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COLOR RESEARCH AND APPLICATION WILEY

RESEARCH ARTICLE

The impact of surface properties on photovoltaics' colour angular sensitivity: A comparison study for façade integration

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Abstract

Façade integrated photovoltaics are a promising way to employ renewable energy technology in the built environment. The colours of façade integrated photovoltaics are essential to the overall aesthetic quality of buildings, especially in urban context. Currently, several brands of coloured photovoltaics are available in the market for architects, however, unlike traditional façade materials, the colorimetric characteristics of coloured PVs are rarely studied. To provide a foundation for further aesthetic research on façade integrated photovoltaics and to develop architectural design guidelines with façade integrated photovoltaics, a series of colour angular sensitivity experiments have been carried out on six different types of opaque coloured photovoltaics. The photovoltaic samples were measured from different distances and at different angles with a PR-655 spectroradiometer, in a series of laboratory and outdoor experiments. The experimental results show that the surface properties including colour, texture, and surface gloss have a strong impact on the photovoltaic's colour angular sensitivity. Goniochromatic phenomena have been found in samples with a spectrally selective coating technique (Kromatix photovoltaics) and samples with anti-reflective coatings with metallic texture (LOF metallic photovoltaics). Samples with selective filter technique and low-gloss rough finishing (ISSOL photovoltaics) show angular insensitivity for hue in different illumination conditions. Samples with mineral coating techniques (Sunage photovoltaics) show colour angular insensitivity in overcast illumination, while matt finishing leads to larger colour angular difference than gloss finishing in direct sunlight illumination. This study also proposed basic design suggestions to integrate different coloured photovoltaics according to their colour angular sensitivity characteristic from architectural perspective.

KEYWORDS

angular sensitivity, colour difference, FIPVs, gloss, goniochromism, PV, texture

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1 | INTRODUCTION

Façade integrated photovoltaics (FIPVs) belongs to one of the most promising strategies to employ renewable energy in the building environment and to reduce greenhouse gas emissions. Traditional PV panels are not ideal for façade integration in many circumstances due to their black or dark blue colors, which are outside of the colour palette of most urban settlements. Recently, advanced techniques have been developed that can provide more colour options for opaque PVs, including (a) coloured anti-reflective coatings on solar cells, (b) products with special solar filters, (c) products with spectrally selective coatings, (d) products with mineral coatings etc.[1]

From the architectural perspective, colour is a key factor of FIPVs that influences the aesthetic quality of building façades and urban images.[2,3] It is essential for architects to understand the colour properties of these newly emerging façade materials and to be able to predict their potential colour appearance in different viewing scenarios illuminated by natural daylight. When integrated into the façades, opaque colour PVs will be seen from a wide range of observation locations, giving rise to different viewing angles and viewing distances, under different weather conditions. To have a better insight into the colour properties of current colour PVs and to promote the architectural application of FIPVs, 10 novel opaque coloured PV samples from 4 brands were collected (Table 1 and Figure 1) and examined in this study. From them, six representative coloured PVs are studied with a focus on their colour angular sensitivities.

The ISSOL white PV employs a technology developed by the Solaxess company. Kromatix green PV from company Swissinso uses a multi-layered coating with the interference effect to obtain a greenish colour. LOF PV samples are from the company LOF Solar: LOF Metallic gold and LOF Disco pink PVs have a highly directional, metallic texture while the Tile red and Lavender PVs have a more evenly distributed brown colour appearances. For the Sunage brand PV products, a mineral coating technique is applied to obtain different colours with a matt or a glossy surface.[1]

2 | RESEARCH QUESTIONS

Choosing the right FIPVs and harmoniously integrating them into façades to match design visions is a challenge for architects. Architects need to know the colour characteristics of coloured PVs and to predict their colour performance in different viewing conditions, including the various viewing angles and distances from which they may be seen. This study aims to answer the following research questions:

1. For the collected opaque PV samples, how do the optical surface properties influence PVs angular colour sensitivities?
2. Is the angular colour sensitivity dependent on the viewing distance?
3. How can architects utilize these PVs for different façade integration scenarios?

TABLE 1 List of 10 photovoltaic samples

Name	Colour technique	Finishing	Numbers in Figure 1
ISSOL white	Selective scattering and reflection filter	Low-medium glossy rough glass	1
Kromatix green	Spectrally selective coating	Low glossy transparent front cover	2
LOF metallic gold	Coloured anti-reflective coatings showing metallic texture	High glossy glass	3
LOF tile red	Coloured anti-reflective coatings hiding metallic texture	High glossy glass	4
LOF disco pink	Coloured anti-reflective coatings showing metallic texture	High glossy glass	5
LOF lavender	Coloured anti-reflective coatings hiding metallic texture	High glossy glass	6
Sunage terracotta glossy	Coloured mineral coating	Low-medium glossy glass	7
Sunage terracotta matt	Coloured mineral coating	Matte glass	8
Sunage light gray glossy	Coloured mineral coating	Low-medium glossy glass	9
Sunage anthracite matt	Coloured mineral coating	Matte glass	10

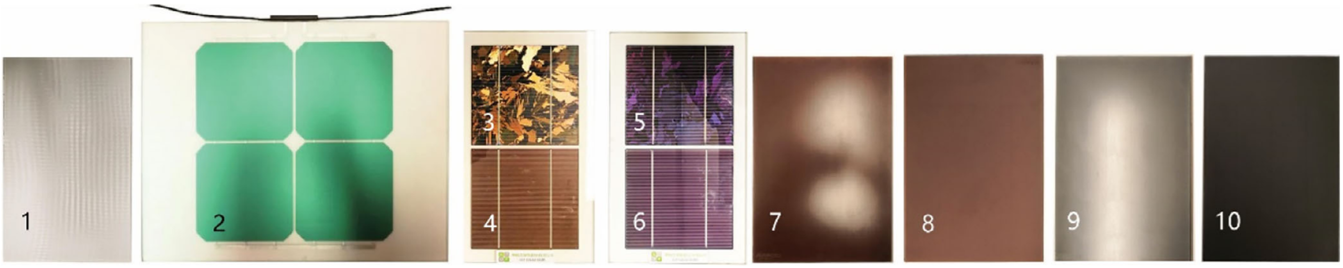

FIGURE 1 Photovoltaic samples

TABLE 2 Experiments list

Experiments	Date	Place	Lighting condition	Measuring devices	Measuring distance and angles
NTNU daylight lab experiment	Mar. 2019 Jan. 2021	NTNU Daylight lab	Artificial light mimics overcast diffusing daylight	RP-655 Lux meter	0.55 m 45°
Outdoor experiment 1	11 AM-1:30 PM July 14, 2019	Urban open space, Trondheim, Norway	Overcast daylight	RP-655 Lux meter	0.55/1.75/3.5/7 m 45°
Outdoor experiment 2	13:40 PM-5:46 PM July 17, 2019	Urban open space, Trondheim, Norway	Direct sunlight	RP-655 Lux meter	0.55/1.75/3.5/7 m 45°

