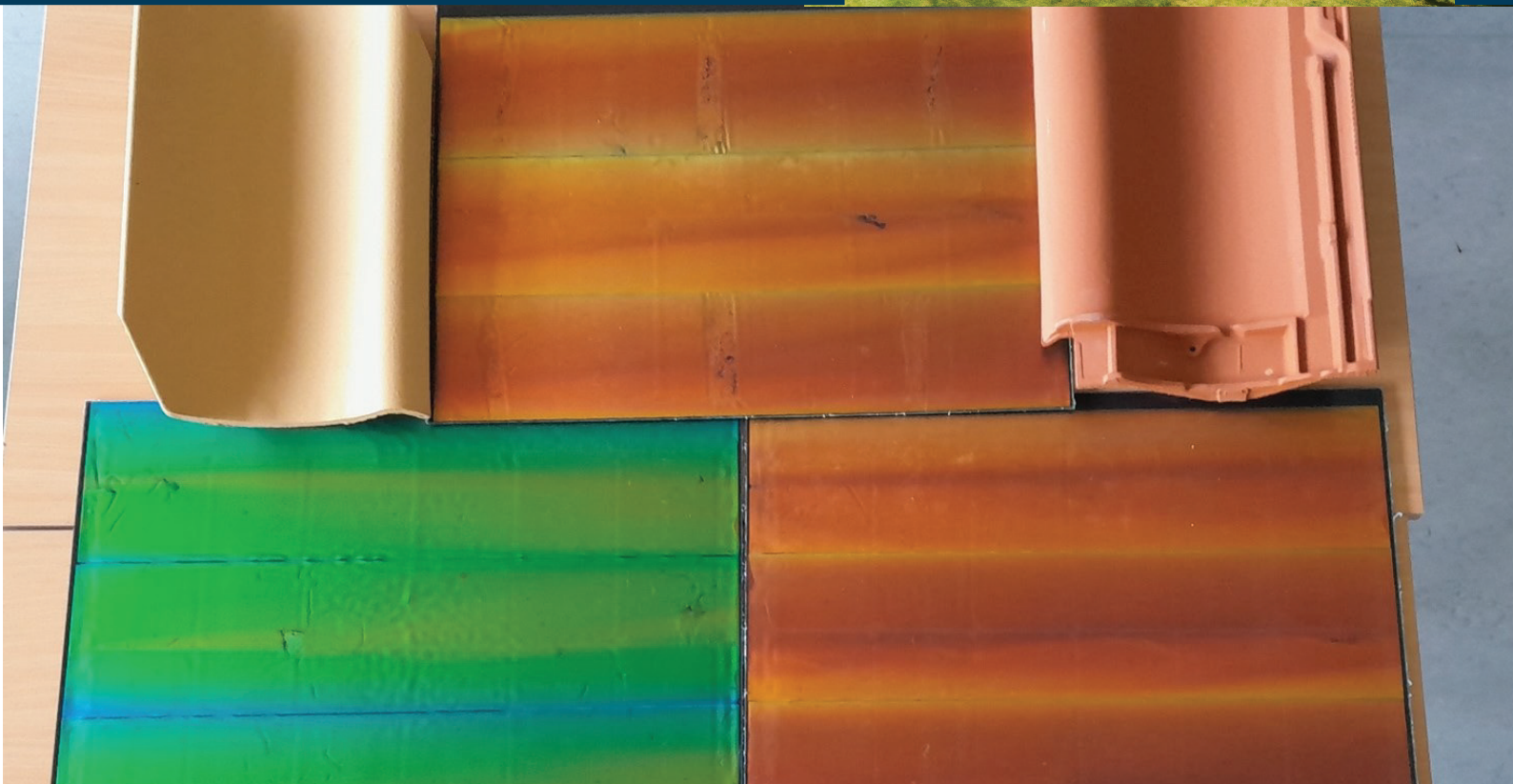


## EUDP 64022-1027

ColorFoil - Polymer foil with structural colors for energy efficient coloration of solar panels

FINAL REPORT



### PROJECT PARTNERS

## 1. Project details

<b>Project title</b>	<b>ColorFoil - Polymer foil with structural colors for energy efficient coloration of solar panels</b>
<b>File no.</b>	J.nr. 64022-1027
<b>Name of the funding scheme</b>	EUDP
<b>Project managing company / institution</b>	Stensborg A/S
<b>CVR number</b> (central business register)	21062693
<b>Project partners</b>	Syddansk Universitet, DTU Electro (former Fotonik) and Racell
<b>Submission date</b>	31 July 2025

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## 2. Summary

### **Project summary:**

The ColorFoil project successfully developed a new structural colored interlayer foil with minimal coloration loss, and angle independent color for coloration of PV panels used in the architectural sector. Structural colors rely on interference and act as optical filter reflecting specific part of the solar spectrum as opposed to absorptive colors where pigments absorb and waste part of the incoming spectrum.

Within the project an optical diffusor has been optimized minimizing the angle dependency of the color. An optical model enabling design of the structural color layers to achieve a specific color has been developed, and further material compatibility investigations has been performed to ensure long lifetime of the colored modules.

Finally scale up of the production process has been investigated and final demonstrators showing the potential of the technology has been fabricated.

### **The purpose of the project:**

The project purpose was to leverage the architectural integration of PV in building enabling strong angle independent colors with minimal coloration loss, which will improve the acceptance of PV in the build environment. Further the objective was to ensure material compatibility and angle independent color.

### **Results, conclusions and perspective:**

Within the project we successfully demonstrated a structural color foil in two colors with low coloration loss of around 10 and 15 % for the green and red color and both colors shows good angular color stability. Further a very efficient optical simulation based tool was developed enabling design of the structural colors to do the best color matching to a target color, which showed the need to use nonperiod thin film stacks especially to achieve red tone colors.

Further diffusor structures were successfully developed to minimize the angular color dependency often experienced in structural colors, as well as materials for the interlayer foil were selected to achieve material compatibility within the PV laminate, where decisions were based on results from accelerated aging tests.

The project concluded with the build of some demonstrators.

Overall, the project have demonstrated the applicability of structural colored interlayer foils for PV applications combining low coloration loss with saturated colors matched to common building materials and the Stensborg is working to scale the technology, enabling BIPV manufactures to produce efficient colourful PV on buildings in a flexible production setting.

## Projekteresumé:

ColorFoil projektet udviklede med succes en ny strukturel farvet mellemlagsfolie med minimalt farvetab og vinkeluafhængig farve til indfarvning af PV-paneler, der anvendes i den arkitektoniske sektor. Strukturelle farver er afhængige af interferens og fungerer som et optisk filter, der reflekterer en specifik del af solspektrret i modsætning til absorberende farver, hvor pigmenter absorberer lyset og spilder en del af det indkommende lysspektrum.

I projektet er en optisk diffusor blevet optimeret, hvilket minimerer farvens vinkelafhængighed. En optisk model, der muliggør design af de strukturelle farvelag for at opnå en specifik farve, er blevet udviklet, og yderligere undersøgelser af materialekompatibilitet er blevet udført for at sikre lang levetid for de farvede moduler.

Endelig er opskalering af produktionsprocessen blevet undersøgt, og demonstrationsmodeller, der viser teknologiens potentiale, er blevet fremstillet.

### Formålet med projektet:

Projektets formål var at løfte den arkitektoniske integration af PV i bygninger, ved at fremstille mættede vinkeluafhængige farver med minimalt farvetab, hvilket vil forbedre accept af PV i byggede miljøet. Yderligere var målet at sikre materialekompatibilitet og vinkeluafhængige farver.

### Resultater, konklusioner og perspektiv:

I projektet har vi succesfuldt demonstrerede en strukturel farvet folie i to farver med lavt farvetab på omkring 10 og 15 % for den grønne og røde farve, og begge farver udviser god vinkelfarvestabilitet. Derudover blev der udviklet et meget effektivt optisk simuleringsbaseret værktøj, der muliggør design af de strukturelle farver for at opnå den bedste farvematchning til en ønsket farve, hvilket viste det er nødvendigt at benytte aperiodiske tynde filmlag, især for at opnå røde tonefarver.

Yderligere blev diffusorstrukturer udviklet for at minimere den vinkelfarveafhængighed, der ofte opleves i strukturelle farver, samt materialer til mellemlagsfolien blev valgt for at opnå materialekompatibilitet inden for PV-laminatet, hvor materialevalget blev baseret på resultater fra accelererede ældningstests.

Projektet afsluttedes med fabrikation af demonstrationsmodeller.

Samlet set har projektet demonstreret anvendelsen af strukturelle farvede mellemlagsfolier til PV-applikationer, der kombinerer lavt farvetab med mættede farver, der matcher almindelige byggematerialer, og Stensborg arbejder på at skalere teknologien, så BIPV-producenter kan producere effektiv farverige PV-produkter til bygninger i et fleksibelt produktionsmiljø.

### 3. Project objectives

The objective of the ColorFoil project was to develop and demonstrate an innovative interlayer foil for photovoltaic modules, using structural color technology to enable efficient, cost-effective, and angle-independent coloration of solar panels. This approach is particularly suited for applications in Building Integrated Photovoltaics (BIPV) and Building Attached Photovoltaics (BAPV), where visual integration into architectural environments is critical.

