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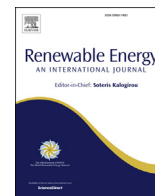
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The solar noise barrier project: 2. The effect of street art on performance of a large scale luminescent solar concentrator prototype



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ABSTRACT

Noise barriers have been used worldwide to reduce the impact of sound generated from traffic on nearby areas. A common feature to appear on these noise barriers are all manner of graffiti and street art. In this work we describe the relative performance of a large area luminescent solar concentrator (LSC) noise barrier before and after application of street art to one surface. Comparisons are made of performance of East/West facing panels during a sunny day. It is shown that the edge mounted solar cells that are further away from the artwork perform at about 80% of their original performance level, while cells mounted nearby show greater performance decreases, suggesting that the effect of street art is primarily a localized effect. Furthermore, we demonstrate that illumination by sunlight from the rear side of the panel, opposite to the artwork shows less of a performance drop. In summary, the overall performance of a large-scale prototype LSC device is affected by the application of street art due to blocking solar access to the surface, but the effect is mostly confined to areas in the immediate vicinity of the surface modification, and the remaining panel area continues to function at a reasonable level.

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1. Introduction

As lessening dependence on oil for energy production has become a priority in many areas, solar panels are becoming ubiquitous with the landscape in many parts of the world. While the silicon-based solar panel has begun appearing on many rooftops, there remains a considerable challenge in bringing them successfully into places of concentrated habitation, such as cities [1,2]. Besides the aesthetic problems of integration (silicon based panels tend to be uniform in size and shape, and in only one color) there are practical problems as well, such as general fragility, and dependence on direct light for best performance [3].

The luminescent solar concentrator, or LSC, has been suggested as an option for bringing solar energy to the city setting [4]. The LSC is generally a simple device consisting of a luminophore (fluorescent dye or inorganic quantum dot) embedded in a polymer host [5–9]. The luminophore absorbs sunlight, and re-emits the light at a longer wavelength. A significant fraction of this light is trapped in the polymer lightguide by total internal reflection, and travels

towards the edges, where photovoltaic cells (PVs) are attached to convert the emission light to electricity (see Fig. 1 for a depiction of LSC performance).

Any solar energy generator destined for use in an urban setting will be subject to various degrees of shading from trees, pedestrians, grime, or a myriad of other sources [10]. The effects of shading on PVs have been well documented [11–14]. In general, PVs are negatively affected by surface shading but there are several concepts that use different cell interconnection approaches to reduce the negative effects of shading [15,16]. There is much less information available about the shading of LSC panels [17].

In this work, we first report on the effect of shading of a scale model LSC device in the laboratory to find the effect on edge output of light blockage of differently sized obstructions at various distances from the edge-attached photovoltaic cells. As part of our program to determine the performance of an LSC device in the built environment, we previously revealed the effects of device frame shading on LSC performance of a full-scale LSC noise barrier (the SONOB project) [18]. For this paper, we use the results of the work on the scale model to help describe the effect of graffiti and street art [19] applied to the lightguide surface of the full-size solar noise barrier.

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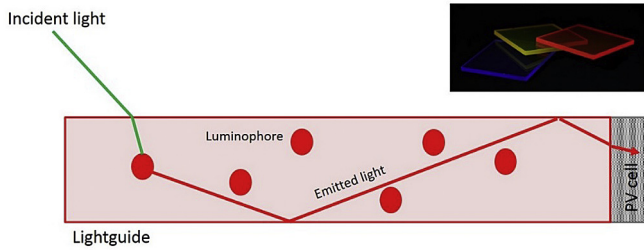


Fig. 1. Depiction of the performance of a luminescent solar concentrator (LSC). Incident light (green arrow) is absorbed by a luminophore and emitted at a longer wavelength (red arrow). The light is conducted down the lightguide and exits the edge into an attached PV cell. (Inset) Photograph of three LSC lightguides under ultraviolet illumination. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Experimental

