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The Colourful Revolution in BIPV Façade Architecture

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Abstract

In architecture, there is an increasing need to meet aesthetic, functional, and ecological requirements equally. Facades, in particular, face the challenge of not only protecting the building but also contributing significantly to its overall appearance. Colored solar modules for facades offer an innovative solution that integrates all these requirements while providing architects with expanded creative freedom. Existing options for coloring solar modules either offer a limited color palette or come with significant efficiency losses. In contrast, the patented enables almost unlimited design opportunities for solar modules with high color saturation, without incurring significant energy efficiency losses. Thanks to their flexible adaptation to architectural designs, facades can now be used as an expressive design element that seamlessly combines both functional and aesthetic aspects. The colors are based on the physical principle of interference. Instead of absorbing sunlight, the color layer printed on the back of the front glass reflects only the desired tone and thus creates the visible color effect. The low opacity leads to an outstanding Color Performance Ratio of up to 98 % compared to uncolored standard glass. The efficiency of the installed solar modules is therefore virtually maintained, making this an ideal solution for energy-efficient buildings. The colors are applied using conventional screen-printing and fused inseparably with the glass through heat.

Keywords

BIPV, PV modules, high efficiency, renewable energy, sustainability, Photonic Pigments, monument protection, historical building preservation, architectural design, facade, rooftop, colorful, customized.

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1. Introduction

The integration of photovoltaic modules into buildings (Building-Integrated Photovoltaics, BIPV) is a key measure for generating renewable energy. While conventional photovoltaic modules are predominantly produced in dark colors such as black or blue to maximize energy yield, BIPV applications often require modules to meet architectural aesthetic requirements. The challenge lies in uniting color design with high energy efficiency.

The Photonic Pigment Technology offers a solution that combines ceramic colors with interference technology, enabling creative facade design. This paper analyzes its functional principles, compares alternative methods of coloring photovoltaic modules, and evaluates the potential applications of this technology.

2. Ci Technological Principles

2.1. The Principle of Light Interference

The perception of color is based on the interaction of light with surfaces. In addition to absorption and reflection, the interference of light waves plays a key role in the coloring of transparent and thin-layered materials. Interference occurs when light waves overlap, leading to constructive interference (amplification of certain wavelengths) or destructive interference (cancellation of wavelengths). This phenomenon is commonly observed in soap bubbles, butterfly wings and oil films on water, which display iridescent colors depending on the viewing angle.

