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CREATIVE USE OF BIPV MATERIALS: BARRIERS AND SOLUTIONS

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ABSTRACT: Inventive use of photovoltaic (PV) materials in architecture can be developed through use of PV in artworks. This is particularly important in increasing the uptake of building-integrated building-integrated photovoltaics (BIPV), by developing novel methods of combining and installing PV materials. Current examples of PV artwork and design are examined, from small to large scale, to assess the current design limitations. The design of two PV artworks is discussed in detail, including an artwork that uses the principle of the luminescent solar concentrator (LSC), to show the way in which design hurdles are discovered and overcome. Challenges range from difficulties in obtaining small quantities of PV materials; the balance between efficiency and artistic effect; through to technical and siting issues that an artist must address when designing a functional PV structure. Methods of overcoming these barriers are explored, including the use of lumogen dyes in encapsulant materials.

Keywords: Design; Fabrication; Performance; Concentrators

1. INTRODUCTION

Artistic use of photovoltaics (PV) encourages experimentation with methods of installing PV, as well as drawing attention to PV installations. This creates further awareness of PV as a way of generating electricity, encouraging wider uptake of building-integrated photovoltaics (BIPV).

1.1 Precedent

Artistic use of PV is defined here as any innovative method of positioning PV or of combining it with other materials specifically to draw attention to the use of PV or to the structure in which the PV is installed. Crystalline silicon PV is currently the type of PV most widely used in artworks. The combination of efficiency and longevity, combined with the fact that individual cells can be positioned as required, currently makes it the most practical choice from the range of available PV materials [1].
There are particular problems associated with use of PV in artworks, as opposed to other materials. The design constraints are summarised by the need to:

- Ensure optimal light is incident on the PV
- Ensure that each PV element in a design functions as part of an electrical circuit, in balance with the other PV cells
- Incorporate accurate cell tabbing and other electrical connections into designs
- Work with the standard, rectilinear shapes of most PV cells and arrays [2]
- Work with the ‘high-tech’ surface finish of PV cells
- Design with the blue or black colour of most PV; or use coloured PV, with lower efficiency
- Design for degradation of PV after 25 to 30 years of installation

Table 1 (below) shows examples of existing PV artworks, demonstrating a range of methods that have been used to work with the current design constraints.

1.2 An alternative: the luminescent solar concentrator (LSC)

One alternative method of incorporating PV into a structure is to use the principle of the luminescent solar concentrator (LSC) [3]. This consists of a sheet of translucent material – normally plastic such as polymethylmethacrylate (PMMA) – containing fluorescent organic dyes. Incident light is trapped between surfaces of the material, with total internal reflection leading to a concentration of light at the edges of the sheet. The light is then guided to thin strips of PV cell, glued to the edge of the plastic (see Figure 1).

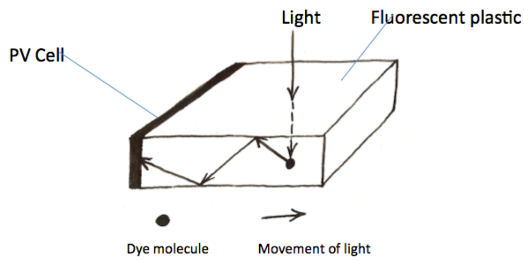
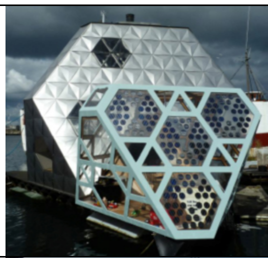
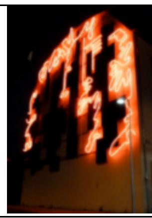


Figure 1: The principle of light collection via an LSC.

LSC’s offer an alternative method of incorporation of PV into artworks, with use of brightly coloured, translucent plastics, and PV cells hidden at the edges. The disadvantage is the low efficiency [4], but they could prove useful where low amounts of power are required at the source of generation; for example, for adjustment of shading-levels, at varying levels of light intensity, in windows [5].

Table I: Examples of PV artworks and innovative use of BIPV in architecture.