The project aimed to solve key challenges in colored PV by introducing a foil-based solution that avoids the trade-off between color saturation and power loss typically seen in conventional dye or pigment-based approaches. Structural coloration allows for vivid and stable colors without significant energy absorption, and the foil-based approach facilitates scalability and compatibility with roll-to-roll manufacturing.

**The project's success criteria were:**

- **Availability of at least three structural colors** (red, green, and blue) with angle-independent appearance.
- **Power loss of less than 10%** compared to reference uncolored modules, for each color matching a RAL chart.
- **Material compatibility and long-term stability**, proven through standardized stress testing according to **IEC 61215**, including damp heat and UV exposure.
- **Color stability after accelerated UV exposure**, simulating 15 years of Danish outdoor conditions (equivalent to 60 kWh/m<sup>2</sup>/year).
- **Roll-to-roll (R2R) production** of the color foil with integrated nano-structuring and thin-film deposition.
- **Material cost** below €5/m<sup>2</sup>, making the solution economically viable for large-scale architectural applications.
- **Energy technology developed and demonstrated:**

The project developed and demonstrated a **structurally colored interlayer foil** for PV modules that offers:

- **High visual quality and architectural adaptability.**
- **Low optical losses**, ensuring energy efficiency.
- **Angular color stability**, essential for aesthetic consistency on building façades.
- **Durable material performance**, verified through environmental testing.
- **Scalable and cost-effective manufacturing**, leveraging R2R nanoimprint lithography and thin-film sputtering.

This technology contributes to the advancement of next-generation solar building materials that combine function and design, promoting wider adoption of PV in urban environments.

## 4. Project implementation

The ColorFoil project evolved smoothly and in close alignment with the original project plan. The consortium was structured around five focused work packages (WP1–WP5), covering project management, small-scale prototyping, material durability testing, upscaling, and final demonstration. Each partner contributed according to their expertise, ensuring progress across technical, scientific, and commercial dimensions.

From the outset, the collaboration was efficient and proactive. Regular monthly progress meetings and dedicated workshops at DTU facilitated close coordination. This helped to mitigate delays and ensure all partners had a practical understanding of the fabrication processes and requirements, especially in relation to PV module production and the role of the coloured foil.

The project had several technical and market risks which were all addressed as early as possible to ensure minimum impact on the project's progress and to allow for a potential change in direction if needed. The project consortium had the needed competences to ensure the technical challenges were addressed. Two major technical risks were identified:

- i) design of structural colors that match the color of conventional building materials
- ii) material incompatibilities within the laminate.

To assist in the design of colored foils capable of realizing a multitude of structural colors matching those of most building materials, and to mitigate risk i), we developed a computer code capable of predicting the color reflected by a given structural color structure and of optimizing the layer configuration necessary to reproduce any target color. This proved to be a very powerful tool for designing colored foils with customized color spanning almost the complete standard RGB color space. It offers a clear advantage over the more intuitive periodic structures commonly employed in colored PV applications, for which the achievable color gamut is far more limited. Indeed, as we demonstrate, the use of such an approach allowed us to perfectly replicate the color of a clay roof tile typically employed in Danish architecture, as detailed in the Results section of this report.

Regarding potential material incompatibilities within the laminate (risk ii)), extensive literature review on material combinations was combined with experimental evaluation of minimodules upon exposure to accelerated damp heat stress and UV. The accelerated tests showed power loss for samples with  $\text{TiO}_2$ , likely due to photocatalytic degradation of the encapsulant when in contact with titanium dioxide. Therefore, we chose to replace  $\text{TiO}_2$  with aluminium-doped zinc oxide (AZO) as the high-refractive-index material in our colored layer configuration. No extra degradation was observed for silicon dioxide ( $\text{SiO}_2$ ), which was then selected for this application.

The project partners are very satisfied with the technical results of the project, fulfilling the milestones on time, and remain confident that the ColorFoil technology will become a compelling solution in a market increasingly demanding energy-producing building skins, especially as solar energy integration into all EU buildings becomes a requirement.

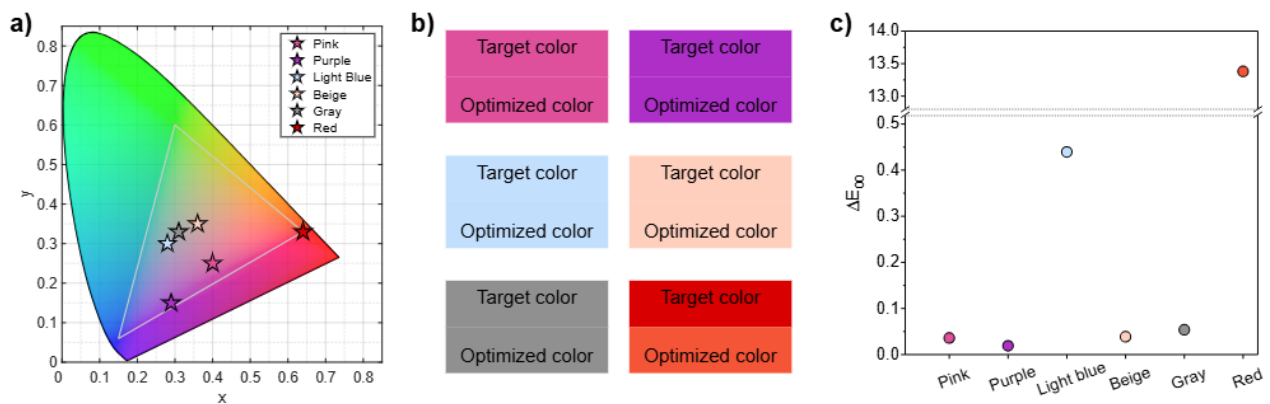
## 5. Project results

All of the original project objectives and milestones were successfully achieved. Below is a detailed description of the results—linked to their realization in the associated work packages and milestones—for each work package (apart from the 1:1 full-scale installation which was in the end decided to be realized on DTUs outdoor BIPV test facility).

### 5.1 Small Scale Prototype Development

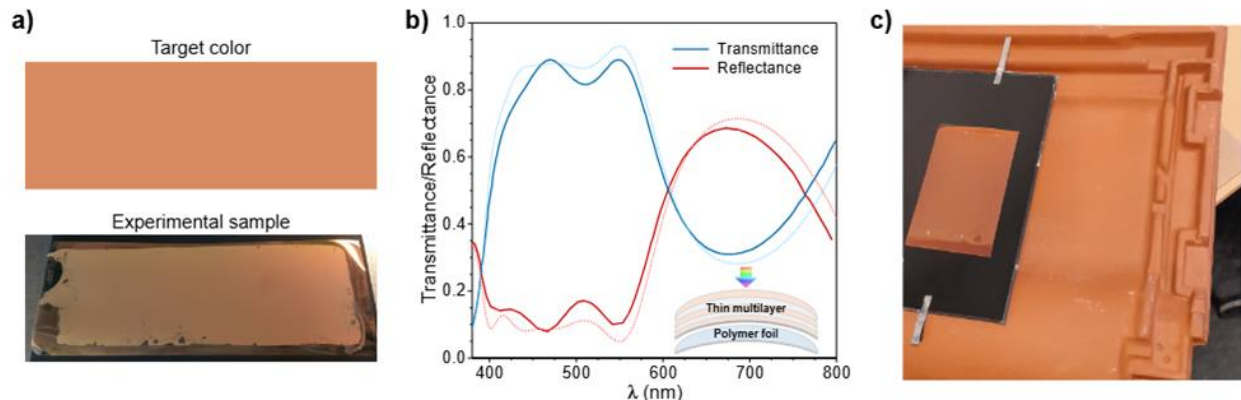
To reduce time, costs, and material consumption during the design and prototyping of different colored foils, we began by developing a computer code capable of accurately determining the color reflected by various layered structures with specified thicknesses. Initially, the code's effectiveness was tested by predicting the reflected color from 5-layer periodic structures designed according to the quarter-wave condition for constructive interference at wavelengths corresponding to green light. The methodology was successfully verified through the experimental fabrication of green colored foils.

Despite the excellent results for green, we soon recognized that such simpler and intuitive periodic configurations would not be sufficient to accurately replicate the colors of various construction materials. To address this, we further developed the code to include an optimization algorithm capable of exploring the entire design space of layer thicknesses to find configurations that best match any target color selected by the user. This methodology dramatically expanded the achievable color gamut, enabling the design of configurations capable of matching nearly every color in the sRGB color space. This is demonstrated in Figure 1, which shows a set of colors typically difficult to reproduce using periodic designs.



**Figure 1:** Testing of our optimization algorithm to reproduce a range of colors within the sRGB color space. (A) Position of colors in the CIE x-y color space; (B) Visual comparison of target vs. achieved colors; (C) Color difference metric ( $\Delta E$ ), with values below 1 indicating no perceptible difference.

Given the excellent theoretical agreement between the target colors and those identified by our optimization algorithm (with  $\Delta E$  values typically  $\ll 1$ , except for pure red), we applied the methodology to replicate the hue of a red clay roof tile commonly found in Danish architecture. The tile's color coordinates were experimentally determined by the consortium. This resulted in an optimized 7-layer stack that perfectly matched the desired hue. The optical performance (transmittance and reflectance) of the fabricated "clay red" foil confirmed the design, and a visual comparison of the resulting PV minimodule placed against a real clay roof tile further demonstrated the success of this approach.



