The Search for Building-Integrated PV Materials with Good Aesthetic Potential: A Survey

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Abstract

Building-integrated photovoltaics (PV) is currently dominated by blue and black rectilinear forms. Greater variety of colour and form could lead to much better uptake of PV in the built environment, also increasing the potential for PV to be used as an artistic material. Listing the available PV technologies by colour gives a clearer picture of the current situation. An assessment of photostability, efficiency and price, for each material, indicates the materials that have the potential to fill the gaps in the colour spectrum. Use of combinations of materials that can be fabricated in different ways from the current, standardised, PV modules will further increase the possibilities for use in building integration, Extending the lifetimes of organic PV, dye-sensitised PV or luminescent solar concentrators will increase the possibilities for development of new PV products.

Introduction

The building-integrated PV market is dominated by silicon PV due to the reliability of this proven technology. But silicon PV modules are generally blue or black rectangular forms. The uniformity of this expensive product is leading to requests for much greater variety, especially in colour ranges [1].

PV materials that are currently being developed could provide a much wider colour palette, whilst being incorporated into buildings in innovative ways. A balance needs to be achieved between colour range and variety of form, weighed up against cost, photostability and efficiency. Crystalline silicon is the most widely used PV material, and can be made in a variety of colours, created by varying the thickness of the anti-reflection coating on the cells, but this leads to a loss of efficiency that is generally considered unacceptable in a product that is required to perform at optimum levels to minimise payback times. (The Havemor project [2] showed efficiencies ranging from 15.0% for black, down to 10.4% for green finishes.) Modules made with coloured silicon cells are normally made in standard, rectilinear designs to avoid complex fabrication and assembly issues. Other PV materials are required in order to generate a wider range of both colour and form at reasonable cost. Creation of a catalogue gives a way for PV materials to be compared in the same way as other building materials.

Availability of PV materials according to colour

Table 1 categorises PV materials according to colour, demonstrating the range of PV technologies and where there are gaps in the range of available products; showing where material and product development are required. The emphasis is on materials that perform well in diffuse light, which restricts the inclusion of concentrating materials to luminescent solar concentrators (LSC). The table shows that blue and black materials dominate the market.

Creating variety in colour, form, texture and translucency of building-integrated PV products

Table 2 shows a comparison of efficiency, warranty and price for PV materials, showing that silicon products demonstrate the best combination of good material stability and price. Other PV materials, that could provide a wider range of PV colour, are either expensive, especially when produced in wide colour ranges, or they lack the dye stability that is necessary in a product intended for use in building design.

There is now a trend to combine PV materials in one product, for example the combination of micro-crystalline and amorphous silicon in PV modules, to give a good balance between increased efficiency and reduced cost. Development of new material combinations offers a way of increasing variety in PV product ranges. Incorporation of PV materials with building materials will further increase the possibilities.

Colour	Commercially-available PV material
Black	**c-Si; mcSi; µc-Si; CdTe; CIS; CIGS**; HIT
Silver/Grey	*mc-Si*; CIS
Red/Brown	Organic PV; **a-Si**; LSC; CIS
Red	LSC; *mc-Si*
Orange	LSC; *mc-Si*
Yellow	LSC;*mc-Si*; CIS
Green	LSC;*mc-Si*; CIS
Blue	**c-Si; mc-Si; µc-Si**; CIS; LSC
Violet	LSC; mc-Si
Translucent	a-Si; LSC; DSSC
White	only achievable with white backing behind translucent materials

Table 1: PV materials categorised according to colour, with bold and italic type indicating **mainstream materials** and *altered anti-reflection coating thicknesses*, respectively.
The abbreviations used in the table are:

Crystalline silicon products

c-Si: mono-crystalline silicon

mc-Si: multi-crystalline silicon

HIT: Hetero-junction with intrinsic thin layer

Thin-film materials

µc-Si: micro-crystalline silicon

a-Si: amorphous silicon

CdTe: cadmium telluride

CIS: Copper Indium Selenide

CIGS: Copper Indium Gallium (di)Selenide

Materials incorporating dyes

DSSC: Dye-sensitised Solar Cells

OPV: Organic photovoltaics

LSC: Luminescent solar concetrator

Colour range

PV colour range can currently be increased by the use of customised CIS modules or crystalline-silicon modules with different thicknesses of anti-reflection coating. In commercially-available modules, this involves loss of efficiency up to 25% for CIS modules [3], or a drop from 17.1% to as little as 13.4% [4]. The higher cost of these bespoke materials, combined with loss of efficiency, significantly increases the system payback time. Glass-glass modules with coloured laminates [5] give a way of introducing variety to PV modules without changing the cell colour.

There are also artistic solutions that could be exploited more to break up expanses of monochromatic PV: using different coloured building materials next to the PV; or using small areas of coloured PV within larger, standard PV installations. This latter solution requires careful circuit construction to ensure that the entire system power is not reduced by current mismatching due to use of materials with different efficiencies.

