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DECORATED BUILDING-INTEGRATED PHOTOVOLTAIC MODULES: POWER LOSS, COLOR APPEARANCE AND COST ANALYSIS

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ABSTRACT: We evaluate three design solutions for BIPV modules: colored encapsulants, ceramic printed glass covers and spectral-selective photonic Morpho structures, regarding their electrical performance, their optical appearance and their cost. We built single-cell samples on which we perform IV measurements at STC and normal-hemispheric reflectance measurements. We derive color coordinates in CIE L*a*b* space out of the reflectance spectra to quantify color and intensity. Colored encapsulants as well as ceramic prints show low color saturation and high power loss relative to a conventional module (-6 to -31%). The spectrally selective Morpho structure shows strongest color saturation, enhanced brightness and best electrical performance (-3 to -7%). We research module component prices and perform a manufacturing cost analysis for glass-glass modules with the respective decoration and find that decoration of BIPV modules increases the specific module cost, caused by less power output and higher material cost. We find the manufacturing cost of decorated BIPV modules (74-163 €/m²) is within the range of classic cladding materials, such as bricks (60-100 €/m²) or wood (50-180 €/m²) but provide additional benefits regarding power generation.

Keywords: BIPV, facades, power loss, manufacturing cost, color appearance, Morpho structure

1 INTRODUCTION

Since European legislation has tightened the requirements for energy-efficient building [1], the interest in aesthetic, efficient and price-competitive building-integrated photovoltaic (BIPV) solutions has been growing steadily [2–4].

Common silicon PV modules often fail to fulfill the architectural desire for a homogeneous and tailorable appearance. They display a strong contrast between the dark solar cells, the white or transparent background (Figure 1, left) and the shiny interconnectors. Furthermore, their overall appearance is dark. To reduce the contrast between cell matrix and background, a black rear encapsulant can be introduced (Figure 1, right). However, homogeneously colored designs are only possible to a certain extend with this approach.

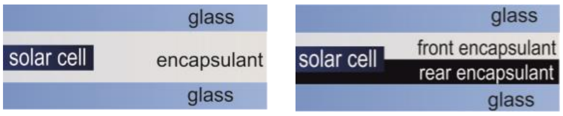

Figure 1: Conventional semitransparent glass-glass module configuration for façade application (left), conventional “black” glass-glass module configuration (right). The top glass cover as well as the encapsulant are suitable design variables for homogenous decoration.

To achieve aesthetic photovoltaic building skins, one approach is to camouflage silicon solar cell appearance by a decorative module component in front of the cell layer, leading to ‘Invisible BIPV’.

We focus only on components that create a homogenous color appearance across the whole module area such as colored encapsulants or uniformly coated glass covers.

Each technology leads to a specific power loss (relative to conventional PV modules with fully transparent front glass/encapsulant) and cause additional material costs.

Within this article, we compare three design solutions for colored BIPV modules regarding their optical appearance, electrical performance and economy.

Colored encapsulants are one suitable design option. The most common encapsulant in PV industry is ethylene vinyl acetate (EVA), but no major EVA manufacturer offers colored interlayer films. Within the glazing industry, colored PVB encapsulants are applied in safety glass. Since PVB is a technically feasible encapsulant for PV modules, we use the colored PVB films to manufacture and characterize module samples [5]. The colored PVB replaces the transparent front encapsulant (Figure 2).

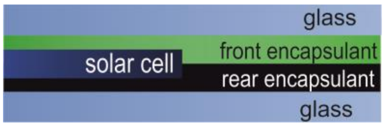

Figure 2 Module configuration with colored encapsulant

Photovoltaic modules with screen-printed or digitally printed glass covers are available on the market. Often partial print patterns are used to obscure the solar cell geometry while keeping transmittance high [6]. The ceramic enamels are stable and UV-resistant. Non-white enamels absorb significant parts of the spectrum, which raises module operation temperature. The print is introduced into the module at the inner side of the glass cover to avoid weathering and soiling exposure. The translucent, light-scattering nature of the applied enamels requires sophisticated measurement equipment to obtain accurate optical data of printed glass panes [7]. Furthermore, the printed glass pane transmittance does not correlate linearly with module performance, as described in [8].