**Figure 2:** Application of the optimization algorithm developed to fabricate clay red colored foils.

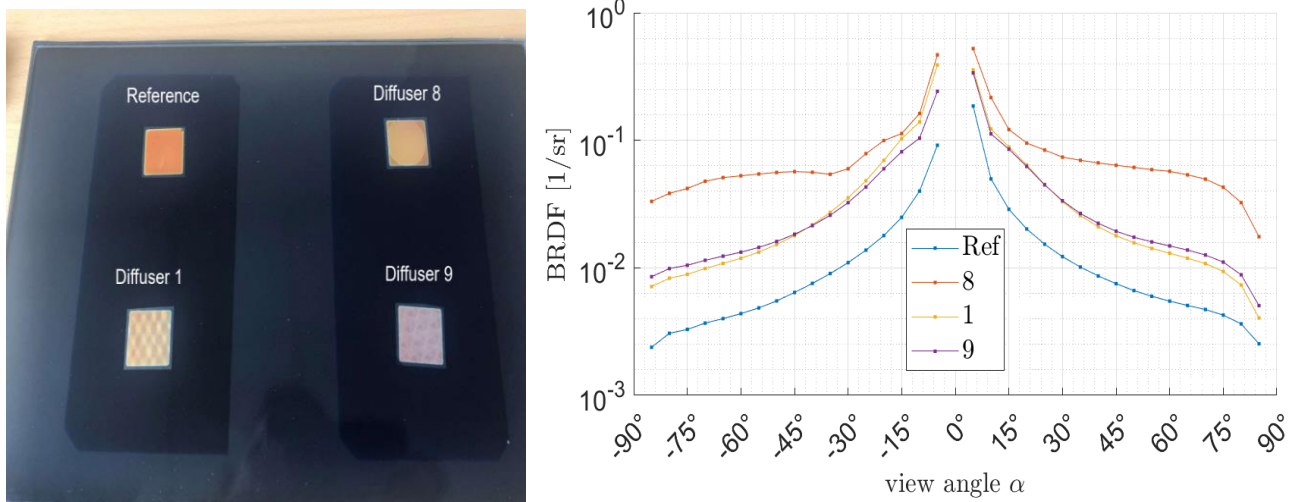
In parallel with the computer code—tuned to optimize reflected color for normal incidence—ColorFoil partners developed an optical diffuser to minimize iridescence and ensure that the same color is observed regardless of the light’s angle of incidence or the viewing angle.

This optical diffuser is composed of an optically transparent carrier foil and a nanoimprint-lithography (NIL) patterned structure formed in a UV-cured resin. For the prototype, three key components of the diffuser had to be identified:

1. Polymeric carrier foil – Required to be optically transparent within the PV absorption spectrum while offering strong and durable adhesion to the resin for long-term stability.
2. UV NIL resin – Needed to accurately replicate nanoscale structures, offering high optical transparency and sufficient durability under PV module processing conditions.
3. Diffuser structure topology – The shape and geometry of the nanopattern needed to deliver angular diffusion while remaining compatible with scaling and lamination.

The selected foils and resins were screened for their suitability in NIL upscaling. Transmittance measurements confirmed their optical transparency, while durability testing assessed resistance to subsequent processing steps involving heat and pressure. An acrylate-based imprinting resin (X311), developed by Stensborg A/S, was chosen to meet the optical and mechanical requirements.

A range of optical diffuser designs were fabricated and evaluated using bidirectional reflectance distribution function (BRDF) measurements, including angle-resolved reflectance and transmittance. Since the diffuser structure is optically index-matched to glass, metallization was applied to render the structure reflective and thus visible when encapsulated in the PV laminate. Based on these results, a design was selected that exhibited high angular scattering uniformity, making it well-suited to enable angle-independent color in the final ColorFoil product.



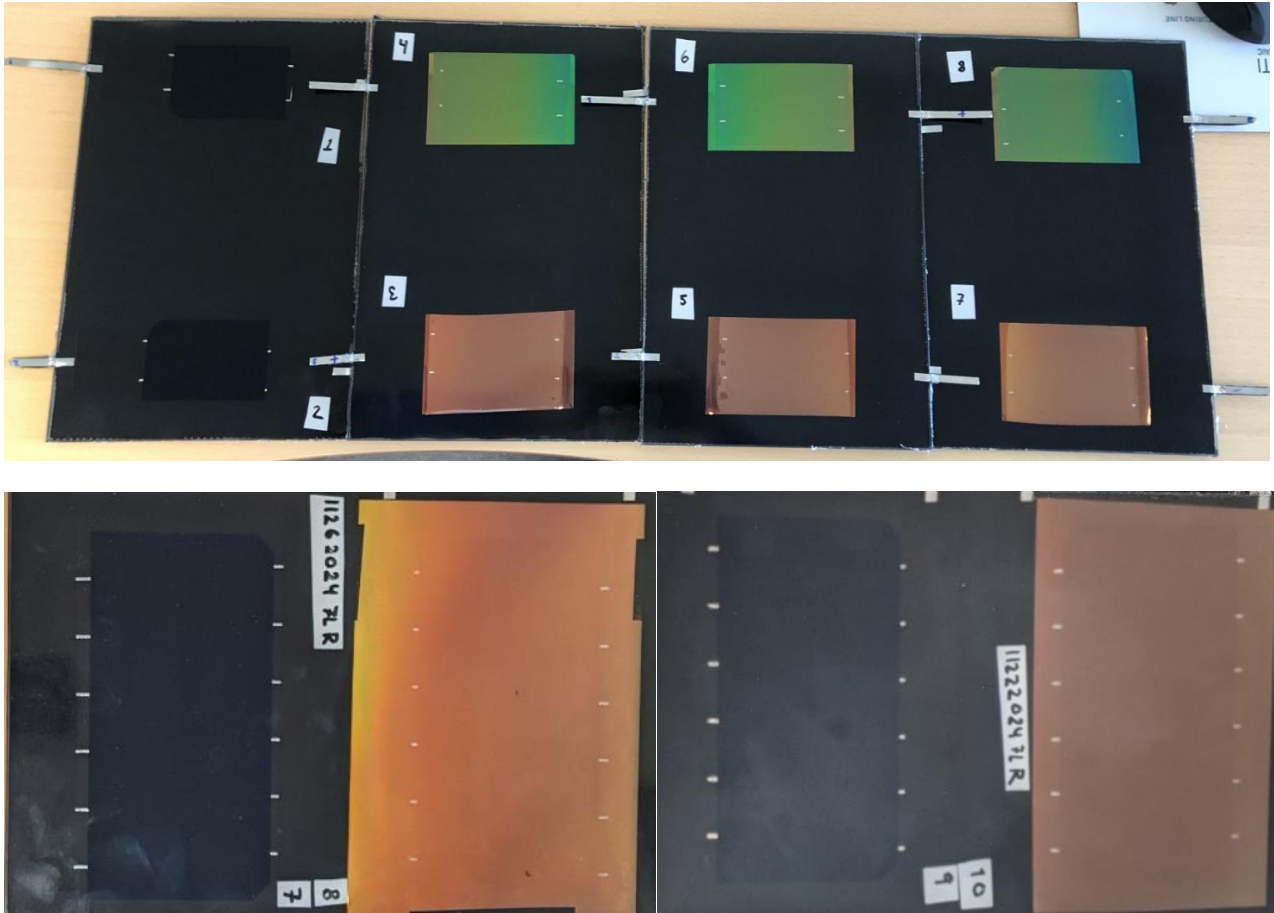
**Figure 3:** Efficacy evaluation of a variety of designed diffuser structures. Left: Photographs of metal-coated diffuser structures. Right: BRDF measurements (angle-resolved reflectance) of diffuser structures. Diffuser 8 exhibits the most angle-independent light scattering.

The fabrication of ColorFoil samples with optically tunable properties requires a process that ensures high uniformity, scalability, and cost-effectiveness. Among available thin film deposition techniques, Roll-to-Roll (R2R) radio frequency (RF) magnetron sputtering was selected as the most suitable, offering precise control over layer thickness, high throughput, and compatibility with flexible substrates.

In the ColorFoil project, dynamic R2R magnetron sputtering was used to conformally deposit alternating layers of AZO and SiO<sub>2</sub>—according to thicknesses determined through computational optimization—to produce green and clay-red colored multilayer films. These coatings were applied onto flexible polymer substrates equipped with the optimized optical diffusers developed within the project. During deposition, the substrate was continuously passed through a vacuum chamber operating at a base pressure of  $6.4 \times 10^{-7}$  mbar and working pressures of  $3.29 \times 10^{-3}$  mbar for AZO and  $7.72 \times 10^{-3}$  mbar for SiO<sub>2</sub>.

PV mini-modules were fabricated using standard photovoltaic lamination processes, incorporating interdigitated back contact (IBC) solar cells, EVA or POE encapsulants, and solar glass with a black backsheet. These modules enabled performance testing of the ColorFoil films in a realistic environment. Optical characterization was performed by measuring transmittance and reflectance through the full laminate stack, and the samples were also subjected to accelerated degradation testing.

To explore the effect of the glass surface texture on the final appearance of the modules, small PV laminates were fabricated using both flat and satin-finished solar glass, allowing comparison of aesthetic and optical performance.