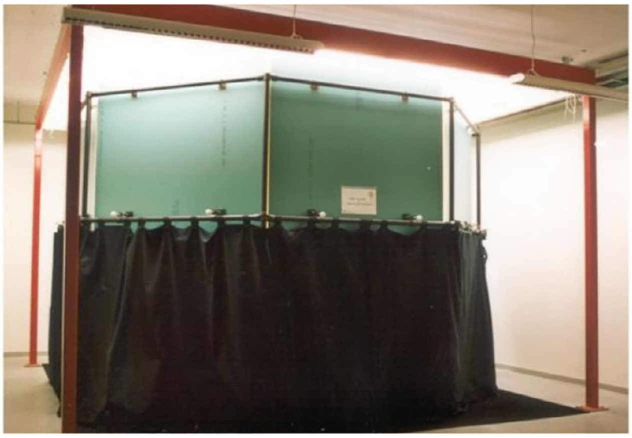

FIGURE 2 Artificial sky in Daylight lab of NTNU

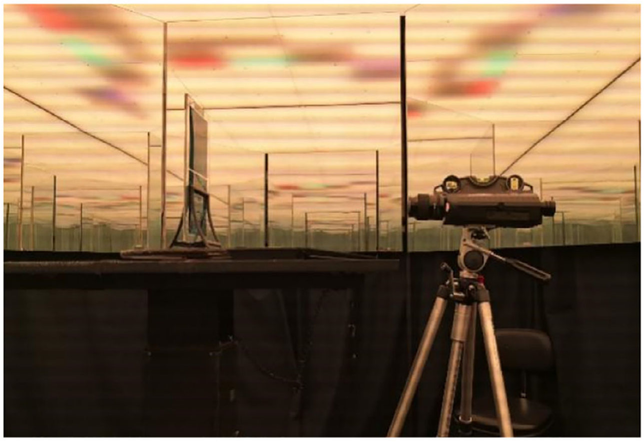

FIGURE 3 Inside the artificial skylight octagonal cylinder

FIGURE 4 Outdoor experiment location (red square)

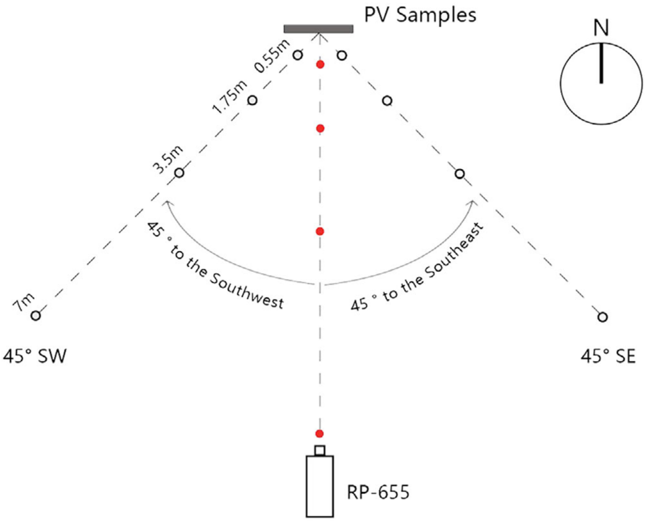

FIGURE 5 Experiment measurement diagram

3 | METHOD

3.1 | Literature review

Previous research shows that specular reflection properties of a surface (ie, gloss) can influence the colour appearance of traditional building materials such as wood. A wooden surface with a glossy coating can appear to have greater colour saturation than a one with a rough surface.[4] Goniochromism (iridescence) is also an interesting phenomenon in which the observed colours of some surfaces change dramatically as the viewing angle changes. When a metallic flake pigment, pearlescent pigment, or light interference pigment is used in the material or coating, goniochromism can occur and may result in a variation of hue, lightness, and saturation.[5] Ji et al present a novel approach of creating bright-coloured photovoltaics panels with excellent angular insensitivity by topping solar panels with a five-layer transreflective color filter. However, this type of PV product is not yet commercialized. Our review of the literature shows a paucity of research specifically addressing the relationship between the surface properties and the colour appearance of opaque coloured PVs for façade integration.

3.2 | Experimental methods

Through a series of measurements made in the laboratory and outdoors (summarized in Table 2), this study investigates the colorimetric properties of collected opaque colour PVs samples with changing parameters including viewing angles and viewing distance. In the first stage, measurements in well-controlled artificial skylight laboratory are conducted. In the second stage, semi-controlled outdoor experiments are carried out in overcast and sunny weather in Trondheim, Norway (63°N, 10°E).

A Photo Research PR-655 Spectroradiometer is used as the main measurement device. The aperture of the instrument has an angular subtense 1°, and thus the area of the

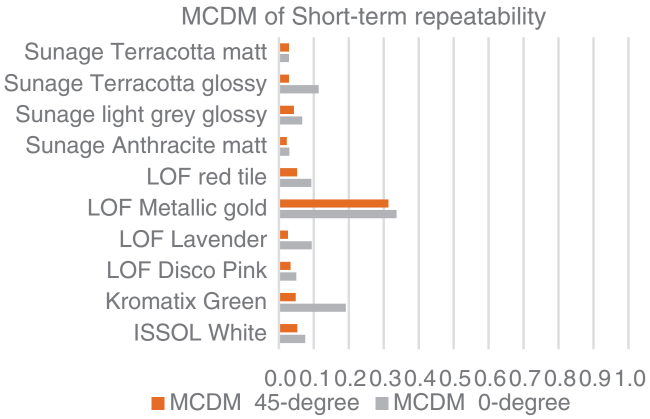

FIGURE 6 Mean colour difference from the mean value for short-term repeatability

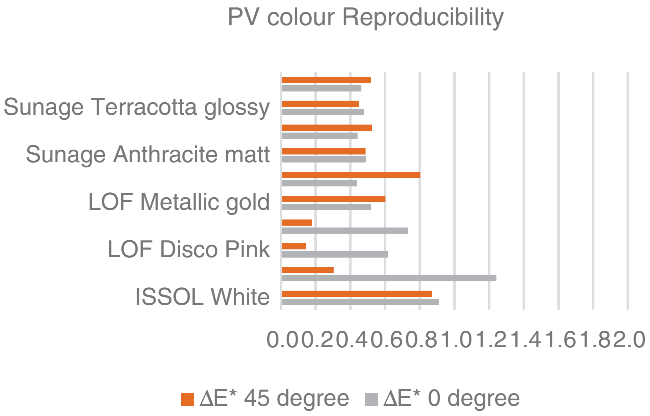

FIGURE 7 ΔE^*_{uv} values for photovoltaic colour reproductivity

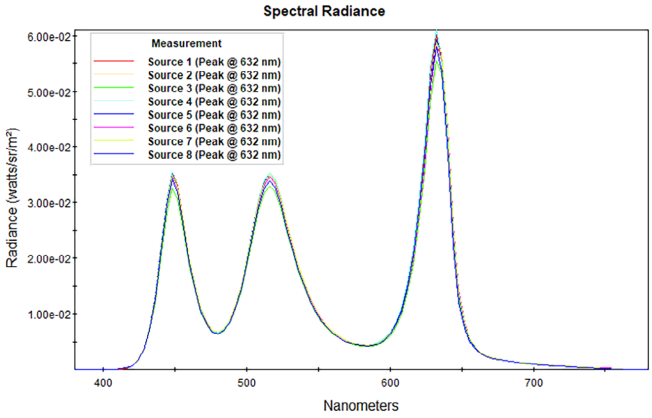

FIGURE 8 Spectral radiances of artificial sky source

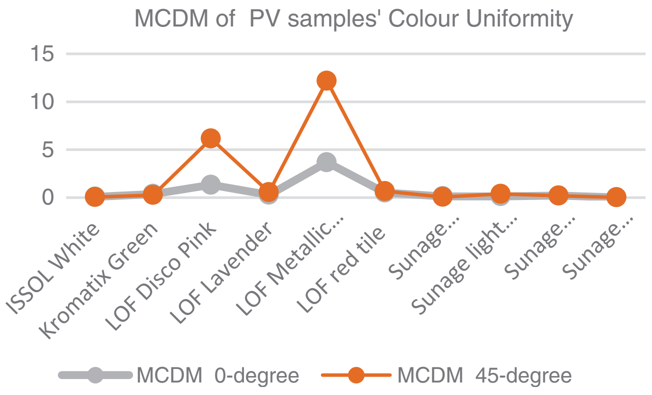

FIGURE 9 Mean colour difference from the mean of photovoltaic samples' colour uniformity

surface which is sampled varies with the measurement distance.

