Improving the aesthetics of photovoltaics in decorative architectural glass

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Abstract

Increasing colour variety in photovoltaics can improve the uptake of this renewable technology, which is vital to the creation of sustainable architecture. However, the introduction of colour into photovoltaics often involves increased cost and decreased efficiency. A method was found to add colour to photovoltaics, using luminescent materials: fluorescent organic dyes (BASF Lumogen). These selectively absorb and emit light, giving a good balance between colour addition and electricity production from underlying photovoltaic cells. Very small amounts of Lumogen dye were added to a silicone encapsulant (Dow Corning Sylgard 184), which was then used hold photovoltaic cells in place between sheets of painted glass. When making sufficient quantities of dyed encapsulant for a 600 x 450 mm testpiece, the dye colours faded, with low levels of fluorescence, although some colour was retained. Improvement of the method, including testing of alternative encapsulant materials, is required, to ensure that the dyes continue to fluoresce within the encapsulant. Although the Lumogen dyes are quite stable when compared to other dye molecules, in general organic dyes are not yet sufficiently durable to make this technology viable for installations that are to last for more than 20 years: the guaranteed lifetime of standard photovoltaic modules. Dye replenishment, or replacement of materials, will be required; or a product with a shorter 'useful' lifetime identified. This method opens up a wide variety of architectural glass design opportunities that incorporate photovoltaics, providing an example of one new medium to make eco-architecture more aesthetically pleasing, whilst generating electricity.

Keywords: photovoltaics, colour, encapsulant, Sylgard 184, architectural glass, luminescent, fluorescent organic dye, Lumogen dye, net-zero-energy building, sustainable.

WIT Transactions on Ecology on The Built Environment, Vol 142, © 2014 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/ARC140331

1 Introduction

Photovoltaics (PV) can be integrated fully into the built environment, so this renewable technology is vital in the move towards net-zero-energy buildings [1]. PV needs to be an attractive proposition for building designers and users, in order to compete with the range of materials that are now available to architects [2]. The majority of standard PV modules contain PV cells made from blue or black squares of crystalline silicon [3] which offer the best combination of efficiency, durability and price [4]. PV can be integrated into in any space on a building surface that is not shaded: roofs and facades are the most common.

Work to improve variety in PV has included addition of colour. One way of achieving this is to alter the thickness of the anti-reflection coating on the surface of crystalline silicon PV cells [5] (Figure 1(a)). This is useful in architecture where the PV cell surfaces are to be on view. Many distinctive PV installations are in light-transmitting applications [6], where the contrast between opaque PV cell shapes and surrounding areas of light-transmitting glazing, are the main feature, as shown in the testpiece in figure 1(b). Colour is noticeable in the spaces between the PV cells, so alternative methods of colour addition need to be used. A variety of architectural glass art has been created, using crystalline silicon PV [7, 8]. It is relatively easy to retrofit glazing into buildings, so improvement of the appearance of PV within architectural glass could increase the uptake of building-integrated PV, by giving a wide range of design options for both new and existing buildings [9]. If PV is to be used in a wide variety of architectural glass, then there needs to be a method of softening both the sharpness of rectilinear patterns and the strong contrasts between opaque and light-transmitting areas of glazing.

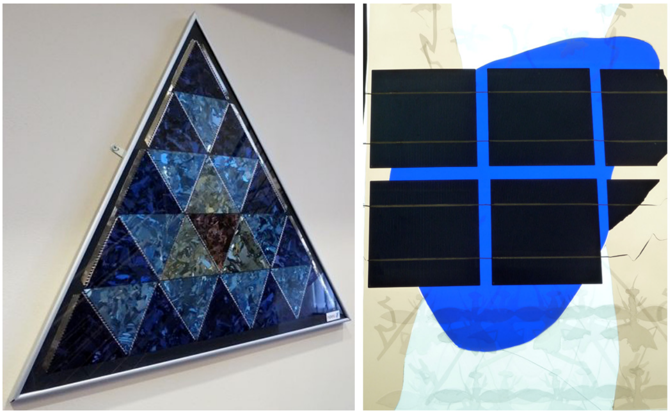
(a) (b)

Figure 1: (a) Triangular module, made up from PV cells that have been coloured by varying the thickness of the anti-reflection coating; published with permission from Solar Capture Technologies, U.K. (b) Opaque, square and broken PV cells in a light transmitting, decorative glass testpiece made by Sigrid Blekastad.