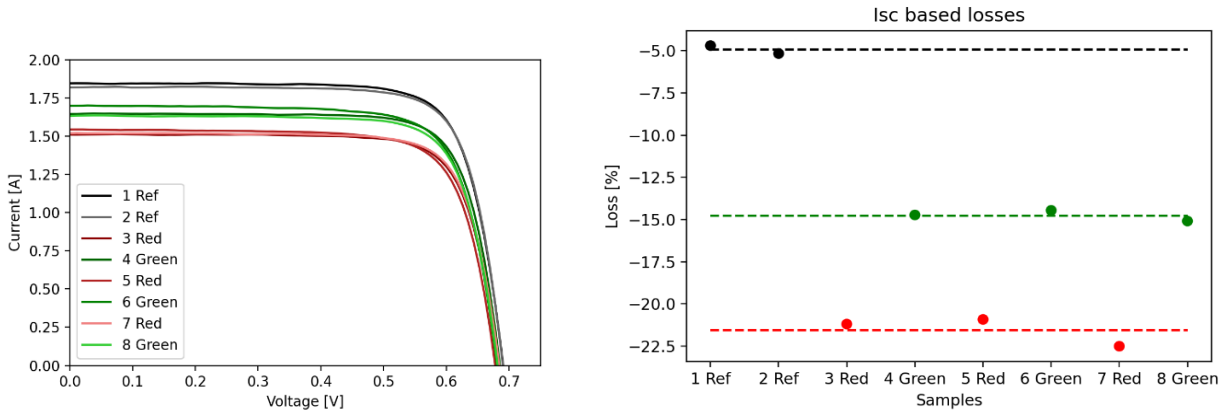


**Figure 4:** Picture of the laminates used for optical characterization. Top row (left to right): Reference sample; samples with green and red foils. Bottom row: Sample with red foil and reference cell under standard glass; sample with red foil and reference cell under satin glass.

The PV mini-modules were characterized across multiple dimensions:

**Electrical performance**

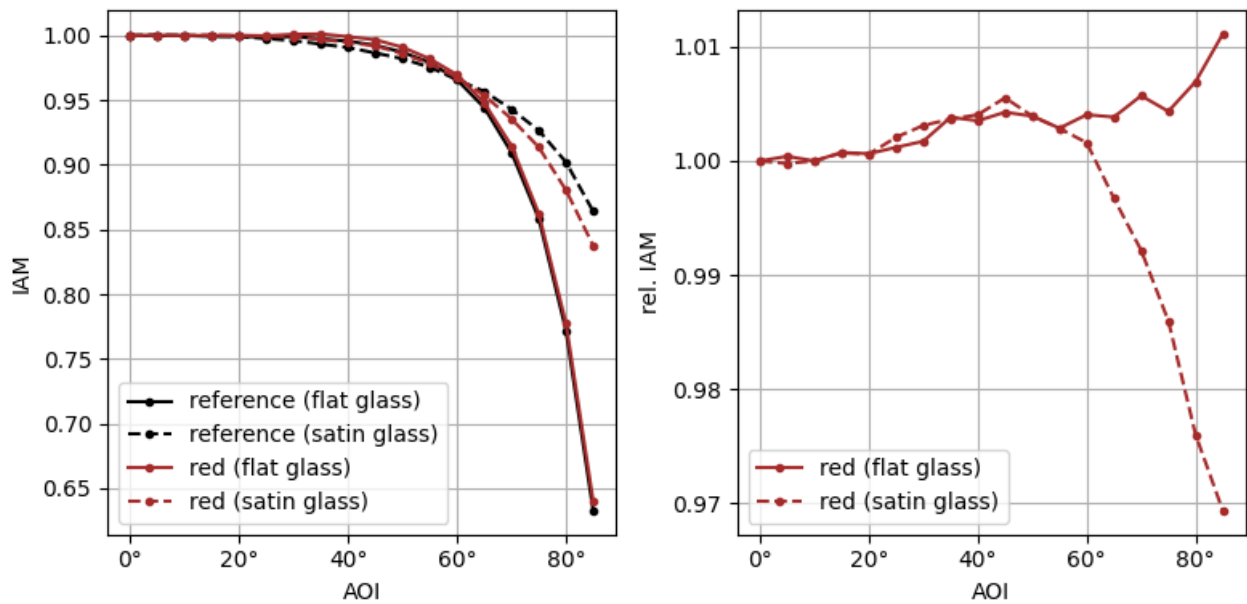
IV measurements were conducted on all cells before and after encapsulation under standard test conditions (STC) using a calibrated solar simulator. This allowed for the quantification of transmission losses introduced by the colored interlayers. Reference samples without colored foils were used to isolate and attribute losses solely to the foil layers, eliminating confounding effects from front glass and encapsulant reflections. Additionally, electroluminescence (EL) imaging was employed to assess the integrity of the PV cells post-encapsulation and to ensure that observed losses were not due to cell damage or processing defects.



**Figure 1:** IV curves (left) and relative loss evaluation of the test samples (right).

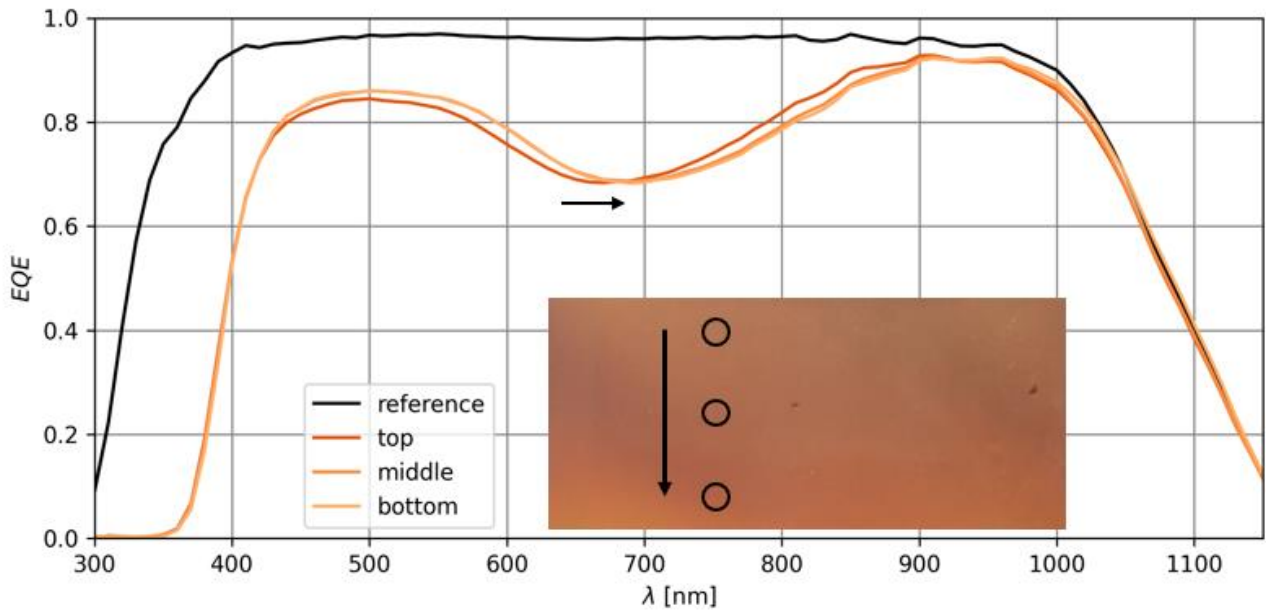
As seen in **Figure 1** for the given bill of material we have an Isc loss for the encapsulation of around 5 % and an additional loss of around 10 % for the green color and around and additional 16 % for the tile red color.

To characterize the angular dependent transmission losses, the incidence angle modifier (IAM) was measured on all suitable samples, showing a similar IAM for red-coloured and reference samples regardless of cover glass used for most of the relevant range. Minor increases in angular dependent transmittance are visible for intermediary incidence angles (30°-60°), while at higher incidence angles, there is a larger variation between samples. These angles are less relevant for overall module and system performance, however.



**Figure 2:** Incidence angle modifier and relative incidence angle modifier for reference and red coloured samples.

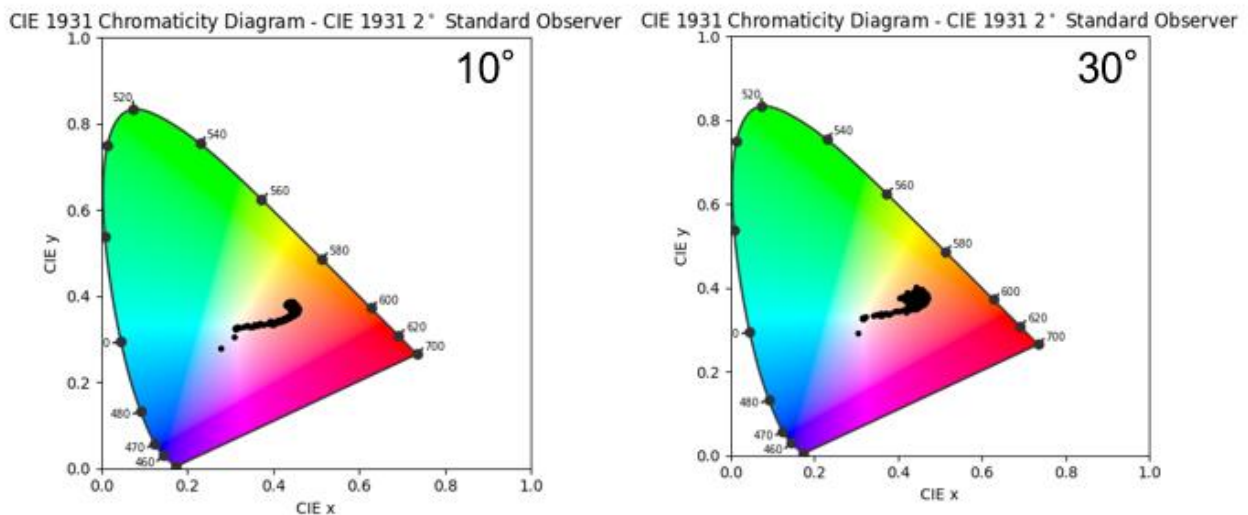
External quantum efficiency (EQE) was measured on selected samples to both determine the spectral transmittance, which was used to validate the simulations presented earlier, as well as assess sample uniformity. Minimal peak shifts were observed for the most homogeneous red samples, indicating that with sufficient optimization of the deposition process, highly uniform PV modules are possible.



