . Each PV cell was individually wired and the outputs were separately accessed through an Amphenol Commercial L77-DC37S connector.

A pyranometer (Kipp&Sons CMP11) was used to collect solar irradiation data at the test site which was then fed to a data logger (Grant Squirrel 2040 series: Type 2F16). The data logger also collected the open-circuit voltage data from cells 1, 2, 4 and 5 on the unpolished side of the prototype. Cell 3 was connected in short-circuit to collect short-circuit current data. The data logger recorded open-circuit voltage and short circuit current data at 10 s intervals from different cells.

The prototype was placed facing south the same location on the roof of the Vertigo building in the Eindhoven University of Technology campus in Eindhoven, the Netherlands (51.4333°N , 5.4833°E) on a pebble ground

with an approximate albedo of 0.1. The reflections off the ground into the device were minimal and not expected to significantly affect the output (see Fig. 2). There were no direct shadows cast on the device throughout the measurement periods. However, minor obstructions such as a nearby ventilation system could reduce the diffuse component of sunlight entering the device.

The efficiency of the LSC device was estimated by:

$$eff = \frac{FF * V_{OC} * I_{SC} * A_E}{A_{PV} * I * A_{LSC}} \quad (1)$$

The fill factor, FF , was taken as 0.8, V_{OC} was determined from cell 2, I_{SC} from cell 3, and A_E being the edge area of the prototype (400 cm^2), A_{PV} was the area of the collecting cell (11.6 cm^2), I was the solar irradiation in W/m^2 and A_{LSC} the surface area of the lightguide (2400 cm^2). The power efficiency is thus calculated based on the ratio between the power generated (by the cells) from the entire edge surfaces of the light guide to the solar irradiation incident on the primary surface of the light guide. The solar irradiation is measured by the pyranometer which faces south. The pyranometer can only measure the direct and diffuse irradiation coming from its front side, whereas the light guide receives some additional diffuse light from behind (from the north). Consequently, the resulting values are not the true efficiencies but serve as a good comparison against mono-facial PV technologies which are opaque to light input from the rear side. In this work, the results are reported as relative efficiencies for ease of comparison.

The fill factor was determined from the interpretation of the IV curve from the sun simulator test at Airbus Defence and Space Netherlands facilities and is assumed to be a constant throughout. However, the fill factor undergoes a small change of up to $\pm 2\%$ due to the change in parasitic resistances at different illumination levels (Bowden and Rohatgi, 2001).

The solar spectrum was measured at different times and under different cloud conditions by a handheld spectrometer (Avantes Avaspec 2048-UA) on a partly cloudy February day.

Fig. 1. (Left) the luminescent solar concentrator prototype, (right) depiction of solar cell placement.

Fig. 2. A photograph depicting the vertically placed pyranometer and the prototype at the test location.

3. Results and discussion

3.1. The light incident on the LSC device

Most measurements of solar energy devices are made under solar simulators which employ a standardized AM1.5 spectrum. However, in outdoor applications this spectrum is rarely realized. The presence of clouds and position of the sun can dramatically impact the spectral qualities. The incident solar spectrum at our measurement location in the Netherlands was measured at different times and under various cloud cover conditions using a handheld spectrometer on a partly cloudy February day. The resulting spectra were normalized with respect to their intensity at 560 nm as this is wavelength where light is least affected by environmental conditions, in particular absorption and scattering by water vapor (Minemoto et al., 2007), and representative spectra are shown in Fig. 3. The absorption spectrum of the Red 305 dye used in the LSC device in a polymer host is superimposed upon the normalized solar spectra for reference.

3.2. Direct vs. indirect incident illumination

A $60 \times 40 \times 2$ cm³ PMMA dye-doped plate locked in an aluminum frame was used as the prototype (see Fig. 1). The dye chosen was Lumogen Red 305 (Seybold and Wagenblast, 1989), a common dye to LSC studies because of its high fluorescence quantum yield (Wilson and Richards, 2009) and excellent photostability (Slooff et al., 2007; Wilson and Richards, 2008).