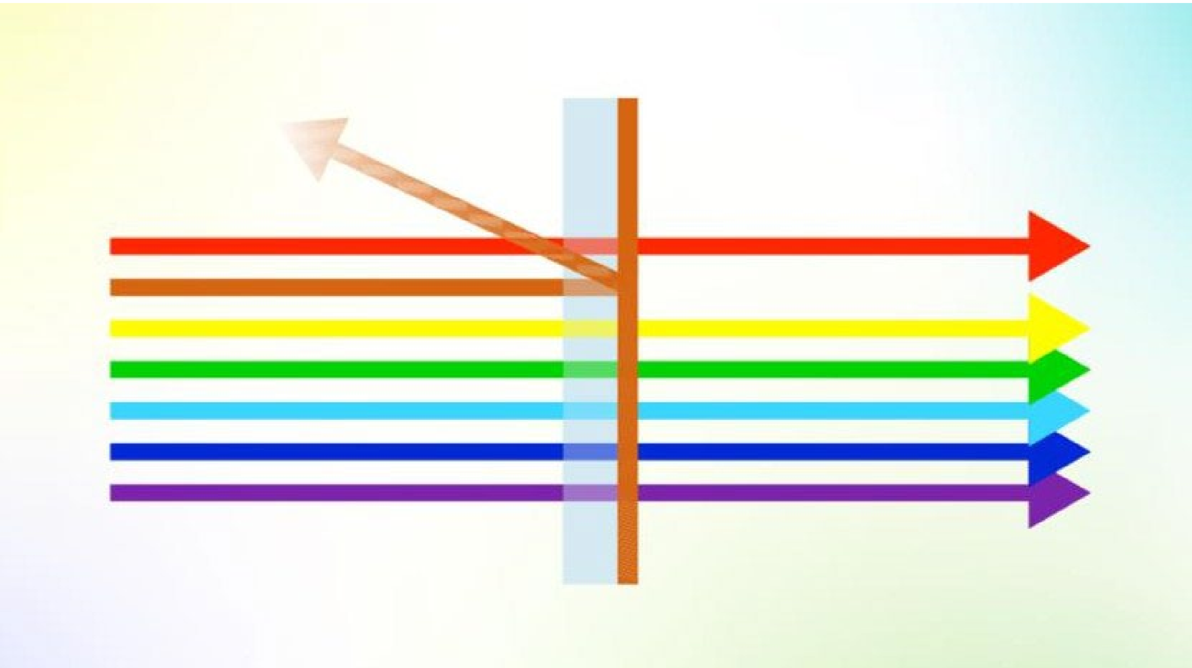


Fig. 1: While waves of the desired color are being reflected, all other wavelengths pass through the printed front glass – the result: effective color perception and high energy transmission.

2.2. Application of Interference for Photovoltaic Coloring

The use of interference in photovoltaics involves the application of a thin ceramic color layer to the back of the front glass of the solar module. This color layer is designed to selectively reflect specific visible wavelengths, which the human eye perceives as color, while allowing other wavelengths to pass through and be absorbed by the solar cells for energy conversion. Unlike conventional color coatings that absorb significant portions of light energy, interference-based coloring preserves a high level of energy transmission to the solar cells, resulting in minimal efficiency losses.

3. Comparison of Different Coloring Technologies in BIPV

There are several approaches to coloring photovoltaic modules, each with varying efficiency, durability, and application areas.

3.1. Ceramic Colors with Interference

Use of a ceramic color layer, fired at high temperatures:

- High mechanical and chemical resistance
- High resistance to UV radiation and other environmental influences
- Consequently: long-term color stability and long lifespan

Controlled interference

- Most of the sunlight is used for energy generation
- Only a small portion is reflected to produce the color effect
- Consequently: high efficiency energy generation

A virtually unlimited color variety (> 1,000 different shades), applied using modern printing techniques

- Individual design requirements can be reliably met
- An optical depth effect can be achieved
- Consequently: flexible options for innovative custom facade design

Simple and fast development of new colors

- Color samples within just a few days, even with special glass surfaces
- Maximum validity of samples due to a reliable simulation of the ultimately intended color effect
- Consequently: maximum design accuracy/reliability from sample to finished module

3.2. Sputtering Technology (Metal Oxide Coating)

- Coating with metal oxides through vacuum deposition
- Use of interference results in high efficiency
- Complex and costly manufacturing process that requires high-precision control
- Offers a limited selection of metallic and iridescent colors, which limits design options
- Very time-consuming and labor-intensive color tone development, which makes flexible adaptation to architectural concepts difficult
- Sensitivity to chemical influences and environmental factors such as UV radiation can lead to changes in color and reduced durability