**Figure 3:** Spectra of external quantum efficiency measured on a reference sample and a red sample in different positions.

Appearance:

DTU’s goniospectrophotometer was used to measure the bi-directional reflectance distribution function (BRDF) on different samples - a parameter that can give insights into both glare risk, colour stability, colour constancy, and overall colour appearance. Consistent with expectations, structured and satinated glass was seen to significantly reduce glare, with some minor effect on the colourfulness of samples due to the increased diffuse reflectance from the cover glass. Minor hue and chroma variations were observed over different combinations of incidence and view angles, however overall samples proved good colour stability:



**Figure 4:** Spread of colour coordinates for different reflection angles at incidence angles of 10° and 30°.

As seen in **Figure 4**, an increase in incidence angle does not change the hue angle for most observation points, mostly leading to a shift in chroma (colourfulness). This indicates good colour stability of appearance of the modules under different lighting conditions, as would occur over the course of a day. As for the spread in colour coordinates within individual incidence angle measurements – representing the angular homogeneity

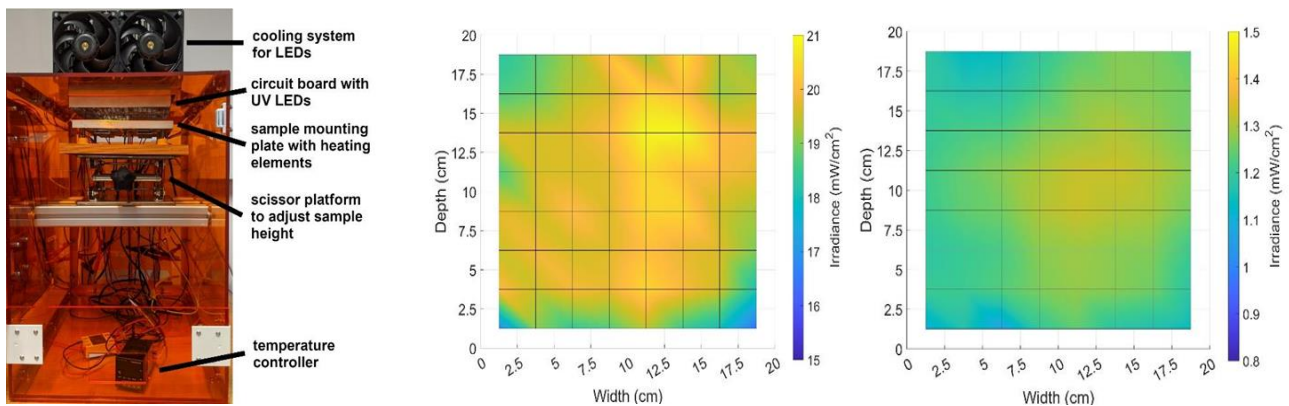
of a BIPV installation when observed from relatively close-by – there is only a limited number of points deviating from the main cluster. These represent very shallow reflection angles, which in most materials will appear less saturated. In addition, there is a slight spread in hue angles, leading to minor variations in colour, which may warrant further optimization.

## 5.2 Material compatibility and durability

The PV laminate is a complex polymeric stack, which for standard modules are fairly well established. However adding a color inside the PV laminate introduces new materials which in itself must be stable inside the laminate and further it must be ensured that this new material is not causing degradation mechanisms to the rest of the materials inside the PV laminate and vice versa- also when the panels are exposed to the expected environmental stressors as UV irradiation, humidity and temperature variations.

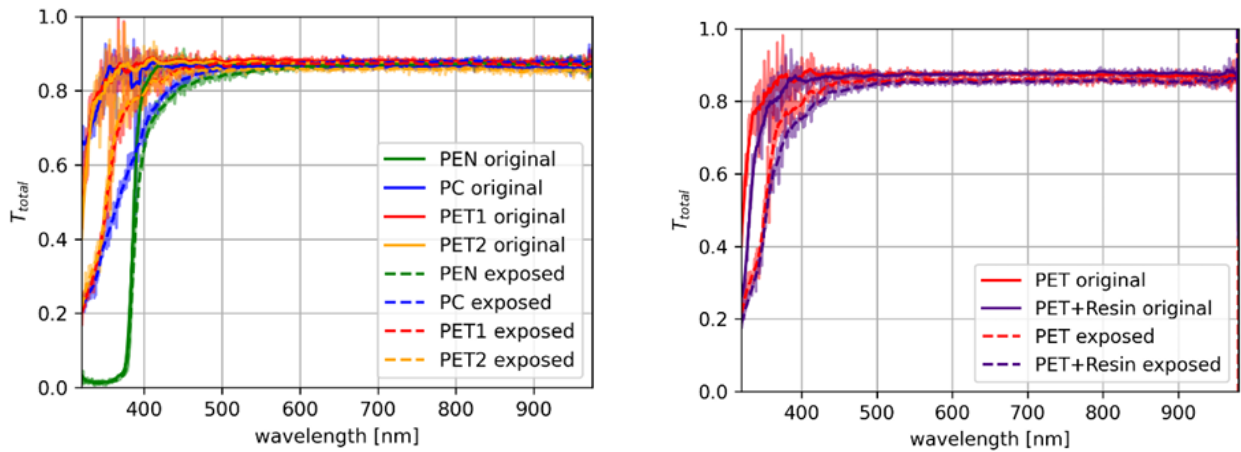
Therefore, accelerated stress testing using UV exposure of 4 candidates of base interlay foil were performed; a polyethylene naphthalate (PEN) foil, a polycarbonate (PC) foil and two polyethylene terephthalate (PET) foils.

The foils were exposed to UV light with light intensity of 210 W/m<sup>2</sup> in special developed LED based UV aging setup. The UV lamp is shown below and consists of a temperature controlled heating chuck and a UVA and UVB LED array. It is developed in compliance to the demands of IEC 61215 and targets the highest possible permissible light intensity of 250 W/m<sup>2</sup>. A picture of one of these setups is shown in **Figure 5** together with spatial light intensity maps for UVA and UVB. As seen an efficient setup is achieved with a homogenous light intensity in a spotside of 20 by 20 cm, and with high UV intensity.



**Figure 5:** UV aging device with UV-A and UV-B uniformity maps.

Using this setup the four base polymer foil candidates were exposed to 15KWh/m<sup>2</sup> in accordance with the prequalification dose prescribed in IEC 61215, and spectral transmittance were measured before and after, as well as the resins UV stability was investigated.

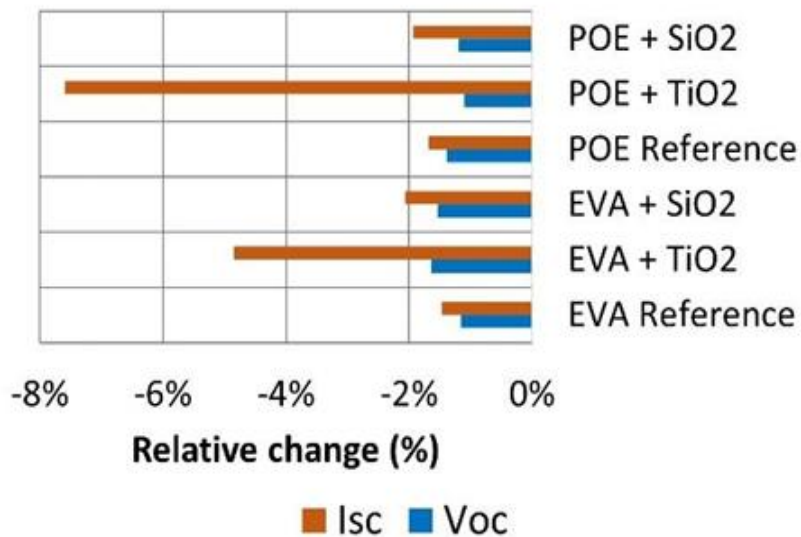


**Figure 6:** Transmittance of the base foil candidates before and after aging (left) and same for the resins (right).

**Figure 6** left figure shows aging and associated transmission losses in all polymer samples, with highest losses in PC foils. PEN foils also show significant losses as well as an overall poor transmission in the UV region. For both PEN and PC foils, clearly visible yellowing of the polymers could be observed after UV exposure. PET foils show lowest losses in the UV region (also after UV exposure), with constant overall losses for visible and NIR wavelengths, resulting in no discernible yellowing. To the right figure shows only slight reductions in overall transmittance for the resin coated foils– mainly for UV wavelengths – and no significant increase of transmission losses due to degradation for resin-coated samples.