Details of artwork and location (All photographs by Dorothy Hardy, 2011)	**Photo**	**Way in which limitations of design with PV are overcome**
Houseboat in Copenhagen, designed by Cecilia Wendt and Rikke Luther		Wide spacing of cells to allow light through to the interior. Use of circular cells and a novel array shape
Anita Jørgensen's PV and neon artwork on the side of Prøvehallen, Valby, Denmark		 Novel array layout with neon lighting over the PV cells.
Photovoltaic array in Eriksgade, Copenhagen		Novel siting and array shape

2. METHOD

Two experimental PV artworks were designed with the aim of finding ways of incorporating PV cells into translucent artworks for display in windows.

The two artworks (as shown in Figure 2) used two different principles:

1. Incorporating PV cells in a standard array;
2. Using the LSC principle to make an artwork.

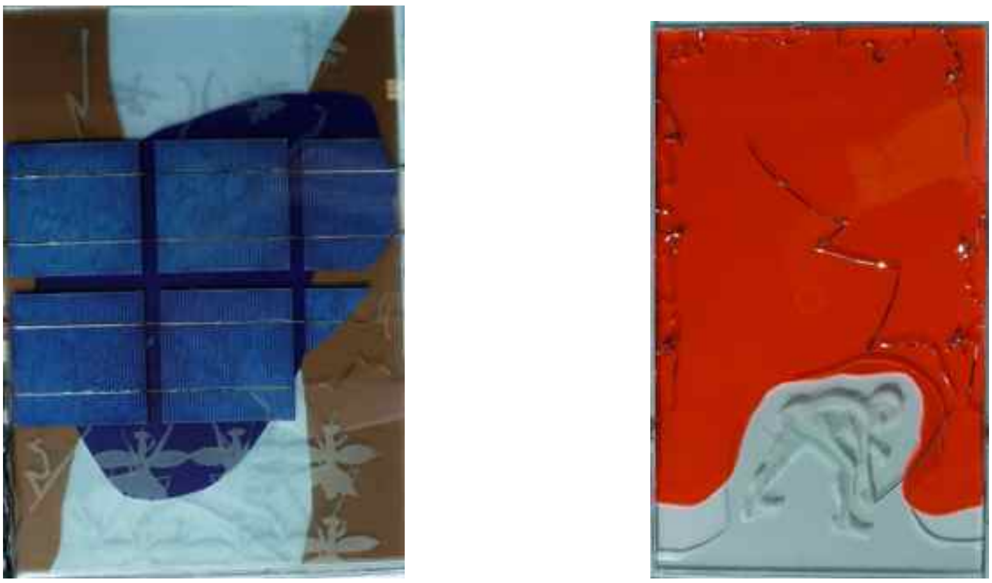


Figure 2: (Left) Artwork incorporating PV in a standard array, with cells positioned perpendicular to incoming light; (Right) LSC-based artwork, with PV strip cells glued to the edges of fluorescent PMMA, to receive light transmitted by total internal reflection.

2.1 Details of both artworks

Silicon cells (X Group, Italy) were used in the standard array construction. Manufacturer's data for these cells gives an expected power between 3.75 to 4.04W at 1000 Wm^{-2} [6].

The LSC artwork incorporated laser-groove, buried-contact (LGBC) silicon strip cells fabricated by NaREC (UK). Tabbing strips were soldered to the `PV strip cells, which were then glued to the edges of fluorescent, red PMMA sheets with a two-part epoxy glue.

Both artworks incorporated engraving on glass: to add detail around the standard array and to provide a focal point in the LSC artwork. In the design of the artwork with a conventional PV array, the aim was to detract attention from the square PV cell shapes by use of a curved piece of blue glass behind the PV cells, and by incorporating broken PV cells into the array shape. These broken cell pieces were not connected into the electrical circuit. Sections of metal tabbing strip were used decoratively across the LSC artwork. These reflected light, especially in conditions of low lighting, adding interest to the artwork. The artworks were secured between sheets of float glass using UV-cure glue. The process of design and construction of the two artworks enabled the main obstacles to PV artwork construction to be identified. Table II gives details of these.