3.3. Colored Foils

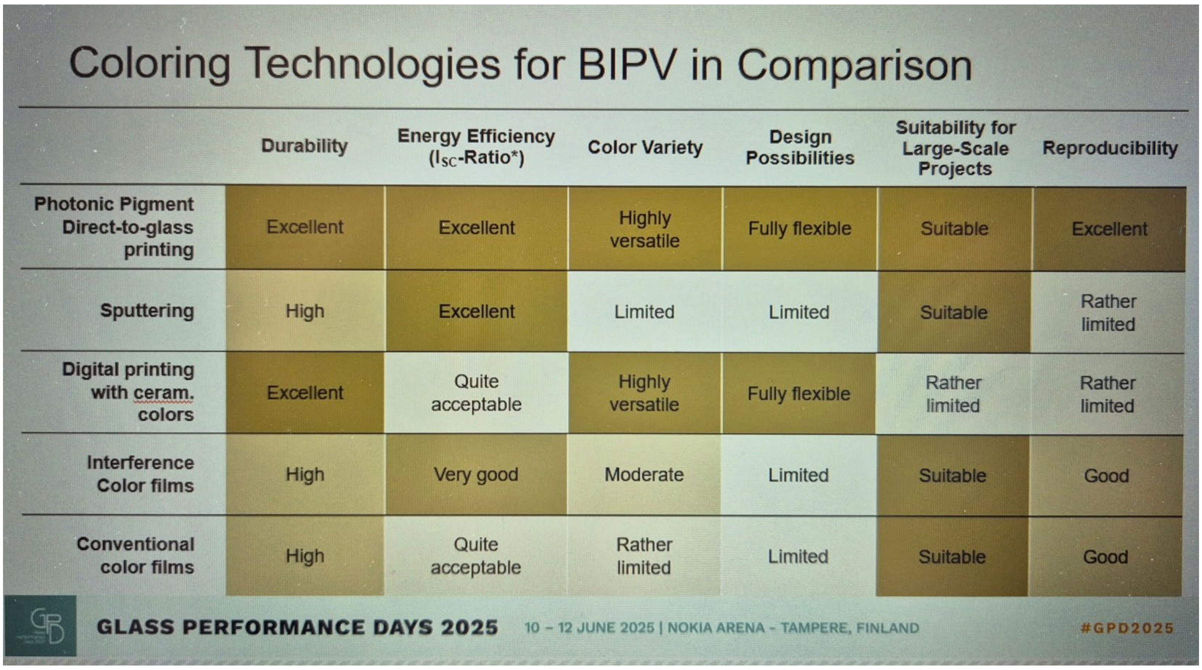
- Application of a colored polymer laminate to the glass surface
- Easy-to-implement solution with disadvantages regarding UV stability (film may discolor over time)
- Limited durability of the foil
- Complex and costly color development process
- Large batch sizes required for color adjustments

3.4. Digital Ceramic Printing

- High flexibility in color design
- Fast color adjustment
- Lower efficiency due to the use of absorptive pigments
  Reduced color chroma due to a high flux content in the color paste

3.5. Comparative Analysis of Coloring Methods

Table 1: The table below provides a direct comparison of the four coloring technologies.



Coloring Technologies for BIPV in Comparison

	Durability	Energy Efficiency (I_{SC}-Ratio*)	Color Variety	Design Possibilities	Suitability for Large-Scale Projects	Reproducibility
Photonic Pigment Direct-to-glass printing	Excellent	Excellent	Highly versatile	Fully flexible	Suitable	Excellent
Sputtering	High	Excellent	Limited	Limited	Suitable	Rather limited
Digital printing with ceram. colors	Excellent	Quite acceptable	Highly versatile	Fully flexible	Rather limited	Rather limited
Interference Color films	High	Very good	Moderate	Limited	Suitable	Good
Conventional color films	High	Quite acceptable	Rather limited	Limited	Suitable	Good

The five most common color-generation systems have been analyzed in more detail. The results are based on practical experience and certainly leave room for further discussion."

4. Structure and Optical Properties of Modules

The photovoltaic modules consists of several optimized layers:

1. Front glass
2. Color layer (interference-based ceramic color layer on position 2)
3. Front encapsulant foil
4. Solar cells (monocrystalline or polycrystalline)
5. Rear encapsulant foil
6. Black color layer (position 3)
7. Back Glass

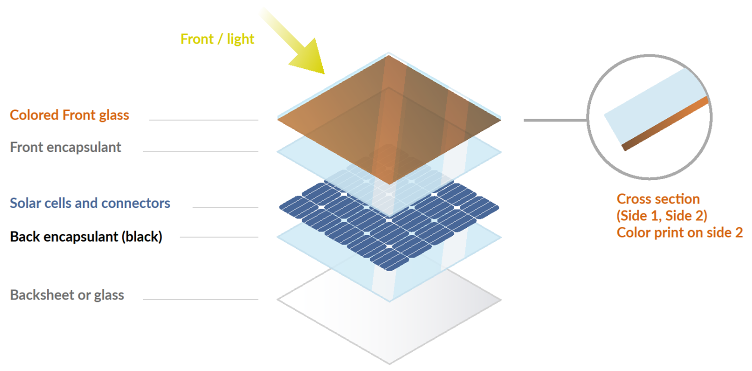


Fig. 2: Structure of the solar module.