In addition, the impact of silicon oxide (SiO<sub>2</sub>) and Titanium oxide TiO<sub>2</sub> as the outer layer of the color stack were tested in minimodules using both POE and EVA as encapsulants that underwent accelerated aging in terms of UV exposure 15 KWH/m<sup>2</sup> and damp heat storage at 85 °C and 85 % rH.

The results of the UV aging is shown in **Figure 7**:

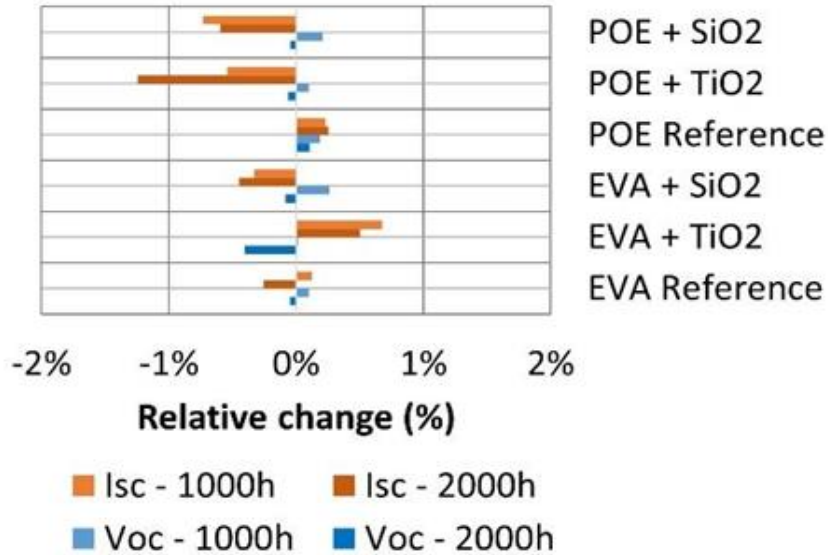


**Figure 7:** UV exposure of encapsulated TiO<sub>2</sub> and SiO<sub>2</sub> films.

It is clearly visible that the samples with SiO<sub>2</sub> hardly degrade more than the reference however for the TiO<sub>2</sub> samples short circuit current losses (transmission losses) of 5 and 8 % is observed, showing that TiO<sub>2</sub> is a less

suited material for use in PV laminates. A review of the literature suggests the loss is caused by photocatalytic degradation facilitated by the TiO<sub>2</sub>.

The results of the Damp heat storage is shown in **Figure 8**:



**Figure 8:** Damp/heat storage of encapsulated TiO<sub>2</sub> and SiO<sub>2</sub> films.

As can be seen (in **Figure 8**) most changes are below 1 %, with a tendency that the POE samples show high degradation and no significant difference is seen between 1000 and 2000 hours. The gains observed for the EVA TiO<sub>2</sub> is considered to be within the measurement uncertainty.

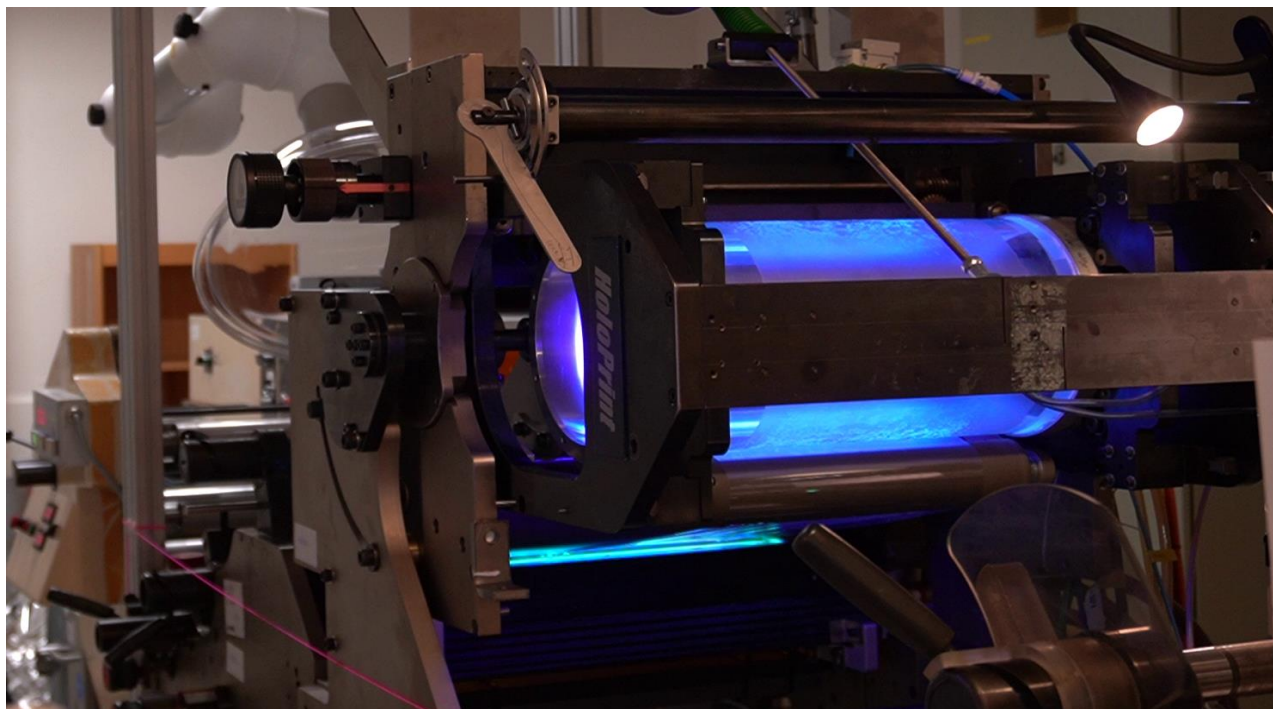
This material investigation concludes thus that PET foils with resins can be used as base foil with good resistance to UV degradation and that the base foil is not introducing significant transmission losses. Further TiO<sub>2</sub> is causing transmission losses upon UV acceleration and should be avoided (or alternatively capped with a thick SiO<sub>2</sub> layer), and all tested material combinations show good stability upon damp heat storage, and therefore its feasible to make durable colored modules using the right material combinations.

### 5.3 Upscaling

Upscaling the fabrication of the diffuser foil involved overcoming technical challenges regarding both the processing methods and the materials involved. The choice was to use Stensborg's roll-to-roll nanoimprint lithography equipment for scaling up the diffuser foil production. Within the production - the imprinting resin X311 needs to be continuously coated on a selected foil, then moulded by a rolling patterned cylinder, cured with a 395nm UV-LED Optical engine, and separated from the imprinting template: forming the flexible diffuser foil, that is used in further processed with the thin film layers forming the structural color.

A key challenge within nanoimprint lithography, is the production and lifetime of imprinting plates (stamps) - where significant developments were made regarding the process making the large imprinting templates, while still maintaining good release and lifetime for mass manufacture. A new stamp material was developed to facilitate the large volume production of polymeric diffuser foil to work with the X311 acrylate-based resin.

Within a single roll-to-roll run fabricating over 80 meters of diffuser structure foil - there were no observed issues with the lifetime or degradation of the imprinting template, and the resulting diffuser foil. In smaller scales, it was demonstrated that the production speed of 8 m/min was possible, and in the continuous upscaled fabrication with roll-to-roll tool: 3 m/min was tested, with a target feature width of 200mm.