Spectral radiance measurements of the panels in different conditions were made with the PR-655. In each condition, a white reflectance standard (RS-3 Reflectance Standard) was also measured, and this measurement used to provide a reference white in colorimetric calculations, using the CIE 1964 standard colorimetric observer. CIE X_{10}, Y_{10}, Z_{10}, and CIELUV L_{10}, u' and v' values were obtained directly from the PR-655 interface, while CIELUV L^*, u^*, v^*, hue, chroma, and ΔE^*_{uv} values were calculated with Equations (1–3) below.

$$L* = 116\mathrm{f}(Y/Y_n) - 16; u* = 13L*(u\prime - u'_n); v* = 13L*(v\prime - v'_n). \tag{1}$$

$$h_{uv} = \arctan(v*/u*); C*_{uv} = \left(u^{*2} + v^{*2}\right)^{1/2}. \tag{2}$$

$$\Delta E*_{\mathrm{uv}} = \left((\Delta L*)^2 + (\Delta u*)^2 + (\Delta v*)^2\right)^{1/2}. \tag{3}$$

where: L^*, h_{uv}, C^* represents lightness, hue, and chroma, respectively.

$f(Y/Y_n) = (Y/Y_n)1/3$ for $Y/Y_n > (6/29)3$ or $f(Y/Y_n) = (841/108)\,(Y/Y_n) + 4/29$ for $Y/Y_n \leq (6/29)3$;

u'_n, v'_n are values of u', v' for the reference white.

When colour difference $\Delta E^*_{\mathrm{uv}} \leq 2$, colours can be said to match. When $\Delta E^*_{\mathrm{uv}} > 5$, two samples can be seen as two different colours with a noticeable difference between them.[6] However, it should be noted that colour difference experiments normally use different viewing conditions than those that apply in our study.

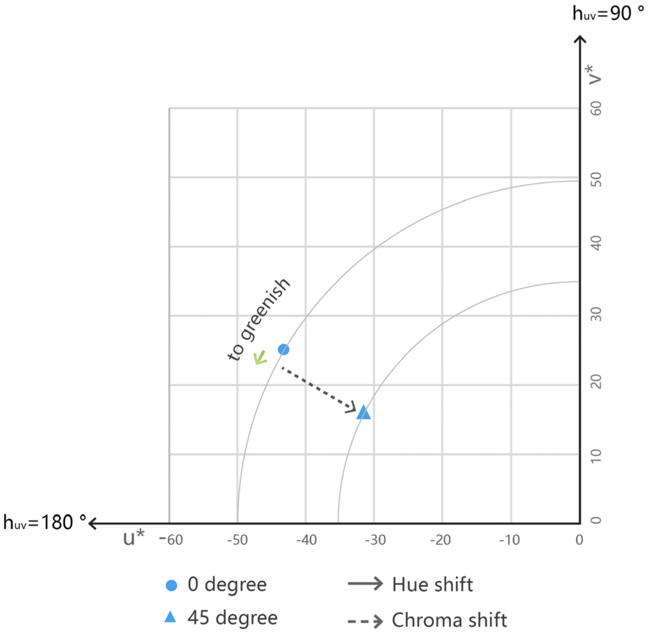

FIGURE 10 SPD of artificial daylight at 6500 K

3.2.1 | NTNU Daylight Lab experiment

Well-controlled experiments were carried out in the Daylight Laboratory in the Department of Architecture and Technology, NTNU. The Daylight Laboratory has a mirror box-type artificial sky, which can mimic evenly illuminated overcast daylight conditions (Figure 2). The ceiling of the artificial sky is made of regularly distributed RGBW LED-chips on top of two layers of diffusing canopy, and

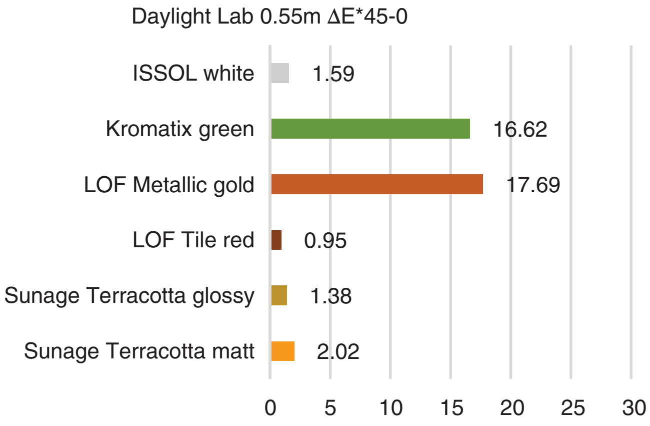

FIGURE 11 Daylight Lab 0.55 m ΔE^*45-0 at 6500 K

TABLE 3 MCDM value for PV colour uniformity

PV	ISSOL white	Kromatix green	LOF disco pink	LOF lavender	LOF metallic gold	LOF red tile	Sunage anthracite matt	Sunage light gray glossy	Sunage terracotta glossy	Sunage terracotta matt
MCDM 0°	0.088	0.371	1.324	0.289	3.685	0.512	0.132	0.127	0.206	0.020
MCDM 45°	0.056	0.267	6.153	0.560	12.188	0.671	0.070	0.387	0.193	0.025

Abbreviations: MCDM, mean colour difference from the mean; PV, photovoltaic.

TABLE 4 Colorimetric values of photovoltaic samples specified in daylight lab

0.55 m distance	Measuring degree	Y_{10}	u'	v'	L^*	u^*	v^*	Hue	Chroma	ΔE^*_{uv}
ISSOL	0	585.8	0.185	0.47	79.49	−11.99	−3.62	16.79	12.52	0.00
	45	560.3	0.1855	0.47	78.09	−11.27	−3.76	18.43	11.88	1.59
Kromatix green	0	225.1	0.1343	0.51	53.43	−43.27	25.49	−30.50	50.22	0.00
	45	163.7	0.1453	0.50	46.43	−30.97	16.78	−28.45	35.22	16.62
LOF metallic gold	0	119.7	0.2535	0.50	40.25	29.77	15.96	28.19	33.78	0.00
	45	135.7	0.2207	0.51	42.65	13.36	22.12	58.87	25.84	17.69
LOF red tile	0	7.601	0.2468	0.50	6.44	4.20	2.90	34.65	5.11	0.00
	45	7.496	0.2362	0.51	6.34	3.26	2.98	42.43	4.42	0.95
Sunage terracotta-glossy	0	49.17	0.2592	0.48	25.81	21.01	4.36	11.73	21.45	0.00
	45	53.43	0.2579	0.48	26.99	21.50	4.88	12.78	22.05	1.38
Sunage terracotta-matt	0	81.04	0.2403	0.48	33.39	18.97	4.17	12.39	19.42	0.00
	45	88.07	0.2416	0.48	34.78	20.34	4.66	12.89	20.87	2.02

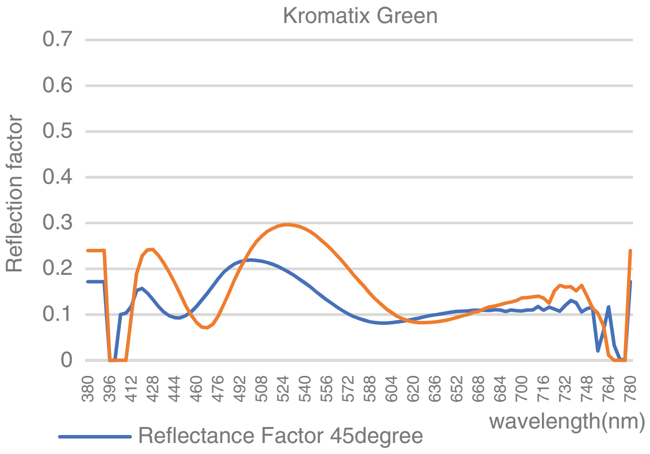

FIGURE 12 Spectral reflectance distribution of Kromatix Green photovoltaic at 0° and 45°