Both artworks and the test piece were tested in solar simulators to discover the amount of electricity that each would generate under standard test conditions. The larger solar simulator, used for the two artworks, contained Osram metal halide lamps (type HMI 1200 W/SEL) with parabolic reflectors. It was necessary to test the artworks at irradiances lower than the standard 1000 Wm^{-2}. An average irradiance of 365 Wm^{-2} was used for the artwork with the standard PV array, and 351 Wm^{-2} for the LSC artwork. Temperatures varied between 22 and 48C in this simulator, but were kept at the standard 25C for measurements in the ABET solar simulator. Individual PV cells of the type used in each artwork were tested with the artworks, in the solar simulator that incorporated metal halide lamps, and then in the ABET solar simulator, at standard test conditions of 1000 Wm^{-2} and 25C.

Table II: Design and construction hurdles for PV artworks: standard and LSC.

Process to be achieved	**Design hurdles for artwork with standard array**	**Design hurdles for LSC artwork**	**Methods of overcoming limitations**
Sourcing PV cells	Difficulties in finding suppliers prepared to sell small quantities of PV cells without encapsulation	Difficult to source the long, thin strip cells needed.	Use high-speed saws or laser cutting to make strip cells from standard, square PV cells
Deciding where to include PV cells in an artwork	Ensuring that the PV receives optimum amounts of light, through correct siting and use of PV cover glass, not standard, float glass	The need for straight edges to attach crystalline PV cells with good optical coupling. Current-matching requirements for optimal power generation	• Casting PV within LSC's • Use of flexible PV (lower efficiency)
Creating an electrical circuit with PV cells	Learn cell tabbing method Solder tabbing to cells accurately	Solder tabbing to thin strips of PV cell then connect up the circuit	Use of conductive tape instead of solder
Connecting charging and dissipation circuits	The need to find/design electrical components that fit in with the artwork.	Find uses for very small amounts of power	Use of off-the-shelf circuits

2.2 LSC made by staining EVA sheet

An LSC test piece was constructed by dyeing EVA encapsulant material. This method gave a way of adding a fluorescent layer without the need to use a sheet of plastic such as PMMA.

Lumogen dyes can be included in encapsulants for luminescent down-shifting [7], or to create a fluorescent layer for use in a LSC [3]. The LSC test piece was constructed using EVA sheet stained with the fluorescent dye, BASF Lumogen Red 305 (Figure 2a). The dye was dissolved in toluene, then the solution was poured onto the EVA sheet and spread out using a glass pipette. Once the EVA sheet had dried, it was laminated between sheets of float glass. A PV strip cell was made by cutting a NaREC 18%-efficient, screenprinted cell into strips. One cell was glued to the side of the glass to create a basic LSC (as shown in Figure 2b).

Figure 2a: EVA sheet stained with Lumogen Red 305 dye, then laminated between sheets of float glass.

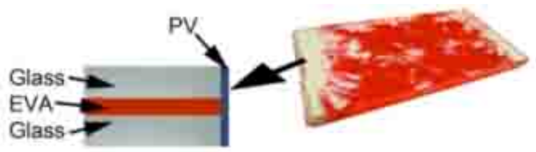


Figure 2b: Structure of the LSC made using the process described in section 2.2.

3. RESULTS AND DISCUSSION

3.1 Artistic results

The design process as carried out was focused on fitting PV into artworks in novel ways. The methods used were:

Standard array

- Translucent, coloured glass shapes behind PV cells to avoid an overall impression of blue and black squares
- Use of broken PV cells, to add contrasting shapes
- Engraved details on glass to add interest

Luminescent solar concentrator artwork

- Use of brightly-coloured, fluorescent PMMA sheet
- PV cells hidden at the edges of the artwork
- Tabbing strip used decoratively

3.2 Ideal design process

Ideally, the electricity use for each artwork would have been decided at the start of the design process, and the solar array sized accordingly. The ideal design process for a PV artwork that is not connected to the grid, is:

- Decide on a use for the electricity to be generated by the artwork
- Decide on the required amount of electricity, including storage options
- Assess lighting levels in the chosen location
- Decide on the type of PV cell to be used and the required array size
- Fit the PV array into the artwork design

Use of this process puts the design of the artwork itself at the end of a long series of decisions. Choosing to focus on ways of fitting PV into artworks highlighted the possibilities for innovative design with PV, but meant that electricity use was not considered until the artworks were completed.