The construction of a smaller-scale $60 \times 40 \times 2 \text{ cm}^3$ prototype LSC made from PMMA in an aluminum frame and mounted with nine $6 \times 4 \text{ cm}^2$ photovoltaic cells along the top and bottom edges was previously described [17]. For the large-scale experimental setup, two cast PMMA plates $1 \times 5 \times 0.012 \text{ m}^3$ were used. One contained the fluorescent dye Lumogen Red305 [20] and one contained the fluorescent dye Lumogen Orange240 (both dyes from BASF). At the top and bottom panel edges were attached with two strips of series connected monocrystalline silicon PV cells, each containing seven $12 \times 78 \text{ mm}^2$ cells with fill factors around 80%. The strip pairs were mounted at four different locations on the LSC plate, labelled TS (Top, Side), TM (Top, Middle), BM (Bottom, Middle) and BS (Bottom, Side) by an optically transparent silicone-based flexible glue. White tape masked the overhang of the mounting frame of the barrier with the edge of the LSC lightguide plate. The performance of each of the four cell strip pairs was independently monitored. A white scatterer was attached to the vertical edges of each LSC panel. The assembly of the panels was overseen by Van Campen Industries.

The assembled noise barrier was installed facing East/West along a major traffic road in the city of ‘s Hertogenbosch, the Netherlands, by Heijmans. The barrier reclined 15° towards the East. The barriers’ wiring to the detectors was performed by SEAC. An EKO MS-802 pyranometer was mounted atop the barrier, in plane with the front and rear side to collect irradiance information. The output of the PV cells was monitored by an EKO MP-160 IV tracer in combination with a number of switching units.

3. Results and discussion

3.1. Model device

A potential advantage of using an LSC device is to maintain performance even when a shadow is cast on the device. The solar cells on the LSC device receive luminescence from all directions within the waveguide and are not explicitly dependent on direct irradiation of the attached PV cells. In order to measure the effect of surface shading of an LSC, we first tested the response of shadows on a $60 \times 40 \times 2 \text{ cm}^3$ LSC. This was done by covering different areas of the LSC surface with opaque aluminum sheets and measuring the output of edge-attached PV cells at various locations. Fig. 2 shows the positioning of a $5 \times 5 \text{ cm}^2$ aluminum mask between the illumination source and the LSC device. Similarly, Fig. 3 demonstrates the positioning of a $10 \times 10 \text{ cm}^2$ aluminum mask in front of the LSC. The results of PV cell outputs for four different locations are depicted in Fig. 4 for these two sets of shading arrangements.

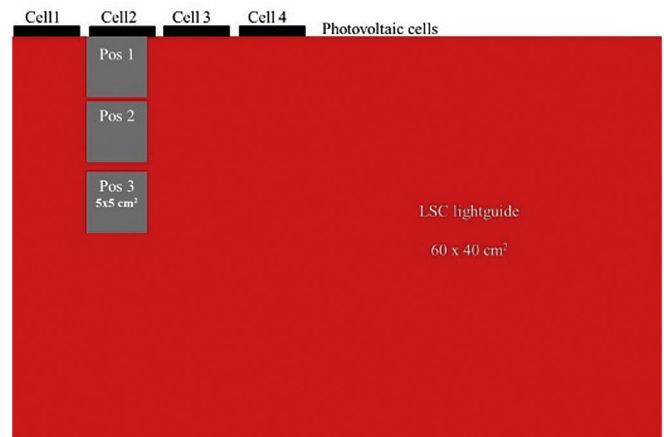


Fig. 2. Positioning of the $5 \times 5 \text{ cm}^2$ obstruction on the LSC prototype. Pos. 1: 5 cm away from the (left) vertical edge, placed at the (top) horizontal edge boundary, Pos. 2: 5 cm away from the vertical edge, 5 cm below the horizontal edge. Pos. 3: 5 cm away from the vertical edge and 17.5 cm below the (top) horizontal edge.

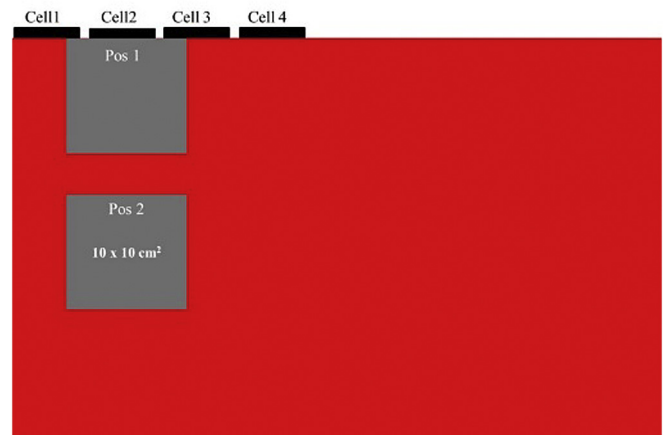


Fig. 3. Positioning of the $10 \times 10 \text{ cm}^2$ obstruction on the LSC prototype. Pos. 1: 5 cm away from the (left) vertical edge, placed at the boundary of the (top) horizontal edge. Pos. 2: 5 cm away from the vertical edge, 15 cm below the (top) horizontal edge.