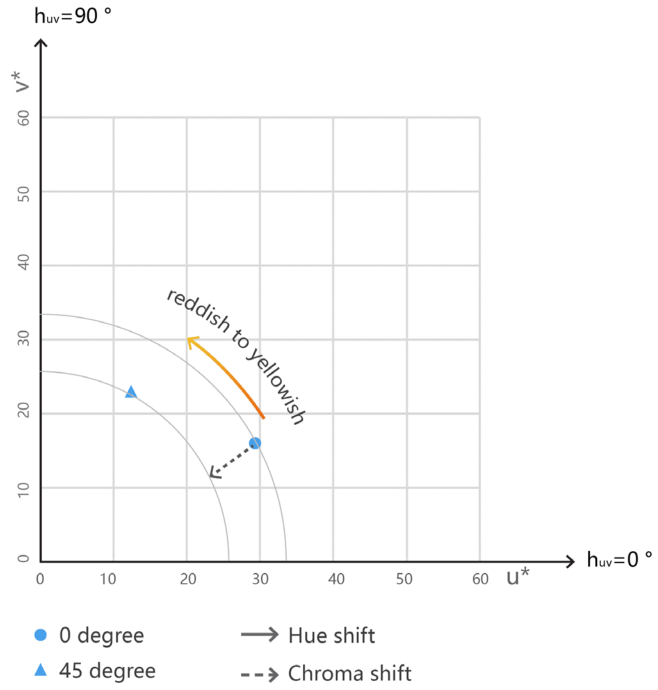

FIGURE 13 Hue and chroma shift of Kromatix Green photovoltaic in Daylight lab 6500 K condition

below the ceiling is an octagonal space where experiments can be carried out. The upper part of the octagonal space is equipped with mirrors to reflect light and the lower part is covered with black curtains to avoid any leakage of light between the interior and exterior. According to Matusiak and Braczkowski, this artificial sky can simulate CCT skylight in the range of 2000 to 18 000 K with a high fit to Planck's curve and possesses a high Colour Rendering Index, that is, $R_a > 85$ in the illuminance range of 2000 to 10 000 K. In the present study, the CCT was set at 6500 K to simulate overcast daylight. PV samples were mounted on a rotatable stage on the top of the operation table situated at the center of the artificial sky, such that change of measurement angle can be achieved by rotation of the stage. The PR-655 was mounted on a tripod, leveled at the same height as the center of the PV panels and was oriented with the optical axis pointed toward this center (Figure 3). The measurement distance was 0.55 m. By rotation of the stage, measurements were made at 0° and 45° to the normal of the panel.

3.2.2 | Outdoor experiments in overcast and sunny weather

Outdoor measurements in overcast weather were carried out at a park near Kristiansten Festning in Trondheim, Norway on 14th of July 2019 (Figure 4). These measurements were made from 11 AM to 1:30 PM (windspeed

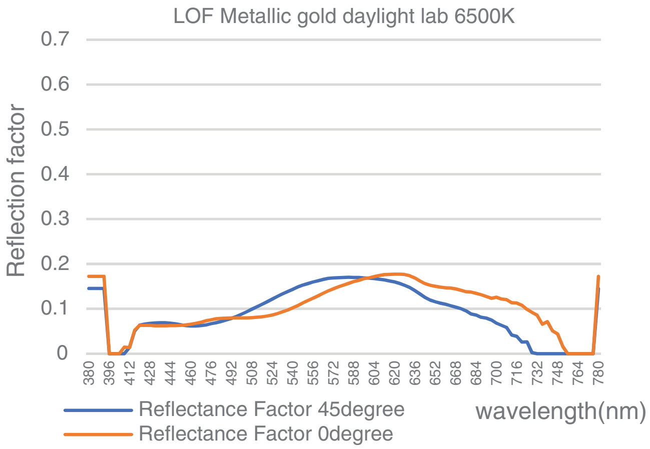

FIGURE 14 Reflectance factor of LOF metallic gold photovoltaic at 0° and 45°

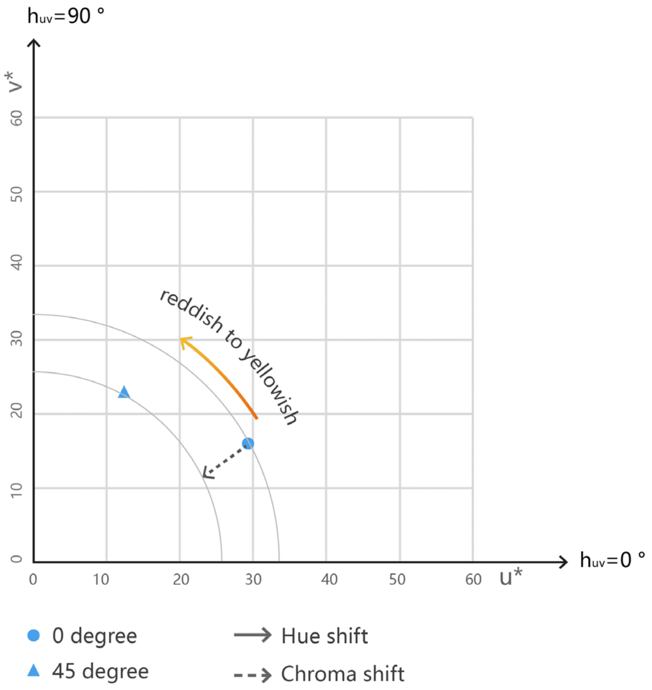

FIGURE 15 Hue and chroma shift of LOF metallic gold sample in Daylight lab 6500 K condition

approx 2-3 m/s, horizontal illumination level gradually rising from 20 100 to 37 000 lx). The PV panels were placed vertically on a tripod facing south at 1.35 m above the ground. The measurement distances were 0.55, 1.75, 3.5, and 7 m. Three different measurement angles were used as variable parameters: 0°, 45° southwest (45SW), and 45° southeast (45SE) (Figure 5).

Outdoor measurements in sunny weather were also made on 17th of July 2019 in Trondheim city, Norway. The measurement period was from 3:40 PM to 5:46 PM. The experimental setup was the same as for the outdoor experiment in overcast sky condition, with measuring angles of 0° and 45°, while the measuring distance changes from 0.55 to 7 m (Figure 5).

4 | RESULTS

4.1 | Laboratory condition

Before the colour angular sensitivity investigation, short-term repeatability, reproducibility, and the colour uniformity of 10 PV samples are tested. The mean colour difference from the mean (MCDM)[7] is used for reporting instrumental short-term repeatability. All PV samples are measured continuously 25 times at 0.55 m distance in 6500 K CCT artificial skylight, with a measurement time interval between 5 and 10 seconds. Figure 6 shows the MCDM values of the 10 coloured PVs with measurement angles of 0° and 45°. The measurement instruments show reasonable short-term repeatability with all MCDMs less than 0.4 and most of them are less than 0.1. Then the colour reproducibility of the PVs and the light source is also tested. The PR-655 and artificial sky have been setup multiple times to measure the same spots on PV samples, Figure 7 shows the ΔE^*_{uv} values between different measurements.

The reproducibility of the artificial sky source and its measurement was tested by measuring the RS-3 Reflectance Standard eight times at a 45° angle and 0.55 m distance, resulting in an MCDM of 0.2072. The spectral radiance of multiple source measurements is demonstrated in Figure 8. The small ΔE^*_{uv} values and MCDM values show reasonable colour reproducibility in this experiment.