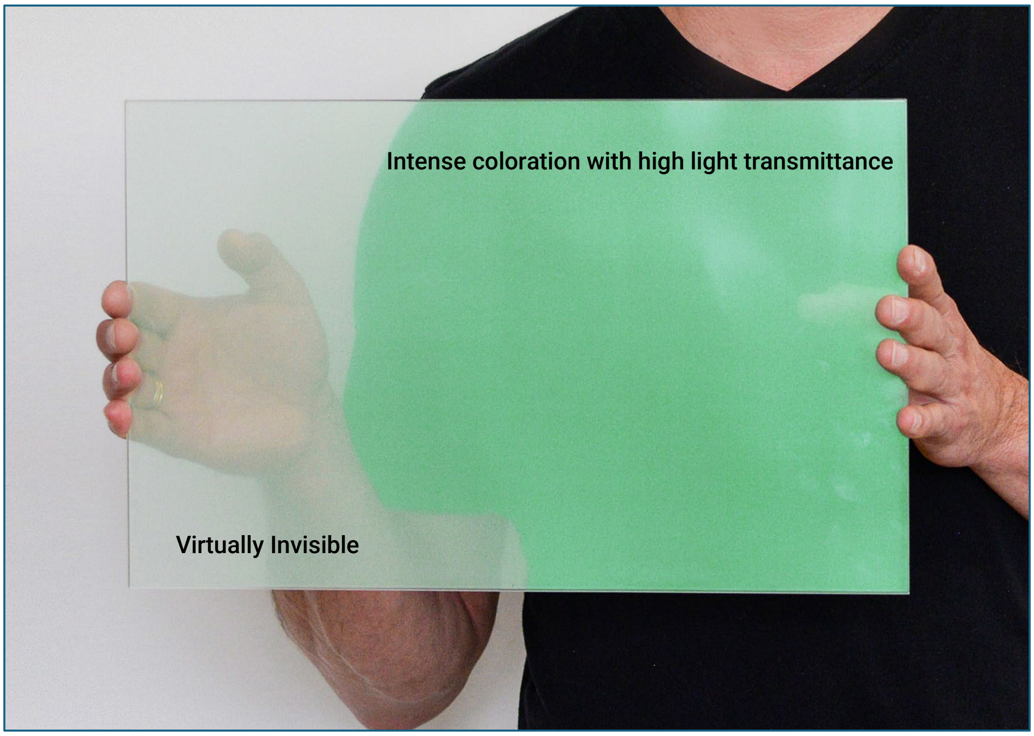


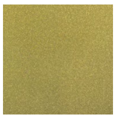
Fig. 3: A pane of glass (like the front glass in Fig. 2) screen-printed with a tone of green: seemingly transparent, the color appears in full intensity against the black background.

5. Proven Quality

5.1. Efficiency Test

The Fraunhofer-Center für Silizium-Photovoltaik (CSP) subjected the colors to a real efficiency test (Fraunhofer 2023). It was found that the Color Performance Ratio of most colors have 90% or higher. Only light gray or dark white have a lower remaining efficiency. (compared to a normal printed standard black module).

Table 2: Color Performance Ratio (=I_{SC}-Ratio) values resulting from efficiency tests, conducted by the Fraunhofer-Center für Silizium-Photovoltaik (CSP).