**Figure 9:** Roll-to-roll manufacture of flexible optical-diffuser foils

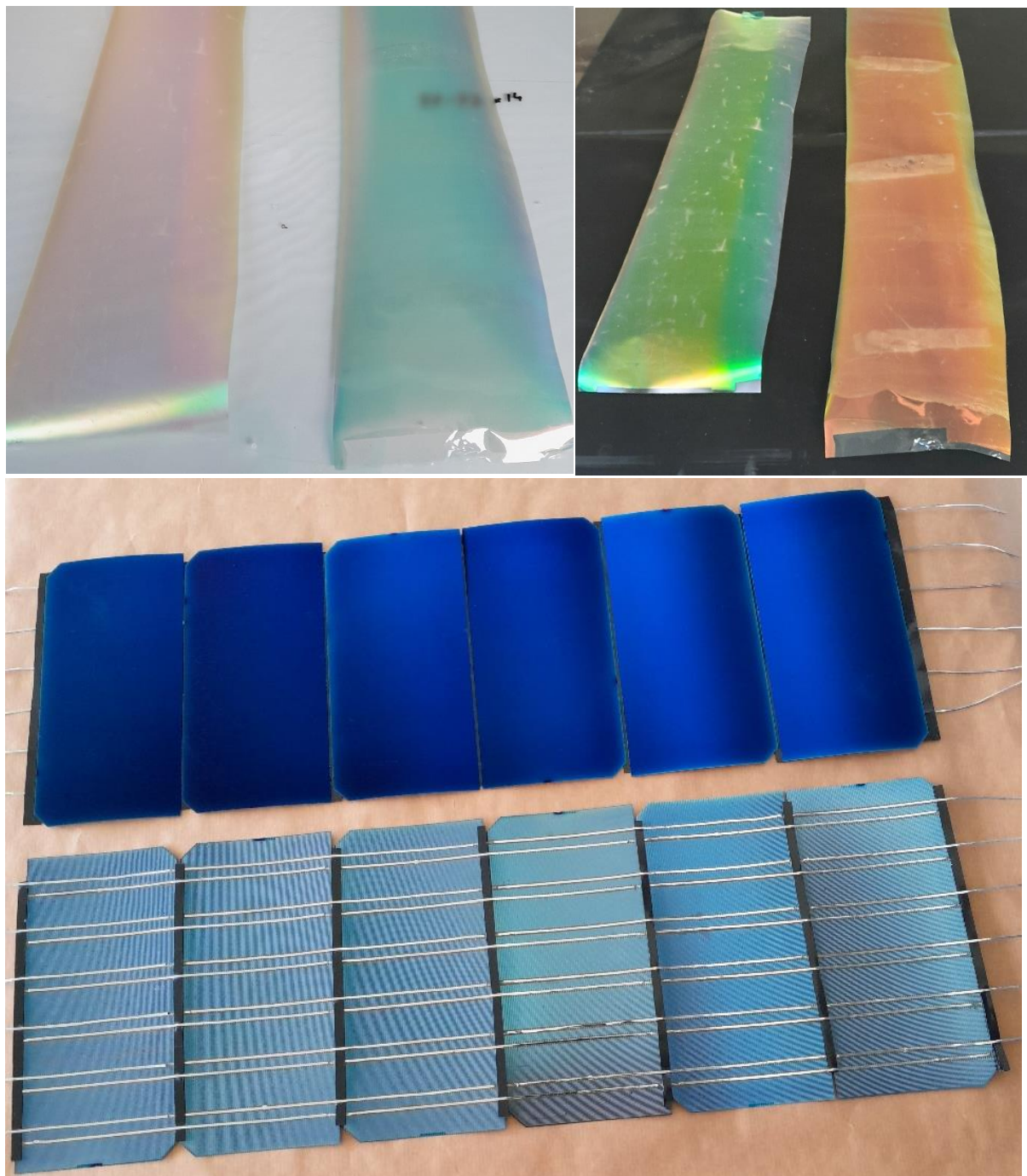
### Scaling up the film deposition

One of the main strengths of the R2R RF sputtering system is its ability to deliver uniform and repeatable large-area coatings. Uniformity across the web was achieved by careful optimization of multiple process parameters, including sputtering power, working gas flow rate, deposition pressure, base pressure, and web velocity. These parameters were finely tuned to maintain thickness consistency and optical uniformity across the entire roll. Despite its advantages, upscaling the process introduced certain challenges, especially with respect to edge uniformity as coating width and length increase. Maintaining precise web tension is critical to prevent substrate wrinkling or distortion, which can compromise film quality. Finally, Roll-to-Roll RF sputtering offers a robust and scalable route for the fabrication of high-performance ColorFoil samples. This process supports both rapid prototyping and high-volume production, making it suitable for a wide range of commercial applications, from decorative and aesthetic films to energy-efficient optical coatings. With continued optimization, R2R RF sputtering stands as a key enabler for bringing ColorFoil technologies from the lab to large-scale deployment.

Within this setup the final foil strips for the final demonstrators were fabricated using the described setup, however as only two sputter targets were used for depositing up to 7 layers the web was brought back and forward between the sputter targets to emulate real roll to roll production.

## 5.4 PV Panel fabrication and demonstration

Larger scale foils of size 55 cm times 15 cm were used to fabricate final demonstrators in green and tile red with a panel size of 55cm by 40 cm which could be suitable as a roof shingle.

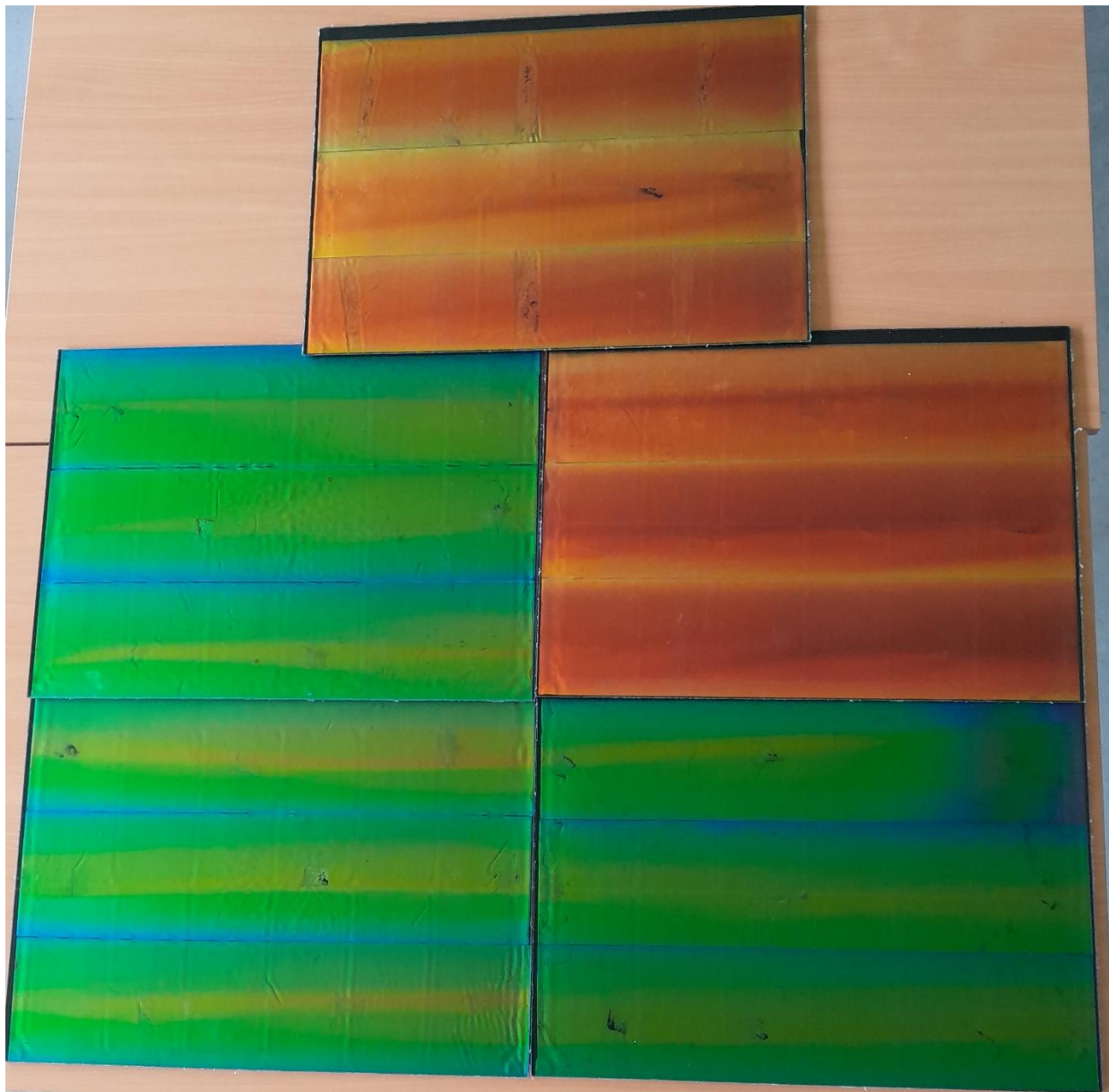


**Figure 10:** Pictures of the colored interlayer foils used on a white and black background. The light color for the white background shows the relative high transparency of the foil and shows the importance of using that there is no optical reflection from the layers behind the foil. Bottom row front and rear side picture of the used cell strings for the laminate.

For these modules 2\*6 half cut interdigitated back contact cells of the Zebra design (efficiency 24%) was used due to its homogenous front side appearance, and the interconnecting ribbons on the backside were covered with black interlayer material between the cells and at the end of the strings which enable invisible cells (see **Figure 10**). The power of a such uncolored module is expected to be around 37 W and 33 W for the green and 31 W for the red.

3 rows of prototype foils were stitched together with a suited tape to cover the full module area, and standard lamination procedure using EVA as encapsulant were used to fabricate the final modules, using a black backsheet.

A picture of the fabricated demonstrator modules is shown in **Figure 11**.



**Figure 11:** Image of the final demonstrators.

In the picture (**Figure 11**) wide homogenous colorful stripes are seen, and the cells are hidden well. However, the stitching of the foils is clearly identified as the black lines, and the color gradient towards the edge of the foil stripes is areas outside the PVD systems area of homogeneity of approximately 12 cm. Both challenges are solved when wider webs in an upscaled version are used.

IV curves of the 5 modules are shown in **Figure 12**, where it can be seen that the module produces power, with the green more efficient than the red which is expected based on the simulations and previous measurements. The measured average power from the 2 best performing green ones are 29,5 W and similar

for the red ones the average power is around 27 W, slightly lower than expected, like owing to deterioration from the manual soldering process used for the prototypes, as well as the inhomogeneity of the films.