In the colour uniformity tests, colours of 5 locations on each panel are measured and the MCDM values calculated (Figure 9 and Table 3). All PVs show good colour uniformity except the LOF PVs with metallic texture: LOF Disco pink PV and LOF Metallic gold PV share obvious colour non-uniformity. Sunage glossy PVs have very good colour uniformity but the matt ones present even better colour uniformity. The colour uniformity test shows that, for various coloured PVs from LOF and Sunage brand, PVs' surface colour uniformity is largely dependent on their surface texture and gloss properties other than colour,; therefore, LOF metallic gold PV and LOF red tile PV could be used to represent the two typical LOF PVs, while Sunage Terracotta glossy PV and Terracotta matt PV are suitable to represent the Sunage brand.

Based on the results from the short-term repeatability, reproducibility, and colour uniformity tests, 6 coloured PVs from 10 samples were chosen for detailed colour angular sensitivity investigation: ISSOL White PV, Kromatix Green PV, LOF metallic gold PV, LOF red tile PV, Sunage Terracotta glossy PV and Sunage Terracotta matt PV. Table 3 shows the colorimetric values of the PV samples measured at 0.55 m in 6500 K CCT artificial skylight (Figure 10), and

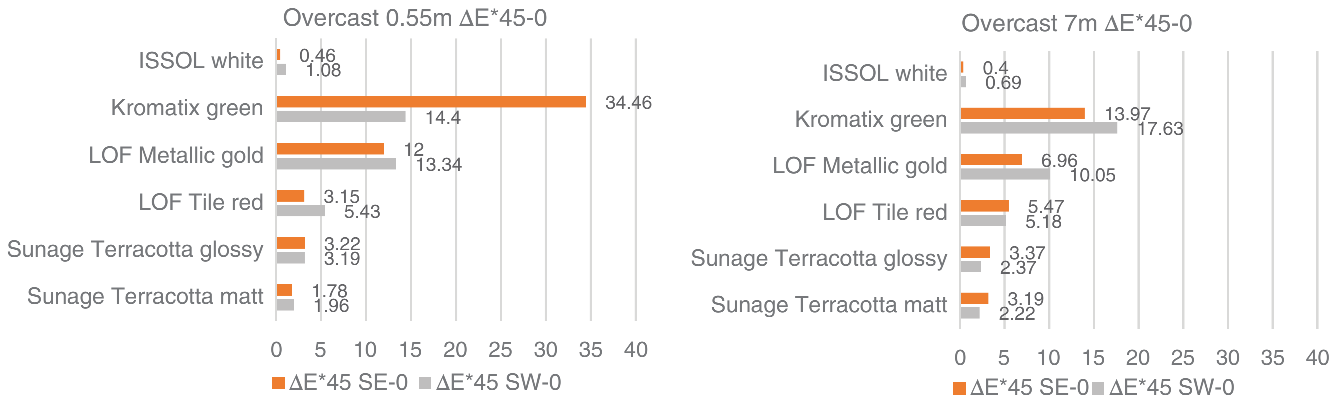

FIGURE 16 ΔE*45SW and ΔE*45SE in overcast condition at 0.55 m(left) and 7 m(right)

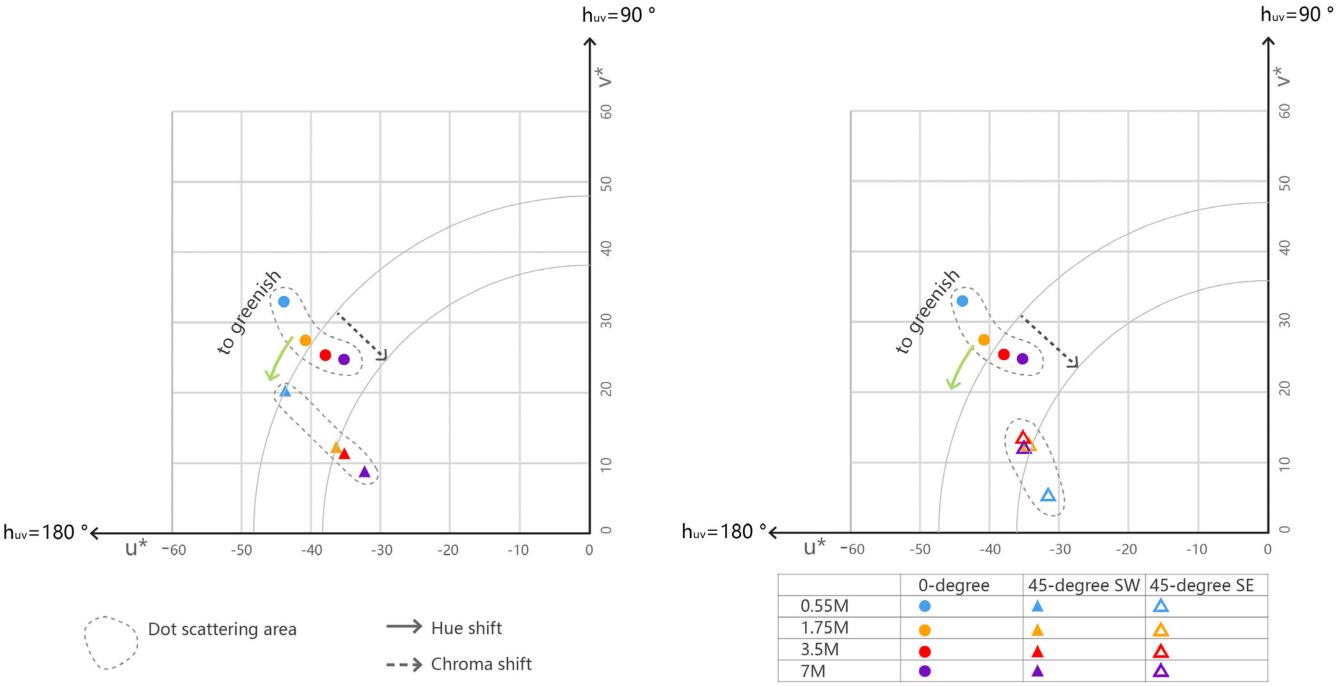

FIGURE 17 Hue and chroma shift of Kromatix Green photovoltaic in overcast condition

the colour difference between 45° and 0° measurements of all PV samples are illustrated in Figure 11 (Table 4).

In the Daylight Lab at 0.55 m measuring distance and measuring angle of 0° and 45°, Kromatix Green PV and LOF metallic gold PV show goniochromatic phenomena with high colour angular sensitivity (colour difference $\Delta E^*_{uv} \geq 10$), while other PV samples demonstrate stable colours (colour difference ΔE^*_{uv} less or close to 2). The detailed results are as below:

1. ISSOL white PV is stable in lightness, hue, and chroma values.
2. Kromatix Green PV shows a small hue shift in a greenish direction and large decreases in chroma (see Figures 12 and 13).
3. LOF metallic gold PV shows a hue shift to yellowish direction, a small chroma decrease (see Figures 14 and 15).
4. LOF red tile PV shows stable hue and chroma values.
5. Both Sunage terracotta PVs show stable hue and chroma values.