Tested color	Color name	Color Performance Ratio
	Silver	82 %
	Anthracite	92 %
	RGB Grey	94 %
	Dark Grey	98 %
	RGB Yellow	90 %
	RGB Blue	95 %
	RGB Green	95 %
	RGB Red	90 %
	Brown	87 %
	Purple	97 %

5.2. Aging Test

The accelerated aging test in accordance with the IEC standard requires 1,000 hours of exposure to strong UV light at a relative humidity of over 85 %. We irradiated the module for 2,300 hours and found virtually no loss of efficiency (International Solar Energy Research Center, 2019).

Table 3: Retained performance after harsh accelerated aging of mini modules:
1) Colored ceramic glass – 1 cell mini module; 2) UV preconditioning (15 kWh/m^2);
3) Damp heat test (85 °C/85 % RH) for 2,330 hours = 2.3 times IEC standard.

Tested color	Initial efficiency	After UV-soaking	After UV + damp heat
	14.28 %	13.92 % - 2.5 %	14.17 % - 0.8 %
	14.06 %	13.66 % - 2.8 %	13.88 % - 1.3 %

5.3. Stress Test

The Mechanical Load Test (Tempered Glass test) in accordance with DIN EN 12150-1:2000, DIN EN 1288-3:2000 and Z-70.1-75 was successfully completed (Friedmann & Kirchner, 2025).

6. Advantages in Solar Module Production

Fig. 4: Employing the technology provides maximum flexibility in solar module production – various possible module surfaces, shapes and color designs expand the creative freedom in architecture.

7. Architectural Applications

7.1. Meteorological Institute, Leipzig, Germany

- Objective: Integration of a subtle, sky-colored facade
- Solution: Modules in 39 different formats with glossy glass
- Installed Area: 730 m²
- Capacity: 71.2 kWp

Fig. 5: Meteorological Institute, Leipzig, Germany. © raumleipzig architekten • modules: SUNOVATION GmbH

7.2. Platinum Building, Wiesbaden, Germany

- Objective: Development of an Energy+ building
- Solution: Matt PV modules with a homogeneous color appearance
- Installed Area: 947 m²
- Capacity: 113.6 kWp

Fig. 6: Platinum Building, Wiesbaden, Germany. © OFB Projektentwicklung GmbH • modules: SUNOVATION GmbH

7.3. Lehner Versand, Schenkon, Switzerland

- Objective: Subtle, energy-efficient building extension
- Solution: 3 facades with uniform modules mounted in various angles
- Installed Area: 866 m²
- Capacity: 109 kWp

Fig. 7: Lehner Versand Building, Schenkon, Switzerland. © Felix & Co. AG • modules: ertex solartechnik GmbH

7.4. Stavanger Town Hall, Stavanger, Norway

- Objective: Building energy renovation with aesthetic facade design
- Solution: Modules homogeneously printed with plain green color

Fig. 8: Stavanger Town Hall, Stavanger, Norway. © K2 Visual / LINK Arkitektur • modules: SolarLab

Fig. 9: Large BIPV Modules produced by SolarLab. © SolarLab

7.5. StadtparkPLUS, Wetzikon, Switzerland

- Objective: Construction of an energy-efficient residential building in a modern style
- Solution: 68 matte modules in 18 different formats, solid anthracite color;
  surplus energy is stored and used to charge electric cars, for example
- Installed Area: 130 m²
- Capacity: 16 kWp

Fig. 10: Residential building "StadtparkPLUS", Wetzikon, Switzerland.
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8. Conclusions

The Photonic Pigment Technology is revolutionizing BIPV facade architecture by combining creative design freedom with high energy efficiency. It enables colorful, durable, and high-performance solar facades that meet both functional and aesthetic requirements. Hence, it offers architects and developers completely new opportunities to create modern buildings that are both energy-efficient and visually appealing. The ceramic colors based on the interference principle are highly durable and very long-lasting, meaning that they withstand environmental influences and remain brilliant over a very long period of time. The technology also renders an important contribution to sustainability in architecture, as it makes renewable energy attractive and versatile for use in buildings. It is therefore a pioneering development for the construction and solar technology industry.

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