LSC edge emission data from an approximately six month period were recorded for a variety of weather and

Fig. 3. Measured solar spectrum using hand-held device on February 3, 2014 in Eindhoven under clear sky at 11:55 (blue) and under cloudy conditions at 16:25 (gray) normalized at 560 nm. Superimposed is the absorption spectrum of Lumogen Red 305 dye in PMMA (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cloud conditions. Performance in rainy conditions was not tested because the prototype was not suitably weather-proofed. Sample plots of the measured solar irradiation and calculated LSC total efficiency on a sunny day rated as 1 okta (February 3rd, 2014) is shown in blue in Fig. 4a, for a cloudy day rated as 8 okta (October 8, 2013) in Fig. 4b, and a day with considerable changes in cloud cover (November 11, 2013) as Fig. 4c. The okta scale ranges from 1 to 9, where 1 represents a cloudless day and 9 represent a completely overcast day. The normalized edge efficiencies of electrical production by at edge attached photovoltaics was calculated using Eq. (1), and arbitrarily set to 1 at its lowest point to allow easy comparison, and is plotted as red lines in the figures.

The most striking trend in the three figures is the dramatic jump in normalized edge efficiency measured simultaneous with the drop in solar irradiance. This drop in irradiance occurred either due to the passage of clouds as seen at about 14:00 in Fig. 4a, or due to changes in solar position, most notably during sunset at 16:30 in the same figure. In both these conditions, the efficiencies are positively affected: normalized electrical output efficiency increases by up to 100% in these conditions. These changes in response are similarly noticeable in Fig. 4b and c.

We offer possible explanations for the increase in apparent efficiency. When a cloud moves over the solar disk, the fraction of light that is diffuse increases significantly. The spectral distribution of diffuse solar light is known to be different than direct light, as shown in Fig. 3 (Hisdal, 1987). It has been shown by ray-tracing modelling techniques that the photon collection efficiency of a Red 305 based LSC is 21% with diffuse light while only 9% with the direct component (Edelenbosch et al., 2013). This is because short wavelength light is scattered more effectively in the atmosphere so the diffuse spectrum is blue rich and can be better harvested by the LSC.

It is clear there is a higher fraction of the spectrum in the red/near IR region under sunny skies than when it was

Fig. 4. Calculated normalized electrical edge efficiency (red) and global vertical solar irradiance (blue) plotted as a function of time for (a) February 3, 2014, where mean cloud coverage on the day was 1 okta. Sunrise at this location is 08:12 and sunset is at 17:31, for (b) October 8, 2013, where mean cloud coverage on the day was 8 oktas. Sunrise at this location is 07:51 and sunset is at 18:59, and for (c) November 11, 2013. Sunrise at this location is 07:50 and sunset is at 16:54. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

cloudy at this location. The Red 305 dye used in the LSC lightguide has peak absorption between 500 and 600 nm. We calculate the Red 305 dye could absorb 30.8% of the incoming photons (to 1300 nm) in the cloudy conditions depicted above and only 27.4% in sunny conditions. Thus, the LSC is able to absorb a greater fraction of the available photons in cloudy conditions than in clear conditions. In absolute terms, the current produced in sunny conditions would still be higher due to the higher absolute number of incident photons. The magnitude of spectral effects by itself is, however, not enough to explain the considerable increase in efficiency in late evenings.

Under sunny conditions, the fraction of light coming in from behind the LSC is small compared to the front side illumination. However, under cloudy conditions and late evenings when the solar disk disappears, the difference between front and back becomes smaller. As a result, this unrecorded rear-side irradiance under cloudy conditions could contribute a larger fraction to the electrical output, affecting the efficiency values.

To test this hypothesis, the pyranometer was switched to face north to measure irradiance coming from the rear side of the device four times in one day. This was first done in sunny conditions at about 12:30 in the afternoon until 13:45 and thereafter in cloudy conditions for short times around 14:00 and 14:30 in the afternoon and finally for about 20 min at about 15:00. The ratio between the measured front (F) and back (B) irradiance are represented by the F/B ratio. As seen from Fig. 5, the F/B ratio is about 8 in sunny afternoons, while it progressively decreases to 1.6 and then 1.2 in cloudy conditions and later afternoon. Thus, during some parts of the day a significant fraction of incoming irradiance is not detected by the pyranometer, resulting in an apparent higher efficiency of the LSC device.