In general, the effect of the obstruction on LSC performance is quite localized, and the performance of nearby cells is modestly affected. When the obstruction is placed close to the edge as in Pos. 1, the performance of cell 2 drops by about 50% in case of a $5 \text{ by } 5 \text{ cm}^2$ obstruction and 70% in case of a $10 \text{ by } 10 \text{ cm}^2$ obstruction (see

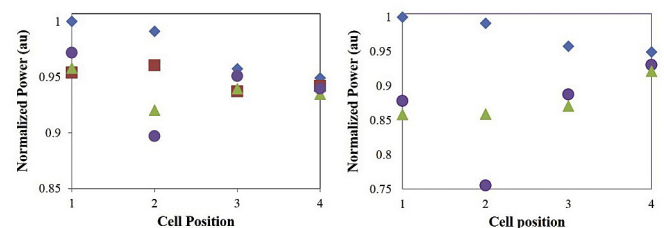


Fig. 4. (Left) Normalized unshaded solar cell power output for top four cells (blue diamonds), and with $5 \times 5 \text{ cm}^2$ obstruction located at Pos. 1 (violet circles), Pos. 2 (green triangles) and Pos. 3 (red squares). (Right) Normalized unshaded solar cell power output for top four cells (blue diamonds), and with $10 \times 10 \text{ cm}^2$ obstruction located at Pos. 1 (violet circle), and Pos. 2 (green triangle) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Figs. 2–4). As the obstruction is moved progressively away from the edge, such as in Pos. 2, the performance of the cell improves, which leads to the obvious conclusion that the LSC surface area closest to the solar cell contributes the most towards the output, consistent with previous findings [21]. Cells to either side, more distant from the obstruction are much less impacted by the shading element (note cells 1, 3, and 4 for the $5 \times 5 \text{ cm}^2$ obstruction and cell 4 for the larger $10 \times 10 \text{ cm}^2$ shading element in Fig. 4). It is worth examining the impact of the cell partial shading of cells 1 and 3 in the two cases. For the $5 \times 5 \text{ cm}^2$ obstruction, there is only a ~5% performance drop at positions 1 and 3, as the obstruction has little direct overlap with the area covered by the attached cells, and is responsible for the 10% performance drop of cell 2 which it directly shades. For the $10 \times 10 \text{ cm}^2$ obstruction, the edges of the blockage extend into the areas covered by cells 1 and 3, and there is a drop of closer to 12%, while the directly covered cell 2 loses 25% in performance.

3.2. Full-scale device

The application of graffiti and street art is a potential risk for any solar noise barrier. Any covering of a solar energy harvesting panel will naturally affect the electrical output as incident light is prevented from entering the lightguide surface. In order to test the effects of surface painting on large-scale LSC devices, we made use of the $5 \times 4 \text{ m}^2$ noise barriers made up of two $5 \times 1 \text{ m}^2$ LSC devices (one red and one orange in appearance) and two $5 \times 1 \text{ m}^2$ silicon-based solar panel installations which were produced as part of the SONOB project. A depiction of the device geometry may be found in Fig. 5.

It is common to employ anti-graffiti coatings for polymeric objects used in areas sensitive to application of undesired street art. Initially, we applied an anti-graffiti coating to the right side (facing the panel) of the device on May 12, 2016. Fig. 6 depicts the performance ratio of the Red filled panels during the measurement period. We have compared performance using the ‘performance ratio’, PR, for the attached cells. The definition of PR is [18]:

$$PR = \frac{\text{Field Efficiency}}{\text{Theoretical Efficiency}} = \frac{P_{\text{measured}}(W)}{P_{\text{rated}}(W)} \times \frac{E_{\text{stc}}(W/m^2)}{E_{\text{measured}}(W/m^2)} \tag{1}$$

where $E_{\text{stc}} = 1000 \text{ W/m}^2$, P_{rated} was the nominal power outputs of the cell, P_{measured} was determined from the maximum power point on the PV cell strip I-V curve as measured before assembling the LSC panels, and the total measured irradiance from both sides of the LSC panel at the test site is E_{measured} . None of the cells demonstrated