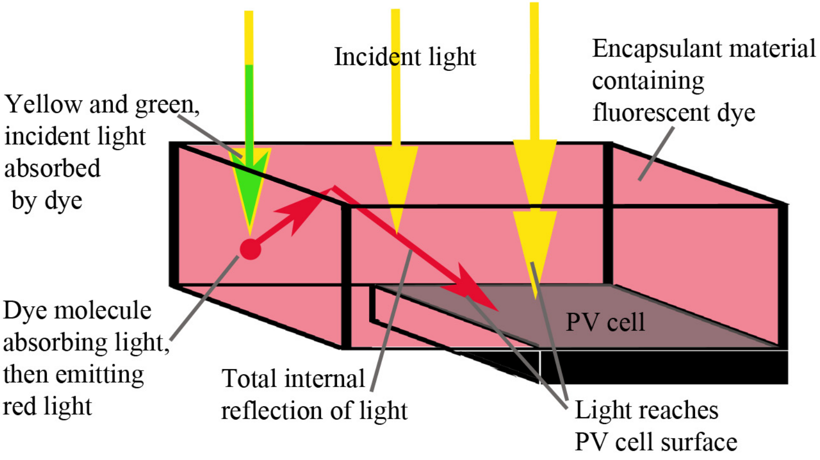

Figure 2: Schematic of light being absorbed by a Lumogen Red 300, fluorescent dye molecule; emitted at a longer wavelength; then moving through the encapsulant material, until it reaches the surface of a PV cell.

2 Aim

The aim of the work described here, was to add colour to light-transmitting PV, whilst blending the stark opacity of square PV cells into a curvilinear design.

3 Theory: use of fluorescent dyes in silicone PV encapsulant

Fluorescent dyes can be used to guide light to PV cells [10], and addition of small amounts of fluorescent dye to PV encapsulants offers a method of adding colour at minimal cost, with minimal change in PV efficiency [11]. Figure 2 shows light incident on a PV cell that is encapsulated in material containing Lumogen Red 300, fluorescent dye. The dye molecules absorb light, particularly in the green to yellow area of the visible spectrum (500–580 nm). The dye molecules then emit red light (585–670 nm). Some of the emitted light is reflected between the two glass surfaces in front of, and behind, the PV cells, in a process of total internal reflection. This process transports light to the PV cell from adjacent areas, meaning that loss of light transmission through the surface layer, due to addition of colour, is compensated for by transport of light from areas adjacent to the PV cell.

4 Materials and method

Materials were chosen as follows:

- Monocrystalline silicon PV cells (Topsky electronics technology (HK) Co. Ltd.) were cut into 52mm × 52mm pieces with central busbars.

- Tabbing strips (E Jordan Brookes) were soldered to the PV cells, using 60/40 tin/lead solder, after application of VOC-free, no-clean flux.
- 4mm-thick, low-iron glass, was used in front of the PV cells, in order to optimise the light spectrum reaching the surface of the PV cells.
- Standard, 4mm-thick, soda lime float glass was used behind the PV cells.

4.1.1 Paints and firing schedules

Blue and black glass paints (Rüger and Günzel GmbH) were mixed with water and a few drops of gum arabic solution, then applied to the low-iron glass with a brush, using sticks to scratch through the painted surface. Some softening of the paint edges was achieved by applying a fine spray of water to the edges of painted areas. Masking was used to leave square areas clear of paint, so that PV cells placed underneath would be exposed to light. Once dry, the paints were fired in a gas oven, and held at 606°C for 10 minutes, then allowed to cool *in situ*.

Platinum paint (Ferro Corporation) was mixed with ceramic thinning medium (Hans Wolbring GmbH), then applied with a brush to the soda lime float glass that was to be placed behind the PV cells. Once dry, the paint was fired onto the glass at 650°C for 40 min. This gave a semi-translucent, mirror finish that covered the grey backs of the PV cells, and reflected a fraction of the incident light back, whilst allowing some light to be transmitted through areas not covered by PV cells (Figures 3(b) and 3(c)). The mirrored surface also reflected movement and colour, adding interest for viewers, whilst matching the silver colour of the tabbing strips used to connect the PV cells.