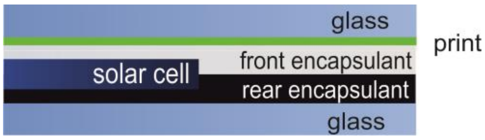

Figure 3 Module configuration with ceramic print

Researchers at Fraunhofer ISE previously presented a spectrally selective photonic structure inspired by the

Morpho butterfly (“Morpho structure”) that shows angle-independent saturated colors and low glare [9]. Any color can be obtained and very low losses can be achieved. The photonic structure applied to the front glass reflects narrow bands of the incident spectrum and shows no significant absorbance.

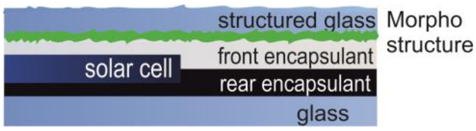

Figure 4 Module configuration with Morpho structure

2 METHOD

2.1 Sample Preparation

To determine the power losses and color saturation associated with each type of decoration, single-cell samples with the respective decorative element were prepared (Figure 5). The lab-scale samples feature no anti-glare layer. Blackened interconnectors increase the homogeneity of the final product appearance but have not been used for the lab-scale samples.

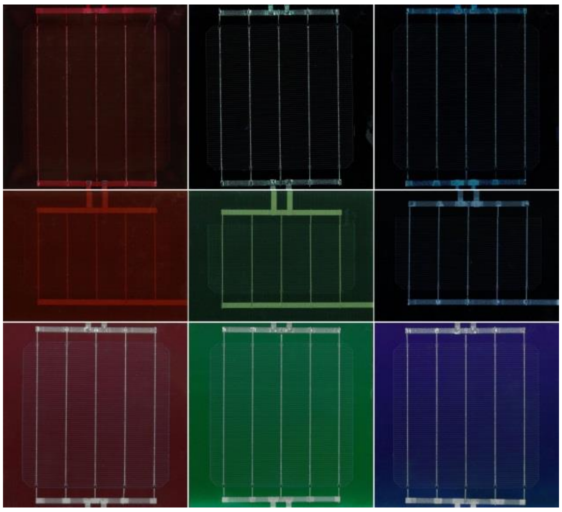

Figure 5: Images of the fabricated single-cell samples under similar illumination conditions of the mentioned design technologies with similar colors (red, green, blue). The metal connectors are deliberately kept visible. From top to bottom: colored encapsulant; full-area digital ceramic print; Morpho structure by Fraunhofer ISE

2.2 Color Analysis

The normal-hemispheric reflectance spectra of the samples in Figure 5 were measured outside the cell area at the TestLab Solar Façades at Fraunhofer ISE with an integrating sphere with a diameter of 220 mm shown in Figure 6 to 8. These spectra represent a lower limit for the reflectance.

The reflectance spectra are plotted in the range from 350 to 800 nm in front of the visible spectrum. The overall reflectance spectra of encapsulants in Figure 6 show low intensities. The red encapsulant shows a reflectance peak with double intensity at 600 nm, providing a better coloration effect compared to the blue and green encapsulant that show no peaks.

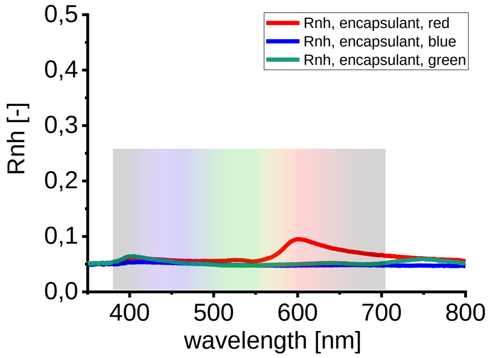

Figure 6 Normal-hemispherical reflectance (R_{nh}) spectra for each module configuration with a colored encapsulant and without solar cell.