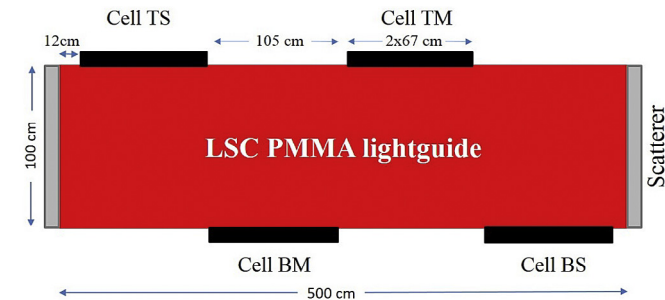


Fig. 5. Schematic of the LSC device, including attachment points of the photovoltaic cells labelled TS (Top, Side), TM (Top, Middle), BM (Bottom, Middle) and BS (Bottom, Side) (Figure reproduced from ref. [18]).

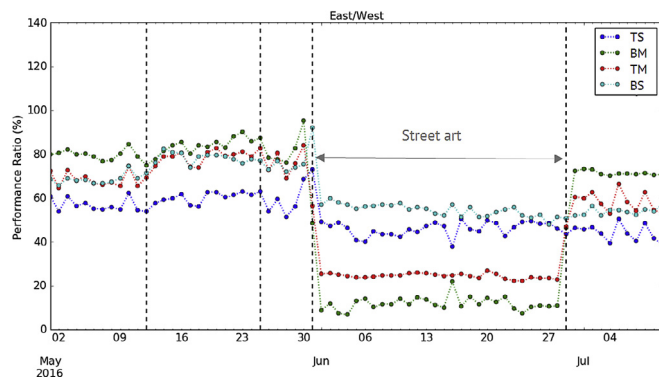


Fig. 6. Performance Ratio of the c-Si cells of the East/West red LSC panel.

obvious performance drops, which is encouraging, suggesting the anti-graffiti coating material had a lower refractive index than the LSC plate and thus did not significantly interfere with the light-guiding of the polymeric plate.

In Fig. 6, a period of two and a half months was chosen to be presented, containing the ‘pre-coated’ period from May 1–12, the ‘coating’ period from May 12–31, the ‘graffiti applied’ period from May 31–June 29 and the ‘graffiti removed’ period from June 29 until the end of the field testing in July.

The graffiti artwork, a portrait of Nikola Tesla, was applied May 31, 2016 using commercial spray paints over the period of about 8 h, and is depicted in Fig. 7. The image effectively blocked incident sunlight from the West in the covered areas.

As may be seen in Fig. 6, the PV cells attached directly adjacent to areas of the LSC coated with the paint demonstrated significant performance drop (>80% drop for the BM and slightly less for the TM). Areas which were more distant to the painted areas, however, showed much smaller drops in performance (closer to 30% drops for the BS and TS). This is consistent with earlier findings [17] and those shown in Fig. 4 which indicate the LSC is mainly affected by shading in the immediate area of the obstruction, while the rest of the device performs relatively normally. Of course, the more distant cells also suffered slightly in performance, probably due to light-guided light lost by outcoupling or absorption by the dark paints.



Fig. 7. Photograph showing street art design on the surface of the LSC panel: position of solar strips indicated in the figure by textured bars (LSC artwork courtesy of Gart Smits, photo courtesy Stijn Verkuilen).

Figs. 8 and 9 sample the performance of the red panel every 10 min over the period of two different days. The first day is May 9, 2016 which was before the application of the graffiti, and the second day is June 9, 2016, after application of the graffiti. There are a number of interesting observations. For cells located more distantly to the image, there is a decrease in the performance due to loss of light traveling from the distant locations (TS and BS in Fig. 8) for both the BS and TS cells; both rear (in the earlier morning, before ~11.00) and front panel illumination (after ~11.00) result in similar responses before and after application of the artwork.