3.3. Effect of gluing the PV cells on performance

The effect of gluing the PVs to the edge of the device was determined by comparing the output of cells pressed firmly against the lightguide edge with those glued to the lightguide edge with an optically clear adhesive: the good optical contact was determined by visual inspection of the joint. As expected, the glued cell performed better than the unglued cell because the air gap between the polymer and PV which causes additional reflections is replaced by the glue which has a significantly higher refractive index,

Fig. 5. Outdoor performance measurements on the 11th of February 2014. The solid blue line represents (vertical) irradiance and the solid red line represents the normalized electrical efficiency. The pyranometer was switched to measure rear side illumination four times during the day, the duration in this situation indicated by black arrows, which results in the sudden drops in the irradiance measurement value. Sunrise time at this location was 07:58 and sunset was at 17:46. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which thus limits reflection (see Fig. 6). However, the performance ratio between the glued to the unglued cell was not constant, as might have been expected. The performance ratio varied with differing sky conditions: the ratio increased under lower light conditions. Specifically, the adhesive seems better equipped to improve light out-coupling under diffuse light conditions than in direct conditions. We speculate that the source of this variation is related to changes in internal light distributions from the anisotropically-emitting fluorophores (Debije et al., 2008; Verbunt et al., 2014, 2013). As the incident light angles vary, so do the emission light distributions, and the distribution of angles for the waveguided light. Encountering the lightguide edge at a steep angle could cause exiting of the waveguide at such a steep angle as to prevent light entering the PV cell for the unglued samples. The improved optical contact of the glue will keep these angles of PV encounter closer to the normal, and thus improved collection probability. Verification of this hypothesis could best be done via ray-trace simulation which would need to include the effective emission profiles of the fluorophores.

3.4. Effect of incident light intensity on performance

In general, the efficiency of solar panels decreases with decreased irradiance (Donovan et al., 2010; Herteleer et al., 2012). However, as seen in Fig. 7, the LSC actually shows increased efficiency at lower irradiance, which results in a power output that is almost linear, even down to very low light levels. This improved performance under low light could also perhaps explain the late day performance improvement of the LSC devices. At the other extreme, PV panels do not perform as well when hot (Davis et al., 2001; Raga and Fabregat-Santiago, 2013; Skoplaki and Palyvos, 2009), while the LSC was shown to run cooler than silicon-based cells, again easing application and minimizing performance impact at high irradiance (Rajkumar et al., 2015). These results suggest the power output of the

Fig. 6. Solar irradiance data (blue line) from the 2nd of April 2014 illustrating the current ratio between glued and unglued solar cells (green line). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 7. Normalized edge mounted PV power output (blue) and normalized edge efficiency (red) as a function of incident solar irradiance. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

LSC device is less prone to spiking than that from a traditional silicon based solar panel, which could be an advantage when moving to increasingly renewable energy streams as a method to reduce the strain on the grid (Ahmed et al., 2008; Daud et al., 2014; Mitchell et al., 2005).

3.5. General discussion

In an urban setting there is a great variety of lighting conditions, both in intensity and spectral distribution. Solar energy generators must contend with clouds, shading, a moving solar disk, and seasonal changes. One of the supposed advantages of employing luminescent solar concentrator devices in the built environment is their relative insensitivity to changes in these lighting conditions. In this work we have attempted to characterize the response of these devices to these types of lighting changes. In general, our results support the widespread assumption that the LSC adapts well to lower light and scattered light situations. In fact, due to the shift of the incident spectra toward bluer light in cloudy situations, the relative efficiency of the device actually increases up to a factor of two, helping maintain a steadier electrical current, even under low light conditions (Figs. 4 and 7).

This research effort is as part of a larger program with the goal of installing a test LSC sound barrier. Photovoltaic-based sound barriers have already been considered or constructed (Bellucci et al., 2003; De Schepper et al., 2012; Nordmann and Clavadetscher, 2004) but for various reasons, whether appearance, fragility or performance, have not yet met with wide acceptance. The LSC could solve many of the challenges associated with using solar energy technologies in roadside constructions (including aesthetics, transparency and durability). The dual-side nature of the LSC device, as evidenced in Fig. 5, should prove to be an additional positive feature of the LSC device, as it is able to process indirect light incident from its rear surface as well.

4. Conclusions

A $60 \times 40 \times 2 \text{ cm}^3$ LSC prototype was subjected to an outdoor performance characterization in Eindhoven, the Netherlands under varied lighting conditions. The key observation was that the LSC device did improve in relative efficiency of the system under cloudy and diffuse light conditions, verifying earlier expectations. The improvement could be quite dramatic with efficiencies more than doubling during such conditions. The reason for this improvement was found to be a combination of the bi-facial nature of an LSC panel and the favorable spectral changes of light under diffuse conditions. For reasons not yet completely understood, it was also determined LSCs employing PV cells adhered to the edges by glue demonstrated higher response to diffuse conditions than the LSC using cells without gluing.