4.2 | Overcast condition

In the overcast condition, measurements from 45° SW and 45° SE are similar. Figure 12 shows the colour differences between different measuring angles at measurement distances of 0.55 and 7 m. LOF metallic gold PV

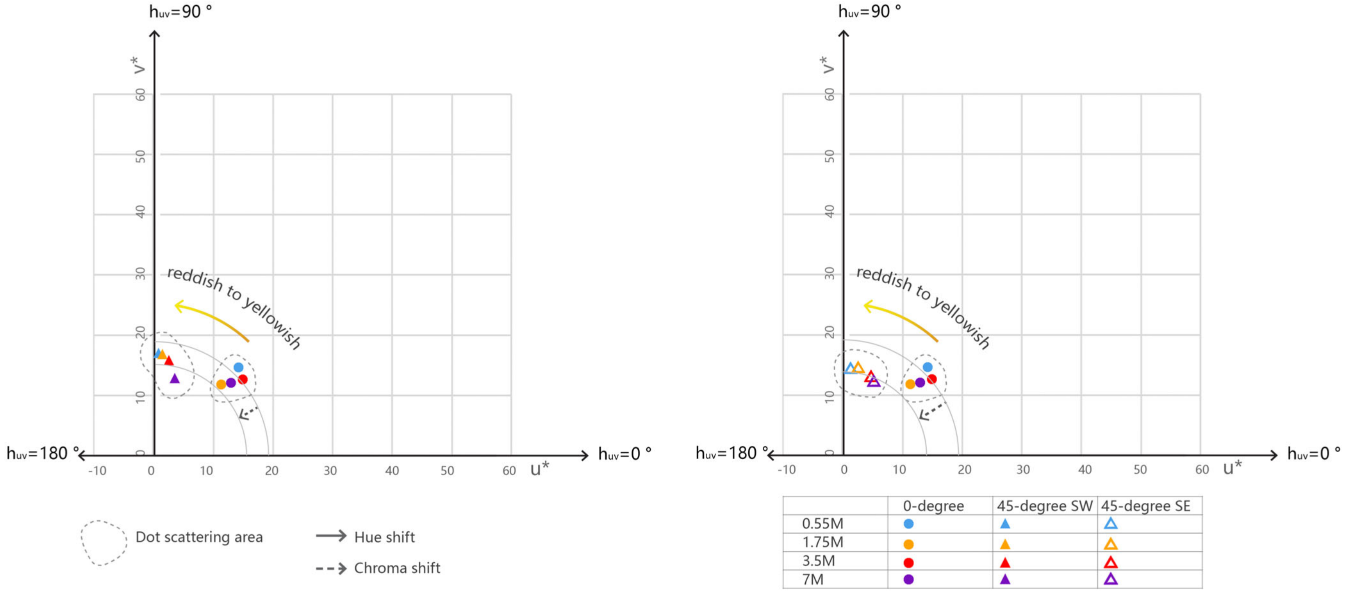

FIGURE 18 Hue and chroma shift of LOF Metallic gold photovoltaic in overcast condition

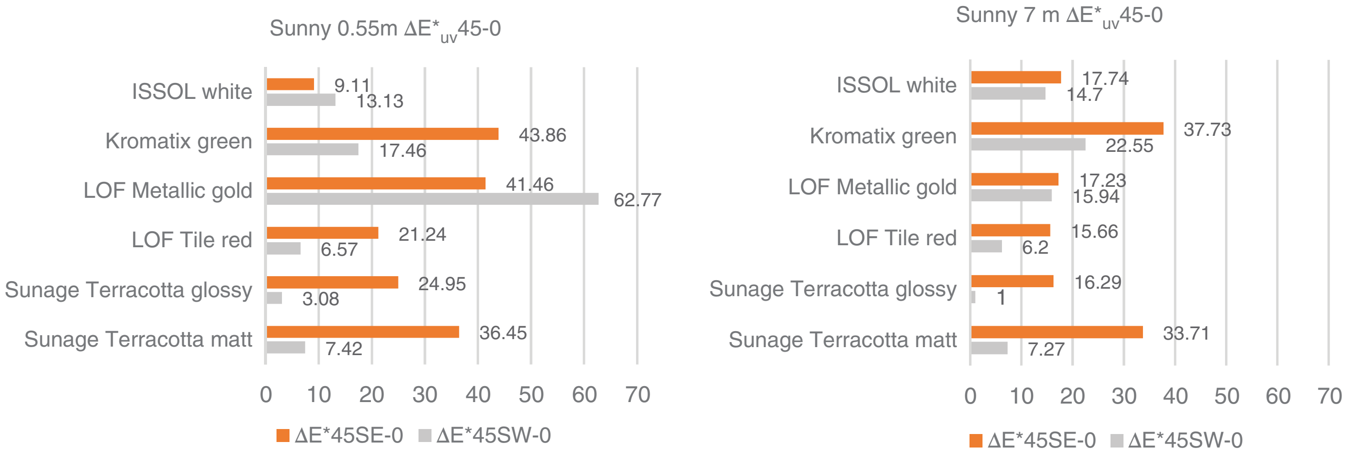

FIGURE 19 ΔE^*_{uv} 45SW and ΔE^*_{uv} 45SE in sunny condition at 0.55 m (left) and 7 m (right)

and Kromatix Green PV have the largest colour difference (ΔE^*_{uv} close or larger than 10), ISSOL white PV has the smallest colour difference (ΔE^*_{uv} close to 1) while other PV samples have colour differences ΔE^*_{uv} in the range of 2 to 6. For measuring distances of 1.75 and 3.5 m, the colour difference results have very similar trends to the data shown in Figure 16. In general, the experimental results in overcast daylight shows a good correlation with the results obtained in daylight lab, although the fluctuations of the outdoor illuminance may also amplify the colour angular difference.

Considering the hue and chroma of the panels: LOF metallic gold PV and Kromatix green PV demonstrated the same trend of hue and chroma shift as in the artificial lighting condition, the LOF red tile PV shows a slight hue shift toward yellow (Figures 17 and 18), and other PV samples show stable hue and chroma values. When measurement distance increased to 7 m, the angular colour difference of LOF metallic gold PV reduced significantly. This could possibly be an effect of sampling a larger area.

4.3 | Sunny weather condition

In sunny weather, for all PV samples, direct sunlight incidence has a strong impact on the angular colour difference, and 45°SW and 45°SE measurements are not always similar. Figure 19 shows the general colour difference of PV samples measured at different angles at 0.55 and 7 m