A charge-dissipation circuit, containing an LED and two AA-size batteries, was constructed for the artwork with the standard PV array. It was necessary to construct a circuit that doubled the voltage from the array in order to charge the batteries effectively. The circuit was designed so that the LED illuminated at low light levels. Siting the array in a window or in a gallery setting with standard illumination would make use of an LED impractical, as lighting levels would not, normally be low enough for the LED to illuminate in daylight hours, when viewers were present. Use of a device generating sound or movement could be more appropriate for these settings, but would have to be designed to fit with the artwork [8].

3.3 Performance of the artworks

The current-voltage (I-V) and power-voltage (P-V) curves were compared (see Figures 3 and 4), to show the deviation from standard test conditions in the larger solar simulator, which was used to measure the performance of the artworks. The simulator containing metal halide lamps was operated at a much lower power than the ABET solar simulator, resulting in much lower current and power from both types of PV cell; with voltage also slightly reduced. The light spectrum from the metal halide lamps differed from that produced by the ABET solar simulator, creating a slightly uneven P-V curve for the X group cell.

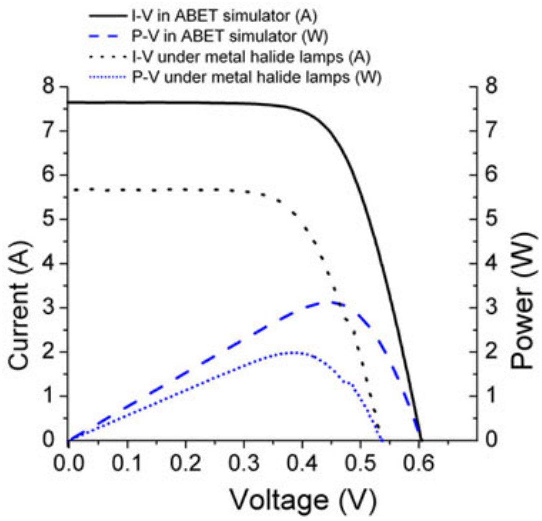


Figure 3: I-V and P-V curves for X group cells under two solar simulators.

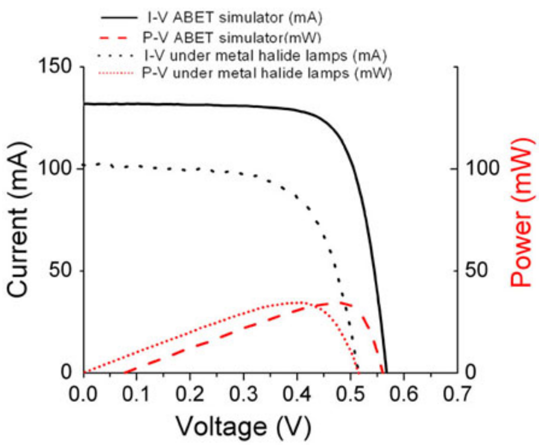


Figure 4: I-V and P-V curves for Narec PV strip cells under 2 solar simulators.

The two artworks were tested in the large solar simulator that contained metal halide lamps. The I-V and P-V curves for the artworks (as shown in Figures 5 and 6) are each compared with an I-V curve from an individual PV cell, of the type used in the artwork: an

X group cell for the artwork with the standard PV array design; and a PV strip cell for the LSC artwork. This shows how performance varies between individual PV cells and cells connected up as part of each artwork.

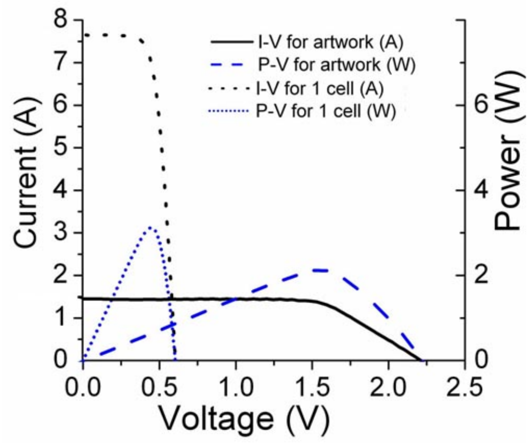


Figure 5: Comparison of I-V and P-V curves for the artwork with the standard PV array and a PV cell of the type used in the artwork under metal halide lamps.