The LSC appears to be less adversely affected by lowered light intensity levels and cloud conditions than the standard PV cell and panel. The LSC could thus be applied in the built environment in a reliable way, with energy output demonstrating less tendency to ‘spike’ under different lighting conditions, and thus making the device easier to integrate in a global energy network, providing a reliable background of power and easing the control mechanisms necessary to deal with rapid changes in performance of renewables. Of course, the absolute output of the LSC is considerably less than a PV panel of the same size. However, the aesthetic difficulty in integrating the PV panel coupled with its sometimes problematic behavior in low light, cloudy, or warm conditions could leave room for the LSC to be used in areas where PV panels are not considered viable.

References

- Ahmed, N.A., Miyatake, M., Al-Othman, A.K., 2008. Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems. *Energy Convers. Manage.* 49, 2711–2719.
- Aste, N., Tagliabue, L.C., Del Pero, C., Testa, D., Fusco, R., 2015. Performance analysis of a large-area luminescent solar concentrator module. *Renew. Energy* 76, 330–337.
- Bakr, N.A., Mansour, A.F., Hammam, M., 1999. Optical and thermal spectroscopic studies of luminescent dye doped poly(methyl methacrylate) as solar concentrator. *J. Appl. Polym. Sci.* 74, 3316–3323.
- Bellucci, P., Fernandez, D., La Monica, S., Schirone, L., 2003. Assessment of the photovoltaic potential on noise barriers along national roads in Italy. In: *Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on*, 2003, vol. 2473, pp. 2474–2477.
- Bowden, S., Rohatgi, A., 2001. Rapid and accurate determination of series resistance and fill factor losses in industrial silicon solar cells. In: *17th European Photovoltaic Solar Energy Conference*, Munich, Germany, p. 5.
- Daud, M.Z., Mohamed, A., Hannan, M.A., 2014. An optimal control strategy for DC bus voltage regulation in photovoltaic system with battery energy storage. *Sci. World J.* 2014, 16.
- Davis, M.W., Fanney, A.H., Dougherty, B.P., 2001. Prediction of building integrated photovoltaic cell temperatures. *J. Sol. Energy Eng.* 123, 200–210.
- De Schepper, E., Van Passel, S., Manca, J., Thewys, T., 2012. Combining photovoltaics and sound barriers – a feasibility study. *Renew. Energy* 46, 297–303.
- Debije, M.G., Verbunt, P.P.C., 2012. Thirty years of luminescent solar concentrator research: solar energy for the built environment. *Adv. Energy Mater.* 2, 12–35.
- Debije, M.G., Verbunt, P.P.C., Rowan, B.C., Richards, B.S., Hoeks, T., 2008. Measured surface loss from luminescent solar concentrator waveguides. *Appl. Opt.* 47, 6763–6768.
- Desmet, L., Ras, A.J.M., De Boer, D.K.G., Debije, M.G., 2012. Monocrystalline silicon photovoltaic luminescent solar concentrator with 4.2% power conversion efficiency. *Opt. Lett.* 37, 3087–3089.
- Donovan, M., Bourne, B., Roche, J., 2010. Efficiency VS. irradiance characterization of PV modules requires angle-of-incidence and spectral corrections. In: *Photovoltaic Specialists Conference (PVSC)*, 2010 35th IEEE, pp. 002301–002305.
- Edelenbosch, O.Y., Fisher, M., Patrignani, L., van Sark, W.G.J.H.M., Chatten, A.J., 2013. Luminescent solar concentrators with fiber geometry. *Opt. Express* 21, A503–A514.
- El-Shahawy, M.A., Mansour, A.F., 1996. Optical properties of some luminescent solar concentrators. *J. Mater. Sci. Mater. Elect.* 7, 171–174.
- Hernandez-Noyola, H., Pottersveld, D.H., Holt, R.J., Darling, S.B., 2012. Optimizing luminescent solar concentrator design. *Energy Environ. Sci.* 5, 5798–5802.
- Herteleer, B., Cappelle, J., Driesen, J., 2012. Quantifying low-light behaviour of photovoltaic modules by identifying their irradiance-dependent efficiency from data sheets. In: *27th European Photovoltaic Solar Energy Conference*, WIP, Frankfurt, pp. 3714–3719.
- Hisdal, V., 1987. Spectral distribution of global and diffuse solar radiation in Ny-Alesund, Spitsbergen. *Polar Res.* 5, 1–27.
- Mansour, A.F., 1998. Outdoor testing of luminescent solar concentrators in a liquid polymer and bulk plate of PMMA. *Polym. Test* 17, 153–162.
- Mansour, A.F., El-Shaarawy, M.G., El-Bashir, S.M., El-Mansy, M.K., Hammam, M., 2002. A qualitative study and field performance for a fluorescent solar collector. *Polym. Test* 21, 277–281.
- Minemoto, T., Nagae, S., Takakura, H., 2007. Impact of spectral irradiance distribution and temperature on the outdoor performance of amorphous Si photovoltaic modules. *Sol. Energy Mater. Sol. Cells* 91, 919–923.
- Mitchell, K., Nagrial, M., Rizk, J., 2005. Simulation and optimisation of renewable energy systems. *Int. J. Electr. Power* 27, 177–188.
- Nordmann, T., Clavadetscher, L., 2004. PV on noise barriers. *Prog. Photovolt. Res. Appl.* 12, 485–495.
- Pravettoni, M., Pravettoni, F., Virtuani, A., Kenny, R.P., Chatten, A.J., Barnham, K.W.J., 2009. Outdoor characterization of luminescent solar concentrators and their possible architectural integration on a historically relevant site in Milan (Italy). In: *Photovoltaic Specialists Conference (PVSC)*, 2009 34th IEEE, Philadelphia, USA, pp. 187–192.
- Raga, S.R., Fabregat-Santiago, F., 2013. Temperature effects in dye-sensitized solar cells. *Phys. Chem. Chem. Phys.* 15, 2328–2336.
- Rajkumar, V.A., Weijers, C., Debije, M.G., 2015. Distribution of absorbed heat in luminescent solar concentrator lightguides and effect on temperatures of attached photovoltaic cells. *Renew. Energy* 80, 308–315.
- Reda, S.M., 2008. Synthesis and optical properties of CdS quantum dots embedded in silica matrix thin films and their applications as luminescent solar concentrators. *Acta Mater.* 56, 259–264.
- Salem, A.I., Mansour, A.F., El-Sayed, N.M., Bassyouni, A.H., 2000. Outdoor testing and solar simulation for oxazine 750 laser dye luminescent solar concentrator. *Renew. Energy* 20, 95–107.
- Seybold, G., Wagenblast, G., 1989. New perylene and violanthrone dyestuffs for fluorescent collectors. *Dyes Pigm.* 11, 303–317.
- Skoplaki, E., Palyvos, J.A., 2009. On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations. *Sol. Energy* 83, 614–624.
- Slooff, L.H., Budel, T., Burgers, A.R., Bakker, N.J., Büchtemann, A., Dantz, R., Meyer, T., Meyer, A., 2007. The luminescent concentrator-stability issues. In: *22nd European Photovoltaic Solar Energy Conference*, Milan, Italy.