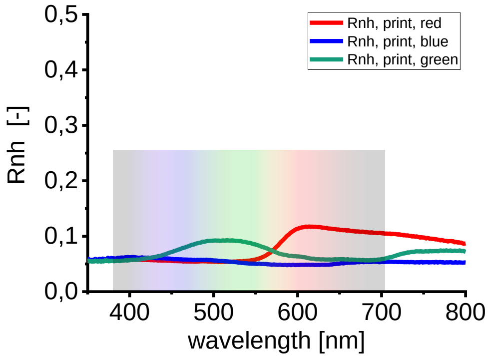

Figure 7 Normal-hemispherical reflectance (R_{nh}) spectra for each module configuration with a digitally printed enamel and without solar cell.

The normal-hemispherical reflectance spectra for red, blue and green digitally printed enamel on glass are shown in Figure 7. The ceramic prints also show low reflectance, with broader reflectance maxima of double intensity for red and green color. The higher reflectance values lead to a better coloration saturation (red>green>blue) of the module (Figure 5).

The overall reflection effect of enamel prints and encapsulants is low compared to the Morpho structure, whose reflectance spectra show narrow and strong maxima of 5-fold increased intensity (Figure 8).

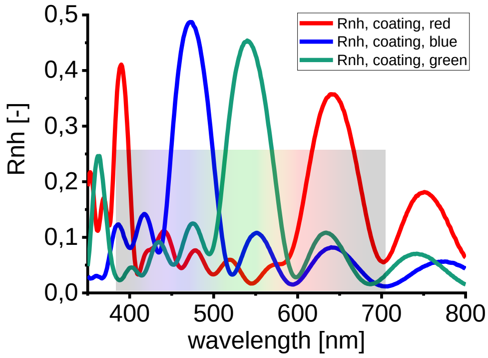

Figure 8 Normal-hemispherical reflectance (R_{nh}) spectra for each module configuration with a spectrally selective Morpho structure from Fraunhofer ISE and without solar cell.

The above plotted normal-hemispherical reflectance spectra are used to derive the CIE L*a*b* color coordinates to quantify brightness and saturation as given in Table 1[10].

Table 1: Color coordinates in CIE L*a*b* space

	L*	a*	b*
Encapsulant, red	30.8	7.4	3.6
Ceramic Print, red	32.5	12.4	7.3
Morpho structure, red	32.9	36.2	0.1
Encapsulant, green	26.5	2.0	-2.6
Ceramic Print, green	33.7	-9.2	2.1
Morpho structure, green	55.3	-42.8	36.3
Encapsulant, blue	26.2	0.4	-1.8
Ceramic Print, blue	27.2	-0.4	-3.5
Morpho structure, blue	39.0	-11.2	-34.7

The L* values show a very similar brightness for the encapsulant and ceramic print system, while the Morpho structure leads to enhanced brightness values for green and blue. The red Morpho Structure sample does not show high brightness due to non-optimized parameters for sample production.

In order to evaluate the color saturation, Figure 9 shows a plot of the a*b* values derived from the reflectance measurements. In this plot, the distance from the origin represents the color saturation. It is evident from this plot that the encapsulant hardly leads to a color effect, the ceramic print shows only a moderate effect, and the Morpho structure features a high color saturation. These results are in good accordance with the subjective impression from Figure 5.