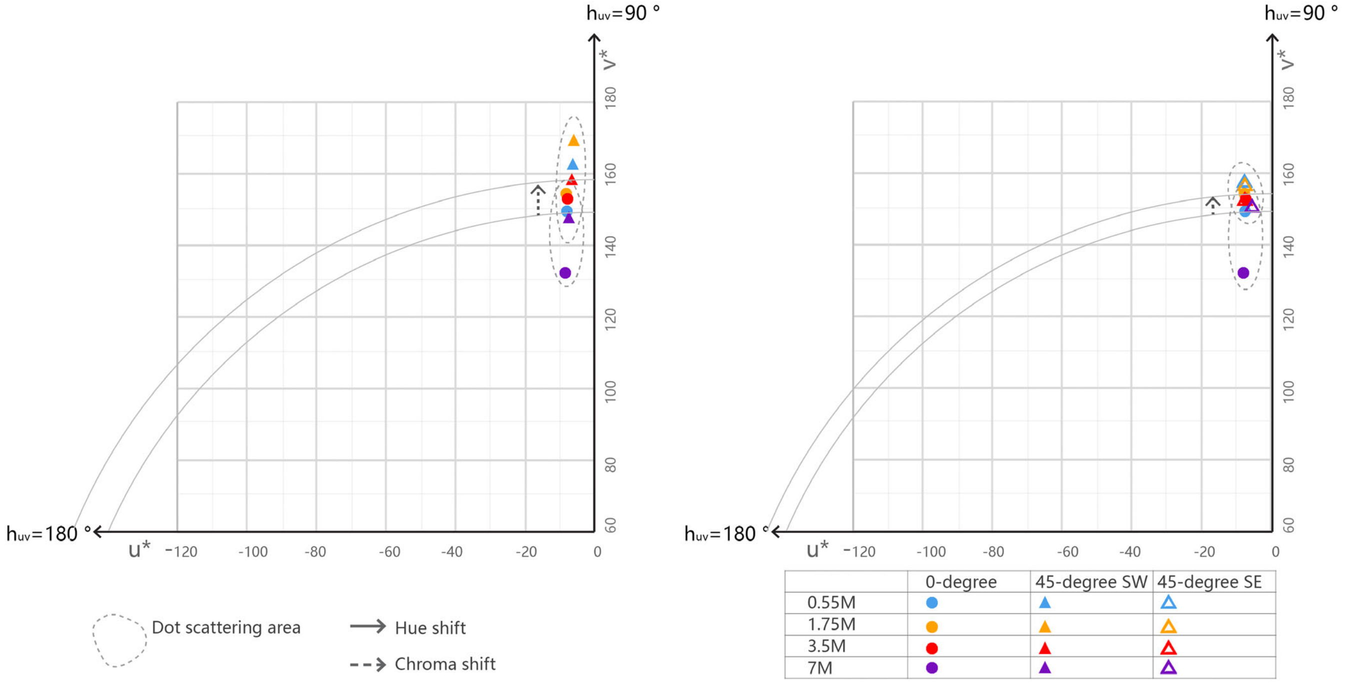

FIGURE 20 Hue and chroma shift of ISSOL photovoltaic in sunny condition

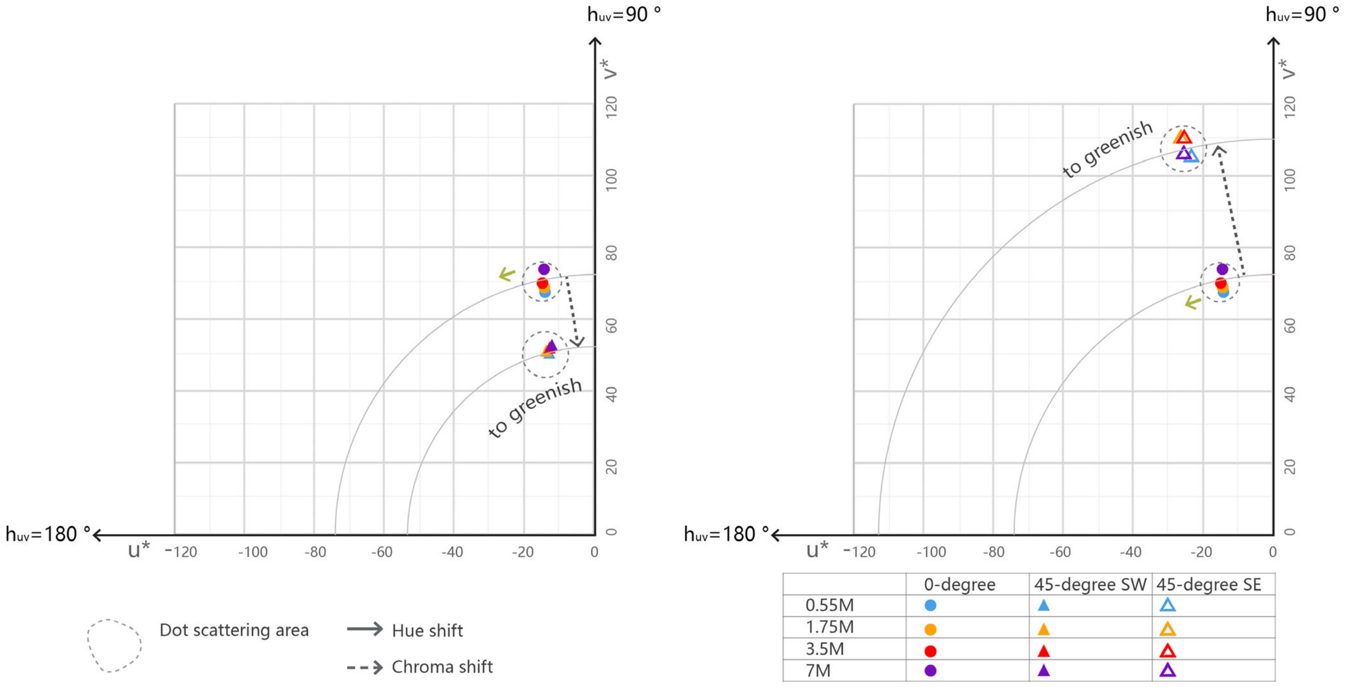

FIGURE 21 Hue and chroma shift of Kromatix green photovoltaic in sunny condition

distances: all PVs show large colour angular difference (ΔE^*_{uv} larger than 10) in at least one measuring angle, which is in common with results from measuring distances of 1.75 and 3.5 m. In detail, ISSOL white PV shows excellent hue angular stability in direct sunlight (Figure 20), while LOF metallic gold PV, LOF red tile PV and Kromatix green PV share the same hue shift trend as in the overcast condition (Figures 21-23). Sunage terracotta glossy PV and Sunage terracotta matt PV show hue stability in different measurement angles but the chroma values fluctuate and contribute to the larger colour difference in sunny daylight compared with overcast condition.