However, the situation is slightly different in the case of the more centrally mounted cells. While both cell locations BM and TM display decreased performance after application of the image (Fig. 9), the front and rear responses appear to show more variation between the unpainted and painted periods. In particular, the BM shows a similar response to illumination in the painted sample as the unpainted in the morning (before ~11.00) while the sun illuminated the rear of the panel (light incident from the East), but the response is very different later in the day (roughly later than ~11.00) as the sun is incident primarily on the front of the panel (light incident from the West). This suggests that the LSC panel continues to process incident light striking the unmodified light-guide surface with reasonable efficiency despite the presence of a painted image on the side opposite the illumination. Previous work has shown a scattering element to the rear side of a device can enhance performance of an LSC device [21]: the painted image in this work is acting as such a scattering element for light incident from the East. The performance is still substantially reduced compared to the pristine lightguide: the painting on the front face will result in additional light outcoupling and perhaps reduced rear side reflection and thus present additional losses of guided light. However, this also demonstrates a potential advantage of the LSC device: even if one face of the device is compromised, the device is still able to absorb and transport light and does not result in the complete failure of performance.

Finally, June 29 the image was removed as shown in Fig. 10. This involved a physical rubbing of the surface of the LSC device and the application of warm water to the anti-graffiti coated side, and a solvent to the non-coated side. The performance of both cells attached close to the painted region (TM and BM) showed an improvement over the painted performance, although not to the level of the original state (See Fig. 6). Personal observation of the plate shows a somewhat hazier surface and evidence of the patterns used by the cloths in cleaning the surface, resulting in additional

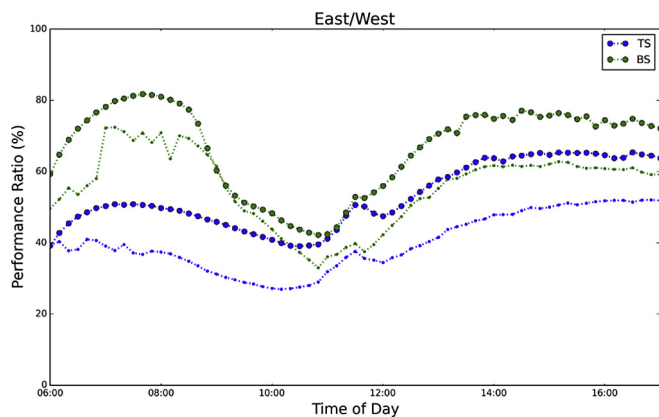


Fig. 8. Measured performance ratio of BS (green) and TS (blue) cells on May 9, 2016 before addition of graffiti (large dots) and June 9, 2016 after addition of graffiti (small dots) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

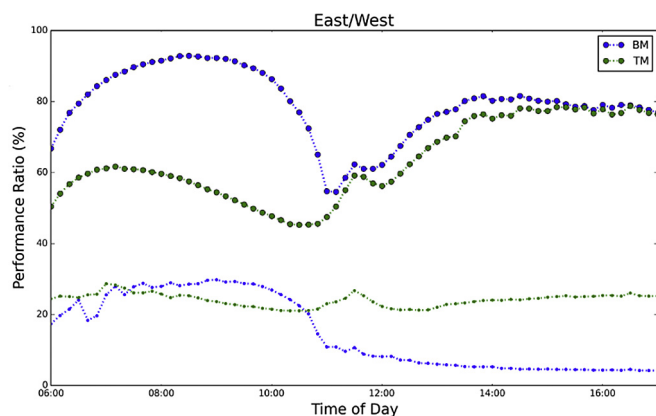


Fig. 9. Measured performance ratio of BM (blue) and TM (green) cells on May 9, 2016 before addition of graffiti (large dots) and June 9, 2016 after addition of graffiti (small dots) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).



Fig. 10. Photograph after partial removal of street art design on the surface of the LSC panel.

surface losses. This would suggest that the polymer surface of the LSCs was negatively affected by removal of the artwork, and in future additional care must be taken to effectively remove the street art and avoid additional surface losses in the device.

4. Conclusions

In this work we describe the effects of adding street art to the surface of a full-scale luminescent solar concentrator device. While the performance of edge-attached photovoltaic cell strips decreases in the immediate vicinity of the covering paint, cells more distant continue to function relatively normally. Light incident upon the rear of the device, that is, opposite to the side on which the obstructive image is applied continues to be absorbed, emitted, and lightguided. As a result, and the LSC still functions, albeit with additional losses resulting from outcoupling of the dye-emitted light by the paint. The LSC proves itself to be a relatively robust outdoor solar energy generator, bringing the device one step closer to commercialization.

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