4.2 Placing and encapsulating the PV cells

Circular stickers were used to secure the backs of the PV cells 1mm above the back glass, allowing liquid encapsulant to flow around the cells. Layers of double-sided tape were used to attach the front and back glass together, keeping a thin gap (approximately 3mm wide) between them. Hot-melt adhesive was applied to seal any gaps. The silicone Sylgard 184 (DowCorning) was chosen to bond the PV cells and glass together, due to precedent as a PV encapsulant [12], and initial tests that showed it could act as a host for Lumogen dyes [13]. Use of a liquid encapsulant also meant that the encapsulation process could be carried out in a studio setting, without the need for use of a PV laminator, that is necessary when using PV encapsulants such as EVA (ethylene vinyl acetate) and PVB (polyvinyl butyral).

To add colour to the Sylgard 184, BASF Lumogen F Red 300 and Yellow 083 dyes [14] were dissolved in toluene. The mixtures were added to Sylgard 184, and stirred in whilst heating to evaporate off the toluene, to make 200ppm solutions of dye in Sylgard 184. The encapsulant was poured into the gap between front and back glass. Small, reference samples of encapsulant were made up, also containing Lumogen dyes at 200ppm concentration.

4.3 Large testpiece

A 600mm × 450mm testpiece was designed to incorporate two strings of six PV cells each: one string encapsulated in Sylgard 184 containing Lumogen Red 300 dye, and the other with Lumogen Yellow 083 (Figure 3). Ceramic paints were used to create an area of pattern around the area in which each PV cell was to be placed, softening the transition from opaque cell edge to clear glass. The design was kept as fluid as possible, with the addition of small, rectangular shapes to mimic the rectilinear PV cell shapes and to symbolise eyes in the design; adding detail and humour. After taping the front and back glass together, the Sylgard 184, containing Lumogen Yellow 083 dye, was poured into the testpiece whilst it was held at an angle. Once this was nearly set, Sylgard 184 containing Lumogen Red 300 was added.

4.4 Dye fluorescence

The fluorescence of the dyes was checked by placing an optical fibre against the edges of the testpiece and samples. The fibre was connected to a spectrometer (HR2000CG-UV-NIR, Ocean Optics, USA), to give relative values of irradiance in the range 200-1100 nm. Measurements were carried out outdoors, and solar irradiance (units W/m^2) was measured with a silicon-based sensor (Mencke and Tegtmeyer Si-01TC-T) to ensure that each sample was tested at a similar irradiance.

4.5 Electrical output

The electrical output, from each string of PV cells in the testpiece, was compared with output from a single PV cell, encapsulated in clear Sylgard 184. A current-voltage (I-V) curve tracer (EKO MP-160) was used to show the variation of voltage plotted against current under a changing electrical load. The tests were carried out with the testpiece and irradiance sensor positioned vertically, inside a window. An irradiance sensor (as in section 4.4) was used to ensure that readings were taken at similar levels of irradiance.

5 Results and discussion

5.1 Testpiece appearance

Photovoltaic cells were successfully fitted into a curvilinear design through use of glass paints and dyes. The appearance of the cells was altered by the dyes in the encapsulant, and the cell opacity and shapes were disguised by the surrounding painted areas. When viewed from the front, in transmitted light, the PV cells merged into the background. Figure 3(a) shows the front of the testpiece, placed over a window and photographed with a flash from inside a room. Under this lighting condition, the dye colour made the PV cells contrast strongly with the surrounding black paint, making the PV cell shapes stand out.

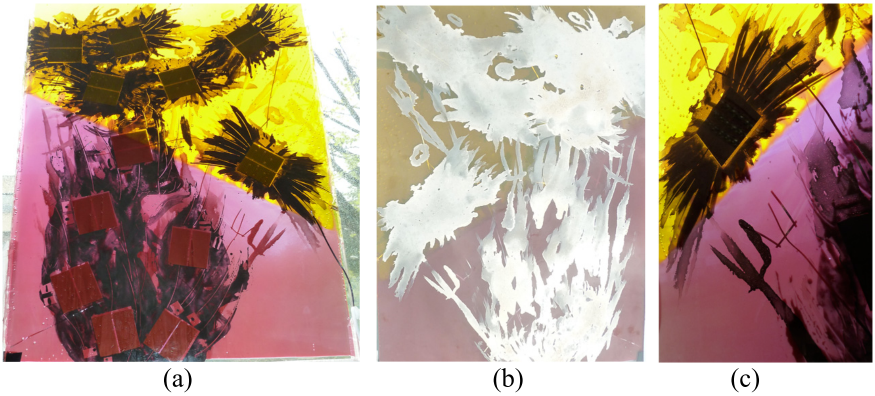

Figure 3: Views of the 600mm × 450mm testpiece placed in a window aperture: (a) front of testpiece photographed with a flash (reflected light); (b) back of testpiece in reflected light; (c) detail of the back in transmitted light.