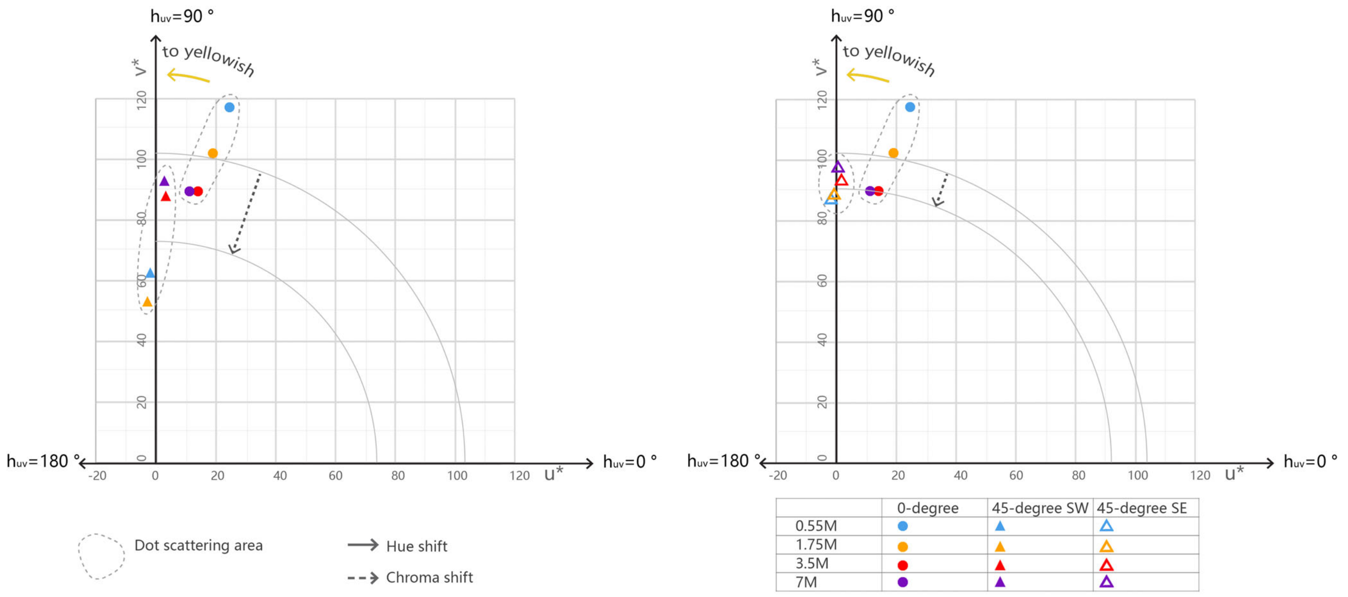

FIGURE 22 Hue and chroma shift of LOF metallic gold in sunny condition

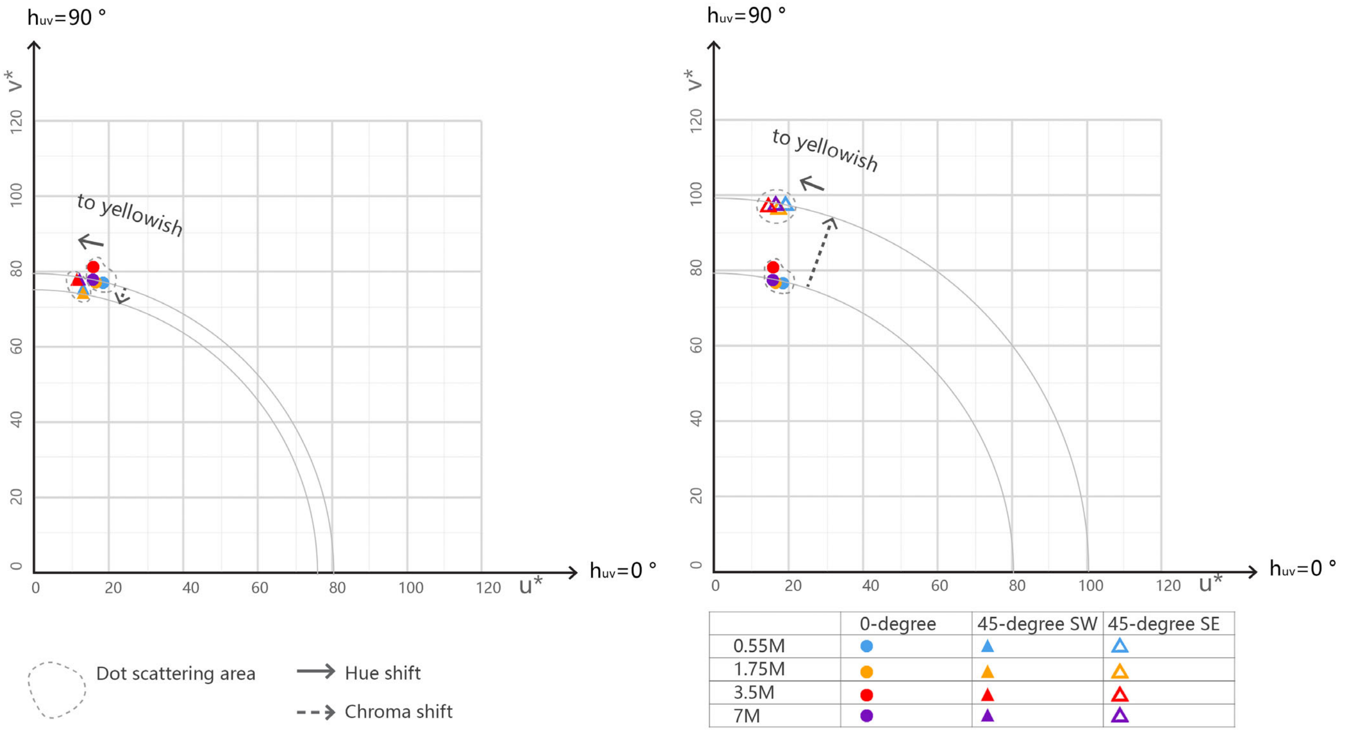

FIGURE 23 Hue and chroma shift of LOF red tile photovoltaic in sunny condition

ISSOL PV also shows hue stability but chroma fluctuation at different viewing distances. Both Sunage terracotta PVs and LOF red tile PV have more stable hue and chroma values than PVs with higher colour angular sensitivities (Kromatix green PV and LOF metallic gold PV).

5 | DISCUSSION

Regarding our first research question (how do the optical surface properties influence PVs angular colour sensitivities?), the measurements described above show that surface properties like coloration technology, texture, and finishing glossiness have a strong impact on the panels' colour angular sensitivity. Kromatix PV with spectrally selective coating technique and LOF Metallic PV with anti-reflective coatings showing metallic texture are strongly goniochromatic. The LOF Tile red PV also shows a noticeable colour difference in overcast conditions. Sunage PVs with mineral coating techniques show very low colour angular sensitivity. ISSOL white PV with selective filter technique and low-gloss rough finishing shows colour angular insensitivity.

The answer for our second question (the impact of the viewing distance) is most clear for the samples having little or no angular colour sensitivity (ISSOL and Sunage Terracota PV) where the distance does not result in a large difference in colour. On the other hand, products with high angular colour sensitivity may change the colour appearance with the viewing distance in a somewhat unpredictable way, and more research is needed to explore these phenomena.

For our third question, for the opaque PV samples in our study, how can architects utilize them for different façade integration scenarios? The following recommendations can be given to architects depending on the urban context:

- For façade integration in a traditional urban context (eg, old city centers) where colour harmony is essential,[8,9] the PVs should fit into the existing urban colour palette and preferably possess low colour angular sensitivity to obtain a stable colour performance. Generally, goniochromatic PVs should be avoided (Figure 24). The only exception could be that the colour of the selected PV changes in a desirable direction, for example, a hue shift from red toward yellow in a neighborhood dominated by yellow-red houses.
- For façade integration in a less sensitive urban context such as suburban areas or districts of new development,[10] PVs with goniochromatic phenomena can be a good solution to create some "moderate complexity"[11] to arouse people's visual experience and create a sense of novelty (Figure 25).

For instance, the Kromatix PVs have already been applied in the International School in Copenhagen at new construction area of Nordhavn.[12] The PVs on façades are tilted at different angles, creating moderate colour variations, which gives an attractive aesthetic effect.

In this study, a spectroradiometer was employed to measure the colour of PV panels. There are possibilities to use other systems such as RGB cameras or multispectral imaging systems to capture an image, allowing the colorimetric values in a given illumination to be calculated from the obtained spectral reflectance measured under uncontrolled illumination.[13-15] Similar linear methods with a cheaper RGB camera could also be used to estimate the spectral and colorimetric coordinates of PV panels in urban environments.

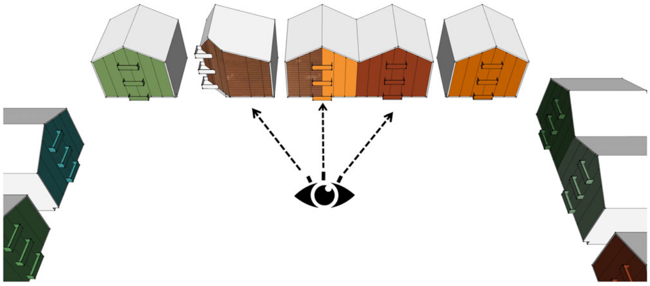

FIGURE 24 Photovoltaics with low angular sensitivity are suitable for traditional context

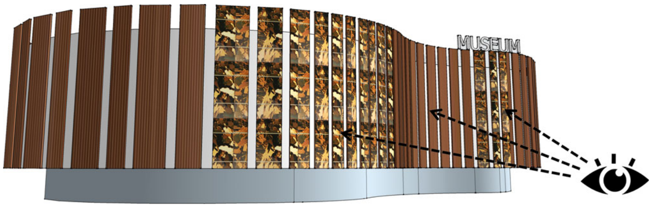

FIGURE 25 Photovoltaics with high angular sensitivity are suitable for new development district

With parameters of changing measuring angles and distances, this study explored the colour difference by analyzing hue and chroma changes of selected PVs. Another factor influencing colour difference that could be investigated in a future study is the relative brightness, which is also an interesting factor associated with electricity productivity.[16]

6 | CONCLUSION

The results reported in this study provide useful information on colour angular sensitivity of six types of opaque colour PV products. Architects can utilize different PVs according to their design purposes and different urban context. Use of coloured PVs for façade integration is still in its infancy, and in further research, psychophysical experiments can be performed to explore, for example, the relationship between specified (nominal) colour angular difference and the perceived colour angular difference. The proposed design recommendations in this study can be applied and evaluated in an urban context.

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DATA AVAILABILITY STATEMENT

Here I confirm that the availability of data presented in the manuscript 'The Impact of Surface Properties on Photovoltaics Colour Angular Sensitivity- A Comparison Study for Facade Integration ', related inquiry and academic communication are very welcome!

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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