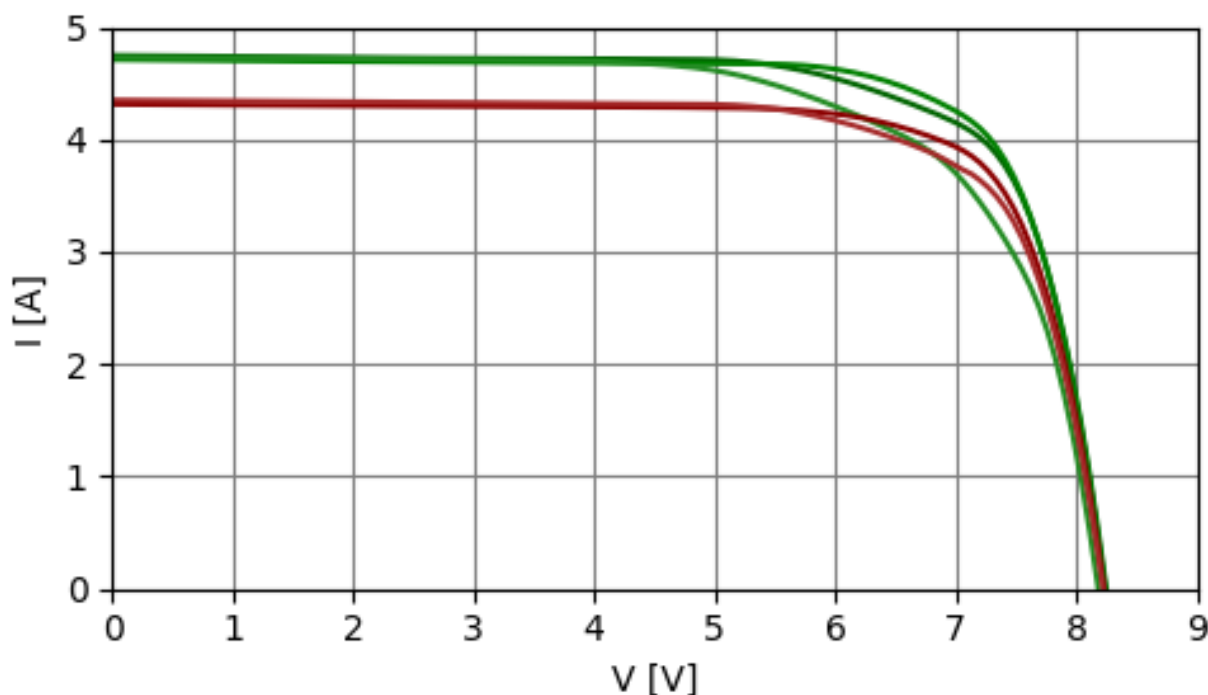


Figure 12: IV curves of the final demonstrators.

Thus, the detailed description of the methodologies and results for each work package reveals a successful project execution meeting the project objectives

The project has been the basis of the following research publications and contributions to research conferences.

Ferreira, C. G., Vyalih, I., Lamminaho, J., Babin, M., Andersen, N. L., Poulsen, P. B., Thorsteinsson, S., Petersons, K., Cox, J. D., & Madsen, M. (2024). Design and Optimization of Structural Colored Interlayers for Building-Integrated Photovoltaic Applications. In *Proceedings of 41<sup>st</sup> European Photovoltaic Solar Energy Conference and Exhibition* Article 020364 EU PVSEC. <https://doi.org/10.4229/EUPVSEC2024/4BV.4.6>

Babin, M., Boccardi, R., Bagci, A., Andersen, N. L., Poulsen, P. B., Thorsteinsson, S., Petersons, K., Yde, L., Stensborg, J. F., Ferreira, C. G., Cox, J. D., Vyalih, I., Lamminaho, J., & Madsen, M. (2024). Reliability Investigation of Structural Colour Interlayers for Coloured PV Modules. In *Proceedings of 41<sup>st</sup> European Photovoltaic Solar Energy Conference and Exhibition* Article 020188 EU PVSEC. <https://doi.org/10.4229/EUPVSEC2024/3AV.2.21>

#### Future submitted publications:

Ananta Paul, Jani Lamminaho, Catarina Ferreira, Markus Babin, Karlis Petersons, Leif Yde, Jan Stensborg, Nanna Lysgaard Andersen, Peter Behrendorff Poulsen, Sune Thorsteinsson, Joel D Cox, Morten Madsen. Customizable Color Foils for Photovoltaic Modules: A New Approach to Aesthetic and Efficient Solar Energy Integration. 4BV.4 at 42<sup>st</sup> European Photovoltaic Solar Energy Conference and Exhibition

Catarina G. Ferreira, Jani Lamminaho, Ananta Paul, Markus Babin, Nanna L. Andersen, Peter B. Poulsen, Sune Thorsteinsson, Karlis Petersons, Leif Yde, Jan Stensborg, Joel D. Cox, Morten Madsen. Optical Design of Structural Colored Interlayers with Low Angular Color Dependence for Building-Integrated Photovoltaic Modules 4BO.16 at *42<sup>st</sup> European Photovoltaic Solar Energy Conference and Exhibition*

Catarina G. Ferreira, Jani Lamminaho, Ananta Paul, Markus Babin, Nanna L. Andersen, Peter B. Poulsen, Sune Thorsteinsson, Karlis Petersons, Leif Yde, Jan Stensborg, Joel D. Cox, Morten Madsen. Optical Design of Structural Colored Interlayers with Low Angular Color Dependence for Building-Integrated Photovoltaic (working title) Invited for submission to Solar RRL

Nanna L. Andersen, Markus Babin, Karlis Petersons, Leif Yde, Jan F. Stensborg, Catarina G. Ferreira, Ananta Paul, Jani Lamminaho, Joel D. Cox, Morten Madsen, Peter B. Poulsen, Sune Thorsteinsson. Predicting Light Scatter and Angular Color Stability in Structural Colored BIPV Modules using Radiance. 4BO.16 at *42<sup>st</sup> European Photovoltaic Solar Energy Conference and Exhibition*

Catarina G. Ferreira, Jani Lamminaho, Ananta Paul, Markus Babin, Nanna L. Andersen, Sune Thorsteinsson, Peter B. Poulsen, K. Petersons, L. Yde, J. F. Stensborg, N. Asger Mortensen, Joel D. Cox, Morten Madsen. Optical design of structural colored photovoltaics for building integration: from periodic configurations to optimization algorithms, *submitted to Advanced Energy Materials*

## 6. Utilisation of project results

The project developed an advanced and very useful design tool for designing the structural colors matching a target color, revealed that the inclusion of the diffusor combined with optimizing the design of the structural colors significantly and lower the angle dependency of the color, and lastly accelerated tests on minimodules have shown durable material combinations. Optical characterization of the prototypes has shown good agreement with the optical models and therefore a very solid proof of concept for a new coloring technology have been established. The findings of the ColorFoil project will be carried forward by especially Stensborg, who will mature and scale the technology, establish a value chain and partnering with partners who supports scaling enabling roll to roll production of the colored foils.

Stensborg is developing a market strategy where they will seek to produce larger demonstration quantities of the foils at partners, and partner with a pilot module producer to facilitate a pilot production of ColorFoil PV modules in an industrial setting. This will prove the market and justify the needed upscaling investments and further take the technology towards higher TRLs.

The general outlook for the BIPV market is positive and expected to increase as the prices on PV steadily declines and the new energy performance directive for buildings demands solar PV on all buildings when fully implemented in 2030. The ColorFoil is a highly innovative and unique coloration material that will be used by BIPV module manufactures competing with other coloring technologies embedded via different methods into the PV module stack. Currently the market for these technologies are diverse and immature with lack of validated long term durability for all coloring technologies, and lack of detailed performance and appearance data. Currently IEAPVPS Task 15 and soon Task 13 is doing a dedicated effort in collecting available data for coloration technologies, their degradation and performance, which is expected to enable a more transparent market.

Once the ColoFoil is successfully scaled, it will be an attractive solution for BIPV and will promote BIPV installations which will increase local production of renewable energy, save on building materials as well as the need of electricity infrastructure expansion, and at the same time contribute to a more terror resilient energy system. Further the unique color matching to existing building materials will make the ColorFoil product a good choice for renovation project, and therefore the ColorFoil can significantly contribute to fulfil both the Danish energy policies and in particular the EU EPBD directive mandate solar PV on all buildings.

## 7. Project conclusion and perspective

The project developed an advanced and very useful design tool for designing the structural colors matching a target color, where it has been shown that aperiodic film stacks enable production of almost the full RGB spectrum. Further experiments have revealed that the inclusion of the diffuser combined with optimizing the design of the structural colors significantly lower the angle dependency of the color, and lastly accelerated tests on minimodules have shown durable material combinations. Optical characterization of the minimodules have shown good agreement with the optical models and demonstrator modules have been made showing good compatibility with existing PV module production. Therefore, a very solid proof of concept for a new coloring technology offering flexible production, low coloration loss and good possibilities of the coloring of the full RGB spectrum have been established.

Despite very successful findings technological challenges for the developed technology the need for maturing the technology still exists and need to continue along 3 tracks.

1. Track is the design tool for the structural colors, where the computational efficiency needs to be improved and detailed modelling of the optical diffuser is required for accurate optical modelling.
2. Track is scaling the roll 2 roll fabrication of the colored foils, with both diffuser deposition and optimization of the film stacks ensuring uniformity, increasing web width and speed.
3. 3 track is demonstration and reliability. Advancing the technology to the higher TRL via validating data from monitored test installation, continue to accelerated testing to prove reliability with relevant material combination and finally seek pilot production at a BIPV module manufacturer.

Simultaneous expanding these 3 tracks are keys to widespread adaption of the coloring technology within the BIPV sector and potentially expanding to other parts of the architectural glazing industry.

## 8. Appendices

None.