The testpiece is likely to be viewed more frequently from the back, as the PV cells will be facing outwards. In reflected light, the platinum paint on the rear of the piece became reflective; completely covering the PV cells (Figure 3(b)). In transmitted light, the black paint disguised the cell shapes, while the platinum paint became translucent, providing some covering for the cell backs, whilst allowing some light to be transmitted through the glass (Figure 3(c)).

The colour of the red dye, within the testpiece, was duller and bleached, when compared with the colour of the small, red 200ppm sample made in the laboratory. The yellow dye showed little difference between testpiece and sample.

5.2 Dye fluorescence

Figure 4 shows the light spectra measured at the edges of the testpiece and the reference samples, using the fibre optic probe. The peaks in Figure 4(a) show that the red dye within the testpiece was emitting very little light compared with the small, 200ppm red sample. The differences in red dye emission, between the small scale samples made in the lab, and the large testpiece, made in the studio, could have been due to contamination or overheating of the materials when working on a larger scale, in the studio.

In Figure 4(b), the yellow edge of the testpiece is shown to have a higher emission peak than the small, 200ppm sample. Neither peak is very intense. Yellow 083 dye appears not to fluoresce well within Sylgard 184, under laboratory or studio conditions, indicating that Sylgard 184 may not be a good host for Lumogen 083 dye. The clear Sylgard 184 sample also shows a small fluorescence peak, and it is known that Sylgard 184 contains fluorescent material [15]. The fluorescence peak of the yellow dye occurs at a wavelength close to the Sylgard 184 emission peak, but it is not clear if the proximity of the two emission peaks could reduce the fluorescence properties of the Yellow 083 dye.

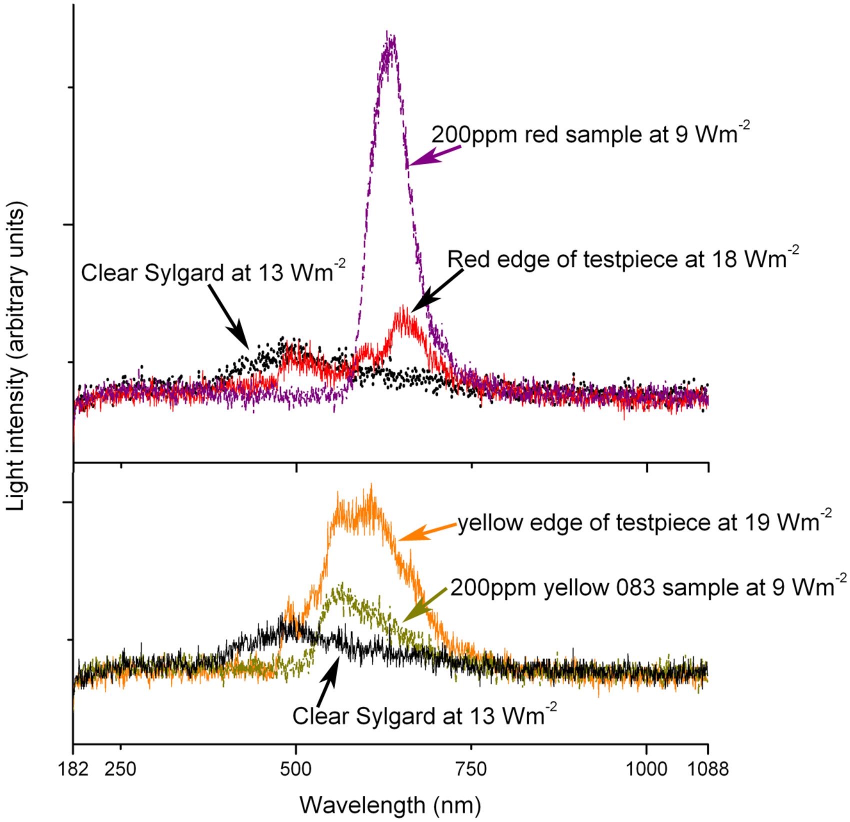

Figure 4: Comparing the light emission from the red and yellow edges of the testpiece with that from Sylgard 184 samples containing 200ppm of Lumogen F Red 300 dye; Lumogen F Yellow 083 dye; and a clear, Sylgard184 sample.