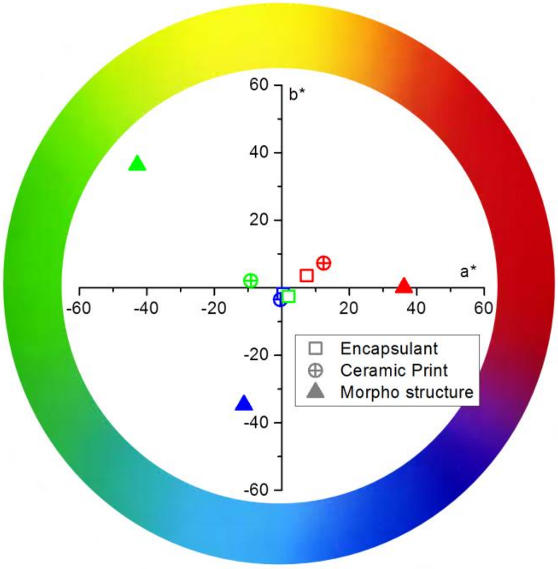

Figure 9 CIE a*b* diagram with the representation of the measured samples. The distance from the origin represents color saturation.

2.3 Electrical Characterization

The electrical characterization was performed at Standard Testing Conditions (STC) at Fraunhofer ISE Module-TEC. The loss in power is determined relative to a reference module, featuring the module configuration in Figure 1 (right) without any decorative components.

The STC Power density $P_{d,MPP}$ [W/m²] is calculated based on the module area and power specified in section 2.4.

Table 2: Measured module power of single-cell samples at STC (Wattpeak Wp) and relative power loss and power density per area

Module	P_{MPP} Wp	loss Δ P_{MPP} %	$P_{d,MPP}$ W/m²
Reference, transparent	4.32	0	194
Encapsulant, red	3.45	-20.1	155
Encapsulant, green	4.07	-5.8	183
Encapsulant, blue	3.59	-16.9	161
Ceramic Print, red	2.97	-31.2	133
Ceramic Print, green	3.46	-19.9.	155
Ceramic Print, blue	3.95	-8.6	177
Morpho structure, red	4.01	-7.2	180
Morpho structure, green	4.15	-4.0	186
Morpho structure, blue	4.19	-3.0	188

We observe that the power loss is strongly dependent on the color for prints and encapsulants. Colored encapsulants achieve 5.8 to 20% less power than a reference module, while whole-area digital enamel prints perform 8 to 30% worse. The spectrally-selective Morpho technology shows by far the lowest power losses on single-cell-modules in the range of 3% to 7%, independent of color.

Calibrated power measurements at Fraunhofer ISE CalLab on full scale modules with the spectrally selective Morpho structures and an additional anti-glare layer confirm these results with a maximum relative loss in efficiency of approx. 7% to a reference module [11].

Significantly more nominal power can be installed on the limited area of the façade using more efficient design technologies. Therefore technologies with higher area specific power feature an advantage when suitable façade areas are limited. In terms of power the Morpho structures clearly outperform the colored encapsulants, while whole-area ceramic prints perform worst.

2.4 Module Cost Analysis

To fulfill structural requirements of BIPV modules for façade applications, glass-glass modules define the calculation baseline for the cost analysis. The 48 cell-modules with an area of 1.32 m x 1 m use 4 mm low-iron front glass cover and 6 mm rear glass. The reference module power is 256 Wp.

Material costs for the respective decorated and standard designs (Figures 1 to 4) have been obtained in a market analysis or estimated based on a sensitivity analysis and are summed up in the tables below.

Table 3: prices of decorative module components

	€/m²
Encapsulant, PVB, colored	12
Ceramic Print	35
Morpho structure	30-100

Table 4: prices of conventional module components

	€/m²	€/Wp
4mm low-iron glass pane	4.5	
4mm structured glass pane	14.9	
6mm rear glass pane	5.5	
Encapsulant, EVA, transparent	1	
Encapsulant, PVB, transparent	5	
Encapsulant, PVB, black	12	
Solar Cells, mono		0.12

The module and manufacturing costs of the respective designs in Figure 1 to Figure 4 are analyzed for a 3-shift production scenario of a single 80 MWp production line in Germany, using the software 'SCost' by Fraunhofer ISE [12]. Labor costs, raw material costs, capital costs and scrap rates are considered along the PV production process.

Using the obtained relative module power decrease (Table 2) and the material cost (Table 3+4), the specific module costs for each decorative design in €/pcs, €/Wp and €/m² are calculated (Table 5).