- Verbunt, P.P.C., de Jong, T.M., de Boer, D.K.G., Broer, D.J., Debije, M.G., 2014. Anisotropic light emission from aligned luminophores. *Eur. Phys. J. – Appl. Phys.* 67, 10201.
- Verbunt, P.P.C., Sanchez-Somolinos, C., Broer, D.J., Debije, M.G., 2013. Anisotropic light emissions in luminescent solar concentrators – isotropic systems. *Opt. Express* 21, A485–A493.
- Vishwanathan, B., Reinders, A.H.M.E., de Boer, D.K.G., Desmet, L., Ras, A.J.M., Zahn, F.H., Debije, M.G., 2015. A comparison of performance of flat and bent photovoltaic luminescent solar concentrators. *Sol. Energy* 112, 120–127.
- Weber, W.H., Lambe, J., 1976. Luminescent greenhouse collector for solar radiation. *Appl. Opt.* 15, 2299–2300.
- Wilson, L.R., Richards, B.S., 2008. High-efficiency dyes for luminescent solar concentrators – photostability and modelling. In: 23rd European Photovoltaics Conference, Valencia, Spain.
- Wilson, L.R., Richards, B.S., 2009. Measurement method for photoluminescent quantum yields of fluorescent organic dyes in polymethyl methacrylate for luminescent solar concentrators. *Appl. Opt.* 48, 212–220.