5.3 Electricity production

The x-axis of Figure 5 shows, as expected, that the maximum voltage across the six-cell strings within the large testpiece is approximately six times that of the voltage across the single cell, encapsulated in clear Sylgard 184. The y-axis shows the difference in current outputs: the current from a single cell, encapsulated in clear Sylgard 184, is greater than that from the cells encapsulated in Lumogen Yellow 083 dye. Cells within the Lumogen Red 300 dye produce even less current. The poor colour intensity and fluorescence emission of the dyes (discussed above in 5.1 and 5.2) are limiting the electrical performance of the PV cells, due to the dyes absorbing part of the incoming light spectrum, but not emitting as much light as expected.

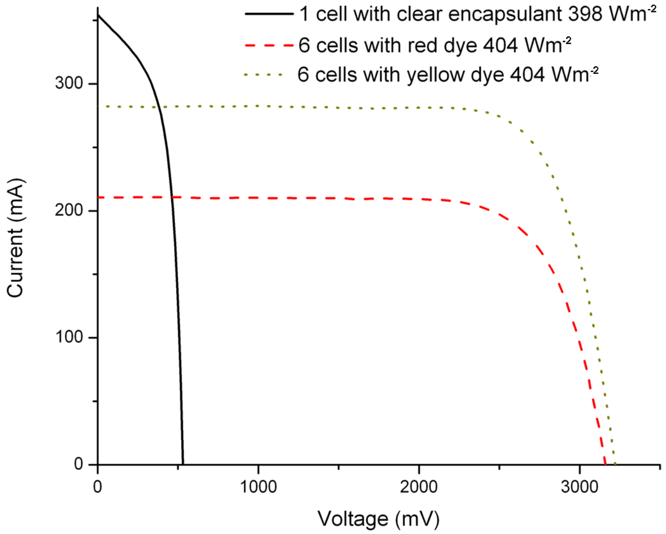

Figure 5: I-V curves, comparing electrical performance of the PV cells within the Lumogen Red and Yellow dyes, inside the 600 mm × 450 mm testpiece, with performance of a single PV cell encapsulated in clear Sylgard 184.

5.4 Effects on efficiency and appearance

Table 1 shows a comparison between the testpiece and a standard PV module. The actual differences in appearance and performance are compared with improvements that would enhance the testpiece appearance and performance.

Improvements in dye colour intensity and PV performance will be achieved through use of a PV encapsulant in which the Lumogen dyes retain their fluorescence properties. Sheets of EVA (ethylene vinyl acetate) can be used as a host for Lumogen dyes [11]. Encapsulation with EVA requires use of a PV lamination process to apply heat and pressure, but the kiln firing processes that were used to fix the glass paint onto the testpiece, warped the glass surface. Glass that is not perfectly flat would be likely to crack under pressure during the PV lamination process, so alternative methods of coating the glass would need to be found. Use of EVA, instead of Sylgard 184, could also prevent the formation of bubbles that occurred when testing the encapsulation method (Figure 6(a)).

Figure 6(b) (i) shows a *gap between the black, painted glass surface and the edge of the PV cells*. These gaps are visible from a distance, as well as close up. Slight misplacement of the PV cells also meant that some cell edges were shaded by black paint (Figure 6(b) (ii)), which could cause a decrease in cell efficiency. These problems could be overcome by applying both black and platinum paint to the back glass of the PV cells, and leaving the front glass free from paint. This would also prevent the contrast between black paint on the front glass, and coloured dyes, shown in Figure 3(a), as both paint and PV cells would be viewed through a layer of dye. Tests showed that it was possible to fire black and platinum paint onto the same sheet of glass, at 610°C.

Table 1: Comparison of appearance and performance between the testpiece and a standard PV module, with details of possible improvements.

	Design differences		Effects on appearance and performance	
Choice of materials	**Standard PV module**	**Coloured testpiece**	**Effect on testpiece compared with standard PV module**	**Required improvements**
PV encapsulant colour	Clear encapsulant	Encapsulant coloured by addition of Lumogen dyes to Sylgard 184 encapsulant	• Colour change • Decreased electrical current from PV cells due to poor dye performance	Better combinations of encapsulant and dye, to maintain dye fluorescence
Encapsulant material	Production methods ensure no bubbles in encapsulant	Bubbles formed in Sylgard 184 encapsulant	Bubbles over cell surfaces could decrease PV efficiency	Improved methodology or alternative encapsulant material, such as EVA
Black paint on front glass	No paint on front glass	PV cell shapes and opacity blended into painted areas	Painted areas cover edges of some PV cells, minimising cell area on which light can fall	Apply paint to back glass only, to avoid covering cell surfaces
Platinum paint on back glass	PV cell backs visible or covered by opaque backing	Cell backs disguised; module appearance different in reflected or transmitted light	Enhanced appearance in both reflected and transmitted light	Use a cheaper, alternative coating, that can be applied to toughened glass
PV cell arrangement	Evenly-spaced rows of PV cells	Curved PV cell strings with unequal cell spacing	Limited number of PV cells per unit area gives space for light transmission and for painted areas, but limits electrical output	A variety of designs with different numbers of PV cells per unit area