The conventional glass-glass concept without any decoration achieves manufacturing cost of 0.27 €/Wp. Adding the black encapsulant raises cost to 0.34 €/Wp. Decorated modules increase manufacturing cost from 0.41 to 0.91 €/Wp.

Table 5: Module manufacturing costs for each technological concept

Concept	€/pcs	€/m²	€/Wp
Conventional glass-glass transparent	67.94	51.47	0.27
Conventional glass-glass black encapsulant	88.22	66.83	0.34
Colored encapsulant glass-glass	97.78	74.08	0.41-0.48
Ceramic print glass-glass	134.86	102.17	0.57-0.75
Morpho structure glass-glass 30€-100€/m²	122.2-215.48	92.5-163.24	0.49-0.91

3 RESULTS AND DISCUSSION

We find that decoration of BIPV modules increases the module price due to by power loss and higher material cost.

Colored encapsulants as well as ceramic prints show low color saturation and high power loss relative to a conventional module (7 to 29.5%). The investigated encapsulants were originally designed for solar radiation control of buildings. As a consequence, the main function of these interlayers is to reduce the solar transmittance, which is why absorptance in the encapsulants reaches significant levels and the reflectance of most encapsulants is low. Nonetheless, for PV applications optimized colored encapsulants featuring higher reflectance and lower absorptance could be a feasible design solution for BIPV in the future. The Morpho technology shows strongest color saturation and enhanced brightness. It shows the lowest performance losses (3 to 7%).

With specific module costs from 74 €/m² (0.41-0.48 €/Wp) for colored encapsulants to 102 €/m² (0.57-0.75 €/Wp) for ceramic prints, the decorated modules are within the range of classic cladding materials, such as bricks (60-100 €/m²) or wood (50-180 €/m²) but provide additional benefits regarding power generation [13].

Table 6: Color saturation, module power under STC and manufacturing costs of all concepts.

Concept	Color saturation	loss Δ P_{MPP} %	Cost €/Wp
Conventional glass-glass transparent	none	0	0.27
Colored encapsulant glass-glass	very low	6 to 20	0.41-0.48
Ceramic print glass-glass	low	9 to 31	0.57-0.75
Morpho structure glass-glass	high	3 to 7	0.49-0.91

The sensitivity analysis regarding material costs of the Morpho structure technology (30-100 €/m²) identifies a specific module cost in the range of 93-163 €/m². This is a very attractive price range considering the improved color saturation and higher efficiency. Further due to the low absorptance of the Morpho structure, a lower module temperature and therefore higher yields over the lifetime are expected compared to ceramic prints and colored encapsulants.

4 CONCLUSION

In this paper we analyze three decorative designs for the application in BIPV modules. We investigate colored encapsulants, ceramic printed glass covers and photonic Morpho structures regarding their electrical performance, cost and optical appearance. We perform normal-hemispheric reflectance measurements on single cells laminates and compute CIE L*a*b coordinates. We find the coloration of colored encapsulants and ceramic prints to be low, while the Morpho structure shows high color saturation. Morpho structures additionally feature enhanced brightness compared to the other technologies. Morpho structures show lowest, maximum power loss of approx. 7% compared to a reference module, independent of color. The power loss of colored encapsulants and ceramic prints ranges from 6 to 31% and is highly color dependent. We perform a manufacturing cost analysis and observe that technologies with better color saturation come at increased cost. Higher material cost and power loss are the significant cost drivers. However, we find module manufacturing cost of decorated modules (74-163 €/m²) in the range of classic cladding materials (60-150 €/m²) but point out that PV modules provide economic benefits due to their power generation.

5 OUTLOOK

Within future work, the Net Present Value (NPV) or Life Cycle Costing (LCC) methods can be applied to determine the overall financial benefit or cost of a BIPV installation of the above mentioned technologies over its entire life-cycle, taking the financial effect of generated power into account [14].

6 ACKNOWLEDGEMENT

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