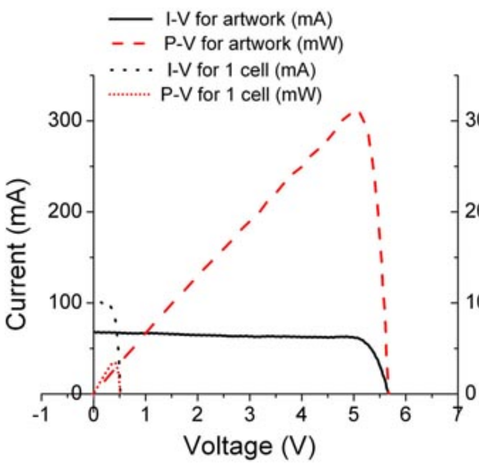


Figure 6: Comparison of I-V and P-V curves for the LSC artwork and for a PV strip cell of the type used in the artwork under metal halide lamps.

The artwork with a standard PV array produced a current and power much lower than expected, as shown in Figure 5, where the current from an individual cell is 7.7A, but the artwork produces only 1.5A. This could be due to faults in the circuitry, or to the use of standard float glass, instead of photovoltaic cover glass, leading to less light reaching the cell. Circuitry in contact with the tin layer, that is present on float glass, could also have caused loss of electrical power.

The LSC artwork contains 11 PV strip cells, and displayed a voltage just over 11 times that of 1 strip cell, but with a reduced current. Light reaches the PV cells, which are attached to the edges of the LSC artwork, by a process of total internal reflection through the PMMA. Losses take place in this process [3] resulting in a reduced current from the PV cells.

3.4 LSC made with dyed encapsulant

A comparison was made between the amount of electricity generated by one PV strip cell, and by the LSC itself (Figure 7). The LSC functioned, producing a small amount of power, proving that the concept worked. The difference between current produced by the strip cell, and that produced by the LSC, is greater than that shown for the LSC artwork and strip cell (Figure 6). This could be due to fluorescent dye being less well distributed through the EVA than through the PMMA, and the fact that the glass layers, with which the PV cell is also in contact, do not contain fluorescent dye, creating an LSC with dye contained in one, thin layer. The boundaries between glass and EVA are also likely to cause some losses as light moves across them, during total internal reflection, resulting in less light reaching the PV cell at the edge of the device.

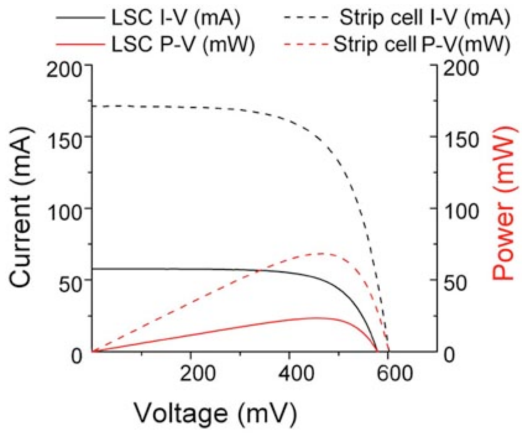


Figure 7: I-V and P-V curves for an LSC made with dyed encapsulant, and for a single PV strip cell, in the ABET solar simulator.

4 CONCLUSIONS

A design process that focused on use of PV as an artistic medium, led to designs that were not dominated by blue and black, square PV shapes, and allowed exploration of several ways of incorporating PV into artworks. Ideally, electricity use would have been considered at the same time as the artistic design process.

Luminescent solar concentrator artworks, where the PV cells are hidden at the edges, offer the most design flexibility, but produce least electricity. They could be useful for applications where very low amounts of power are required. Use of fluorescent dyes in PV encapsulant materials is also promising as a way to add variety to PV arrays at minimal additional cost.

5 ACKNOWLEDGEMENT

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