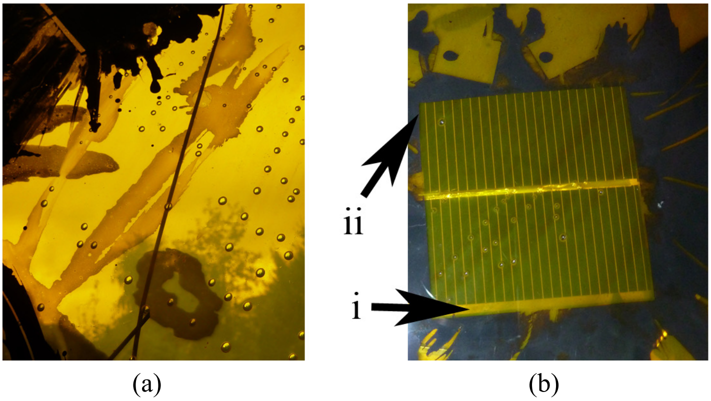

Figure 6: Details of the testpiece: (a) bubbles in the encapsulant; (b) (i) gap between black paint and PV cell edge; (ii) shading of PV cell edge by black paint.

The platinum paint applied to the back glass was successful in disguising the PV cell backs. It is not possible to toughen glass coated with platinum paint, as the reflective surface prevents the heat treatment from being carried out correctly. This could be a problem in making glazing safe for use in some locations [16]. An alternative to platinum paint is required: a method of applying a translucent, reflective coating to selected areas of the glass before or after glass toughening.

The curvilinear strings of PV cells, with wide spaces between cells, and large areas of paint, gave minimal electricity generation per unit area. For each design, a balance has to be achieved between areas of clear glass, areas of paint and the amount of glass that can be covered by PV, to generate electricity.

5.5 Use of alternative types of PV

Most existing, decorative, architectural glass incorporates individual crystalline silicon PV cells. These, individual PV cells can be placed wherever they are required within a design. Many other types of PV are made by direct application of semiconducting thin films to substrates [17-19]. These methods could be ideal for use in architectural glass, but the rectilinear modules that are produced are often unsuitable for designs where variable placement of opaque and light-transmitting areas is required. If the challenges of improved thin film PV efficiencies and lifetimes can be combined with choice of substrate colour and variations in translucency, then alternatives to crystalline PV will become more useful for applications where aesthetics are to be taken into account.

6 Conclusions

A 450 mm x 600 mm architectural glass testpiece was made, incorporating curvilinear PV cell strings; Lumogen F dyes within the Sylgard 184 PV encapsulant; and glass paints. This demonstrated that it was possible to change the colour of the PV encapsulant Sylgard 184, in a studio setting, through use of fluorescent Lumogen dyes. The dye properties were altered by addition to Sylgard 184, so that the Lumogen F Red colour became faded when the mixing process was moved from small-scale laboratory preparation to a larger scale, in the studio. Both dyes exhibited poor fluorescence emission within the Sylgard 184 host. There was a resulting fall in current produced by the PV cells that were covered by the dyed encapsulant. Alternative materials and methods are required in order to maintain good PV cell efficiency, and EVA is suggested as a better host material.

The opacity and rectilinear shapes of the PV cells were successfully blended into a curvilinear design, through use of glass paint. Development of this methodology demonstrates that PV cells can be blended in a wide range of architectural glass art, including curvilinear and colourful designs, as long as cell properties such as opacity are taken into account.

Acknowledgements

The authors are grateful for the support from the following organisations: Peters Studios, Paderborn, Germany, where the test designs were developed; The Levehulme Trust (UK), for funding the project; The Spires network (UK), for travel funding; Sunovation, Germany, for a PV encapsulant and stickers; E. Jordan Brookes, for tabbing strip.

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