Form

Standard module designs are now dominating the PV market. Frameless modules can be used to create uniform, flat surfaces, but greater variety of module form will improve the possibilities for use of PV in building design. Silicon PV modules can be made in different, flat shapes, but the use of square PV cells to create a non-rectilinear shape is rarely aesthetically pleasing. Novel shapes also require careful design of the electrical connections to ensure that voltages and currents are balanced. Crystalline silicon modules can also be made into slightly-curved shapes without breaking the PV cells, but thin film PV offers much more flexibility, and is already being used in products such as curved roof tiles [6].

Application of PV to cloth or other flexible substrates is providing a much greater flexibility of form. Experimental flexible films such as SmartWrap® [7] use thin-film PV in conjunction with lighting and insulating materials. These are still at an early stage of development, but would allow an excellent variety of form, at the same time as fulfilling other requirements of a building skin.

For more solid, permanent structures, large, customised PV modules can be made up, ensuring a high level of product quality, as assembly is carried out in a factory. These modules are difficult to handle on site, requiring the use of cranes, and need to be designed and fabricated to order.

The use of very small PV modules or bricks, would enable design of PV mosaics. Each element would require an electrical connection, so a new style of connection would need be developed to prevent this solution from being prohibitively expensive.

Translucency

Translucency is currently achieved by leaving gaps between PV cells in glass-glass laminates, allowing light to penetrate through the gaps. Thin film materials with transparent substrates are also be used to give translucent products. The trade-off between allowing light to pass through the module, or interrupting the passage of light to allow it to be used to generate electricity, means that overall module efficiency is lower for translucent materials. DSSC and LSC's offer ways of using translucent materials in PV applications, but require more development, especially of dye stability, before they can be used extensively in building structures.

PV material	**Efficiency of module or * indicates cell efficiency**	**Warranty** % indicates percentage of nominal power [8]	**Price**	**In BIPV?**
Mono-crystalline silicon	19.66% Sunpower SPR-425E-WHT-D [8]	80% at 25 years	Low <2 €/W_p	Yes
Multi-crystalline silicon	15.4% CNPV-300P [8]	80% at 25 years	Low	Yes
Micro-crystalline silicon	9.2% AEET [8]	80% at 25 years	Low	Yes, normally used in combination with amorphous silicon
Ribbon silicon	13.7% Sovello [8]	80% at 25 years	Low	Yes
Amorphous silicon	7.3% Masdar & Signet Solar [8]	80% at 25 years	Low	Yes
CIS Copper Indium Selenide	8.0 or 7.3% with warranty Sulfurcell [8]	80% at 25 years	Medium? >2 €/Wp	Yes
CIGS Copper Indium Gallium (di)Selenide	12.7% Q-Cells [8]	80% at 25 years	Medium	Yes
CdTe Cadmium Telluride	11.1% First Solar [8]	80% at 25 years	Low	Yes
HIT Hetero-junction with intrinsic thin layer	19.0% Sanyo [8]	76% after 25 years	Medium?	Yes
GaAs Gallium Arsenide	28% [9]	Designed to operate well for 15 years: typical space mission length [10]	High 180 €/W [11]	Only in space and in solar cars
Organic	*8.3% for 1cm^2 [12]	1 to 3 years [13]	Low	On bus shelters [13]
Dye-sensitised	*9.9% for 17.1 cm^2 [12]	1 year for indoor applications [14]	Low	Yes, experimentally
LSC (Combined with GaAs PV cells)	7.1% in combination with GaAs [15]	Not available	High	Small area experimental designs only
LSC (Combined with silicon PV cells)	2% in combination with silicon PV [16]	Not available	Low 88 €/m^2 [16]	Artworks and experimental designs only

Table 2: Comparison of efficiency, warranty and price for commercially-available PV materials

Texture

Variation of surface texture is important to architects. Most PV modules have shiny surfaces in the form of the cover sheet and this can give a 'high-tech' appearance that is unsuitable for certain building styles. Texture can be achieved by methods such as sandblasting module surfaces or using textured polymer covers. This can affect PV efficiency, but this could be offset by a resulting increase in building surfaces on which the PV could be used.

Conclusion

A greater variety of colour, form, texture and translucency will assist in making PV into a more mainstream building material.

There is now a good selection of PV products for use on roofs, including PV roof slates and tiles. A much greater choice of PV materials are required for use on building facades, including in glazing. Products incorporating several features, such as insulation and lighting, will assist in creation of PV products that are truly building-integrated, not just an addition to the building skin.

The cost of silicon PV products means that the development of cheaper, alternative materials should ensure the increasing use of PV in architecture. Overcoming stability issues, in organic PV; dye-sensitised PV; and LSC's, will be crucial in allowing this to happen. The increasing use of combinations of materials, including different PV materials, in one product, is a good way of capitalising on the strengths of each material.

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